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Geothermal Studies at Kirtland Air Force Base, Albuquerque, New Mexico

Linda Riddle, Bob Grant

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GEOTHERMAL STUDIES AT KIRTLAND AIR FORCE BASE ALBUQUERQUE, NEW MEXICO

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ABSTRACT

Due to an effort by government installations to discontinue use of natural gas, alternative energy sources are being investigated at Kirtland Air Force Base, Albuquerque, New Mexico. New Mexico has geologic characteristics favorable for geothermal energy utilization. Local heat flow and geochemical studies indicate a normal subsurface temperature regime. The alluvial deposits, however, extend to great depths where hot fluids, heated by the normal geothermal gradient, could be encountered.

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GEOTHERMAL STUDIES AT KIRTLAND AIR FORCE BASE
ALBUQUERQUE, NEW MEXICO

Introduction

New Mexico is a hot spot for geothermal energy. New Mexico Energy and Minerals Department estimates the state's geothermal potential of up to 3500 MW electrical and 2500 trillion Btu of direct use applications (Geothermal Report, 1980). Eight sites in the state have been designated by the United States Geological Survey as "known geothermal resource areas" (KGRA's). Two of these areas are being developed. Union Oil Company of California has plans for a 50 MW power plant in the Jemez Mountains and New Mexico State University is successfully using geothermal sources for space heating at Las Cruces. Exploration at other sites is continuing through commercial interests and also through funding by the New Mexico Energy Institute. In addition to the known areas, New Mexico's geologic conditions are favorable for geothermal activity which has no obvious surface manifestation. Recent faulting along the Rio Grande Rift associated with young volcanic deposits, high heat flow and an anomalous crustal zone, are all positive factors. The basins of the rift are quite deep and may supply sufficient water at high temperatures.

The Kirtland Air Force Base is situated along the edge of the Rio Grande Rift and is in the deepest of the rift basins. The local area also has recent volcanic deposits and extensive faulting.

Research Program

Exploring for geothermal resources requires the collection and integration of a variety of information. This information ranges from the requirements of the user to the details of the subsurface geology. A well-organized exploration program should minimize the cost of a preliminary study and have the flexibility to change direction or terminate as the data warrant. Most important is that the data collected form an integrated base of knowledge from which conclusions can be drawn. These requirements necessitate a step-by-step approach so that the data at each step are evaluated and decisions are made either to end the study or to continue. A typical program will include an information search, geological, hydrological, geophysical, and geochemical investigations, exploratory drilling, and, if all goes well, developmental drilling. The program at Kirtland Base is outlined below. This report contains information gathered from the library search and from studies conducted as a result of this exploration program.

Kirtland Exploration Program

I. Literature Search

   A. Geothermal Studies

   B. Geology

   C. Hydrology

   D. Geochemistry

   E. Geophysical Studies

II. Hydrologic study

A. Data Acquisition

B. Analysis

III. Geochemical Sampling

A. Spring selection

B. Sampling

C. Analysis

IV. Geophysical study--audio magnetotelluric

A. Site selection

B. Data collection

C. Analysis

Geologic Setting

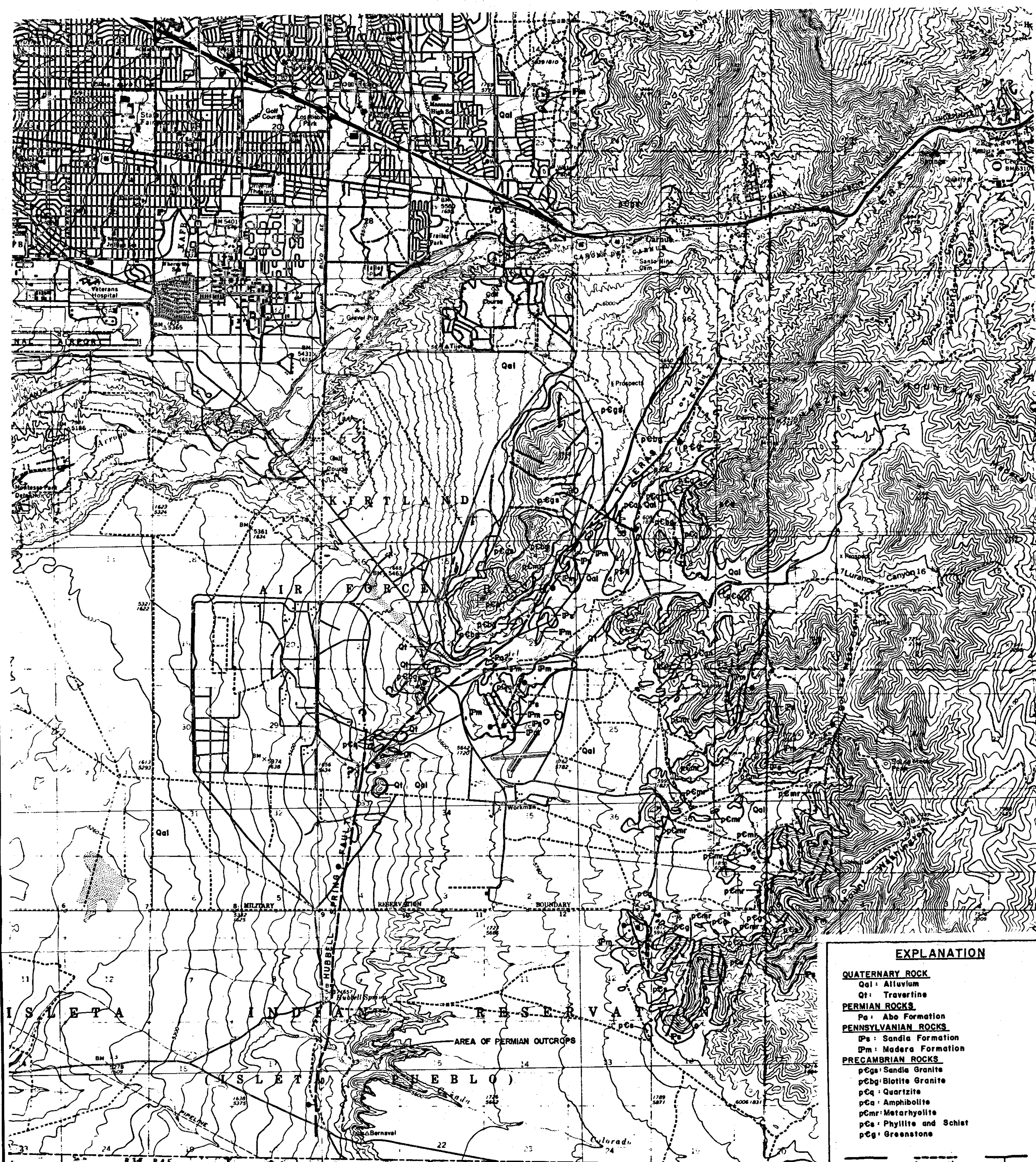
The Kirtland Air Force Base is located along the far eastern margin of the Rio Grande rift in the Albuquerque-Belen Basin. The rift is characterized by recent extensional faulting, high heat flow, crustal and mantle anomalies, and young volcanic activity. Six structural basins arranged in a step pattern make up the rift zone which extends from Leadville, Colorado to El Paso, Texas (Chapin, 1971). The Albuquerque-Belen Basin is in the central rift area and is the largest and deepest of the basins (Kelley, 1977). The basin is believed to have a horst-and-graben structure allowing subsidence of the central graben along a series of normal faults. The basin is asymmetrical, with the east boundary dipping more steeply than the west. The east and south portions of the basin are the deepest. Unconsolidated to moderately consolidated sand and gravel (valley fill) fill the basin. This material was derived from the adjacent highlands during erosion. The thickness of the fill varies from thin at the margins to thick in the center. A cross section through the rift shown in Figure 1 illustrates these characteristics. The maximum thickness of the fill is unknown, however, the Shell Isleta well #2 possibly remained in the sediments down to 22,000 feet.

The geology on the Kirtland Base has been studied by Kelley and Northrup (1975), Kelley (1977), Reiche (1949), and Myers and McKay (1970, 1976). We field checked their work and summarized the geology as shown in Plate 1. Outcrops occur in the eastern half of the base area and alluvium covers the western half. Several faults cross the area; especially notable are the Tijeras fault and the Hubbell Springs fault. The Tijeras fault zone is a major structural feature that extends for miles to the northeast. This zone has had recurrent movement since the Precambrian and may represent a weakness in the crystalline basement (Kelley, 1977). The Tijeras fault outcrops in a large road cut on the Manzano Base and in a small mound to the southwest. Its southwest continuation is uncertain, as it disappears under the alluvium. The Hubbell Springs fault has a north-south trend and may be a primary rift fault. This fault is represented by a fault scarp on the Isleta Indian property south of Kirtland. Here, Permian beds are exposed. The northern continuation of this fault has not been confirmed, although Kelley and others suggest its presence west of the Manzano base. These two faults divide the base into at least 3 provinces. North of the Tijeras fault the geologic character is similar to the Sandia uplift.

ERA	SYSTEM	SERIES	UNIT	THICKNESS (FEET)	LITHOLOGY	WATER-BEARING CHARACTERISTICS
CENOZOIC	QUATERNARY	RECENT	ALUVIUM	0 TO 120±	COBBLES, GRAVEL, SAND, SILT, AND CLAY; UNCONSOLIDATED. GENERALLY UNDERLIES VALLEY FLOOR.	YIELDS LARGE QUANTITIES OF WATER OF GOOD TO FAIR QUALITY TO IRRIGATION, INDUSTRIAL, STOCK, AND DOMESTIC WELLS. WATER GENERALLY HAS A HIGH SILICA CONTENT.
			BAJADA DEPOSITS	0 TO 200±	BOULDERS, COBBLES, GRAVEL, SAND, AND SILT, CONSISTING OF FRAGMENTS OF FELDSPAR, QUARTZ, AND IGNEOUS AND METAMORPHIC ROCKS; UNCONSOLIDATED TO LOOSELY CONSOLIDATED.	GENERALLY LIE ABOVE THE WATER TABLE EXCEPT ALONG THE MOUNTAIN FRONT AT THE CONTACT WITH PRE-TERTIARY ROCKS. YIELD SOME WATER TO CONTACT SPRINGS AND MAY YIELD WATER TO A FEW DOMESTIC AND STOCK WELLS.
		PLEISTOCENE (?)				
	TERTIARY	MIOCENE (?)	SANTA FE GROUP	0 TO 6,100+	BOULDERS, COBBLES, GRAVEL, SAND, SILT, AND CLAY; UNCONSOLIDATED TO CONSOLIDATED BUT GENERALLY WEAKLY CEMENTED. INCLUDES INTERBEDDED VOLCANIC MATERIAL LOCALLY.	YIELDS LARGE QUANTITIES OF WATER OF GOOD QUALITY TO MUNICIPAL, INDUSTRIAL, IRRIGATION, STOCK, AND DOMESTIC WELLS. WATER GENERALLY HAS A HIGH SILICA CONTENT.
		EOCENE	ESPINASO VOLCANIC ROCKS OF STEARNS (1943)	400 TO 1,400	BRECCIA, CONGLOMERATE, AND TUFF.	DEEPLY BURIED IF PRESENT; NO WELLS ARE KNOWN TO BE COMPLETED IN THIS FORMATION.
		EOCENE AND OLIGOCENE (?)	GALISTEO FORMATION	900 TO 4,000	SANDSTONE, SAND, CLAY, AND SHALE.	DO.
MESOZOIC	CRETACEOUS	UPPER	MESAVERDE GROUP	1,500 TO 2,000	PREDOMINANTLY GRAY TO BLACK SHALE, INCLUDES SEVERAL PROMINENT BEDS OF BUFF-COLORED TO GRAY SANDSTONE AND SOME THIN BEDS OF COAL.	NO WELLS TAP THIS UNIT BECAUSE OF GREAT DEPTH. SANDSTONE BEDS YIELD WATER OF FAIR TO POOR QUALITY TO STOCK AND DOMESTIC WELLS IN ADJOINING AREAS.
			MANCOS SHALE	900 TO 2,500	PREDOMINENTLY GRAY TO BLACK SHALE; INCLUDES SEVERAL BEDS OF BUFF-COLORED TO GRAY SANDSTONE.	DO.
		LOWER	DAKOTA SANDSTONE	75 TO 110	SANDSTONE, BUFF TO TAN; INTERBEDDED SHALE.	DO.
	JURASSIC	UPPER	MORRISON FORMATION	210 TO 860	SHALE, GREEN, PINK, GRAY, AND MAROON, AND WHITE AND BUFF SANDSTONE MEMBERS.	DO.
			(ZUNI SANDSTONE) BUFF SANDSTONE	100 TO 140	SANDSTONE, BUFF.	DO.
			SUMMERVILLE FORMATION	60 TO 120	SANDSTONE AND SANDY SHALE, RED TO GRAY.	DO.
			TODILTO LIMESTONE	40 TO 250	TWO BEDS OF LIMESTONE SEPARATED BY A THICK BED OF GYPSUM.	BURIED DEEPLY; YIELDS LITTLE OR NO WATER. WATER HAS A HIGH SULFATE CONTENT.
			ENTRADA SANDSTONE	160 TO 220	SANDSTONE, CROSS-BEDDED, RED TO GRAY.	BURIED DEEPLY; YIELDS WATER TO STOCK AND DOMESTIC WELLS IN ADJOINING AREAS. QUALITY OF WATER GENERALLY POOR BECAUSE OF HIGH SULFATE CONCENTRATION.
	TRIASSIC	UPPER	CHINLE FORMATION	1,100	SHALE, RED, AND CHANNEL DEPOSITS OF SHALY SANDSTONE; CONTAINS BEDS OF RED SANDSTONE AT TOP AND BOTTOM.	BURIED DEEPLY; YIELDS NO WATER TO WELLS. SANDY ZONES YIELD WATER TO DOMESTIC AND STOCK WELLS IN ADJOINING AREAS. QUALITY OF WATER GENERALLY IS POOR.
PALEOZOIC	PERMIAN		SAN ANDRES LIMESTONE	47 TO 470	INTERBEDDED LIMESTONE, GYPSUM, AND SANDSTONE.	BURIED DEEPLY; YIELDS WATER TO STOCK AND DOMESTIC WELLS IN ADJOINING AREAS.
			GLORIETA SANDSTONE	70 TO 220	SANDSTONE, FINE-GRAINED, BUFF TO WHITE, CONTAINS GYPSUM IN SOME AREAS.	DO.
			YESO FORMATION	400 TO 1,100	SANDSTONE AND SILTSTONE, TAN-BROWN TO RED.	BURIED DEEPLY; YIELDS LITTLE OR NO WATER TO WELLS.
			ABO FORMATION	810 TO 950	SANDSTONE, FINE- TO COURSE-GRAINED, AND SILT STONE; RED TO GRAY.	BURIED DEEPLY; YIELDS SMALL QUANTITIES OF WATER TO STOCK WELLS IN ADJOINING AREAS.
	PENNSYLVANIAN		MADERA LIMESTONE	450 TO 2,000	LIMESTONE, GRAY TO RED; UPPER PART INCLUDES MORE CLASTIC MATERIAL THAN LOWER PART.	BURIED DEEPLY; ARKOSIC MEMBER YIELDS SMALL QUANTITIES OF WATER TO STOCK AND DOMESTIC WELLS IN ADJOINING AREAS.
			SANDIA FORMATION	0 TO 415	SANDSTONE, SHALE, AND LIMESTONE, BROWN, GRAY, RED, AND BLACK; UPPER PART GENERALLY CLASTIC MATERIAL, LOWER PART GENERALLY LIMESTONE.	BURIED DEEPLY; YIELDS SMALL QUANTITIES OF WATER TO STOCK AND DOMESTIC WELLS IN ADJOINING AREAS.
	PRECAMBRIAN			18,000+	METAMORPHIC AND IGNEOUS ROCKS.	SURFICIAL WEATHERED AND FRACTURED ZONES YIELD SMALL QUANTITIES OF WATER OF SPRINGS AND WELLS ALONG MOUNTAIN FRONT FOR STOCK AND DOMESTIC SUPPLIES.

*BJORKLUND AND MAXWELL, 1961.

Figure 1. Generalized Section of Geologic Formations in the Albuquerque Area, Bernalillo and Sandoval Counties, New Mexico.



GEOLOGIC MAP OF KIRTLAND AIR FORCE BASE and VICINITY, BERNALILLO CO., NEW MEXICO

SCALE 1:50 000

1/2 0 1 2 3 4 MILES

3000 0 3000 6000 9000 12000 15000 18000 21000 FEET

1 .5 0 1 2 3 4 5 KILOMETRES

CONTOUR INTERVALS 20 FEET AND 80 FEET

EXPLANATION

QUATERNARY ROCK
- Qal : Alluvium
- Qt : Travertine

PERMIAN ROCKS
- Pa : Abo Formation

PENNSYLVANIAN ROCKS
- IPs : Sandia Formation
- IPm : Madera Formation

PRECAMBRIAN ROCKS
- p€gs : Sandia Granite
- p€bg : Biotite Granite
- p€q : Quartzite
- p€a : Amphibolite
- p€mr : Metarhyolite
- p€s : Phyllite and Schist
- p€g : Greenstone

fault (inferred) downthrown

Geology from published maps of Reiche (1949); Myers and McKay (1970, 1976); Kelley (1977); and reconnaissance, Riddle and Grant, 1980.

SEPTEMBER 1980

The granite exposure on the Manzano Base dips at least 45° under the alluvium to the west (see discussion of geophysical surveys). South of the Tijeras and east of the Hubbell Springs fault the strata form a flat-lying bench covered with a thin veneer of alluvium. This flat, low-lying province is probably associated with the Manzanita uplift. West of the Hubbell Springs fault the basement drops off drastically to form the deep basin.

The Tijeras fault and the Hubbell Springs fault intersect near the center of the Base. The configuration of this intersection is unknown. The interpretation shown on Plate 1 is merely one of many, and agrees with Reiche (1949). Other faults cross the area, some of which are shown on Plate 1. Chuck Reynolds, of Reynolds and Associates, believes 3 faults cross the south base boundary in section 4 (personal communication). This idea is based on a seismic line that he conducted in 1976. Some limited evidence suggests a subsurface fault near the eastern edge of the golf course.

During our field investigation, we located extensive travertine deposits and plotted them on Plate 1. Detailed field investigation should be conducted to define the limits of this unit. The travertine has a variable character ranging from massive to conglomeritic. In places the conglomerate is composed of angular pink quartzite pebbles and cobbles. This particular conglomerate overlies a massive travertine and was found in Coyote Arroyo. Another conglomeritic travertine is composed of limestone boulders and cobbles derived from the Madera foundation. This conglomerate was found in a road cut west of the Solar Power Tower. In addition to the outcrops in the arroyo, the travertine forms mounds of considerable topographic relief southwest of Manzano Base. The overall character of the travertine suggests deposition by springs. Also interesting to note is that the mounds occur along the Tijeras fault and at the supposed intersection of the Tijeras and Hubble Springs faults. The mound near Coyote Springs, however, is an exception. It may be related to other faulting not indicated on plate 1, but suggested by Myers and McKay (1970).

Hydrology

Unfortunately, the hydrology of the Albuquerque basin is practically unknown below 5000 feet. Most wells in the area are completed in the Santa Fe formation above 1500 feet. A few oil and gas wells have been drilled through the Santa Fe and provide minimal yet valuable information. The following is a summary of data and speculation concerning the hydrology of the area.

The groundwater in the Rio Grande basin is under water table conditions. The water table slopes down from the Sandia and Manzano mountains in the east and from the Rio Puerco in the west. The depth to the water table increases away from the inner valley from 10 to 1000 feet toward the west mesa, and to 600 feet toward the east mesa. At the Kirtland base the water table occurs between 400-600 feet below the surface. Recharge to the groundwater system is accomplished by infiltration of precipitation and irrigation water, seepage from streams, canals, and surface reservoirs, and by flow from adjacent areas. The water is discharged through springs, seeps, drains, wells, and evapotranspiration (Bjorklund and Maxwell, 1961).

The principal aquifer in the basin is the valley fill. This fill is composed of Quaternary alluvium and the Santa Fe formation. The alluvium is a unit of unconsolidated sand and gravel with local occurrences of silt, clay, and dune sand. This unit has a maximum thickness of 1000 feet and will yield 500-1000 gallons per minute (g/m) of fresh water. Below the alluvium is the extensive Santa Fe formation. This formation is thought to be 10,000+ feet thick. Locally, it may be found 22,000 feet below the surface. The Santa Fe consists of unconsolidated to moderately consolidated sand, gravel, silt, clay, and volcanics. Wells completed in the Santa Fe can produce 500 to 2000 g/m and will yield fresh to slightly saline water. Underlying the valley fill is a series of consolidated sedimentary strata ranging from Mississippian to Tertiary age. The stra are interbedded limestones, sandstones, and shales. A stratigraphic section is shown for reference in Figure 1. These units are not well known in the basin, but are generally not considered to be aquifers. Near their outcrops, however, the Permian-Mississippian rocks yield up to 500 g/m of moderately saline to fresh water. At the base of the sedimentary units are Precambrian basement rocks. These rocks are igneous and metamorphic and contain groundwater only in highly fractured and weathered zones.

The water quality depends on the depth of the water-bearing zone (Kelly, 1974).

T. E. Kelley (1974) divides the groundwater in the Rio Grande Basin into four units classified by salinity. In the Albuquerque-Belen Basin he shows three units present: fresh, slightly saline, and moderately saline (Fig. 2). The saline and brine units have not been encountered in drillholes but would be expected if the sediments are present at depth. Kelly relates these salinity zones to aquifer temperature. Of interest are the moderately saline (3-10 g/l) and saline units (10-35 g/l). He predicts yields from these aquifers to be 100 to 500 g/m and aquifer temperatures to be 80°-100°C and 100°-150°C respectively. In the Albuquerque area the 100°C to 150°C zone would be found between 9000 and 14,000 feet. These predicted temperature zones are confirmed by local oil and gas wells, as shown by Figure 3.

Heat Flow

The Rio Grande rift is characterized by regional and local thermal anomalies. The regional anomaly may be the result of a thinning lithosphere with heat supplied by the upper mantle [Decker (1969) and Chapin (1971)]. Reiter et al (1975) suggest hydrothermal fluid migrations in deep fracture zones and possible shallow magma bodies as the cause. Cook et al (1978) also attribute high heat flow to the emplacement of shallow magma bodies. Other researchers favor emplacement of deep (15-30 km) magma bodies [Harder et al (1980), Reiter et al (1978)]. Local thermal anomalies could be the result of shallow, young (< 50,000 yrs)

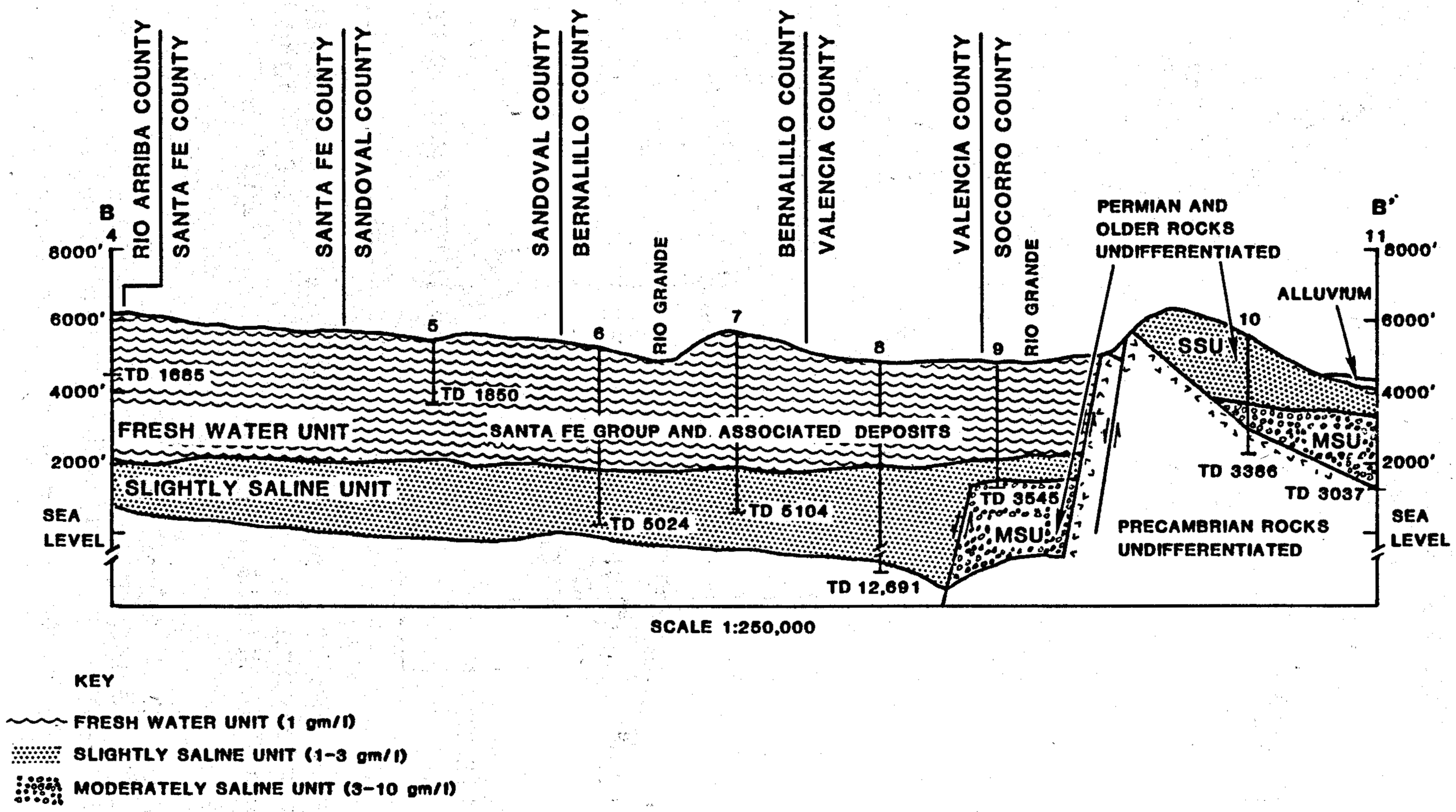


Figure 2. Groundwater Units in the Albuquerque-Belen Basin (Kelly, 1974).

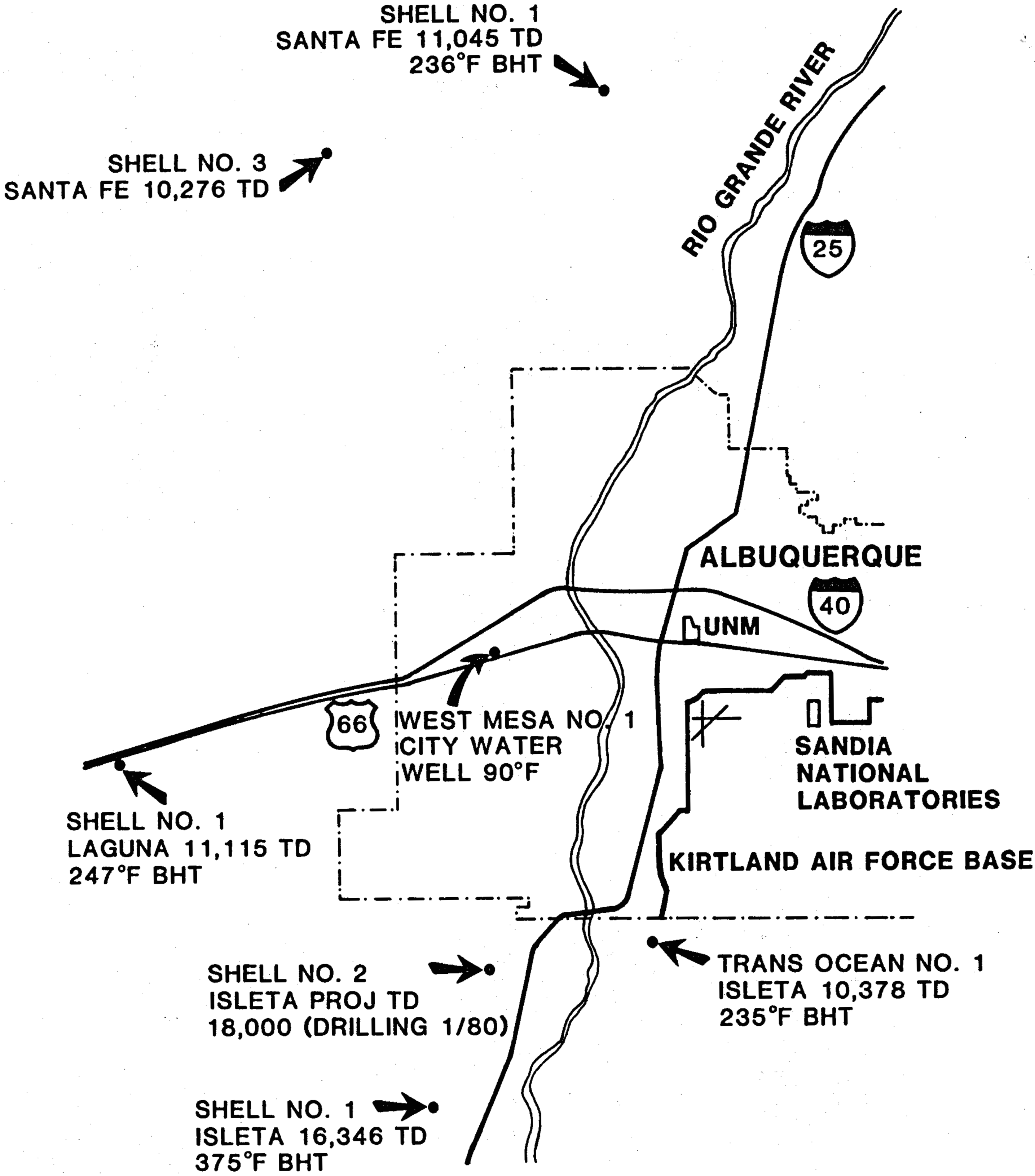


Figure 3. Location, Depth and Bottom Hole Temperature of Local Wells.

intrusions, but forced groundwater convection is considered more reasonable [Harder et al, (1980), Parker and Jiracek, (1980)].

The north-south trend of the regional anomaly was mapped by Reiter et al (1975, 1979). This heat flow map is included in Figure 4. Reiter et al (1979) also calculated the heat flow for the Albuquerque-Belen Basin to be 2.35 HFU. However, the three heat flow holes tested near Albuquerque have measurements of 1.08, 1.56, and 1.43 HFU (Reiter et al, 1978, 1979). In addition, the Kirtland base is located at the edge of the anomaly where the heat flow ranges from less than 1.5 to 2.0. These low heat flow values are not considered abnormal and are similar to values measured in the Great Plains province.

Parker and Jiracek (1980) have conducted a geothermal exploration program in Albuquerque. They used temperature gradients in oil and gas and water wells to evaluate the local geothermal potential. They discovered several anomalies: Llano de Atrisco west of Albuquerque; Volcanoe Cliffs, West Mesa; and several well fields east of the Rio Grande. They interpret one of these anomalies as the result of deep water being forced over a buried magnetic feature. Except for these areas, the basin at Albuquerque has a normal geothermal gradient. Above 3 km, a gradient of 33°C/km should be expected, and below 3 km, 40°C/km is expected.

Water wells at Kirtland do not produce abnormally warm water (J. Richardson, personal communication) and thus, no geothermal anomaly is expected. The alluvial section, however, may be deep

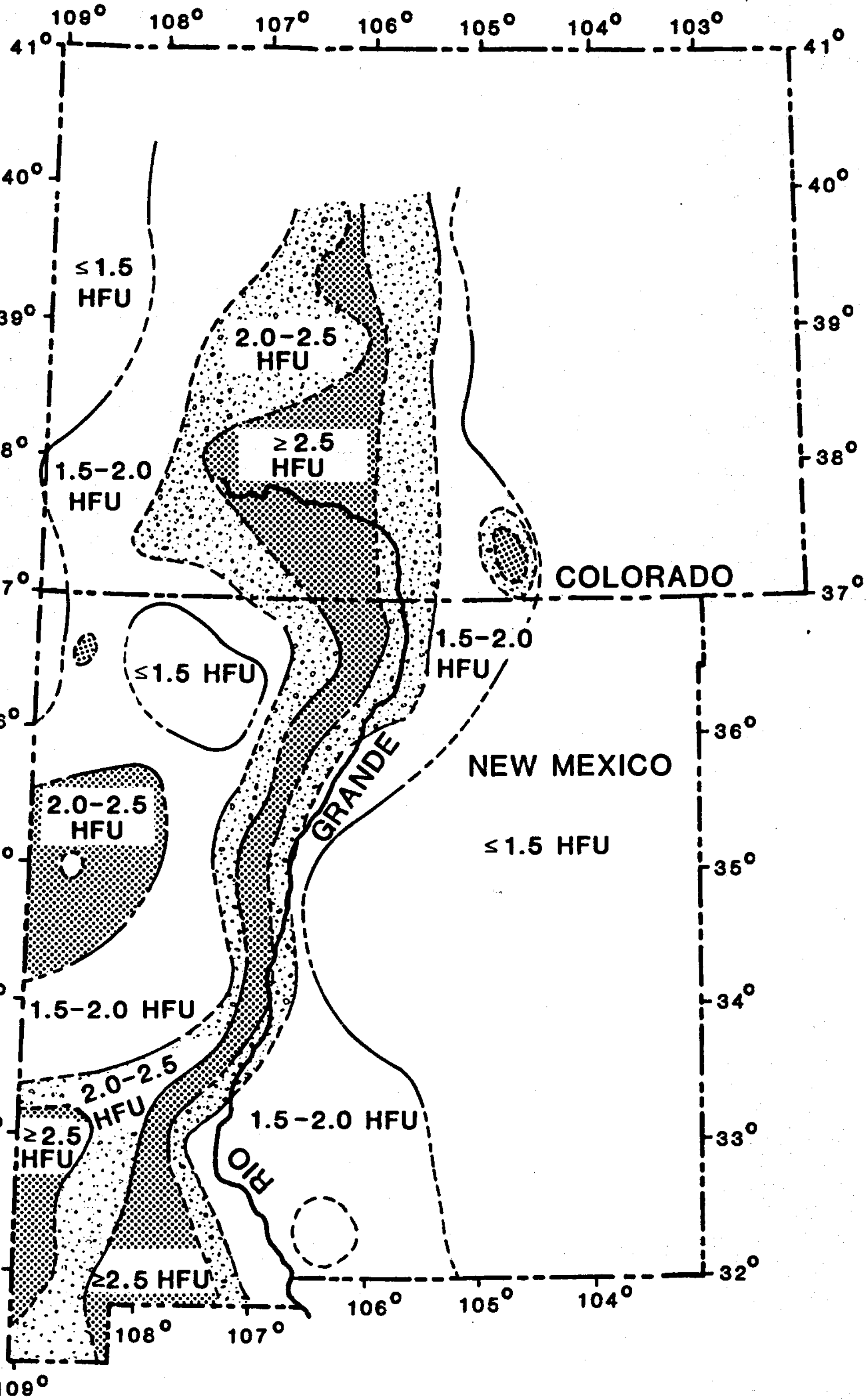


Figure 4. Heat flow map of New Mexico and Colorado (Reiter et al, 1979).

enough to produce hot water heated by the normal geothermal gradient. Using the graph constructed by Parker and Jiracek (1980), shown in Figure 5, 300°F water could be found between 12,000 and 14,000 feet. These data agree with predictions supplied by T. E. Kelly (1974), as discussed in the previous section.

Geophysics

Several geophysical studies have been conducted on the Rio Grande Rift (Cordell, 1978). In general, these studies have been focused on regional trends. The results suggest that mantle material has penetrated the crust (Cordell, 1976), Precambrian structures have influenced the Cenozoic faulting (Cordell, 1978) and the rift has relatively low seismicity compared to other continental rift zones (Cordell, 1978). The steep gravity gradients shown on Cordell's gravity map (Cordell et al, 1973) indicate the basin boundary faults. Cordell's interpretation is illustrated in Figure 6. The Hubbell Springs fault shown crosses the Kirtland Base.

The Albuquerque-Belen Basin has received considerable attention in recent years. Most studies, though, have been located near Socorro and are programed toward characterizing a shallow (19 km) magma body thought to exist there [Reilinger et al (1980), Chapin et al (1978), Rinehart et al (1979), Sanford et al (1977)]. Other studies include seismicity analysis, a detailed gravity profile, and a magnetic study. The seismicity near Albuquerque can be related to known fault zones [Olsen et al (1979) and

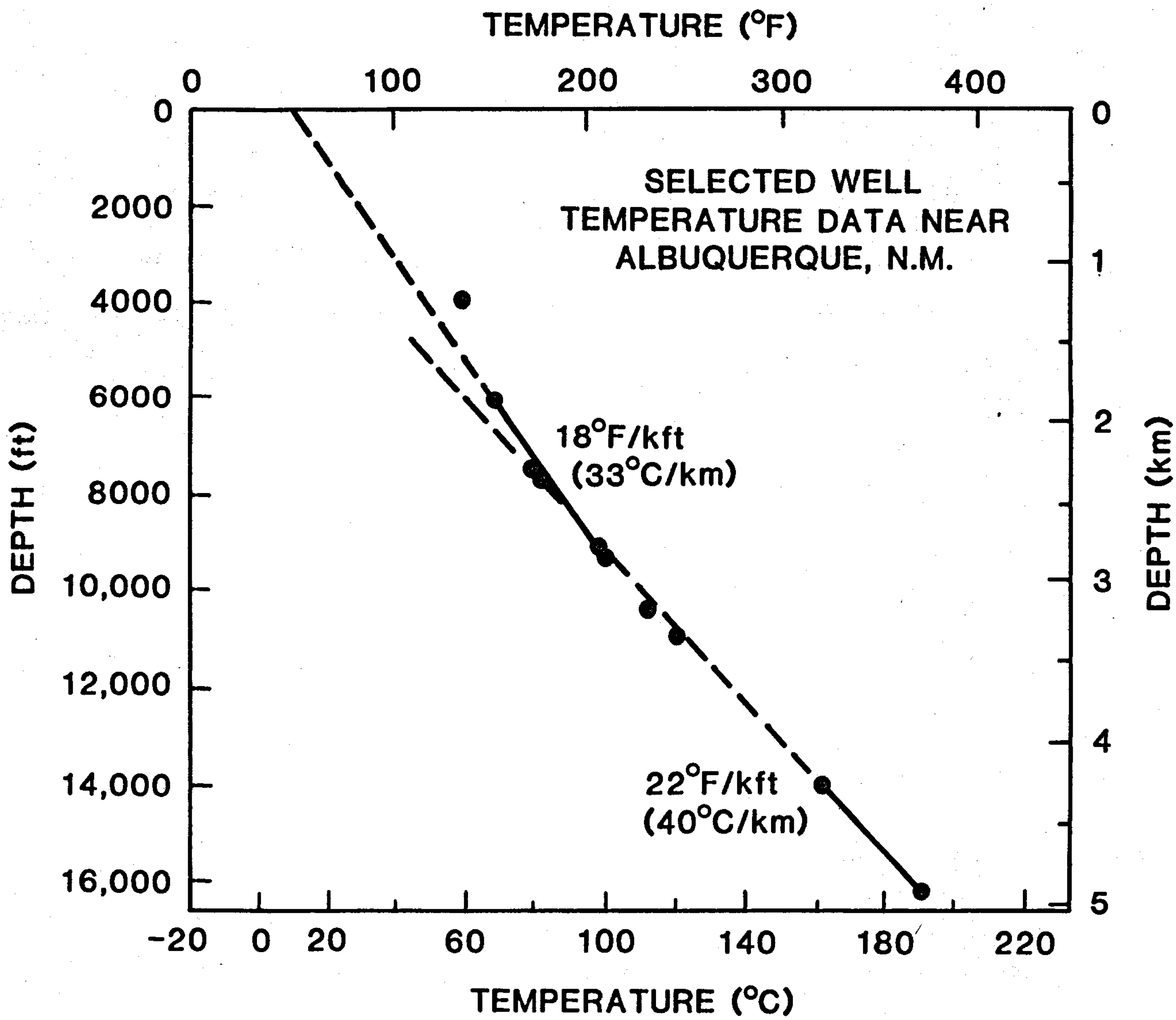


Figure 5. Temperature gradients at Albuquerque, New Mexico (Parker and Jiracek, 1980).

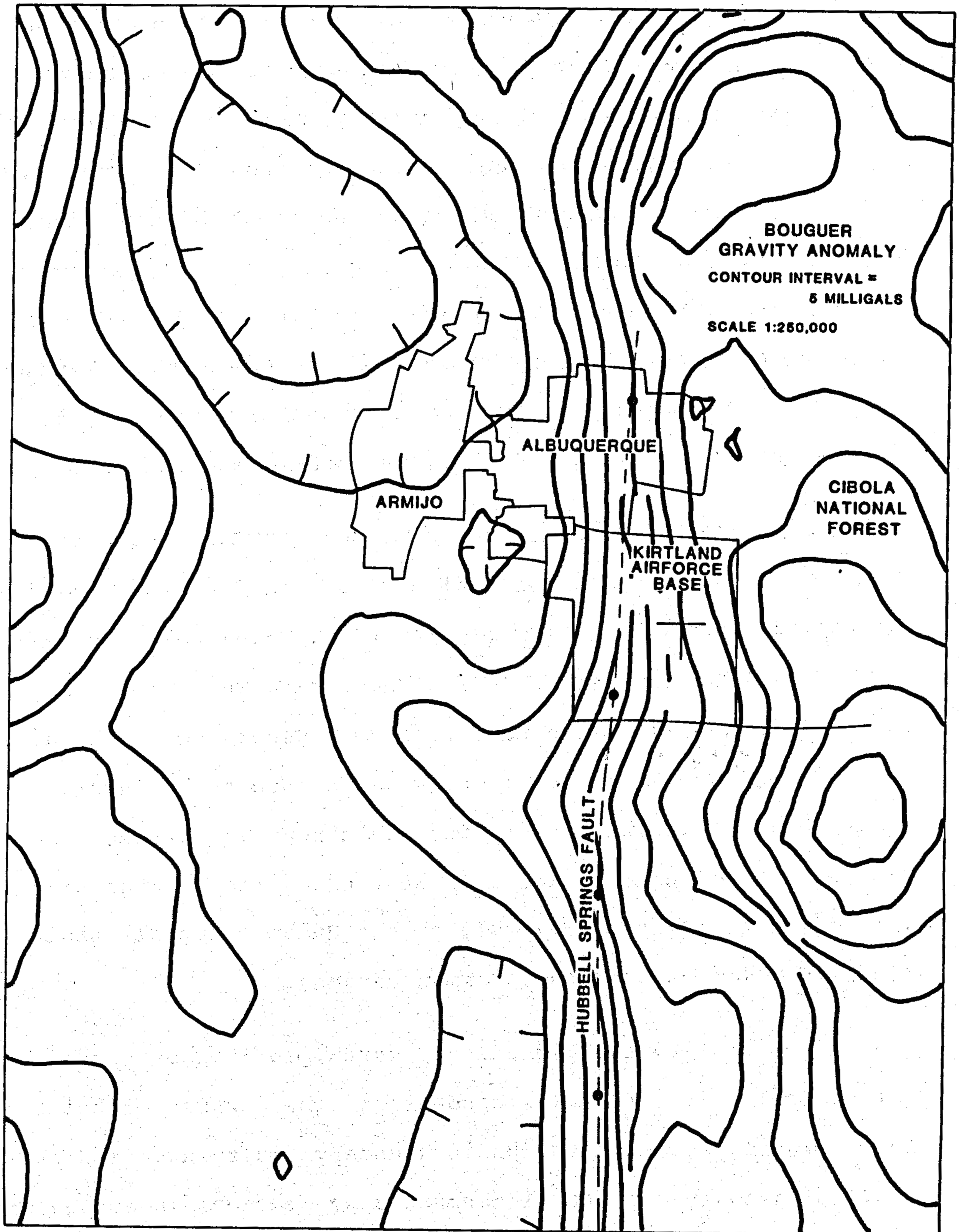


Figure 6. Bouguer Gravity Map of Albuquerque-Belen Basin Cordell (1973).

Jaksha et al (1979)]. Cordell's detailed gravity profile is located along Tramway Road. His data suggest the presence of two buried faults. One of the faults probably has increasing relief southward and the other has decreasing relief southward. At Tramway, the structural relief on one fault is approximately 1-2 kilometers (Cordell, 1978b). Cordell's gravity data were further utilized in a basin analysis by Birch (1980). One of Birch's maps shows the deepest part of the basin under Kirtland (Fig. 7). The magmatic study is in progress; therefore, no results are available (M. Parker, personal communication).

Geophysical studies at the Kirtland Air Force Base are limited. A local engineering firm, Koogle and Pools, conducted gravity readings and a Sandia group (Org. 2326) collected seismometer readings in Tech Area I. These data were used for experimental purposes and have no direct geological applications. In 1975 and 1976, a seismic survey was conducted by Charles Reynolds and Associates along the south boundary of the base. The results indicate at least three faults crossing the boundary in section 4. One of these may be the Hubbell Springs fault (Charles Reynolds, personal communication).

As part of this exploration program, an in-house audio-magneto-telluric survey was conducted. The purpose of this survey was to look for the basin boundary fault suggested by the regional gravity map, and interpreted by previous investigators (Reiche 1949, and Kelley and Northrup, 1975, Kelley, 1977). A description of the equipment and method used is described by

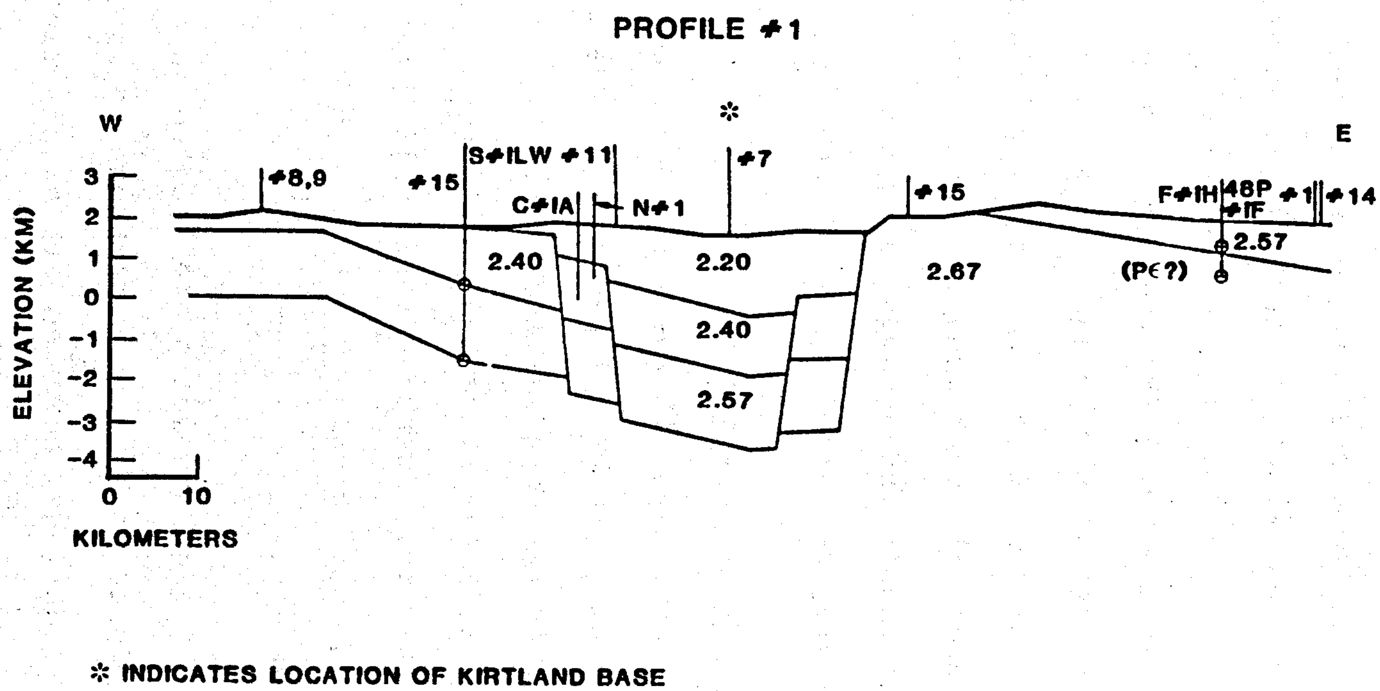


Figure 7. Cross Section of Albuquerque-Belen Basin, Birch (1980).

Bartel in the appendix. His interpretation is also included. The Precambrian outcrop on the Manzano base dips under the alluvium with at least a 45° angle (L. Bartel, personal communication). Near the western limit of their survey, Bartel believes a fault is present. The alluvium at the site of the survey is a minimum of 1300 m thick (Bartel, see appendix). If this trend continued westward or the beds are down-faulted further west, a sedimentary section 15,000 feet thick or greater could be encountered under the Tech Area I. Thus, with the average geothermal gradient, and assuming a sufficient aquifer, water with temperatures near 150°C could be realized.

Geochemistry and Geothermometry

Geochemistry and geothermometry have been used to characterize and develop geothermal resources. The information acquired in these studies has been applied to exploration. The exploration sites have, however, been concentrated in areas of obvious geothermal activity. Swanberg (1975) illustrates that these techniques can also be used to detect a thermal component in non-thermal waters.

Several springs and wells are located on and around the Kirtland Air Force Base. None are known to have abnormal temperatures. Coyote Springs, however, are highly mineralized and one emits a considerable amount of CO_2. The chemical data presented here were acquired through three sources: the USGS WATSTORE file, the base engineering office, and from samples that we collected in the course of the study. The WATSTORE file contains information from both springs and wells. The locations of these springs and wells are shown in Figure 8.

The sampling method we used was recommended by Fraser Goff of Los Alamos Scientific Laboratory and is described in detail by Goff et al (1977) and Thompson. At each location, temperature, flow rate, pH, and chloride were measured. Three sample bottles were also collected per site.

125 ml bottle containing 90 ml distilled water, to which 10 ml filtered sample water was added

500 ml bottle filtered sample water

500 ml bottle filtered sample water acidified to a ph $\leq$ 2

The samples were analyzed for major cations at the Los Alamos Laboratory. Atomic absorbtion spectros copy was used to determine concentrations of SiO_2, Fe, Mn, Ca, Mg, Na, K, and sulfuric acid titration was used to determine HCO_3 concentration. In addition, isotope samples were collected at Coyote Springs, well 10, and Hubble Spring. These samples were each contained in 125 ml glass bottles. The isotope samples were analyzed for ^{18}O and deuterium concentrations by L. Merlivat, Department de Recherche et Analyse, Saclay, France, by standard methods. The results of all analyses are shown in Table 1.

The chemical analyses performed allow the calculation of subsurface temperatures using equations developed by Fournier and Truesdell (1973), Fournier and Potter (1979), and Fournier and Rowe (1966). These equations are based on the assumptions

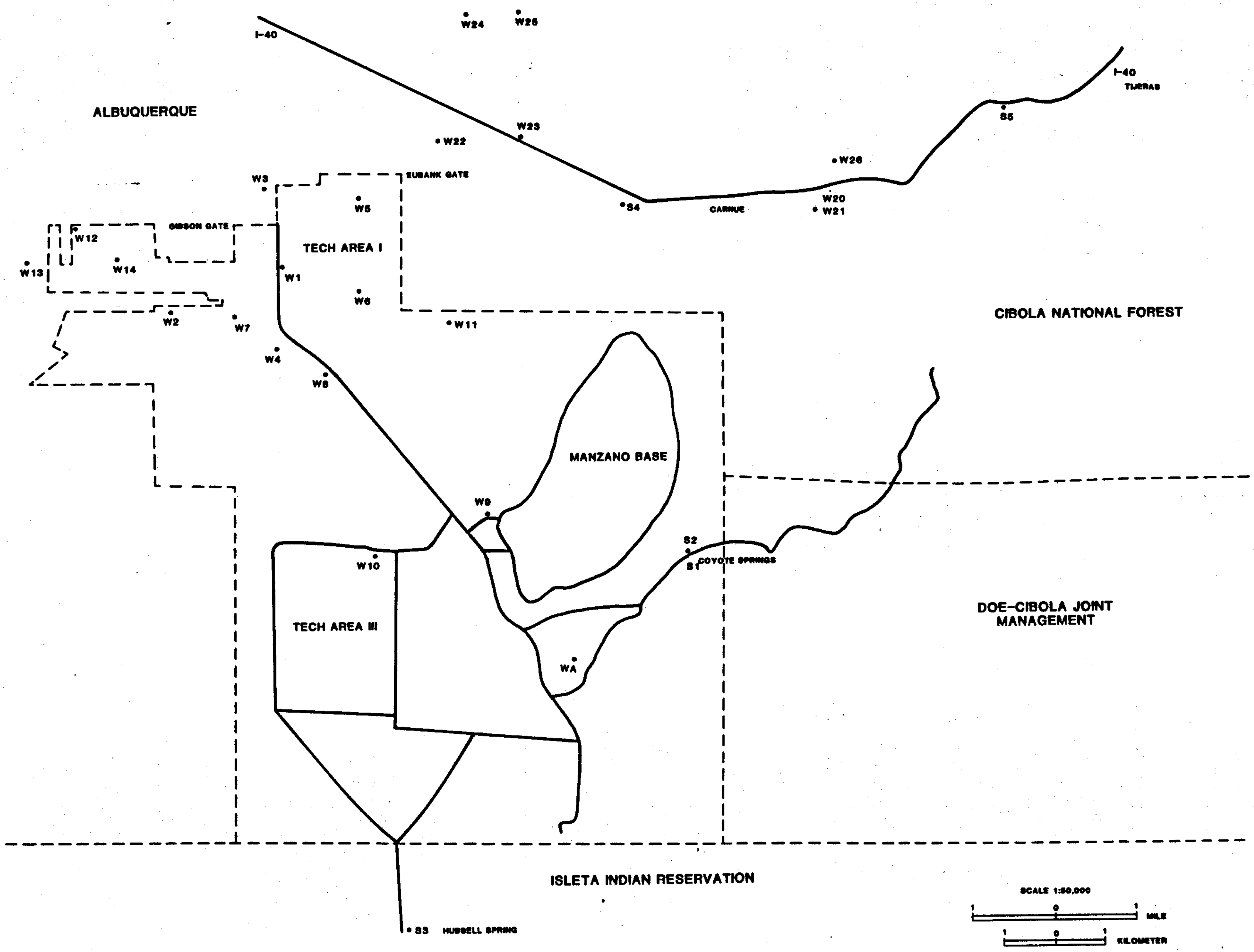


Figure 8. Location of Springs and Wells.

Table 1. Chemical Analyses[a] from the Kirtland Air Force Base Area[b]

Well or Spring	(Ft) Depth	SiO_2	Na	Ca	K	Mg	Fe	Mn	HCO_3	SO_4	Cl	F	B	NO_2/NO_3	pH	G
S_1		18	329.	260	26.0	55.7			1133		478.0		0.97		6.0	3200
S_2		19	179.	184	11.2	39.8			730		323.0		0.41		6.0	1990
S_3		27	53.	79	1.3	29.6			228		220.0		0.00		5.0	870
S_4		19	39.	114	4.8	25.0			273		96.0		0.00		6.0	980
S_5		17	18.	100	1.4	17.7			288		46.0		0.00		6.0	710
WA	250	10	30.	68	4.0	9.2			221		37.0		0.00		6.0	570
W_1	1199	25	26.	52	2.9	7.3	1.10	.01	169	62	13.0	0.6		0.69	8.0	450
W_2	1000	35	23.	34	2.3	5.1	0.02	.00	136	28	13.0	0.5		0.12	6.8	308
W_3	900	27	22.	37	2.3	4.7	0.45	.00	148	24	95.0	0.6		0.56	6.8	305
W_4	1000	29	25.	50	3.0	8.7	0.02	.00	185	50	11.0	0.6		0.68	8.4	434
W_5	1004															
W_6	1006	24	25.	59	2.8	9.8	0.07	.00	199	61	12.0	0.6		2.10	7.7	494
W_7	1010	25	21.	36	2.3	5.8	2.10	.00	147	26	9.0	0.5		0.50	7.9	318
W_8	1000	28	27.	64	2.7	11.0	0.57	.00	206	61	15.0	0.5		3.70	7.0	505
W_9	650															
W_{10}	1050	29	51.	62	4.2	19.4			278		46.0		0.05		5.0	720
W_{11}	1327	26	28.	71	3.0	13.0	2.10	.00	212	59	16.0	0.5		8.90	7.6	586
W_{12}	1032	38	21.	41	3.0	7.2	0.11	.03	127	44	21.0	0.4		0.50	7.9	381
W_{13}	1000	38	17.	31	3.0	5.5	2.10	.00	124	31	8.3	0.5		0.01	7.9	387
W_{14}	1000	43	20.	32	4.7	5.2			116		51.0		0.00		5.0	300
W_{20}		25	40.	170	2.6	31.0	0.01		560	120	36.0	1.6	0.05	0.83	6.9	1180
W_{21}		30	37.	180	3.8	40.0	0.01		726	110	25.0	1.8	0.05	0.14	6.8	1230
W_{22}		26	37.	26	2.8	3.7	0.00			34	7.5	1.2			7.6	350
W_{23}	1800	24	28.	37	2.4	3.3	0.04		151	83	6.9	0.7	0.03		8.0	339
W_{24}	1411	34	41.	19	1.9	0.9	0.04	0.00	139	21	5.4	1.0	0.006		8.2	283
W_{25}			4.4	100	0.8	7.8		0.01	353	24	3.8	0.2	0.04		7.0	562
W_{26}		24	7.8	77	0.7	7.3			257	18	3.2	0.2			7.7	426

a) Samples S_1–D_5, WA, W_{10}, W_{14} analyzed at Los Alamos Labs
Samples W_1–W_8, W_{11}–W_{13} data from Base Engineering
Samples W_{20}–W_{26} from USGS WATSTORE file
Units in mg/l except pH, G, and depth
G = conductance in μMhos
depth = feet

b) See Area Map for Spring and Well Locations that certain element concentrations in subsurface water are dependent on temperature and that their concentrations do not change during ascent to the surface. The geothermometer equations used are:

$$\text{NaKCa} \quad T(^\circ C) = \frac{1647}{\log(\frac{Na}{K}) + \beta\log(\frac{Ca^{1/2}}{Na}) + 2.24} - 273.15$$

where

Na, K, Ca are in molality

and β = 4/3 for low temperature and 1/3 for high temperature waters

$$SiO_2 \text{ (quartz)} \quad T(^\circ C) = \frac{1315}{(5.205 - \log(SiO_2))} - 273.15$$

$$SiO_2 \text{ (amorphous } SiO_2\text{)} \quad T(^\circ C) = \frac{731}{(4.52 - \log(SiO_2))} - 273.15$$

where SiO_2 is in mge

The results of these calculations can be found in Table 2. The temperatures indicate that normal subsurface conditions prevail.

As shown by the isotope plot in Figure 9, the waters follow the Craig Meteoric Trend and thus are primarily meteoric. Coyote Spring has high Cl and a high N-K-Ca temperature. This may be due to a component of connate water mixing with the meteoric water. The low SiO_2 temperature supports this observation. All other geo-thermometer temperatures indicate normal conditions.

Table 2. Subsurface Temperature Calculations from Geothermometers

Well or Spring	Temperature (°C)	T_{NaKCa}(°C)	$T_{SiO_2(Q)}$(°C)	$T_{SiO_2(AS)}$(°C)
S_1	15.5	87.0	59.8	-49.2
S_2	15.2	61	61.8	-47.6
S_3	17.0	11.1	75.3	-36.5
S_4		33.1	61.8	-47.6
S_5		32.7	57.7	-50.9
W_A		35.0	39.6	-65.5
W_1		30.3	72.3	-39.0
W_2		30.6	86.0	-27.5
W_3		28.8	75.3	-36.5
W_4		31.4	78.2	-34.1
W_5				
W_6		27.1	70.7	-40.3
W_7		28.6	72.3	-39.0
W_8		25.6	76.8	-35.3
W_9				-
W_{10}	23.0	42.4	78.2	-34.1
W_{11}		26.7	73.8	-37.7
W_{12}		33.3	89.6	-24.5
W_{13}		36.2	89.6	-24.5
W_{14}	22.0	49.1	95.0	-19.9
W_{20}	16.0	10.3	72.3	-39.0
W_{21}	16.0	20.0	79.6	-32.9
W_{22}	26.5	44.1	73.8	-37.7
W_{23}	24.5	31.8	70.7	-40.3
W_{24}	25.0	40.3	84.8	-28.5
W_{25}	13.5	-17.1		
W_{26}		-13.1	70.7	-40.3

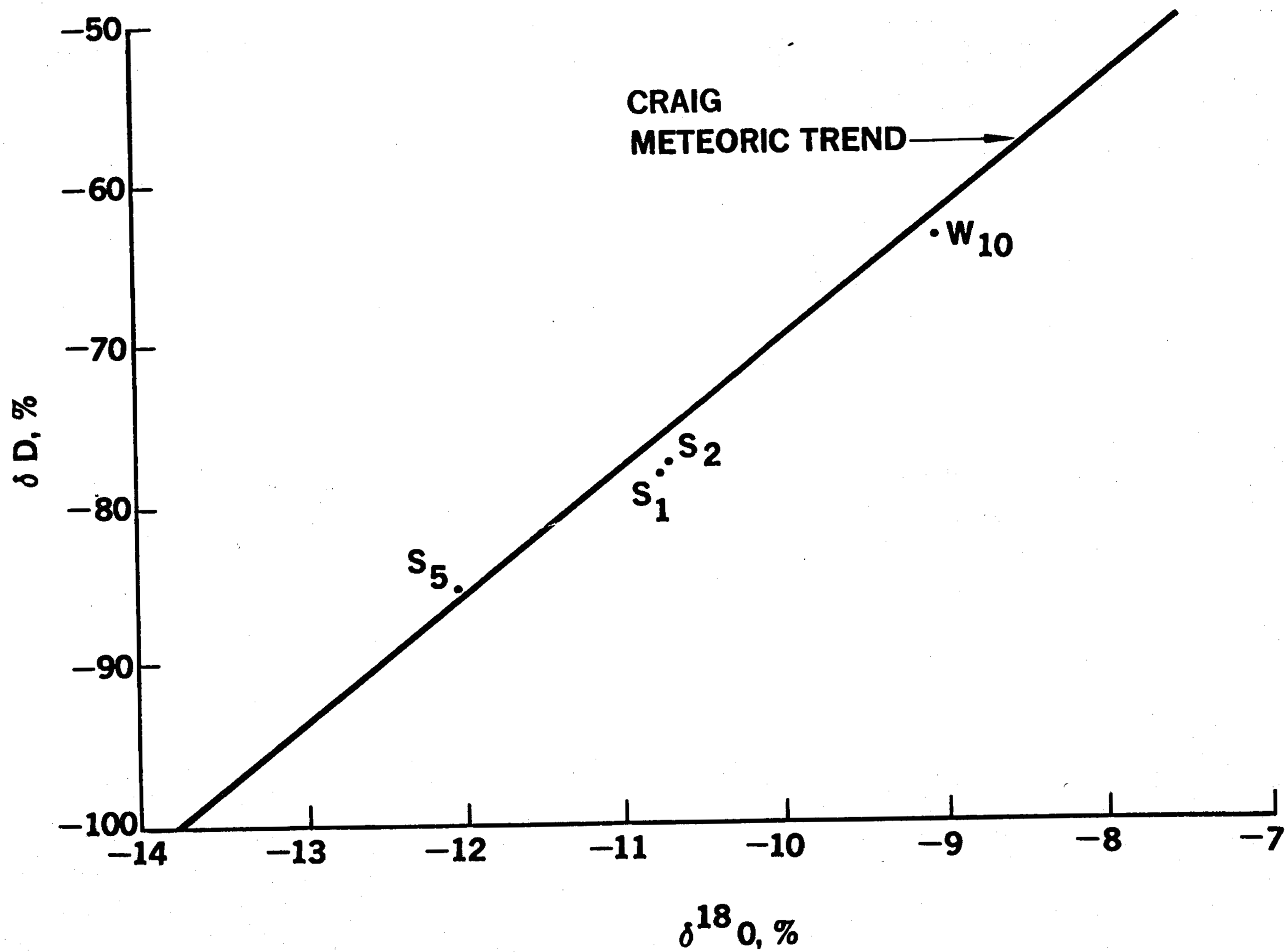


Figure 9. Ratio of Deuterium to ^{18}O Concentration for Spring Water Samples.

Summary of Results

This investigation has revealed two potential models for tapping geothermal energy: the basin model and the fault model. The basin model will allow a deep well to be drilled near the existing steam circulation system. This close proximity to the system would eliminate losses due to fluid transport from a remote area. The fault model on the other hand could eliminate deep drilling. Due to remote fault location, the fault model would, however, require transport of the fluids 1-2 miles to user location. These models are illustrated in Figure 10.

Basin Model

The deep Albuquerque-Belen Basin possibly extends east to the Kirtland Base area. Thus, a thick, water-saturated, alluvial section may underly the Kirtland Base. Below the alluvium, the Mesozoic and Paleozoic strata, if present, may contain limited amounts of water. These units would be useful if sediments are not present at depths required for sufficient temperature. A normal geothermal gradient of 33°/km down to 3 km and 40°C below 3 km is expected. To encounter 300°F, the well would have to be drilled to 13,500 feet (Parker and Jiracek, 1980). The water at these depths is expected to be slightly to moderately saline and would rise to the water table under hydrostatic head.

Fault Model

Several major faults cross the Base area and extensive travertine has been deposited at their intersection. The

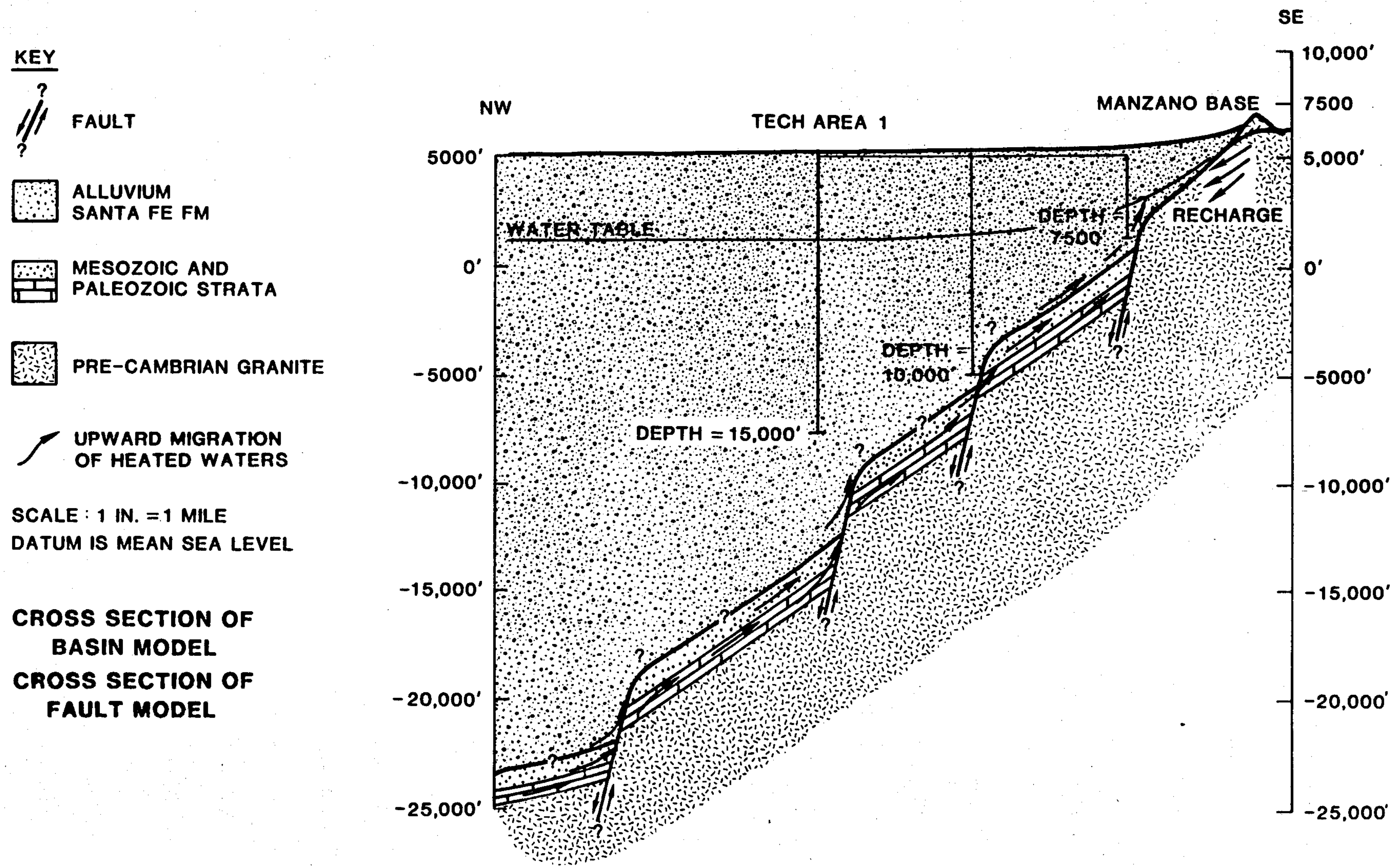


Figure 10. Cross Section Showing Basin and Fault Models.

travertine does not require hot waters, but is common to hot spring activity. The travertine does suggest that large quantities of water have migrated in the faults. The geochemical data do not support thermal fluids. The geochemical data may, however, be masked by the large amounts of cold meteoric water injected in the nearby mountains. If water in the basin is heated, it would become buoyant and migrate along faults to the surface. Depending on the depth of origin of the water, its temperature and salinity would have a wide range of possibilities.

The above models each have a fundamental question to be answered. Are the sediments thick enough and water-saturated under the Kirtland Base? Is there water of sufficient quantity and temperature in the fault zones? We have initiated a program to answer these questions. We have communicated with Larry Jaksha of the U.S. Geological Survey Seismological Lab and several workers at the Civil Engineering Research Facility (CERF). We hope to use the upcoming CERF explosive tests and possibly monitor explosives at the Jackpile Mine near Grants, New Mexico in a seismological exploration program. Sufficient equipment may be acquired in-house or elsewhere to monitor these explosives. The results of these studies could be used to estimate basin thickness and to pinpoint subsurface faults.

In addition to the above program, other studies should be conducted to complete the preliminary survey. Depending on the amount of equipment available, and the quality of the results, the project may move on to temperature gradient holes. The value of shallow temperature-gradient holes should be investigated. Several factors, including current knowledge of gradients, effect of the water table and cold water recharge, and depth necessary for reliable results, must be considered before the expense is taken to acquire these data. Studies also need to be conducted to further define the limits of the travertine and the nature of exposed fault zones. Extensive seismological studies may be required, such as a series of of VIBROSEIS lines, to acquire definitive subsurface data.

APPENDIX A

Use of CSAMT Technique to Map a Fault on KAFB

APPENDIX A

Use of CSAMT Technique to Map a Fault on KAFB

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R. D. Jacobson and P. M. Drozda, 4734

The controlled source audio-magnetotelluric (CSAMT) electromagnetic (EM) geophysical prospecting technique was used to locate a major fault on Kirtland Air Force Base. The CSAMT technique utilizes signals produced by a transmitter operating at selected frequencies. The ordinary AMT technique utilizes random occurring signals from natural sources. Under certain circumstances the plane wave interpretations of data for the ordinary AMT can be applied to the CSAMT.

The CSAMT technique is an EM induction technique where the primary EM field is produced by a long dipole (bipole) laid out on the surface of the earth and grounded at both ends with a transmitter located at the center of the dipole. The receiving antenna used for these measurements consists of a relatively short dipole in contact with the earth at both ends to measure the electric field and a ferrite wound coil to measure the magnetic field. Figure A-1 illustrates the technique where the transmitting and receiving antennas are shown. The electric field (E_x) is measured parallel to the transmitting antenna, and the magnetic field (H_y) is measured perpendicular to the transmitting antenna. The z-direction is into the earth. Data were recorded using a microprocessor controlled data acquisition system.

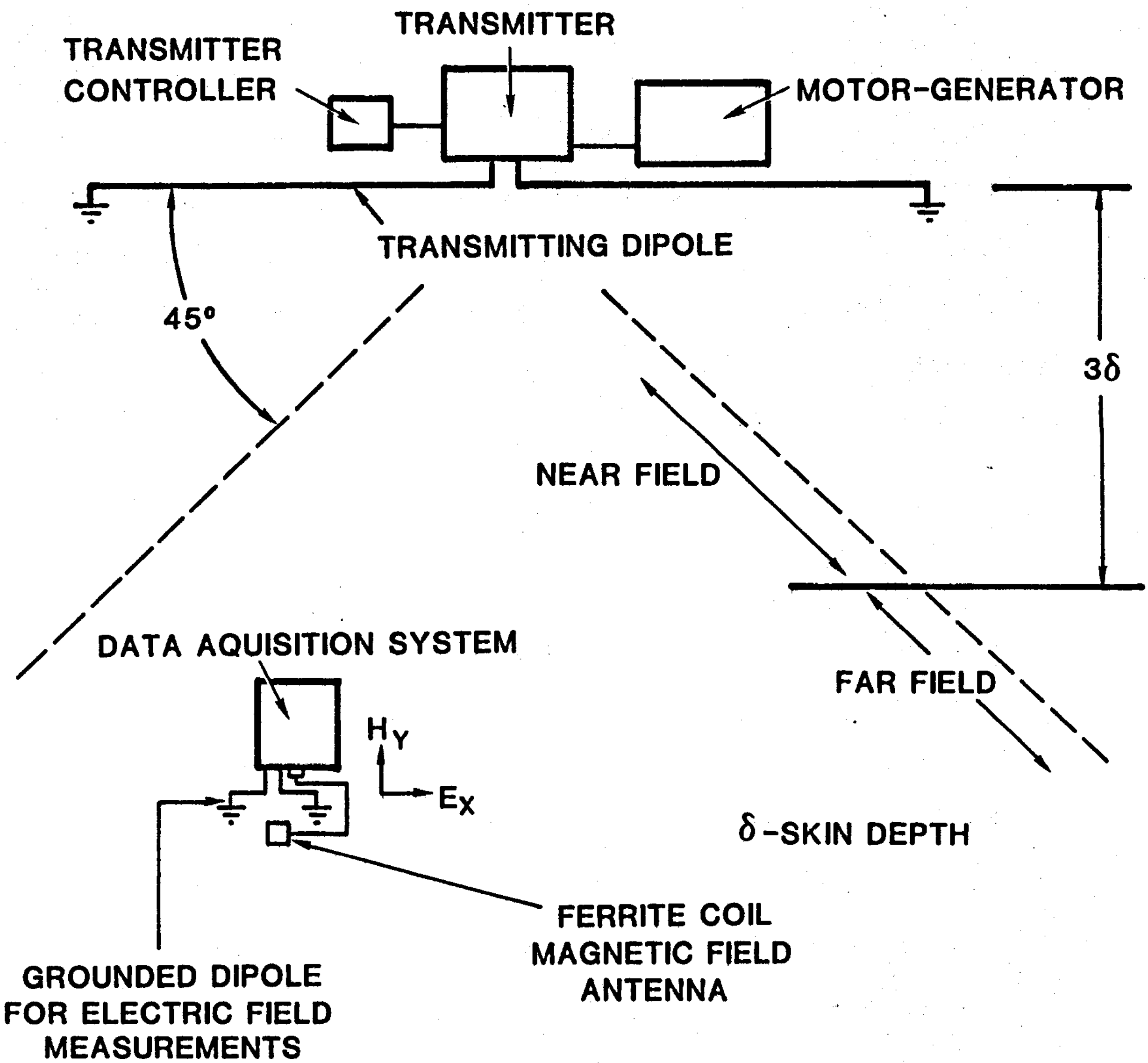

Figure A-1. CSAMT Geometry

The wave impedance is related to E_x/H_y and the apparent resistivity ρ_a in ohm-metres is given by

$$\rho_a = \frac{1.26 \times 10^5}{f} \left(\frac{E_x}{H_y}\right)^2 , \qquad (1)$$

where E_x is measured in volts/metre, H_y is measured in volts/amp, and f is the frequency. The skin depth δ is given by

$$\delta = 503\sqrt{\rho_a/f} \quad . \qquad (2)$$

When measurements of the EM fields are made at distances greater than 3δ (far field region) from the transmitting antenna, the apparent resistivity calculated using Eq. (1) corresponds to the "true" apparent resistivities. In the far field region plan wave solutions are appropriate. Measurements made at distances less than 3δ (near field region) yield an apparent resistivity which will be higher than the "true" apparent resistivity. Even though the near field resistivity values do not represent the "true" apparent resistivities, the near field measurements can be used to delineate subsurface variations if there are sufficient resistivity contrasts. Note that in order for the far field measurements to represent the "true" values of apparent resistivity, the measurements must be taken in the region within 45° about the perpendicular to the dipole, through the transmitter, as shown in Figure A-1.

The location of the survey lines along with the transmitter locations are shown in Figure A-2. The survey was done in parts of sections 9 and 10. The bearing of the transmitter line and

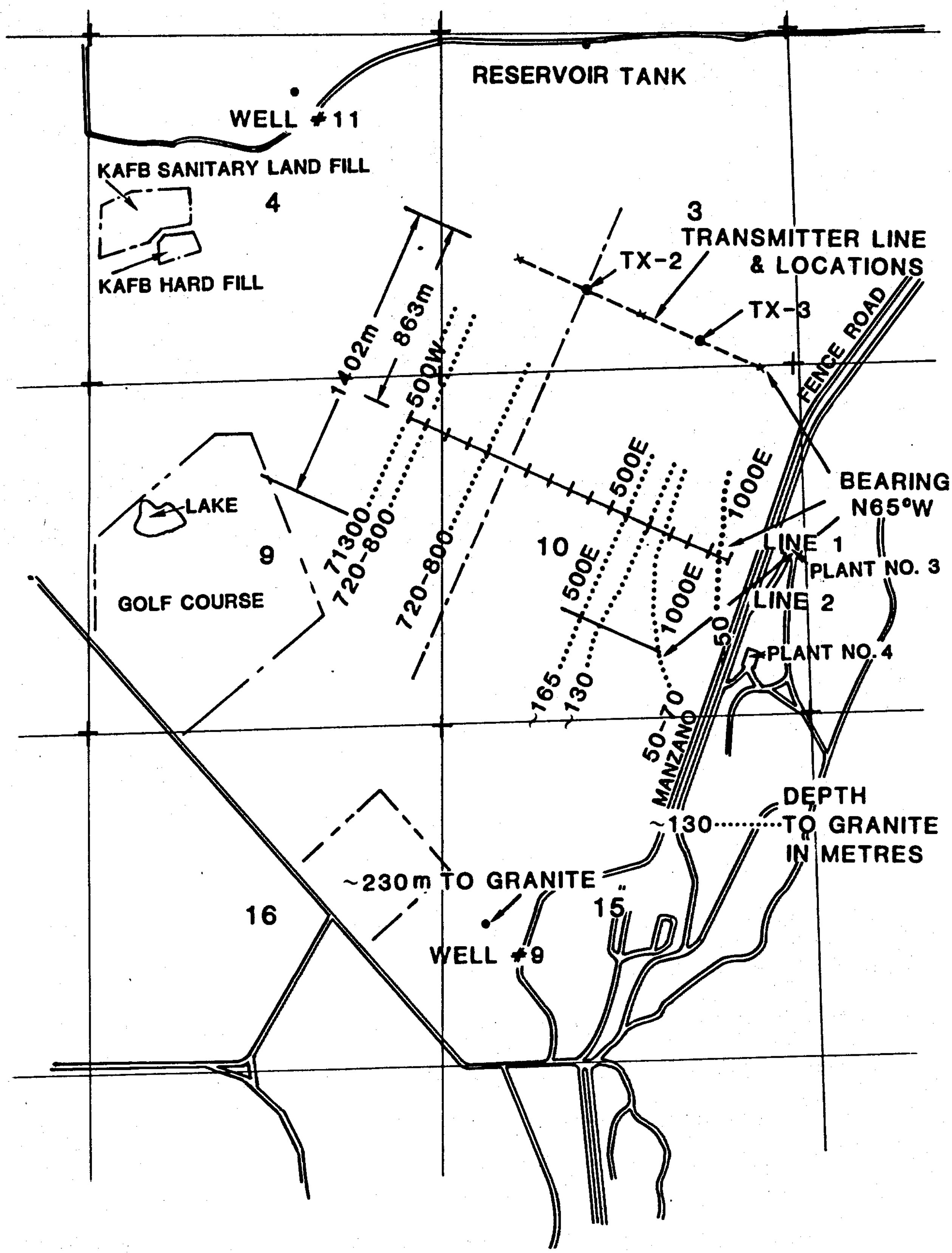

Figure A-2. Locations of Transmitter and Survey Lines. Depth to granite is indicated.

the survey lines is N65°W. The length of the transmitting dipole was 610 m (2000 ft) and the length of the receiving dipole was 100 m (328 ft). The station numbers refer to east and west of the centerline of transmitter -2 (Tx-2); e.g. 800E means 800 m E of centerline. To accommodate stations 800 E through 1100 E, the transmitter was moved to the Tx-3 location with again a 610 m dipole antenna. The two survey lines were located 863 m (2831 ft) and 1402 m (4600 ft), respectively, from the transmitter antenna, as shown in Figure A-2.

Contours of equal apparent resistivity are displayed in Figures A-3 and A-4 for the two survey lines. The horizontal axis is station location and the vertical axis is log frequency. Because of skin depth affects, the vertical axis has the appearance of depth. The dashed lines separate the far (above the line) from the near (below the line) field data. The sediments have a much lower resistivity than the granite basement rock. The resistivity contours point up sharply the sediments-granite interface. The resistivity values displayed in the lower left hand corner are extremely large because these are near field results and do not accurately portray the "true" apparent resistivity values.

Using a three-layered earth plane-wave impedance calculation, the depths to the granite were estimated for various station locations. The three layers consisted of a resistive surface layer as evidenced by the higher resistivities at the higher frequencies, a fairly conductive intermediate layer as evidenced

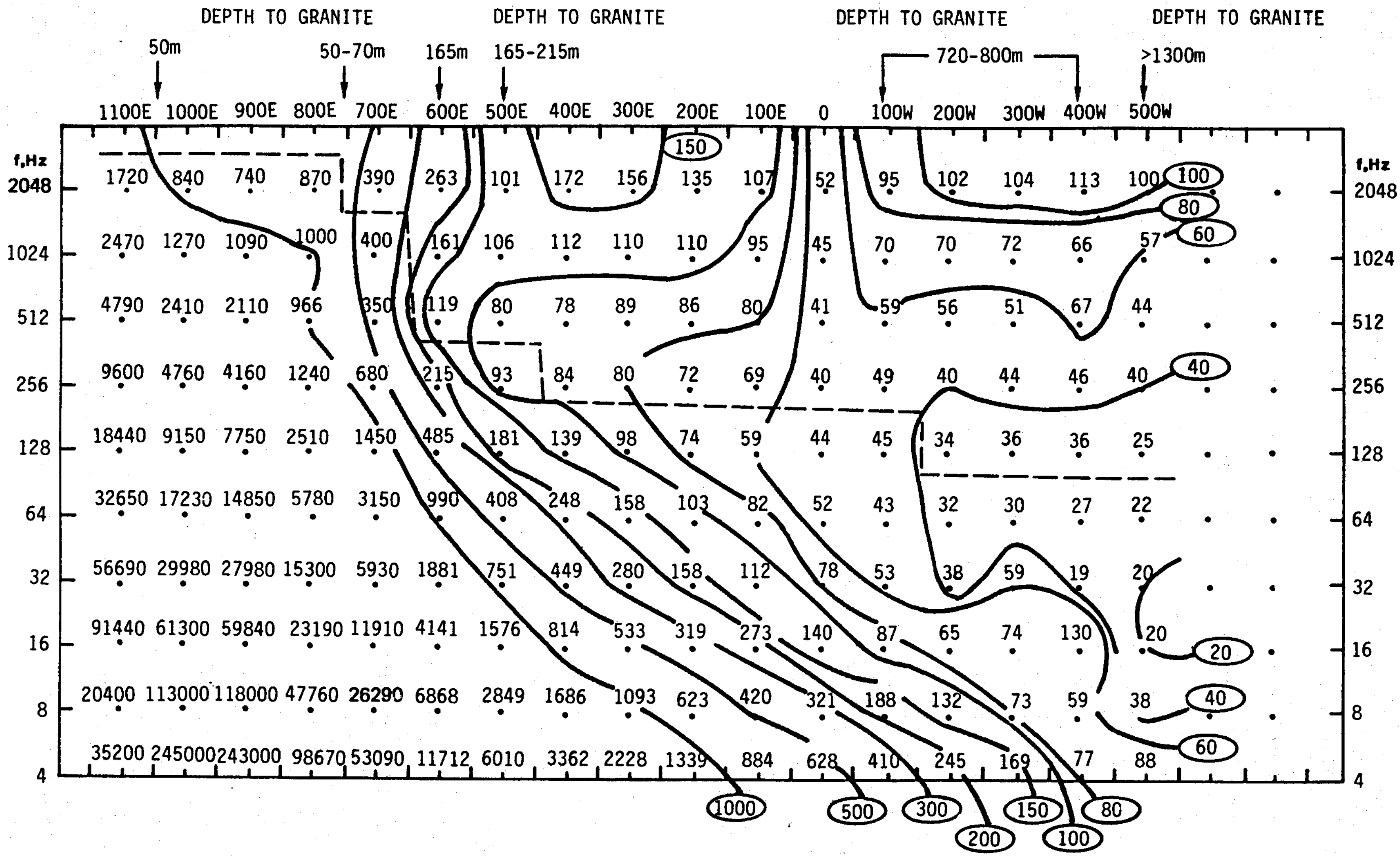

Figure A-3. Apparent Resistivity Contours for Survey Line in Fig. A-2.

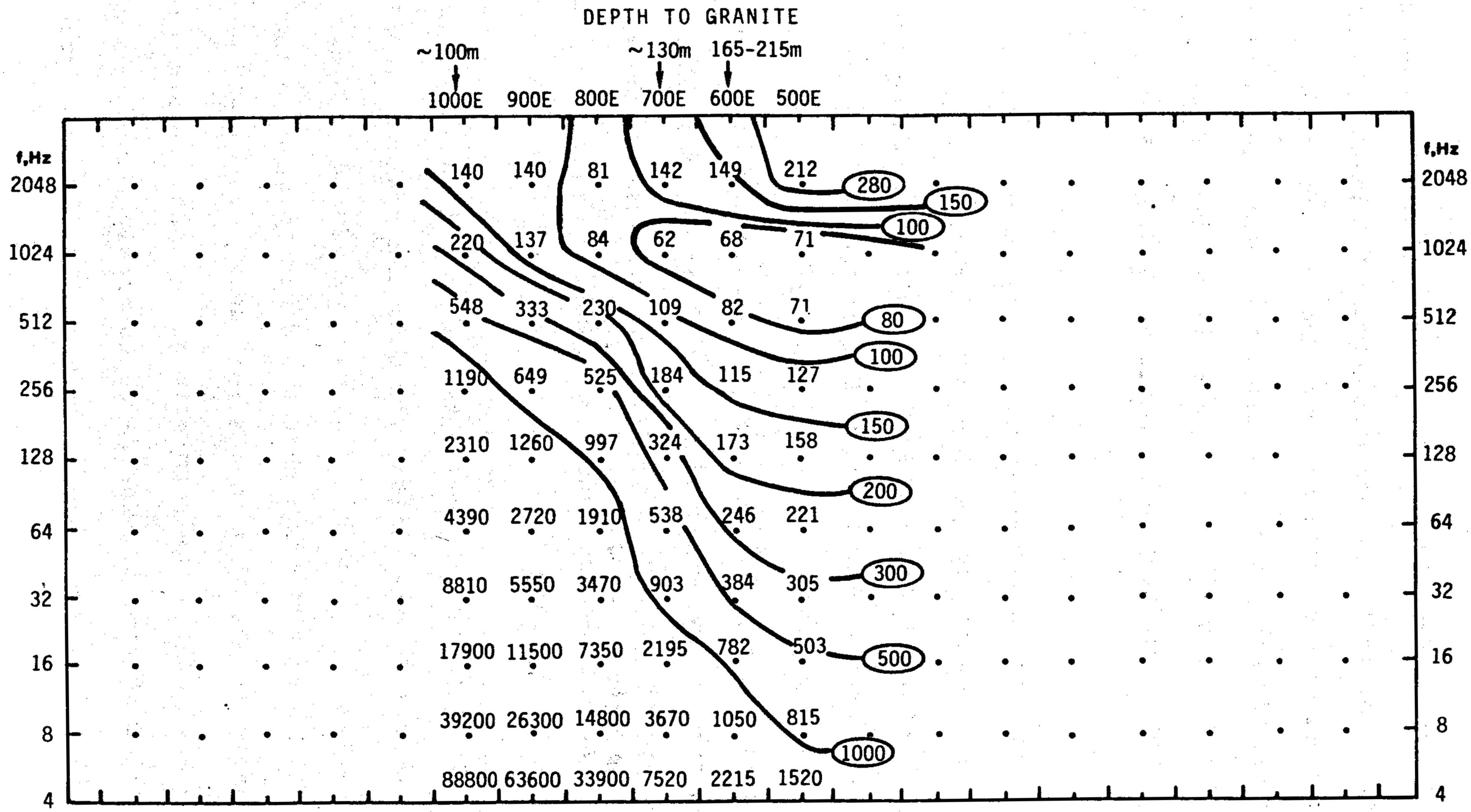

Figure A-4. Apparent Resistivity Contours for Survey Line in Fig. A-2.

by the lower resistivities at the intermediate frequencies, and a high resistive granite basement. The depth estimates at a given station were made by comparing the frequency at which the far field resistivity increases for decreasing frequency (e.g., 256 Hz at station 400 E line 1) to the calculated resistivities. The depth to granite estimate is 165-215 m at station 400 E on line 1.

At some stations the far field data do not exhibit this increase in resistivity for decreasing frequency. At these stations, depth estimates are only inferred by noting the frequency for which there is a significant increase in the near field resistivity data for decreasing frequency. It is noteworthy that the near field apparent resistivity is always larger than the "true" apparent resistivity. For example, at station 400 W on line 1 there is a significant increase in the near field resistivity at frequency 16 Hz corresponding to a depth to granite of ~720-800 m.

The depth to granite estimates are shown in Figures A-3 and A-4 for the two survey lines. The data taken along line 1 suggest that there may be a "bench" at a depth of 720-800 m between stations 100 W to 400 W and that the depth to granite increases significantly to ~1300 m at station 500 W. The depth to granite decreases more or less uniformly in going from station 0 to station 700 E of line 1. The depth to granite between stations 700 E to 1100 E is a depth of ~50-70 m. The depth to granite shown in Figure A-4 for line 2 corresponds to those for line 1. The depths to granite are also indicated in Figure A-2.

The depths to granite estimated from the CSAMT data agree favorably with the depth measured in Well #9, Figure A-2. At the Well #9 location the depth is ~230 m. East of the survey line the granite out-crops. Analysis of the data indicates that the CSAMT technique can be used to map this fault.

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