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**Geothermal Potential of
West-Central New Mexico from
Geochemical and Thermal Gradient Data**

University of California

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Geothermal Potential of West-Central New Mexico from Geochemical and Thermal Gradient Data

D. Levitte*
D. T. Gambill

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*Long-Term Visiting Staff Member. Israel Geological Survey, Jerusalem, ISRAEL.

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GEOTHERMAL POTENTIAL OF WEST-CENTRAL NEW MEXICO
FROM GEOCHEMICAL AND THERMAL GRADIENT DATA

by

D. Levitte and D. T. Gambill

ABSTRACT

To study the low temperature and Hot Dry Rock (HDR) geothermal potential of west-central New Mexico, 46 water samples were collected and geothermal gradient measurements were made in 29 wells. Water chemistry data indicate that all the samples collected are meteoric waters. High temperatures of samples taken from wells between Gallup and Tohatchi indicate these wells may derive water from a warm aquifer below the depth of the wells. The chemistries of the samples farther south on the Zuni Indian Reservation suggest these waters are not circulating below 600 m of the surface. Geothermometry calculations support the conclusion that the waters sampled are meteoric. The geothermometry also indicates that the deep reservoir between Gallup and Tohatchi may be greater than 60°C.

Thermal gradient data indicate an area of high gradient on the Zuni Indian Reservation with a measured maximum of 67°C/km between 181 m and 284 m. This high probably is not hydrologically controlled. The maximum gradients in the study area are 76°C/km and 138°C/km, measured just east of Springerville, Arizona. These gradients are undoubtedly controlled by circulating water, possibly heated by a magmatic source at depth and circulating back to the surface.

The Gallup-Tohatchi and Springerville areas appear suitable for further work to define the low-temperature geothermal potential. In the Gallup-Tohatchi area, further work must include gradient measurements and water samples taken from below the Chinle to eliminate near-recharge effects. Future studies near Springerville must also include deep gradient measurements, at least one of which should penetrate to basement to help define the HDR potential of this area. The HDR potential of the Zuni Indian Reservation appears promising, but must be more clearly defined by further gradient measurements in wells penetrating to the basement and at least one well drilled significantly into the basement in the delineated gradient high.

I. INTRODUCTION

The Zuni Uplift area of west-central New Mexico (Fig. 1) was selected for evaluation of its low-temperature geothermal potential and as a possible Hot Dry Rock (HDR) geothermal site mainly on the basis of high-heat flow and recent volcanism. Reiter et al. (1975) report greater than 2 HFU in the Zuni Mountains area. Work by Shearer (1979), Edwards et al. (1976), and C. Stone, Bureau of Geology and Mineral Technology, University of Arizona, Tucson, Arizona (personal communication, 1979), supports the presence of a high-heat flow anomaly in the Zuni area. Basaltic flows ranging in age from about 27 Myr b.p. to 700 yr b.p. are extensive to the east, south, and within the Zuni Mountains. Of further interest for HDR evaluation is the presence of impermeable Precambrian granitic rock which crops out in the Zuni Uplift and lies within 610 to 914 m of the surface below the Gallup Sag to the west. The significant population center of Gallup in the study area, with more than 20,000 inhabitants, also makes the area attractive for geothermal exploration.

Two regions, the Zuni Indian Reservation and the Springerville area, were found promising for further HDR geothermal investigations. Further study of the low-temperature geothermal potential is warranted for the Springerville area and the San Juan basin between Gallup and Tohatchi.

II. GEOLOGIC STRUCTURE

The dominant structural feature in the northeastern section of the study area is the Zuni Uplift. It is an elongate ellipse with a northwesterly trend, measuring about 120 by 48 km. This is the most highly-faulted uplift on the Colorado plateau with several northwest-trending faults ranging in length from 29 to 48 km (Kelley and Clinton, 1960). Precambrian crystalline rocks form the core of the uplift and are rimmed by gently-dipping Paleozoic and Mesozoic sediments. Several periods of subsidence and uplift in the Zuni Mountains occurred between the Pennsylvanian and the Laramide orogenies and are evidenced by wedgeouts and thickening of the sedimentary section in the area (Kelley and Clinton, 1960).

The Zuni Uplift is bordered on the east by the low-amplitude folds of the Acoma Sag. To the west the uplift is bounded by the broad, shallow folds of the Gallup Sag.

At the contact of the Gallup Sag and the Zuni Uplift is the Nutria Monocline. Between Gallup and Nutria the monocline is close to vertical with a

Fig. 1
Major structural provinces of study area.

steep westerly dip and reverse faulting. South of Nutria, the dip angle of the monocline decreases abruptly and the monocline disappears about 8 km south of Nutria.

To the south, the Gallup Sag grades into the Mogollon Slope. North of the uplift lies the San Juan Basin. The large volcanic fields of Bandera, Zuni Centers, and North Plains stretch to the south of the Zuni Mountains.

III. STRATIGRAPHY

Precambrian gneissic granite, minor metarhyolites, and porphyritic aplites form the core of the Zuni Uplift (Goddard, 1966) underlie the Gallup Sag at relatively shallow depths.

A thin-sequence of argillaceous limestone, shale, and sandstone, which in places overlies the Precambrian and underlies the Permian in the Zuni Uplift, was assigned to the Pennsylvanian. The Permian section is comprised of about 240 m of red beds of the Abo and Yeso Formations, 90 m of Glorieta Sandstone, and 30 m of San Andres Limestone (Read and Wanke, 1967). The lowermost Triassic unit is the Chinle Formation. The Chinle consists of conglomerates, siltstones, mudstones, sandstones, and limestone with local gypsum layers. Above the Chinle the Wingate Sandstone represents the upper part of the Triassic section in the Zuni Mountains area. The Entrada Sandstone, which forms prominent massive red cliffs around the Zuni Uplift, is the lowermost Jurassic formation (Smith, 1959, 1967). Total thickness for the Entrada is about 61 m near Gallup and about 46 m near Grants and Zuni Pueblo. Eight to 16 km south of Zuni Pueblo the Entrada disappears and grades vertically into the gypsum-rich Todilto Limestone. North of Gallup, the Todilto varies in thickness from 1.5 to 9 m and pinches out between Gallup and Nutria Springs. Overlying the Todilto is the Zuni Formation, also called the Thoreau which forms massive cliffs about 61 m thick in the Zuni Pueblo-El Morro area. The Zuni Formation also pinches out just south of Zuni Pueblo.

Above the Zuni Formation lies the Morrison Formation, which increases in thickness northward from 0 m just south of Zuni Pueblo to about 165 m near Gallup. The Morrison is comprised of inconsistent units of siltstone and mudstone with minor sandstone lenses and a massive, cliff-forming sandstone unit, which is mined for uranium.

Dakota Sandstone 0 to 30 m thick is the earliest Cretaceous formation (Gadway, 1959). The Dakota is covered by up to 610 m of dark gray Mancos

Shale. At its lower and upper contacts, the Mancos Shale interfingers with the Dakota and Gallup sandstones, respectively. Above the Gallup Sandstone are the marine and nonmarine Dilco Coal, Dalton Sandstone, Bartlett Barren Shales, and Gibson Coal members of the Crevasse Canyon Formation. An irregular and changing shoreline and partial erosion during deposition, created a very complex interfingering of the Crevasse Canyon members and the overlying Point Lookout Sandstone and Menefee Shales throughout the study area.

In the southeastern part of the study area, silicic volcanic flows, tuffs, and sedimentary tuffs of the Tertiary Datil Formation overlie the Cretaceous sediments (Willard, 1959). Red and purple arkosic sediments and conglomerates of the Baca Formation conformably overlie the Datil in the southeast. Between Zuni Pueblo and Gallup the Tertiary is represented by sandstone and gravel of the Bidahochi Formation.

Volcanic activity in the Zuni area occurred during mid-Tertiary (about 27 Myr b.p.) accompanied by intrusion of north-south trending dikes (Laughlin, 1976). Bordering immediately to the east and south of the uplift are the very young Bandera volcanic field, McCartys flow (700 yr b.p.) and Laguna flow (1.57 Myr b.p.). The Cerro Colorado, Paxton Springs, and Zuni Canyon flows erupted within the Zuni Mountains and, judging by their fresh appearance, are probably less than 1 Myr old. To the south stretches the Zuni Centers field with ages from 0.94 to 16 Myr b.p. (Heiken, personal communication). Southeast of the Zuni Centers lies the North Plains basaltic field, which has the same composition and appearance as the Laguna flow and may be the same age. Mt. Taylor, a large composite shield volcano just northeast of Grants, shows a full development from basaltic to rhyolitic lavas (Crumpler, 1976). Southwest of the study area lies the large Springerville volcanic field, which has erupted intermittently from 32 Myr b.p. to at least as recently as 10 000 yr b.p. (Arizona Bur. Geol. and Miner. Tech., 1980).

IV. HYDROGEOLOGY

A. General

Numerous small, local studies of the hydrogeology have been previously conducted in the study area. Two in-depth hydrogeologic investigations were performed by Summers (1972) and Cooley et al. (1969). The U.S. Geological Survey (USGS) Water Resources Division (in Albuquerque, New Mexico) is

presently conducting a study in the area. For detailed hydrogeology, the reader is referred to the authors mentioned above.

With the exception of a study of the Zuni Pueblo water supply by Summers (1972), previous investigations have not clearly defined recharge areas or ground water flow directions. Future geothermal investigations for conventional and low-temperature resources in the study area must define these parameters more clearly.

B. Hydrogeologic Units

Crystalline rock is generally considered to have a very low permeability. Water movement in the Precambrian basement of the Zuni Mountains is therefore probably controlled by faults and fractures, rather than by intergranular permeability.

Very little is known of the hydrogeologic properties of the Abo and Yeso Formations in this region, although a correlative unit in Arizona, the Coconino Sandstone, is a major aquifer. The Glorieta Sandstone and the San Andres Limestone above the Yeso are treated by Summers (1972) as one aquifer. They are excellent aquifers in the Grants-Bluewater area (3785 g/min^2), though at the Zuni Pueblo they yield small amounts of water. A large freshwater spring (76 g/min^2) at the mouth of Nutria Canyon, south of McGaffey, is fed by this aquifer. In places large amounts of brackish or saline water have been found in the aquifer at depth (0.1 to 1000 ppm = fresh; 1001 to 10,000 ppm = brackish; 10,001 to 10,000 ppm = saline).

Generally, the Chinle Formation is a poor aquifer due to the abundance of silts and clays. However, sandstone zones within the Chinle are the main source of water for the Zuni Pueblo. According to Summers (1972), the hydraulic conductivity of the Chinle aquifer is determined by the degree of fracturing.

The Wingate Sandstone, the Entrada Sandstone, the Zuni Sandstone, and part of the Morrison Formation constitute one thick aquifer system. This system yields minor amounts of water in springs and wells in the Navajo Reservation (Cooley et al., 1969). Its hydrologic properties are determined by fracturing rather than by rock porosity and permeability. This is shown by the significant difference in yield among individual wells tapping this aquifer (Summers, 1972).

The main Cretaceous aquifers are the Dakota Sandstone and the Gallup Sandstone, which are separated by the Mancos Shale aquiclude. The Dakota is

connected in places with the Morrison Formation and Cow Springs Formation to make one large hydrogeologic unit. The Gallup Sandstone is the main water source in the southern San Juan basin and the Gallup Sag.

The sedimentary section ends with the sandy Bidahochi Formation. Summers (1972) derives hydraulic conductivity values of $3055 \text{ d}/\text{day-m}^2$ from wells in this formation.

The Cenozoic basalts, which cover vast areas south and west of the Zuni uplift, are a good aquifer due to extensive fracturing in flow tops and along flow boundaries, but they contain very young meteoric waters.

V. GEOCHEMISTRY

Forty-six water samples of springs and wells from the study area were collected and chemically analyzed (Fig. 2 and Table I; see App. A for sampling methods). The purpose of the analyses was to search for possible geochemical trends in the waters and to determine reservoir temperatures by chemical geothermometry methods.

Sampling was controlled by availability of sources. Of the 21 springs sampled, 9 are considered to be seeps. Twelve springs tap aquifers below the soil horizon, but only two (DL-9 and DL-36) are considered to represent deep aquifers. For most of the well samples, depth of well and source aquifer are not available. This lack of information precludes further correlations between water chemistry and aquifer than are presented. Chemical analyses are shown in Table II. For comparison and classification the analyses are plotted on a Piper diagram (Piper, 1944; Fig. 3).

Comparative Chemistry of Springs and Wells

The chemistry of the waters indicates that most did not circulate at depth. The samples from seeps (with the exception of DL-8) plot near 100% bicarbonate in the anion triangle on the Piper diagram, indicating a shallow source (Freeze and Cherry, 1979).

Stinking Spring (sample DL-20) is a warm (23.2°C) seep in the Chinle on the Nutria Monocline. It is a calcium-bicarbonate water with significant sulfate. The sulfate is probably derived from gypsum in the Chinle, as with samples DL-7 and DL-8. The water oozes from the soil along about 100 m and collects to form a stream, which was sampled within the zone of seepage. Thus the high temperature may be anomalous since the water depth of the seep is shallow and the day was hot when the sample was collected.

Fig. 2
Water sample locations.

TABLE I
LOCATIONS, FIELD DATA, AND SOURCE FORMATION OF 43 NATURAL WATERS IN THE
ZUNI MOUNTAINS REGION, NEW MEXICO

Sample No.	Name	Date	Location		Temp. (°C)	Field pH	Flow Rate (L/min)	Rock Type
			Latitude	Longitude				
DL-1	Blue M Well	4-79	35.43°	108.73°	9.4	6.5	-	Alluvium
DL-3	Breadsprings School Well	4-79	35.41°	108.67°	13.8	6.5	-	?
DL-4	Ya-Ta-Hey Well	4-79	35.64°	108.78°	45.5	7.2	-	Dakota ^a
DL-6	Pescado Springs	4-79	35.12°	108.59°	12.5	7.0	227	Basalt
DL-7	Grasshopper Spring	4-79	35.33°	108.58°	10.5	7.0	7.6	Chinle
DL-8 ^s	Scotty's Spring	4-79	35.30°	108.58°	11.5	6.8	9	Chinle
DL-9	Rainbow Spring	4-79	34.91°	108.97°	21.0	7.0	>500	Chinle
DL-10	Taaiyalone Spring	5-79	35.22°	108.80°	-	7.0	0.4	Chinle-Wingate Contact
DL-11	Artesian Well	6-79	35.72°	108.69°	23.0	6.8	76-95	Menefee
DL-12	14T-510	6-79	35.70°	108.70°	23.0	8.7	12-57	Menefee ^a
DL-13	Coal Mine Spring Well	6-79	35.71°	108.65°	18.5	8.1	19	Menefee
DL-14	14T-540	6-79	35.7°	108.64°	16.5	-	13	Dakota ^a
DL-15 ^T	Toh Sah Toh	6-79	35.87°	108.68°	37.0	8.9	1135	Menefee
DL-16 ^T	14K-311	6-79	35.85°	108.68°	16.0	7.4	-	Menefee
DL-17	14T-324	6-79	35.81°	108.66°	17.5	8.7	12	Point Lookout ^a
DL-18 ^s	Turkey Spring	6-79	35.40°	108.53°	13.6	7.3	-	Chinle
DL-19 ^s	Tompica Spring	6-79	35.36°	108.52°	11.4	7.8	4-8	Granite
DL-20 ^s	Stinking Spring	6-79	35.36°	108.60°	23.2	8.2	19	Chinle-Entrada Contact
DL-21	Standing Rock Spring	6-79	35.81°	108.37°	21.0	9.1	>30	Mesa Verde
DL-22	Zuni Salt Lake Spring	6-79	34.45°	108.77°	18.2	7.4	4	Basalt Cinders
DL-23	Appaloosa Well	7-79	34.87°	109.05°	15.2	7.3	8	Chinle
DL-24	Rainbow Spring	7-79	34.91°	108.97°	22.0	7.0	>500	Chinle
DL-25	Garcia Spring	7-79	34.52°	108.64°	-	7.5	-	Gallup-Mancos Contact
DL-26	Jerry Well	7-79	34.47°	108.73°	24	8.5	21	Mancos
DL-27	Vanderwagen Well	9-79	35.28°	108.75°	15	7.3	-	Mesa Verde
DL-28	ECW-1	9-79	35.18°	108.75°	14.2	6.9	-	Mancos
DL-29	RWP-34	9-79	35.17°	108.72°	15.4	8.2	-	Mancos
DL-31	New Santa Rita Spring	8-79	34.56°	108.73°	16.4	6.0	3	Gallup-Mancos Contact
DL-32	Pueblo Windmill	8-79	34.54°	108.78°	33.8	6.0	-	Gallup-Mancos Interfingering
DL-33	Goat Spring	8-79	34.37°	108.97°	12.6	-	-	Mesa Verde
DL-34 ^s	Dan Valley Spring	8-79	35.22°	108.42°	-	-	-	Chinle
DL-35	Windmill	8-79	35.17°	108.42°	12.8	6.0	-	Chinle
DL-36	Sacred Spring	8-79	34.91°	108.97°	21.0	7.1	-	Chinle
DL-37	Paxton Spring	8-79	35.04°	108.14°	6.6	7.8	>120	Basalt
DL-38	Wells Spring	8-79	35.22°	108.29°	10.0	7.2	-	Glorietta
DL-39 ^s	Seep	8-79	35.24°	108.34°	-	-	-	Abo
DL-40 ^s	La Jara Spring	8-79	35.10°	108.06°	17.8	7.8	4	Granite Gneiss
DL-41	Windmill	8-79	35.03°	107.97°	13.8	7.9	-	Abo
DL-42	Mujeres Camp Well	8-79	34.65°	108.32°	15.8	6.8	17	Basalt
DL-43	Windmill	9-79	35.23°	108.78°	17.0	7.6	-	Gallup
DL-44	Nutria Spring	9-79	35.29°	108.56°	12.2	7.4	76	Glorietta
DL-45	Dent Windmill	9-79	34.86°	108.82°	23.4	7.2	-	Chinle
DL-46	Church Rock School Well	9-79	35.55°	108.61°	20.0	-	-	Entrada

T = sample from holding tank.

a = aquifer.

s = seep.

TABLE II
CHEMICAL ANALYSES OF 43 WATER SAMPLES FROM ZUNI MOUNTAINS AREA, NEW MEXICO.
(all numbers in ppm)

Sample	Measured Temp. (°C)	SiO ₂	Fe	Mn	Ca	Mg	Na	K	Ba	Sr	B	Li	HCO ₃	SO ₄	Cl	F
DL-1-NM	9.4	10.4	0.08	0.04	107.38	28.75	179.4	5.3	0.12	1.7	0.12	0.06	464.1	340.5	14.5	0.55
DL-3-NM	13.8	14.1	0.0	0.04	42.13	9.38	106.3	1.9	0.0	1.24	0.14	0.252	269.0	154.9	12.2	0.42
DL-4-NM	45.5	23.55	0.001	0.006	1.65	0.04	205.33	0.64	0.083	0.072	0.056	0.102	222.0	214.5	15.4	0.33
DL-6-NM	12.5	31.3	0.08	0.04	44.25	14.0	38.75	3.4	0.12	0.4	0.11	0.035	236.7	58.0	11.2	0.37
DL-7-NM	10.5	15.1	0.0	0.0	265.0	60.0	28.5	1.8	0.0	4.22	0.14	0.122	240.3	789.0	9.1	0.33
DL-8-NM	11.5	12.8	0.0	0.0	112.5	25.75	80.0	92.0	0.0	2.01	0.15	0.19	269.6	330.0	13.8	0.44
DL-9-NM	21.0	16.8	0.0	0.0	138.5	40.0	53.67	5.48	0.096	1.34	0.096	0.138	275.7	320.0	32.9	0.5
DL-10-NM	-	14.3	0.0	0.007	71.6	7.72	34.25	0.96	0.08	0.71	0.12	0.09	276.94	29.5	15.2	0.55
DL-11-NM	23.0	13.03	0.034	0.002	1.21	0.12	94.0	0.98	0.028	0.046	0.11	0.024	219.6	30.21	2.7	0.42
DL-12-NM	23.0	11.55	0.03	0.003	1.28	0.08	204.0	1.0	0.049	0.096	0.15	0.035	335.5	159.77	8.1	0.95
DL-13-NM	18.5	13.05	0.1	0.090	15.63	5.80	248.0	2.04	0.085	0.48	0.056	0.068	370.88	330.0	5.8	0.29
DL-14-NM	16.5	16.13	0.42	0.24	54.3	17.6	186.0	2.7	0.029	1.6	0.12	0.155	392.84	366.99	3.6	0.26
DL-15-NM	37.0	20.45	0.008	0.002	1.54	0.0	144.0	0.52	0.061	0.083	0.14	0.163	180.56	138.11	5.9	0.4
DL-16-NM	16.0	8.4	0.041	0.008	34.65	19.0	32.33	8.3	0.083	0.96	0.0	0.062	213.5	40.4	16.4	0.13
DL-17-NM	17.5	8.25	0.031	0.0	2.26	2.32	595.0	1.44	0.016	0.34	0.83	0.157	649.04	621.0	115.2	4.85
DL-18-NM	13.6	15.95	0.125	0.128	101.8	12.5	10.5	1.9	0.392	0.0	0.15	0.016	285.48	36.49	8.4	0.18
DL-19-NM	11.4	20.7	0.06	0.0	55.0	7.5	64.8	1.7	0.02	0.24	0.41	0.308	169.6	102.4	17.7	3.25
DL-20-NM	23.2	13.73	0.14	0.112	118.0	16.7	24.75	1.1	0.2	0.0	0.2	0.131	369.66	95.03	8.2	0.34
DL-21-NM	21.0	9.63	0.17	0.024	2.7	0.5	450.0	1.2	0.0	0.0	0.79	0.142	557.54	538.3	43.2	3.32
DL-22-NM	18.2	10.48	4.3	3.8	338.3	1115.0	44000.0	287.0	0.0	0.0	8.32	0.02	425.78	11421.0	62700.0	0.43
DL-23-NM	15.2	12.78	4.0	0.36	135.33	38.0	144.0	3.47	0.023	2.8	0.13	0.344	323.3	505.0	46.4	0.38
DL-24-NM	22.0	15.93	6.4	0.54	144.67	42.0	50.67	4.53	0.024	1.8	0.0	0.292	332.45	360.0	34.2	0.52
DL-25-NM	0.0	10.0	0.01	0.0	12.0	2.8	240.0	1.6	0.0	-	0.3	-	536.0	180.0	19.0	1.0
DL-26-NM	24.0	12.0	0.06	0.002	1.2	0.1	190.0	0.9	0.0	-	0.47	-	451.0	51.0	18.0	1.6
DL-27-NM	15.0	15.55	0.023	0.012	26.0	3.9	72.5	1.61	0.223	0.34	0.0	0.0	254.98	16.2	11.7	0.28
DL-28-NM	14.2	9.25	12.1	0.40	117.67	25.0	23.4	2.24	0.089	1.2	0.43	0.082	201.3	288.0	7.2	0.12
DL-29-NM	15.4	14.55	0.038	0.125	41.27	17.0	175.0	2.33	0.03	1.76	0.045	0.11	250.71	317.5	5.9	0.27
DL-31-NM	16.4	10.38	0.02	0.012	14.93	3.6	152.67	0.96	0.048	0.4	1.65	0.15	374.54	118.0	10.4	0.48
DL-32-NM	33.8	14.0	1.6	0.1	130.0	29.0	140.0	13.0	0.0	-	0.36	-	561.0	310.0	68.0	3.4
DL-33-NM	12.6	17.0	0.05	0.001	20.0	14.0	56.0	2.9	0.0	-	0.16	-	244.0	49.0	9.6	0.5
DL-34-NM	-	8.25	0.072	0.26	67.4	5.2	2.6	0.55	0.154	0.24	0.0	0.262	206.18	22.5	4.8	0.11
DL-35-NM	12.5	9.28	0.092	0.006	66.67	13.8	21.73	0.86	0.344	0.92	0.0	0.182	308.66	30.6	4.8	0.23
DL-36-NM	21.0	17.4	0.03	0.001	144.0	38.5	53.0	5.2	0.027	1.14	0.069	0.156	317.2	396.0	33.1	0.48
DL-37-NM	6.6	19.7	0.016	0.0	36.67	5.5	7.27	3.93	0.164	0.18	<0.1	-	151.28	25.8	5.6	0.23
DL-38-NM	10.0	17.0	0.052	0.012	87.27	16.2	5.33	0.53	0.218	0.184	<0.1	-	329.4	15.1	6.4	0.16
DL-39-NM	0.0	11.85	0.052	0.01	54.67	29.0	8.47	3.25	0.392	0.206	<0.1	-	268.4	24.5	11.0	0.15
DL-40-NM	17.8	24.18	0.056	0.02	61.33	10.2	10.6	1.97	0.536	0.248	<0.1	-	237.9	13.5	6.2	0.53
DL-41-NM	13.8	21.93	0.056	0.012	45.53	19.0	11.67	1.12	0.202	0.208	<0.1	-	187.88	35.4	9.8	0.93
DL-42-NM	15.8	19.83	0.1	0.103	35.33	13.4	37.33	2.37	0.196	0.72	<0.1	-	240.34	25.6	10.9	0.28
DL-43-NM	17.0	11.65	0.015	0.016	12.65	2.8	136.0	1.4	0.115	0.36	0.32	0.068	330.62	44.4	19.9	1.74
DL-44-NM	12.2	11.4	0.0	0.001	88.0	18.5	9.7	0.87	0.035	0.38	0.0	0.002	283.	56.0	6.2	0.32
DL-45-NM	23.4	14.7	2.6	0.064	149.33	53.0	61.5	4.87	0.043	1.4	0.03	0.004	359.9	309.0	39.1	0.6
DL-46-NM	0.0	2.9	0.0	0.11	40.19	25.1	172.0	3.4	0.016	0.46	0.043	0.206	114.68	635.0	19.4	1.69

Fig. 3

Piper diagram of water chemistries: x - sample north of I-40; + - samples DL-9/14, -36 and -45; o - other samples.

The only true, warm springs are DL-9 and DL-24, 22°C (Rainbow Spring), and DL-36, 21°C (Sacred Spring), which are within 0.8 km of each other on the Zuni Indian Reservation. Their waters are calcium-magnesium-sulfatic. Both springs probably ascend along the Ojo Caliente fault and are almost identical in their chemical content, indicating both are fed by the same hydrogeologic system. Outcrops in the vicinity of these springs are of Shinarump conglomerate at the base of the Chinle, so it is likely that the two springs are fed by the San Andres Limestone - Glorietta Sandstone aquifer.

The chemistries of samples DL-9/DL-24, and DL-36 are very similar to that of DL-45. Sample DL-45 is from a well drilled 195 m through the Chinle about 27 km southeast of DL-9/DL-24 and DL-36. Considering the similarities in chemistry to DL-9/DL-24 and DL-36, and that the Chinle is probably less than 200-m thick at this point and is a poor aquifer, it is likely that DL-45 also taps the San Andres Limestone - Glorietta Sandstone aquifer.

The warm temperatures of DL-9/DL-24 and DL-36 are significantly greater than the mean annual temperature of about 12°C. This difference may be due to ground water from near 400-m depth circulating to the surface after being warmed by a normal gradient of about 25°C/km. A second explanation is that warmer water from a greater depth is circulating to near the surface and mixing with shallow ground water, which then surfaces in the springs. However, 4 km southeast of DL-9/DL-24 and DL-36, the measured thermal gradient from 104 to 160 m is 22°C/km. This gradient is much lower than would be expected if warm water from depth was circulating near the surface, which supports the hypothesis of water circulating to the surface from about 400 m.

The same mechanism could explain the warm temperature of DL-45 (Dent Windmill). A gradient of 58°C/km is necessary to give a temperature of 23°C at the bottomhole depth of 195 m of this well. However, the similarities in chemistry noted previously suggest a similar origin of deep circulation for the DL-9/DL-24, DL-36, and DL-45 waters. This would require a normal gradient between 25°C/km and 10°C/km. Insufficient thermal gradient data are available to determine which gradient is correct at DL-45, but the correlation with the DL-9/DL-24 and DL-36 chemistries supports the lower gradients.

The well waters within the artesian basin on the southern flanks of the San Juan Basin are warmer than the average sampled. This system contains the wells north of Gallup between Tohatchi and Crown Point (DL-4, 37.6°C; DL-11, 23°C; DL-12, 23°C; DL-13, 18°C; DL-14, 16.5°C; DL-15, 37°C; DL-16, 16°C;

DL-17, 17.5°C; and DL-21, 21°C). The dominant cation in these waters is sodium; the dominant anion is either bicarbonate or sulfate (see Piper diagram, Fig. 3).

The chemistry of sample DL-14 is more similar to sample DL-29 than to other artesian well waters (see Piper diagram and chemical tables). Sample DL-29 is from a well known to draw from the Dakota Sandstone. The source of sample DL-14 is an artesian well drilled 649 m through the Mesa Verde near Coal Mine Spring. The dip of the beds in the vicinity and the elevation of the Dakota outcrops to the south of sample DL-14 put the Dakota at about 649 m below Coal Mine Spring. This correlation of well depth and depth to the Dakota, and the chemical similarities between sample DL-29 and DL-14, shows that the source aquifer of sample DL-14 is the Dakota. Recharge for sample DL-14 is probably the cliffs just north of I-40 near Gallup and 12 km up-dip to the south. Such close proximity to the recharge area possibly explains the low 16.5°C temperature from 649 m for sample DL-14.

Comparison of analyses from samples DL-21 and DL-17 shows they may be related to each other. Sodium and chloride are much more abundant in DL-17 than in DL-21, but otherwise the chemistries are very similar and the two waters probably have the same source aquifer.

Samples DL-4, a well at Ya-Ta-Hey, and DL-15, about 26 km northeast of Ya-Ta-Hey, are also probably related. The chemistries of these waters are almost identical, although Na, Cl, and SO₄ are enriched in DL-4. The highest recorded temperature at the DL-4 well is 45°C. At DL-15 the measured temperature is 37°C. These are the warmest waters in the study area.

The depth of the DL-4 well is 367 m; depth for the DL-15 well is unknown. A bottomhole temperature of 45°C at 367 m gives a geothermal gradient of 91°C/km for the DL-4 well. This is not a reasonable gradient for the area; two other wells 15 km to the south (24 and 25, Fig. 7) have gradients of 30 and 32°C/km and the DL-14 well 15 km east supplies water at 16.5°C from 649 m. Most likely the DL-4 well is tapping water circulating from a much greater depth. Since the waters appear related, the same is probably true for DL-15.

The ultimate source of water for both the DL-4 and DL-15 wells may be a deeper common aquifer. Boron and lithium contents of both the waters is very low, as are B/Cl and Li/Cl ratios. Therefore, the waters are probably meteoric water that has circulated to moderate depths, rather than exotic connate waters or true thermal waters of deep origin (White, 1957).

Analyses of the remaining samples from north of Gallup are chemically similar but appear to be from separate aquifers. On the Piper diagram all the samples but DL-13, DL-14, and DL-16 plot in the Na + K corner of the cation triangle. However, absolute values of Na, K, Ca, Cl, and F and the spread of values in the anion triangle of the Piper diagram show these samples represent several different systems.

Sample DL-22, from a spring south of Zuni, is unique relative to the other waters sampled because of its high salinity (62 700-ppm Cl). All other samples are fresh or slightly brackish. The source spring of DL-22 feeds Zuni Salt Lake, which occupies a maar volcano about 32 km northwest of Quemado. During the summer, evaporation often raises the salt concentration in the lake to more than 30%. A well drilled in the salt beds beside the lake bottomed at about 305 m, still in salt. Presumably, water feeding the spring percolates up through these beds along a deep conduit zone, deriving its salt content from the salt beds.

Two wells in the southern part of the area (DL-26 and DL-32) yield warmer than average temperatures of 24 and 33.8°C from less than 304 m and about 304 m, respectively. The depth of sample DL-32 indicates the source aquifer is probably the Glorieta-San Andres system. However, the chemistry of DL-32 is not related to other samples from the Glorieta or San Andres and the true source of DL-32 is unclear. Sample DL-26 correlates most closely with the artesian well samples from north of Gallup. Without more well information and chemical analyses in the area, further analysis of these samples is not meaningful.

To find a relation between temperature and water chemistry, the cation and anion concentrations were plotted vs measured temperatures. Artesian wells north of Gallup show a rough correlation of silica concentration with increasing temperature (Fig. 4). However, the four samples from the Glorieta-San Andres (DL-9, 24, 36, and 45) show a decrease in silica content with an increase in temperature.

Calcium behaves in an expected way because its solubility generally increases with decreasing source temperature (Fig. 5). Exceptions to this are DL 9, 24, 36, and 45. These relatively warm waters flow through the Calcium-rich San Andres Limestone, which may explain the high proportion of Calcium. Magnesium behaves similarly to calcium (Fig. 6).

Fig. 4

Plot of measured T°C vs ppm SiO₂ for water samples: o - artesian wells north of I-40; r - DL-9/24, -36 and -45; x - other samples.

Fig. 6
Plot of measured T°C vs ppm Mg for water samples: o - artesian wells north of I-40; r - DL-9/24, -36 and -45; x - other samples.

The other elements analyzed (Na, Ba, Sr, Mn, Fe, B, Li, F, and Cl) show no distinct relation of concentration to temperature. Rock lithology and chemistry must affect the chemistry of these waters and obscure temperature dependent behavior.

For all waters sampled, B/Cl ratios are significantly less than 0.05 and F/Cl ratios are all less than 0.2. All samples for which Li was analyzed have Li/Cl ratios less than 0.03. Only two samples have more than 0.85 ppm of B and most F does not exceed 1.0 ppm. The highest F content is associated with a cold seep in granitic gneiss. Lithium concentrations are all less than 0.35 ppm. These low concentrations of trace elements and low chloride ratios indicate that the waters are not thermal waters but are meteoric waters in all cases.

VI. GEOTHERMOMETRY

Results from the SiO_2 geothermometer (Fournier and Rowe, 1966) are not meaningful. This geothermometer is generally considered to be useful only for high-temperature thermal waters. However, most of the waters sampled are cold-to-warm and their chemistry suggests they had no previous thermal history. Thus, the SiO_2 geothermometer yields anomalously high estimates.

Reservoir temperature estimates using the Na-K-Ca geothermometer (Fournier and Truesdell, 1973; Fournier and Potter, 1979) support the conclusion that the waters sampled are meteoric (Table III). An estimate within $\pm 30^\circ\text{C}$ of the measured temperature for $\beta = 4/3$ generally indicates the water is meteoric and had no previous thermal history (Goff, personal communication, 1980). The Na-K-Ca $\beta = 4/3$ temperature estimates meet these criteria for almost every sample south of Gallup, indicating further that these waters are meteoric.

The estimated reservoir temperatures from the Na-K-Ca geothermometer for the waters sampled north of Gallup are all greater than 60°C with the exception of DL-14. The temperatures estimated for $\beta = 4/3$ exceed the measured temperature for these samples by much more than 30°C . The high-measured temperatures suggest these waters are circulating up from depths below the deepest wells sampled. However, these wells are also supplied by a number of shallow aquifers (Mercer and Cooper, 1970) and represent mixed waters. Thus the Na-K-Ca geothermometry results may be minimum reservoir temperature

TABLE III
GEOTHERMOMETRY DATA FOR 43 WATER SAMPLES IN THE
ZUNI MOUNTAINS AREA, NEW MEXICO.

Sample No.	Measured Temp.	Quartz Water Vapor	Na-K-Ca $\beta =$		R	Na-K-Ca (Mg corrected) Δt_{Mg}		Est. Temp. (°C)
			4/3	1/3				
DL-1-NM	9.4	42	51	-	-	0		51
DL-3-NM	13.8	52	36	-	-	0		36
DL-4-NM	32.0	71	72	62	-	0		62
DL-6-NM	12.5	83	41	-	-	0		41
DL-7-NM	10.5	55	-2	-	-	0		-2
DL-8-NM	11.5	49	141	315	20.9	182		133
DL-9-NM	21.0	58	37	-	-	0		37
DL-10-NM	-	53	4	-	-	0		4
DL-11-NM	23.0	49	84	-	10.3	0		84
DL-12-NM	23.0	45	92	77	6.8	0		77
DL-13-NM	18.5	49	63	-	-	0		63
DL-14-NM	16.5	57	45	-	-	0		45
DL-15-NM	37.0	66	63	63	-	0		63
DL-16-NM	16.0	35	69	-	-	0		69
DL-17-NM	17.5	34	105	63	-	0		63
DL-18-NM	13.6	56	5	-	-	0		5
DL-19-NM	11.4	66	25	-	-	0		25
DL-20-NM	23.2	51	-2	-	-	0		-2
DL-21-NM	21.0	39	90	62	-	0		62
DL-22-NM	18.2	42	296	118	79.1	0		118
DL-23-NM	15.2	49	34	-	-	0		34
DL-24-NM	22.0	56	31	-	-	0		31
DL-25-NM	-	40	61	-	-	0		61
DL-26-NM	24.0	47	89	75	9.0	0		75
DL-27-NM	15.0	56	36	-	-	0		36
DL-28-NM	14.2	38	12	-	-	0		12
DL-29-NM	15.4	53	46	-	-	0		46
DL-31-NM	16.4	42	39	-	-	0		39
DL-32-NM	33.8	52	71	-	25.9	0		71
DL-33-NM	12.6	59	54	-	-	0		54
DL-34-NM	-	34	-21	-	-	0		-21
DL-35-NM	12.8	38	-0	-	-	0		-0
DL-36-NM	21.0	60	35	-	-	0		35
DL-37-NM	6.6	64	34	-	-	0		34
DL-38-NM	10.0	59	-21	-	-	0		-21
DL-39-NM	-	46	24	-	-	0		24
DL-40-NM	17.8	72	13	-	-	0		13
DL-41-NM	13.8	68	6	-	-	0		6
DL-42-NM	15.8	65	35	-	-	0		35
DL-43-NM	17.0	46	51	-	-	0		51
DL-44-NM	12.2	45	-9	-	-	0		-9
DL-45-NM	23.4	54	34	-	-	0		34
DL-46-NM	-	5	56	-	-	0		56

estimates for the area north of Gallup. The temperature of the reservoir for the deep circulating water in this area may therefore be greater than 60°C.

VII. THERMAL GRADIENT

Twenty-nine reliable thermal gradients were measured in boreholes in the study area (Fig. 7 and Table IV; see Appendix A for data collection method). Their depths vary from less than 30 m to 792 m. The reliability of the measurements increases with depth as the influence of surface climatic conditions and shallow, flowing aquifers decreases.

In most cases, the thermal gradient was determined as the least square fit of the segment with a positive slope, or of the lower part of this segment. Temperature vs depth plots, with lithology (where available), are shown in Appendix B. Most of the thermal gradients do not change significantly across lithologic boundaries. However, it is likely that the measured gradients are disturbed by flowing aquifers which the boreholes intersect and which may underlie the boreholes. The gradients that are known to be hydrologically perturbed have been noted as such in the text, but the reader must bear in mind that most of the gradient wells may overlie flowing aquifers and the reported gradients may not be true gradients.

The two wells 1 and 2 (Figs. 8 and 9) in the southwestern part of the study area are the warmest wells measured, with gradients of 70°C/km and 138°C/km respectively. Well 2 was probed 20 hours after drilling, which lasted one day; well 1 had been completed about 48 hours before probing. The temperatures measured probably would have been higher if more time had passed between drilling and probing. Because the wells were filled with mud when probed, it was not possible to detect the water levels directly. However, it is possible that the abrupt increase in gradient between 21 m and 30 m in well 2 is due to a water influx at that depth.

The anomalously high-geothermal gradients in these two wells undoubtedly are hydrologically controlled. Heat is probably derived from near-surface radioactive decay and/or deep magmatic sources. Tertiary and Quaternary volcanics are abundant throughout the Quemado-Springerville area which lies on the Jemez Lineament. Although the extrusions themselves are not heat sources, their young ages indicate that magma or hot rock may be present at depth as a heat source for deep circulating water. Uranium deposits are believed to be

Fig. 7
 Thermal gradient measurement locations.

TABLE IV
THERMAL GRADIENTS AND LOCATIONS OF GRADIENT WELLS SHOWN IN FIGURE 7

Well No.	Total Depth m	Thermal Gradient C/km	Depth Interval m	Location	
				Long.	Lat.
1	51.8	76	21.3 - 51.8	109.13	34.12
2	121.9	138	9.1 - 121.9	109.13	34.14
3	195.1	37	12.2 - 195.1	108.76	34.29
4	292.6	35	91.4 - 292.6	108.71	34.27
5	85.3	27	42.7 - 73.2	108.01	34.37
6	79.2	6	51.8 - 79.2	108.79	34.45
7	160.2	22	103.6 - 160.2	108.95	34.88
8	127.1	63	58.8 - 127.1	108.84	34.91
9	151.8	-63	24.4 - 149.4	108.78	34.95
10	161.5	23	146.6 - 161.5	108.69	34.92
11	323.1	67	181.1 - 283.8	108.77	35.03
12	347.5	24	274.3 - 347.5	108.83	35.14
13	114.9	59	106.7 - 114.9	108.65	35.11
14	67.4	22	24.4 - 67.4	108.71	35.16
15	33.5	32	12.2 - 33.5	108.63	35.27
16	132.3	27	105.2 - 132.3	108.77	35.24
17	34.1	-121	0 - 34.1	108.60	35.27
18	44.5	41	7.3 - 44.5	108.60	35.23
19	296.3	29	116.1 - 296.3	108.22	35.72
20	475.5	17	274.3 - 475.5	108.30	35.59
21	481.6	24	85.3 - 481.6	108.33	35.59
22	189.0	28	85.3 - 189.0	108.66	35.39
23	307.8	45	36.6 - 307.8	108.83	35.41
24	131.1	32	67.1 - 131.1	108.75	35.49
25	127.1	30	51.8 - 127.1	108.67	35.50
26	182.9	24	109.7 - 182.9	108.60	35.54
27	176.8	22	36.6 - 170.7	108.17	35.38
28	792.5	38	426.7 - 792.5	108.21	35.50
29	591.3	24	109.7 - 530.4	108.12	35.53

Fig. 8
Depth vs T°C plot and lithology for gradient well #1.

Fig. 9
Depth vs T°C plot and lithology for gradient well #2.

present in the near-surface sediments in the southern part of the study area and may contribute to high-heat flow at shallow depths.

In the center of the study area, on the Zuni Indian Reservation and the immediate vicinity, are seven gradient measurements. Two of these are from wells over 305-m deep; five have normal gradient curves.

Three deep wells on and near the Zuni Reservation define a NE-SW trending area of high-thermal gradient centered on the east-central part of the reservation (Fig. 10). A lack of data poorly defines the east and west borders of this high; the southern extent was determined by considerations of water chemistry data as well as gradient measurements.

This anomaly is located over a shallow basement at about 1-km depth. The source of the heat in this region is unknown; no source of volcanic or uranium deposits are nearby. However, the wells probed all encountered at least one aquifer and are affected by the local hydrology. Low-fluoride and boron contents in well waters (Summers, 1972) indicate near-surface waters have not circulated at depth in this area. It is doubtful, therefore, that the high gradients measured are due to circulation of hot water.

Wells close to, but west of the Nutria monocline (wells 15, 17, 18, 19, 22, and 25) have low gradients compared to wells farther west, with the exception of well 18. These low gradients are probably caused by close proximity to the Nutria Monocline which is a recharge area.

The low gradients in wells 10, 14, and 16 can also be explained by the closeness of these wells to a recharge area.

Low gradients are also found in the wells north of I-40 (Fig. 10). Although the shallowest well probed in this area is 475-m deep, the gradients in all are controlled by the local hydrology, with one possible exception. The aquifer for wells 20, 21, and 29, and almost all the other wells in the same valley, is the Morrison Formation. Recharge is provided in the Entrada and younger units along the cliffs just north of I-40, 4- to 10-km south and up-dip of the wells probed. Well 28 is closest to this recharge area. When penetrating the Morrison with the probe in well 28, the temperature fluctuated continuously over a 0.2 to 0.5°C range; it did not stabilize again until it was lowered below the Morrison at about 425 m. From 425 m to the bottom, equilibration was again attained within about 15 seconds at each reading. This temperature instability in the Morrison Formation indicates a significant flow of water was encountered. Although no such large fluctuations were

Fig. 10
Thermal gradient contour map of study area.

encountered in wells 20, 21, and 29 it is certain the relatively low temperatures encountered in these wells is due to movement of cool water. This is further supported by comparing the gradients in wells 20 and 21. Located within 750 m of each other and with essentially identical total depths, their gradients are 24°C/km and 17°C/km, respectively. This variation must be hydrologically controlled.

VIII. DISCUSSION

The geothermal gradient and water chemistry data indicate three areas of interest for further geothermal exploration: Gallup to Tohatchi, the Zuni Indian Reservation, and the Springerville area.

North of Gallup toward Tohatchi waters are very warm at relatively shallow depth. The low Li, B, and F contents show these are probably meteoric waters; the high (37-45°C) temperatures indicate these meteoric waters are probably circulating up from depth. Geothermometry calculations suggest a possible reservoir temperature greater than 60°C. Near Gallup, gradient measurements show the geothermal gradient increases west from 30°C/km near the Nutria monocline to 45°C/km, 2 km west of Gallup, indicating recharge along the monocline. Cool temperatures measured for water samples in this area are due to recharge by meteoric water relatively close to the well sampled. These data suggest warmer water may be encountered between Gallup and Tohatchi below the sediments that crop out in the Nutria monocline, or below the Chinle. Further work may find a suitable reservoir for low-temperature applications in this area, but this can not be determined at this time.

Low-temperature geothermal applications also appear promising for the Springerville, Arizona area in the very southwest corner of the study area. Stone and Hahman (Stone, personal communication, 1979) measured one gradient of 70°C/km south of Springerville at 304 m. Wells 1 and 2 measured in this project (Fig. 7) show very warm water circulating to shallow depths east of Springerville. The extent and young ages of the volcanics in the area suggest these phenomena are caused by water circulating up from depth after being warmed by a deep heat source. However, shallow uranium deposits may contribute to high temperatures in the shallow waters encountered in wells 1 and 2. Further thermal gradient and geochemistry work, coupled with geophysical methods to determine the presence or absence of a deep magma source, should be able to determine which effect is more significant and should further

delineate the low temperature potential of the area. If a deep-seated heat source is found to be dominant, the Springerville area may have potential as a Hot Dry Rock site.

The low-temperature geothermal potential of the Zuni Indian Reservation indicated from this study is insignificant. It is likely that the waters of Rainbow and Sacred Springs are warmed by a normal gradient at about 400 m and then circulate back to the surface. Two kilometers east of these springs granitic basement is at about 610 m depth. The low-fluoride and boron content of these waters and the related water of Dent Windmill farther east, compared to sample NM-17, a seep in granitic rock, show these waters do not circulate to the basement rock. This conclusion is supported by low F & B contents in waters from deep wells reported by Summers (1972).

These data indicate that deep circulating water is not available at shallow depth in the southern and eastern parts of the reservation. Circulation into the granitic basement is probably not significant due to low permeability and sealing of fractures in the basement rock. If so, circulation in the Zuni Indian Reservation is limited to the approximately 600 m of sediments above the basement. Assuming the maximum measured gradient on the reservation of $67^{\circ}\text{C}/\text{km}$, the maximum temperature for the ground water at the base of the sediments would be about 50°C . Such a low temperature is not promising for hydrogeothermal energy.

These same conditions, however, are ideal for Hot Dry Rock geothermal development. Basement rock is relatively shallow, yet with a sufficient insulating blanket of sediments. The low seismic activity in the Zuni Mountains area is conducive to fractures sealing in the basement rock (Laughlin, 1976). The apparent lack of circulation in the basement suggests the basement is impermeable. The high geothermal gradients indicate reservoir temperatures of 200°C at depths comparable to those currently encountered in the Hot Dry Rock project at Los Alamos Scientific Laboratory (LASL's Fenton Hill Project). These factors all contribute to a positive prospect for HDR in the Zuni Indian Reservation.

IX. SUMMARY AND RECOMMENDATIONS

Three regions within the study area are cited as having geothermal potential. The Gallup-Tohatchi area may have sufficient temperatures below the Chinle for low-temperature, direct-utilization applications. The Zuni Indian

Reservation holds possibilities for HDR geothermal energy, although the hydrogeothermal potential does not look promising from the available data. The highest gradients encountered in the project are in the Springerville area which may have both low temperature and HDR potential.

Further work in all three areas must be undertaken to sufficiently define the boundaries and sizes of the reservoirs that may exist in each. In the Gallup-Tohatchi area detailed hydrology of deep aquifers must accompany gradient measurements taken at depths below the Chinle to avoid influence from recharge along the cliffs just north of Gallup. Analyses of water samples from below the Chinle should help decipher the hydrology at depth and provide information on a potential low-temperature geothermal reservoir.

Water samples from deep wells in the Zuni Reservation should also give an indication of the hydrology at depth in this area. If circulation through the Precambrian basement is significant, this should be evident in the chemistry of water near the sediment-Precambrian contact. Gradient measurements below 500 m will better delineate the gradient high east of Zuni. To sufficiently define the potential HDR reservoir, at least one well should be drilled into the basement in the gradient high after deep measurements in the sediments are completed.

A more complete analysis with detailed recommendations has been completed by the Arizona Bureau of Geology and Mineral Technology for the Springerville area (Arizona Bureau of Geology and Mineral Technology, 1980). Our work supports their recommendation that this area should be considered for further geothermal evaluation. We emphasize their recommendation that further gradient measurements must penetrate the volcanic pile to eliminate ground water effects; to effectively determine the potential for HDR in this area, at least one well should penetrate to basement after more shallow wells have defined the gradient high.

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APPENDIX A

METHODS

I. WATER SAMPLING

Samples DL-1 through DL-22 were filtered with hand-held syringes through eight micron filter paper. All other samples were filtered with a peristaltic pump and four micron filter paper. Syringes and pump were rinsed thoroughly before each sampling. All containers were rinsed at least twice with filtered water before filling.

Three samples were taken at each location:

- 1 - 1ℓ filtered, unacidified (for pH and anions);
- 1 - 250 ml filtered and acidified with 20 drops of 6 molar HCl
 (for cations and SiO_2);
- 1 - 125 ml filtered, unacidified (for SiO_2).

Initially the 125-ml sample for SiO_2 was diluted with distilled water. However, this practice was discontinued after the first eight samples because SiO_2 concentrations encountered were so low.

Analysis of the samples was performed at LASL by Dale Counce. Cations were determined using an atomic absorption spectrophotometer machine. Titration methods for Cl and HCO_3 were done using mercuric nitrate and H_2SO_4 , respectively. A turbidometric method with BCl was used to determine SO_4 . Fluoride was analyzed with a select ion electrode.

II. GRADIENT MEASUREMENTS

Downhole temperature measurements were made using a thermistor in a LASL-designed housing on a kilometer long, four-lead cable. Readings were taken on a ohm meter as resistance, converted to temperature from calibration tables, and are accurate to $\pm 0.01^\circ\text{C}$.

The thermistors used were calibrated by the equation

$$T = C(1) + C(2)/(\log(R) + K),$$

where T is temperature in degrees celsius, C(1), C(2), and K are empirical constants, and R is resistivity. Calibration tables were constructed using the derived values for the constants. The thermistor was recalibrated once and checked against a mercury thermometer. From time to time in an ice bath and/or a large water bath.

Measurements were taken generally every 3 to 6 m from 6 m below surface to total depth. In-air readings did not equilibrate even after two hours, so readings above water level are nonequilibrium measurements.

Below the water level, equilibration generally occurred within 15 seconds. In all wells in which the water level was determined with a downhole water level meter, a marked change in resistance was measured with the thermistor at the water level. We are therefore confident in using a sudden change in resistivity, accompanied by the first reading which equilibrates in less than a minute, to determine the water level in a well.

APPENDIX B
THERMAL GRADIENT DATA

TEMPERATURE DEPTH DATA FOR WELL NO. 1

Temperature Gradient: 76°C/km
Gradient Interval: 21.3 m to 51.8 m

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
9.1		30	16.06
15.2		50	16.08
21.3		70	16.18
30.5		100	16.80
36.6		120	17.35
42.7		140	17.84
51.8		170	18.44

Temperature vs depth plot and gradient vs depth plot for Well No. 1

TEMPERATURE DEPTH DATA FOR WELL NO. 2

Temperature Gradient: 138°C/km
 Gradient Interval: 9.1 m to 121.9 m

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
9.1		30	16.04
15.2		50	16.42
21.3		70	16.82
30.5		100	18.46
36.6		120	19.48
42.7		140	20.70
48.8		160	21.87
54.9		180	22.66
61.0		200	23.26
67.1		220	23.85
73.1		240	24.41
79.2		260	25.10
85.3		280	26.24
91.4		300	27.35
100.6		330	28.54
103.9		341	28.89
109.7		360	29.56
116.1		381	30.22
121.9		400	30.81

Temperature vs depth plot and gradient vs depth plot for Well No. 2

TEMPERATURE DEPTH DATA FOR WELL NO. 3
T-4705

Temperature Gradient: 37°C/km

Gradient Interval: 12.2 m to 195.1 m

Depth		
<u>Meters</u>	<u>Feet</u>	<u>Temperature °C</u>
6.1	20	12.08
12.2	40	12.73
18.3	60	12.84
24.4	80	13.06
30.5	100	13.24
36.6	120	13.48
42.7	140	13.60
48.8	160	13.95
54.9	180	14.12
61.0	200	14.34
67.1	220	14.53
73.2	240	14.68
79.2	260	14.86
85.3	280	15.14
91.4	300	15.36
97.5	320	15.66
103.6	340	15.90
109.7	360	16.11
115.8	380	16.36
121.9	400	16.54
128.0	420	16.76
134.1	440	16.98
140.2	460	17.18
146.3	480	17.47
152.4	500	17.71
158.5	520	17.93
164.6	540	18.13
170.7	560	18.35
176.8	580	18.58
182.9	600	18.84
189.0	620	19.11
195.1	640	19.35

Temperature vs depth plot and gradient vs depth plot for Well No. 3

TEMPERATURE DEPTH DATA FOR WELL NO. 4
T-601

Temperature Gradient: 35°C/km

Gradient Interval: 91.4 m to 292.6 m

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
6.1		20	15.82
12.2		40	15.41
18.3		60	15.06
24.4		80	14.96
30.5		100	15.20
36.6		120	15.23
42.7		140	15.00
48.8		160	15.30
54.9		180	15.42
61.0		200	15.57
67.1		220	15.84
73.2		240	16.06
79.2		260	16.23
85.3		280	16.24
91.4		300	16.06
97.5		320	16.36
103.6		340	16.54
109.7		360	16.72
115.8		380	16.98
121.9		400	17.14
128.0		420	17.34
134.1		440	17.61
140.2		460	17.88
146.3		480	17.94
152.4		500	18.16
158.5		520	18.32
164.6		540	18.46
170.7		560	18.71

TEMPERATURE DEPTH DATA FOR WELL NO. 4 (Cont'd.)
T-601

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
176.8		580	18.92
182.9		600	19.12
189.0		620	19.35
201.2		640	19.65
207.3		660	19.90
213.4		680	20.13
219.5		700	20.41
219.5		720	20.65
225.6		740	20.66
231.6		760	20.92
237.7		780	21.08
243.8		800	21.31
249.9		820	21.61
256.0		840	21.89
262.1		860	22.14
268.2		880	22.26
274.3		900	22.43
280.4		920	22.68
286.5		940	22.92
292.6		960	22.97

Temperature vs depth plot and gradient vs depth plot for Well No. 4

TEMPERATURE DEPTH DATA FOR WELL NO. 5
FE-1

Temperature Gradient: 27°C/km
Gradient Interval: 42.7 m to 73.2 m

Depth		<u>Temperature °C</u>
<u>Meters</u>	<u>Feet</u>	
9.1	30	12.83
14.9	49	12.71
24.4	80	12.66
30.5	100	12.62
36.9	121	12.60
42.7	140	12.21
48.8	160	12.34
54.9	180	12.54
61.0	200	12.70
67.4	221	12.86
73.2	240	13.00
79.2	260	13.80
85.3	280	13.60

Temperature vs depth plot and gradient vs depth plot for Well No. 5

TEMPERATURE DEPTH DATA FOR WELL NO. 6
ZUNI SALT LAKE

Temperature Gradient: 6°C/km
Gradient Interval: 51.8 m to 79.2 m

Depth		
<u>Meters</u>	<u>Feet</u>	<u>Temperature °C</u>
15.2	50	17.10
21.3	70	17.26
27.4	90	17.45
33.5	110	17.52
39.6	130	17.35
45.7	150	17.18
51.8	170	17.12
57.9	190	17.14
64.3	211	17.20
70.1	230	17.23
79.2	260	17.29

Temperature vs depth plot and gradient vs depth plot for Well No. 6

TEMPERATURE DEPTH DATA FOR WELL NO. 7
RWP 26

Temperature Gradient: 22°C/km
Gradient Interval: 103.6 m to 160.2 m

Depth		
<u>Meters</u>	<u>Feet</u>	<u>Temperature °C</u>
24.4	80.0	14.58
30.5	100.0	14.31
36.6	120.0	14.27
42.7	140.0	14.26
48.8	160.0	14.27
54.9	180.0	14.30
61.0	200.0	14.33
67.1	220.0	14.37
73.2	240.0	14.42
79.2	260.0	14.49
85.6	281.0	14.54
91.4	300.0	14.60
97.8	321.0	14.70
103.6	340.0	15.68
109.7	360.0	15.84
115.8	380.0	15.96
121.9	400.0	16.08
128.0	420.0	16.21
134.1	440.0	16.39
140.2	460.0	16.54
146.6	481.0	16.64
152.4	500.0	16.79
158.5	520.0	16.87
160.2	525.5	16.91

Temperature vs depth plot and gradient vs depth plot for Well No. 7

TEMPERATURE DEPTH DATA FOR WELL NO. 8
ECW-18

Temperature Gradient: 63°C/km
Gradient Interval: 58.8 m to 127.1 m

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
6.1		20	22.04
12.2		40	21.46
18.3		60	21.23
24.4		80	20.95
29.3		96	20.72
34.1		112	20.55
39.0		128	20.41
43.9		144	20.25
49.1		161	20.12
53.9		177	14.89
58.8		193	14.95
63.7		209	15.25
68.6		225	15.61
73.5		241	15.98
78.3		257	16.34
83.2		273	16.69
88.1		289	16.98
93.0		305	17.23
97.8		321	17.64
102.7		337	17.95
107.6		353	18.19
112.5		369	18.48
117.3		385	18.72
122.2		401	18.97
127.1		417	19.11

Temperature vs depth plot and gradient vs depth plot for Well No. 8

TEMPERATURE DEPTH DATA FOR WELL NO. 9
ECW 5

Temperature Gradient: $-63^{\circ}\text{C}/\text{km}$
Gradient Interval: 24.4 m to 149.4 m

Depth		<u>Temperature °C</u>
<u>Meters</u>	<u>Feet</u>	
12.2	40.0	27.75
24.4	80.0	24.68
36.6	120.0	22.72
49.1	161.0	21.23
61.3	201.0	19.83
73.5	241.0	19.05
85.6	281.0	18.46
97.8	321.0	17.95
110.0	361.0	17.68
122.2	401.0	17.40
134.7	442.0	17.22
146.6	481.0	17.11
149.4	490.0	16.85
151.8	498.0	17.04

Temperature vs depth plot and gradient vs depth plot for Well No. 9

TEMPERATURE DEPTH DATA FOR WELL NO. 10
ECW-7

Temperature Gradient: 23°C/km
Gradient Interval: 146.6 m to 161.5 m

<u>Meters</u>	Depth <u>Feet</u>	<u>Temperature °C</u>
12.2	40.0	15.13
14.6	48.0	14.94
19.5	64.0	14.89
24.4	80.0	14.84
29.3	96.0	14.64
34.1	112.0	14.61
39.0	128.0	14.60
43.9	144.0	14.60
49.1	161.0	14.62
53.9	177.0	14.64
58.8	193.0	14.66
63.7	209.0	14.70
68.6	225.0	14.73
73.5	241.0	14.79
78.3	257.0	14.84
83.2	273.0	14.89
88.1	289.0	14.96
93.0	305.0	15.04
97.8	321.0	15.10
102.7	337.0	15.19
107.6	353.0	15.33
112.5	369.0	15.47
117.3	385.0	15.61
122.2	401.0	15.77
127.1	417.0	15.96
132.3	434.0	16.31
137.2	450.0	16.79
142.0	466.0	17.14
146.6	481.0	18.34
151.8	498.0	18.43
156.7	514.0	18.60
161.5	530.0	18.64

Temperature vs depth plot and gradient vs depth plot for Well No. 10

TEMPERATURE DEPTH DATA FOR WELL NO. 11
ZUNI OIL WELL

Temperature Gradient: 67°C/km
Gradient Interval: 181.1 m to 283.8 m

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
4.9		16.0	22.22
9.8		32.0	21.30
14.6		48.0	20.14
19.5		64.0	19.07
24.4		80.0	18.58
29.3		96.0	18.43
34.1		112.0	18.11
39.0		128.0	17.88
43.9		144.0	17.80
49.1		161.0	17.78
53.9		177.0	17.76
58.8		193.0	17.78
63.7		209.0	17.78
68.6		225.0	17.23
73.5		241.0	17.26
78.3		257.0	17.29
83.2		273.0	17.35
88.1		289.0	17.42
93.0		305.0	17.49
97.8		321.0	17.74
102.7		337.0	18.18
107.6		353.0	18.81
112.5		369.0	19.33
117.3		385.0	19.40
122.2		401.0	19.41
127.1		417.0	19.45
132.3		434.0	19.46
137.2		450.0	19.50
142.0		466.0	20.03
146.9		482.0	23.83

TEMPERATURE DEPTH DATA FOR WELL NO. 11 (Cont'd.)
ZUNI OIL WELL

151.8	498.0	24.70
156.7	514.0	24.82
161.5	530.0	24.88
166.4	546.0	24.91
171.3	562.0	24.96
176.2	578.0	25.03
181.1	594.0	25.19
185.9	610.0	25.42
190.8	626.0	25.69
195.7	642.0	26.01
200.6	658.0	26.28
205.4	674.0	26.60
210.3	690.0	26.88
215.5	707.0	27.17
220.4	723.0	27.54
225.2	739.0	27.86
230.1	755.0	28.17
235.0	771.0	28.48
239.9	787.0	28.84
244.8	803.0	29.22
249.6	819.0	29.56
254.5	835.0	29.88
259.4	851.0	30.20
264.3	867.0	30.49
269.1	883.0	30.87
274.0	899.0	31.34
278.9	915.0	31.62
283.8	931.0	31.88
286.2	939.0	32.00
298.7	980.0	32.52
323.1	1060.0	33.55

Temperature vs depth plot and gradient vs depth plot for Well No. 11

TEMPERATURE DEPTH DATA FOR WELL NO. 12
VANDERWAGEN WELL

Temperature Gradient: 24°C/km
Gradient Interval: 274.3 m to 347.5 m

Depth		
<u>Meters</u>	<u>Feet</u>	<u>Temperature °C</u>
6.1	20	23.24
12.2	40	21.97
18.3	60	19.70
24.4	80	17.56
30.5	100	16.84
36.6	120	16.06
42.7	140	15.72
48.8	160	15.47
54.9	180	15.44
61.0	200	15.44
67.1	220	15.41
73.2	240	15.40
79.2	260	15.43
85.3	280	15.48
91.4	300	15.69
97.5	320	15.94
103.6	340	16.33
109.7	360	16.62
115.8	380	16.88
121.9	400	17.05
128.0	420	17.20
134.1	440	17.37
140.2	460	17.60
146.3	480	18.20
152.4	500	18.80
158.5	520	19.27
164.6	540	19.60
170.7	560	19.90
176.8	580	20.16
182.9	600	20.31

TEMPERATURE DEPTH DATA FOR WELL NO. 12 (Cont'd.)
VANDERWAGEN WELL

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
189.0		620	20.46
195.1		640	20.63
201.2		660	20.94
207.3		680	21.40
213.4		700	21.72
219.5		720	21.97
225.6		740	22.97
231.6		760	23.28
237.7		780	23.61
243.8		800	23.91
249.9		820	24.23
256.0		840	24.54
262.1		860	24.83
268.2		880	25.08
274.3		900	25.26
280.4		920	25.41
286.5		940	25.55
292.6		960	25.64
298.7		980	25.87
304.8		1000	26.04
310.9		1020	26.21
317.0		1040	26.29
323.1		1060	26.46
329.2		1080	26.62
335.3		1100	26.76
341.4		1120	26.92
347.5		1140	26.94

Temperature vs depth plot and gradient vs depth plot for Well No. 12

TEMPERATURE DEPTH DATA FOR WELL NO. 13
HG-1

Temperature Gradient: 59°C/km
Gradient Interval: 106.7 m to 114.9 m

Depth		
<u>Meters</u>	<u>Feet</u>	<u>Temperature °C</u>
9.8	32.0	19.04
12.2	40.0	18.66
14.6	48.0	18.09
17.1	56.0	17.58
19.5	64.0	17.14
21.9	72.0	16.68
24.4	80.0	16.56
26.8	88.0	16.45
29.3	96.0	16.34
31.7	104.0	16.10
34.1	112.0	15.91
36.6	120.0	15.78
39.0	128.0	15.64
41.5	136.0	15.55
43.9	144.0	15.45
46.3	152.0	15.38
49.1	161.0	15.33
51.5	169.0	15.28
53.9	177.0	15.25
56.4	185.0	15.23
58.8	193.0	15.21
61.3	201.0	15.23
63.7	209.0	15.25
66.1	217.0	15.28
68.6	225.0	15.34
71.0	233.0	15.39
73.5	241.0	15.54
75.9	249.0	15.61

TEMPERATURE DEPTH DATA FOR WELL NO. 13 (Cont'd.)
HG-1

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
78.3		257.0	15.68
80.8		265.0	15.77
83.2		273.0	15.90
85.6		281.0	16.04
88.1		289.0	16.24
90.5		297.0	16.44
93.0		305.0	16.63
95.4		313.0	16.76
97.8		321.0	16.92
100.3		329.0	17.12
102.7		337.0	17.26
105.2		345.0	17.38
107.6		353.0	18.46
110.0		361.0	18.56
112.5		369.0	18.76
114.9		377.0	18.86

Temperature vs depth plot and gradient vs depth plot for Well No. 13

TEMPERATURE DEPTH DATA FOR WELL NO. 14
RWP 34

Temperature Gradient: 22°C/km
Gradient Interval: 24.4 m to 67.4 m

Depth		<u>Temperature °C</u>
<u>Meters</u>	<u>Feet</u>	
9.1	30	15.32
18.3	60	13.70
24.4	80	12.75
20.5	100	12.93
36.6	120	13.07
42.7	140	13.20
49.1	161	13.30
55.2	181	13.40
61.0	200	13.64
67.4	221	13.71

Temperature vs depth plot and gradient vs depth plot for Well No. 14

TEMPERATURE DEPTH DATA FOR WELL NO. 15
CCC 77-62

Temperature Gradient: 32°C/km
Gradient Interval: 12.2 m - 33.5 m

Depth		Temperature °C
<u>Meters</u>	<u>Feet</u>	
2.4	8	16.83
4.9	16	16.71
9.8	32	11.62
12.2	40	11.43
14.6	48	11.46
17.1	56	11.54
19.5	64	11.63
21.9	72	11.71
24.4	80	11.79
29.3	96	11.94
33.5	110	12.09

Temperature vs depth plot and gradient vs depth plot for Well No. 15

TEMPERATURE DEPTH DATA FOR WELL NO. 16
MONTGOMERY WELL

Temperature Gradient: 27°C/km
Gradient Interval: 105.2 m to 132.3 m

<u>Meters</u>	Depth <u>Feet</u>	<u>Temperature °C</u>
2.44	8.00	12.05
4.88	16.00	11.66
7.32	24.00	11.60
9.75	32.00	11.61
12.19	40.00	11.64
14.63	48.00	11.67
17.07	56.00	11.69
19.51	64.00	11.70
21.95	72.00	11.71
24.38	80.00	11.73
26.82	88.00	11.77
29.26	96.00	11.78
31.70	104.00	11.80
34.14	112.00	11.83
36.58	120.00	11.85
39.01	128.00	11.87
41.45	136.00	11.91
43.89	144.00	11.99
46.33	152.00	12.00
49.10	161.00	12.05
51.50	169.00	12.22
53.90	177.00	12.32
56.40	185.00	12.41
58.80	193.00	12.49

TEMPERATURE DEPTH DATA FOR WELL NO. 16 (Cont'd.)
MONTGOMERY WELL

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
61.30		201.00	12.55
63.70		209.00	12.64
66.1		217.0	12.75
68.6		225.0	12.89
71.0		233.0	13.09
73.5		241.0	13.16
75.9		249.0	13.25
78.3		257.0	13.33
80.8		265.0	13.48
83.2		273.0	13.55
85.6		281.0	13.61
88.1		289.0	13.69
90.5		297.0	13.83
93.0		305.0	13.89
95.4		313.0	14.00
97.8		321.0	14.04
100.3		329.0	14.09
102.7		337.0	14.14
105.2		345.0	15.10
107.6		353.0	15.22
110.0		361.0	15.27
112.5		369.0	15.29
114.9		377.0	15.34
117.3		385.0	15.41
119.8		393.0	15.50
122.2		401.0	15.59
124.7		409.0	15.66
127.1		417.0	15.70
129.8		426.0	15.79
132.3		434.0	15.80

Temperature vs depth plot and gradient vs depth plot for Well No. 16

TEMPERATURE DEPTH DATA FOR WELL NO. 17
CCC 77-64

Temperature Gradient: $-121^{\circ}\text{C}/\text{km}$
Gradient Interval: 0 m to 34.1 m

Depth		
<u>Meters</u>	<u>Feet</u>	<u>Temperature $^{\circ}\text{C}$</u>
2.4	8	15.96
4.9	16	15.12
7.3	24	14.76
9.8	32	14.44
12.2	40	14.19
14.6	48	13.89
17.1	56	13.64
19.5	64	13.36
24.4	80	12.91
29.3	96	12.78
34.1	112	11.66

Temperature vs depth plot and gradient vs depth plot for Well No. 17

TEMPERATURE DEPTH DATA FOR WELL NO. 18
CCC 77-72

Temperature Gradient: 41°C/km
Gradient Interval: 7.3 m - 44.5 m

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
4.9		16	10.92
7.3		24	10.96
9.8		32	11.22
12.2		40	11.28
14.6		48	11.27
17.1		56	11.38
19.5		64	11.40
21.9		72	11.50
24.4		80	11.56
26.8		88	11.72
29.3		96	11.86
31.7		104	11.94
34.1		112	12.08
36.6		120	12.15
39.0		128	12.34
41.4		136	12.48
44.5		146	12.56

Temperature vs depth plot and gradient vs depth plot for Well No. 18

TEMPERATURE DEPTH DATA FOR WELL NO. 19
15T-560

Temperature Gradient: 29°C/km
Gradient Interval: 116.1 m to 296.3 m

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
40		50	22.63
76		100	20.94
23.2		76	13.60
46.3		152	13.50
58.2		191	13.84
69.8		229	14.50
81.4		267	15.09
93.0		305	15.62
104.5		343	16.25
116.1		381	16.83
127.7		419	17.07
139.3		457	17.35
150.9		495	17.63
162.5		533	17.91
174.0		571	18.29
185.3		608	18.67
196.9		646	19.03
211.5		694	19.37
220.1		722	19.68
231.6		760	19.94
243.2		798	20.17
254.8		836	20.53
267.0		876	21.01
278.0		912	21.55
289.6		950	21.92
296.3		972	22.06

Temperature vs depth plot and gradient vs depth plot for Well No. 19

TEMPERATURE DEPTH DATA FOR WELL NO. 20
MARIANO LAKE NO. 1

Temperature Gradient: 17°C/km
Gradient Interval: 274.3 m to 475.5 m

<u>Meters</u>	<u>Depth</u>	<u>Feet</u>	<u>Temperature °C</u>
12.2		40	15.06
24.4		80	13.04
36.6		120	12.88
48.8		160	12.76
61.0		200	12.74
73.2		240	12.86
85.3		280	13.04
97.5		320	13.20
103.6		340	13.41
109.7		360	13.69
115.8		380	13.87
121.9		400	14.50
128.0		420	14.65
134.1		440	14.83
140.2		460	15.01
146.3		480	15.19
152.4		500	15.38
158.5		520	15.66
164.6		540	15.99
170.7		560	16.33
176.8		580	16.82
182.9		600	17.64
189.0		620	18.43
195.1		640	18.42
201.2		660	18.90
207.3		680	19.15
213.4		700	19.34
219.5		720	19.60
225.6		740	19.79
231.6		760	19.98
237.7		780	20.10
243.8		800	20.20
249.9		820	20.32
256.0		840	20.38
262.1		860	20.39
268.2		880	20.44
274.3		900	20.49
280.4		920	20.70
286.5		940	20.89
292.6		960	20.98

TEMPERATURE DEPTH DATA FOR WELL NO. 20 (Cont'd.)
 MARIANO LAKE NO. 1

Depth		Temperature °C
<u>Meters</u>	<u>Feet</u>	
298.7	980	21.10
304.8	1000	21.10
310.9	1020	21.20
317.0	1040	21.40
323.1	1060	21.39
329.2	1080	21.50
335.3	1100	21.62
341.4	1120	21.84
347.5	1140	21.95
353.6	1160	22.07
359.7	1180	22.19
365.8	1200	22.35
371.9	1220	22.52
378.0	1240	22.57
384.0	1260	22.65
390.1	1280	22.78
396.2	1300	22.82
402.3	1320	22.91
408.4	1340	22.98
414.5	1360	23.05
420.6	1380	23.11
426.7	1400	23.11
432.8	1420	23.16
438.9	1440	23.23
445.0	1460	23.31
451.1	1480	23.52
457.2	1500	23.64
463.3	1520	23.76
469.4	1540	23.82
475.5	1560	23.87

Temperature vs depth plot and gradient vs depth plot for Well No. 20

TEMPERATURE DEPTH DATA FOR WELL NO. 21
MARIANO LAKE NO. 2

Temperature Gradient: 24°C/km
Gradient Interval: 85.3 m to 481.6 m

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
6.1		20	18.77
12.2		40	16.96
18.3		60	15.96
24.4		80	15.29
30.5		100	14.78
36.6		120	14.58
42.7		140	14.45
48.8		160	14.34
54.9		180	14.28
61.0		200	14.31
67.1		220	14.29
73.2		240	14.23
79.2		260	14.21
85.3		280	14.21
91.4		300	14.33
97.5		320	14.48
103.6		340	14.66
109.7		360	14.82
115.8		380	14.98
121.9		400	15.13
128.0		420	15.30
134.1		440	15.48
140.2		460	15.75
146.3		480	15.87
152.4		500	16.15
158.5		520	16.35
164.6		540	16.53
170.7		560	16.72
176.8		580	16.93
182.9		600	17.09
189.0		620	17.26
195.1		640	17.42
201.2		660	17.60
207.3		680	17.83
213.4		700	17.87
219.5		720	18.02
225.6		740	18.17
231.6		760	18.35
237.7		780	18.51
243.8		800	18.67

TEMPERATURE DEPTH DATA FOR WELL NO. 21 (Cont'd.)
 MARIANO LAKE NO. 2

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
249.9		820	18.83
256.0		840	18.98
262.1		860	19.13
268.2		880	19.28
274.3		900	19.41
280.4		920	19.56
286.5		940	19.70
292.6		960	19.81
298.7		980	19.96
304.8		1000	20.10
310.9		1020	20.24
317.0		1040	20.36
323.1		1060	20.48
329.2		1080	20.60
335.3		1100	20.72
341.4		1120	20.83
347.5		1140	20.94
353.6		1160	21.06
359.7		1180	21.21
365.8		1200	21.34
371.9		1220	21.47
378.0		1240	21.69
384.0		1260	21.74
390.1		1280	21.88
396.2		1300	22.00
402.3		1320	22.12
408.4		1340	22.26
414.5		1360	22.38
420.6		1380	22.51
426.7		1400	22.63
432.8		1420	22.73
438.9		1440	22.99
445.0		1460	23.03
451.1		1480	23.06
457.2		1500	23.08
463.3		1520	23.37
469.4		1540	23.59
475.5		1560	23.62
481.6		1580	23.64

Temperature vs depth plot and gradient vs depth plot for Well No. 21

TEMPERATURE DEPTH DATA FOR WELL NO. 22
BREADSPRINGS WELL

Temperature Gradient: 28°C/km
Gradient Interval: 85.3 m to 189.0 m

Depth		Temperature °C
<u>Meters</u>	<u>Feet</u>	
30.5	100	12.85
36.6	120	13.20
42.7	140	13.95
48.8	160	13.99
54.9	180	13.91
61.0	200	14.15
67.1	220	14.29
73.2	240	14.26
79.2	260	14.74
85.3	280	15.74
91.4	300	15.88
97.5	320	16.33
109.7	360	16.84
115.8	380	16.96
121.9	400	16.96
128.0	420	17.18
134.1	440	17.50
140.2	460	17.74
146.3	480	17.58
152.4	500	17.82
158.5	520	18.02
164.6	540	18.02
170.7	560	18.40
176.8	580	18.40
182.9	600	18.46
189.0	620	18.54

Temperature vs depth plot and gradient vs depth plot for Well No. 22

TEMPERATURE DEPTH DATA FOR WELL NO. 23
MANUELITO WELL

Temperature Gradient: 45°C/km
Gradient Interval: 36.6 m to 307.8 m

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
6.1		20	22.79
51.8		52	21.56
22.9		75	20.50
31.4		103	13.39
36.6		120	13.50
42.7		140	13.61
48.8		160	13.75
54.9		180	13.87
61.0		200	13.99
67.1		220	14.15
73.2		240	14.40
79.2		260	14.60
85.3		280	14.85
91.4		300	15.09
97.5		320	15.31
103.6		340	15.55
109.7		360	15.79
115.8		380	16.05
121.9		400	16.33
128.0		420	16.60
134.1		440	16.89
140.2		460	17.16
146.3		480	17.49
152.4		500	17.84
158.5		520	18.20
164.6		540	18.53
170.7		560	18.90
176.8		580	19.33
182.9		600	19.76
189.0		620	20.15

TEMPERATURE DEPTH DATA FOR WELL NO. 23 (Cont'd.)
MANUELITO WELL

Temperature Gradient: 45°C/km
Gradient Interval: 36.6 m to 307.8 m

Depth		<u>Temperature °C</u>
<u>Meters</u>	<u>Feet</u>	
195.1	640	20.52
201.2	660	20.83
207.3	680	21.15
213.4	700	21.47
219.5	720	21.71
225.6	740	21.97
231.6	760	22.12
237.7	780	22.28
243.8	800	22.51
249.9	820	22.73
256.0	840	22.87
262.1	860	23.00
268.2	880	23.26
274.3	900	23.47
280.4	920	23.62
286.5	940	23.76
292.6	960	23.84
298.7	980	23.94
304.8	1000	24.01
307.8	1010	24.03

Temperature vs depth plot and gradient vs depth plot for Well No. 23

TEMPERATURE DEPTH DATA FOR WELL NO. 24
MONTANO WELL

Temperature Gradient: 32°C/km
Gradient Interval: 67.1 m to 131.1 m

Depth		
<u>Meters</u>	<u>Feet</u>	<u>Temperature °C</u>
6.1	20	21.98
12.2	40	21.26
18.3	60	20.46
24.4	80	19.56
30.5	100	18.77
36.6	120	17.81
42.7	140	17.05
48.8	160	16.50
54.9	180	15.72
61.0	200	14.06
67.1	220	14.13
73.2	240	14.27
79.2	260	14.51
85.3	280	14.67
91.4	300	14.92
97.5	320	15.03
103.6	340	15.23
109.7	360	15.41
115.8	380	15.62
121.9	400	15.82
125.0	410	15.89
128.0	420	16.07
131.1	430	16.21

Temperature vs depth plot and gradient vs depth plot for Well No. 24

TEMPERATURE DEPTH DATA WELL NO. 25
DOOR CHURCH WELL IN SOUTHERN GALLUP, NM

Temperature Gradient: 30°C/km
Gradient Interval: 51.8 m to 127.1 m

<u>Meters</u>	Depth <u>Feet</u>	<u>Temperature °C</u>
4.9	16.0	16.17
9.8	32.0	15.08
14.6	48.0	14.90
19.5	64.0	14.78
24.4	80.0	14.68
29.3	96.0	14.58
34.1	112.0	14.44
39.0	128.0	14.32
43.9	144.0	14.28
49.1	161.0	14.28
53.9	177.0	14.34
58.8	193.0	14.50
63.7	209.0	14.69
68.6	225.0	14.90
73.5	241.0	15.18
78.3	257.0	15.45
83.2	273.0	15.69
88.1	289.0	15.86
93.0	305.0	15.99
97.8	321.0	16.17
102.7	337.0	16.20
107.6	353.0	16.29
112.5	369.0	16.33
117.3	385.0	16.34
122.2	401.0	16.35
127.1	417.0	16.40

Temperature vs depth plot and gradient vs depth plot for Well No. 25

TEMPERATURE DEPTH DATA FOR WELL NO. 26
CHURCH ROCK SCHOOL WELL

Temperature Gradient: 24°C/km

Gradient Interval: 109.7 m to 182.9 m

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
6.1		20	16.84
12.2		40	16.42
18.3		60	16.62
30.5		100	17.13
42.7		140	17.09
48.8		160	17.13
54.9		180	17.40
61.0		200	17.68
67.1		220	17.91
73.2		240	18.30
79.2		260	18.56
85.3		280	18.99
91.4		300	19.37
97.5		320	19.59
103.6		340	19.88
109.7		360	20.17
115.8		380	20.46
121.9		400	20.77
128.0		420	21.07
134.1		440	21.32
140.2		460	21.41
146.3		480	21.64
152.4		500	21.76
158.5		520	21.86
164.6		540	22.01
170.7		560	22.09
176.8		580	22.31
182.9		600	22.44

Temperature vs depth plot and gradient vs depth plot for Well No. 26

TEMPERATURE DEPTH DATA FOR WELL NO. 27
MARTINEZ CAMP WELL

Temperature Gradient: 22°C/km
Gradient Interval: 36.6 m to 170.7 m

Depth		Temperature °C
<u>Meters</u>	<u>Feet</u>	
12.2	40	14.78
24.4	80	15.72
30.5	100	15.94
36.6	120	15.28
42.7	140	15.30
48.8	160	15.62
54.9	180	15.84
61.0	200	16.06
67.1	220	16.11
73.2	240	16.11
79.2	260	16.22
85.3	280	16.44
91.4	300	16.28
97.5	320	16.06
103.6	340	16.26
109.7	360	16.48
115.8	380	16.62
121.9	400	16.78
128.0	420	17.18
134.1	440	17.30
140.2	460	17.18
146.3	480	17.58
152.4	500	17.96
158.5	520	18.12
164.6	540	17.90
170.7	560	17.96
176.8	580	20.24

Temperature vs depth plot and gradient vs depth plot for Well No. 27

TEMPERATURE DEPTH DATA FOR WELL NO. 28
WESTERN NUCLEAR

Temperature Gradient: 38°C/km

Gradient Interval: 426.7 m to 792.5 m.

Depth		<u>Temperature °C</u>
<u>Meters</u>	<u>Feet</u>	
12.2	40	14.26
24.4	80	13.55
36.6	120	13.43
48.8	160	13.22
61.0	200	13.55
73.1	240	14.05
85.3	280	14.16
97.5	320	14.35
109.7	360	14.74
121.9	400	14.98
134.1	440	15.25
146.3	480	15.75
158.5	520	15.98
170.7	560	16.21
182.9	600	16.87
195.1	640	17.06
213.4	700	17.56
219.5	720	17.66
225.5	740	17.68
274.3	900	18.14
335.3	1100	19.72
371.9	1220	20.45
396.2	1300	20.90
426.7	1400	22.24
438.9	1440	22.79
451.1	1480	23.05
463.3	1520	23.46
475.5	1560	23.98
487.7	1600	24.48
493.8	1620	24.65
499.9	1640	24.81
506.0	1660	25.02
512.1	1680	25.24
518.2	1700	25.48
524.3	1720	25.72
530.3	1740	25.96
536.4	1760	26.04
542.5	1780	26.25

TEMPERATURE DEPTH DATA FOR WELL NO. 28 (Cont'd.)
WESTERN NUCLEAR

Temperature Gradient: 38°C/km
Gradient Interval: 426.7 m to 792.5 m

Depth		
<u>Meters</u>	<u>Feet</u>	<u>Temperature °C</u>
548.6	1800	26.50
554.7	1820	26.65
560.8	1840	27.00
566.9	1860	27.40
573.0	1880	27.58
579.1	1900	27.73
585.2	1920	27.81
591.3	1940	28.27
597.4	1960	28.41
603.5	1980	28.69
609.6	2000	28.94
615.7	2020	29.17
621.8	2040	29.38
627.9	2060	29.62
634.0	2080	29.93
640.1	2100	30.16
646.2	2120	30.45
652.3	2140	30.72
658.4	2160	31.01
664.5	2180	31.23
670.6	2200	31.43
676.7	2220	31.64
682.7	2240	31.84
688.8	2260	31.98
694.9	2280	32.20
701.0	2300	32.34
707.1	2320	32.46
713.2	2340	32.63
719.3	2360	32.86
725.4	2380	33.17
731.5	2400	33.60
737.6	2420	33.96
743.7	2440	34.22
749.8	2460	34.48
755.9	2480	34.72
762.0	2500	34.96
768.1	2520	35.14
774.2	2540	35.41
780.3	2560	35.71
786.4	2580	36.02
792.5	2600	36.27

Temperature vs depth plot and gradient vs depth plot for Well No. 28

TEMPERATURE DEPTH DATA FOR WELL NO. 29
SMITH LAKE WELL

Temperature Gradient: 24°C/km
Gradient Interval: 109.7 m to 530.4 m

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
6.1		20	24.58
12.2		40	22.18
18.3		60	19.28
24.4		80	17.96
30.5		100	16.80
36.6		120	16.48
42.7		140	15.53
48.8		160	15.02
54.9		180	14.65
61.0		200	14.56
67.1		220	14.54
73.2		240	14.55
79.2		260	14.56
85.3		280	14.57
91.4		300	14.60
97.5		320	14.67
103.6		340	15.43
109.7		360	16.08
115.8		380	16.29
121.9		400	16.57
128.0		420	16.85
134.1		440	17.11
140.2		460	17.35
146.3		480	17.62
152.4		500	17.81
158.5		520	17.98
164.6		540	18.12
170.7		560	18.28
176.8		580	18.45
182.9		600	18.63
189.0		620	18.74
195.1		640	18.86
201.2		660	18.97
207.3		680	19.08
213.4		700	19.20
219.5		720	19.31
225.6		740	19.38
231.6		760	19.44
237.7		780	19.56
243.8		800	19.70
249.9		820	19.81

TEMPERATURE DEPTH DATA FOR WELL NO. 29 (Cont'd.)
SMITH LAKE WELL

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
256.0		840	19.95
262.1		860	20.13
268.2		880	20.30
274.3		900	20.58
280.4		920	20.87
286.5		940	20.89
292.6		960	21.06
298.7		980	21.26
304.8		1000	21.47
310.9		1020	21.60
317.0		1040	21.77
323.1		1060	21.94
329.2		1080	22.20
335.3		1100	22.28
341.4		1120	22.30
347.5		1140	22.44
353.6		1160	22.64
359.7		1180	22.79
365.8		1200	22.98
371.9		1220	23.13
378.0		1240	23.29
384.0		1260	23.39
390.1		1280	23.55
396.2		1300	23.76
402.3		1320	23.88
408.4		1340	23.96
414.5		1360	24.03
420.6		1380	24.15
426.7		1400	24.25
432.8		1420	24.35
438.9		1440	24.48
445.0		1460	24.60
451.1		1480	24.69
457.2		1500	24.78
463.3		1520	24.96
469.4		1540	25.04
475.5		1560	25.15
481.6		1580	25.28
487.7		1600	25.44
493.8		1620	25.59
499.9		1640	25.74
506.0		1660	25.95

TEMPERATURE DEPTH DATA FOR WELL NO. 29 (Cont'd.)
SMITH LAKE WELL

<u>Meters</u>	Depth	<u>Feet</u>	<u>Temperature °C</u>
512.1		1680	26.10
518.2		1700	26.20
524.3		1720	26.27
530.4		1740	26.52
536.4		1760	26.67
542.5		1780	26.68
548.6		1800	26.70
554.7		1820	26.72
560.8		1840	26.82
566.9		1860	27.07
573.0		1880	27.20
579.1		1900	27.23
585.2		1920	27.24
591.3		1940	27.26

Temperature vs depth plot and gradient vs depth plot for Well No. 29