# NEW MEXICO STATEWIDE GEOTHERMAL ENERGY PROGRAM

DOE/ID/12546--1

DE88 012417

## FINAL TECHNICAL REPORT

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Work Performed under DOE Grant No. DE-FG07-84ID12546

Prepared for the
U.S. Department of Energy



April 1988

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## FOREWORD

This report summarizes the results of geothermal energy resource assessment work conducted by the New Mexico Statewide Geothermal Energy Program during the period September 7, 1984, through February 29, 1988, under the sponsorship of the U.S. Department of Energy (Grant No. DE-FG07-84ID12546) and the State of New Mexico Research and Development Institute (Contracts 2-74-4207, 2-74-4212, 2-75-5204, and 2-75-5605). The research program was administered by the New Mexico Research and Development Institute and was conducted by professional staff members at New Mexico State University and Lightning Dock Geothermal, Inc.

The report is divided into four chapters, which correspond to the principal tasks delineated in the above grant. This work extends the knowledge of the geothermal energy resource base in southern New Mexico with the potential for commercial applications.

We acknowledge the efforts of Rose Mary Carrera, Joyce Miller, and Gloria Vasquez, who assisted in the typing and preparation of the initial draft of Chapter 1; Barbara Romero, who provided drafting assistance for the illustrations in Chapter 1; Ramona Lujan, who provided assistance in many aspects of the preparation of the report; and Audrey Lopez, who typed numerous drafts and the final version of the complete manuscript.

Larry Icerman

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# CHAPTER 1

# GEOLOGIC, GEOHYDROLOGIC, AND THERMAL SETTINGS OF SOUTHERN NEW MEXICO GEOTHERMAL RESOURCES*

## 1.0 Introduction

This chapter integrates published geoscience information into a geothermal overview of southern New Mexico. Three information categories are used: (1) geologic, (2) groundwater, and (3) subsurface temperature. Category selection comes from the essential elements of geothermal systems, all of which have a heat source, a circulation framework or storage reservoir, a recharge source, and a discharge mechanism. Geologic data define structures and stratigraphy which establish the circulation and storage in geothermal systems. Groundwater information defines the recharge sources and the nature of discharge. Subsurface temperature and heat flow provide information on heat content and thermal dynamics. Analysis of these diverse data facilitates the prediction of resource occurrence. This discussion provides a framework for planning, exploration, and research that will contribute to future development of geothermal resources in southern New Mexico. Maps and discussions presented in this chapter are designed to supplement and complement previous compilations.

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## 1.1 Background

### 1.1.1 Study Area

The study area encompasses Catron, Dona Ana, Grant, Hidalgo, Lincoln, Otero, Sierra, and Socorro counties in southwestern New Mexico. This area is a part of the southern Basin and Range physiographic province (SBRP). Portions of two sections of the SBRP, the Mexican Highland and the Datil-Mogollon section, are present. The latter is transitional with the Colorado Plateau (see Figure 1-1). The eastern portion of the Mexican Highland section in south-central New Mexico is often referred to as the southern Rio Grande rift (SRGR) tectonic province.

In the Mexican Highland section, north and northwest striking mountain ranges, between 5,000 and 10,000 feet (1,524 and 3,048 m) in elevation, are separated by generally undissected alluvial plains 3,500 to 4,500 feet (1,067 to 1,372 m) in elevation. Internal drainage exists for most southwestern New Mexico basins except for basins astride the Rio Grande. Lucero, Playas, and Animas playas typify the internal drainage of the region.

The Gila and San Francisco River drainages entrench the Datil-Mogollon section, 5,500 to 10,500 feet (1,676 to 3,200 m) in elevation, to form deep and rugged canyons between mountain ranges and adjoining mesas. Mesa surfaces represent former alluvial plains and pediments prior to drainage entrenchment or integration with regional stream systems. The Plains of San Agustin west of Socorro is an undissected exception with internal drainage into the San Agustin playa.

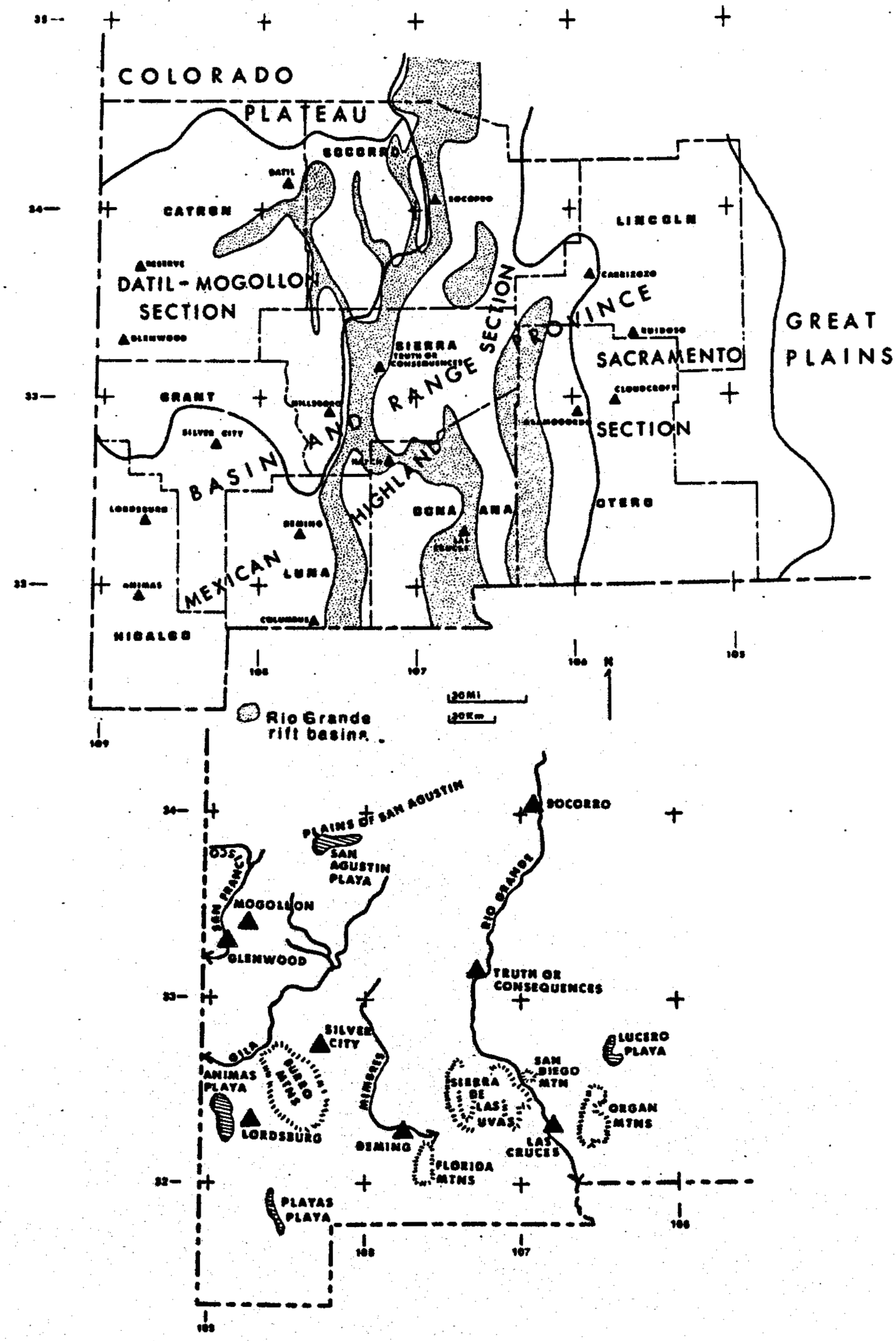



Figure 1-1. Location maps of the study area. The boundaries of the study area are: on the north, the Catron, Socorro, and Lincoln county lines; on the south, the New Mexico-Texas-Mexico border; on the east, the Lincoln and Otero county lines; on the west, the New Mexico-Arizona border.

### 1.1.2 Previous Studies

New Mexico geothermal resource maps published at 1:500,000 scale provide excellent sources of information (Swanberg, 1980; Swanberg, 1983). Important regional geothermal resource discussions include Summers (1976), Mariner and others (1977), Swanberg (1979), Callender (1981), Morgan and Daggett (1981), Morgan and others (1981), Elston (1981), Lohse (1982), and Norman and Bernhardt (1982). Several site-specific geothermal discussions present survey techniques or models (Swanberg, 1975; Jiracek and Smith, 1976; Sanford and others, 1979; Dellechaie, 1977; Chapin and others, 1978; Callender, 1981; Elston and others, 1983; Gross and Iceman, 1983; Iceman and Lohse, 1983; Snyder, 1986; Gross and Wilcox, 1981).

## 1.2 Geology

This discussion focuses on geologic features well known to economic geologists. Many ore deposits were formed from ancient geothermal systems. These deposits occur where the crust has been extensively fractured and the rock has favorable chemical, mechanical, or fluid transport properties. Present-day systems are no exception. Highly fractured rocks adjacent to faults and folds, along cauldron ring-fracture zones and on the margins of intrusions, may provide important vertical conduits to underlying geothermal reservoirs.

Large, silicic intrusions less than one million years old may drive some geothermal systems by releasing large quantities of heat over relatively small areas. Other systems derive heat from diffuse sources in the mid-to-lower crust and upper mantle. Deep-seated regional heat may result from mechanical thinning of the lithosphere, magmatic underplating, or lithosphere extension by basaltic diking at lower crustal levels (Lachenbruch and Sass, 1978). Abnormal diffuse heat is also possible from high radiogenic heat production by some plutonic rocks.

Several types of rocks may provide reservoir hosts. Crystalline basement rocks, when fractured sufficiently to create good permeability, make excellent reservoirs. Carbonate rocks, limestone and dolomite, may break when deformed to create fracture permeability. Dissolution of limestones creates solution porosity, which will enhance fracture permeability. Course-grained clastic rocks have excellent intergranular porosity, depending on clay content, sorting, and lithification. Older sequences of clastics are usually very lithified but these sequences may have secondary-fracture or solution permeability.

Shales and clay-rich clastics act as aquitards. Clay-rich rocks have low primary permeability, do not fracture when deformed, and are relatively resistant to dissolution. Fine-grained, clay-rich clastics are important in three respects. First, these rocks have low permeability and act as reservoir caps to prevent mixing of deep hot water with shallow colder water. Secondly, clay-rich rocks tend to have low thermal conductivity. As a result, high temperature gradients may occur even in areas with regional or normal heat flow. Thirdly, clays have high porosity which allows storage of large quantities of fluid. Complex depositional heterogeneity causes clastic sequences to show much greater horizontal than vertical permeability. This anisotropicity is important in understanding groundwater flow and flow relationships with geothermal resources.

Volcanic rocks may act as either reservoirs or as impermeable cap rocks. Unaltered basaltic rocks may have excellent permeability between flow units and along joint fractures. Silicic domes and vents may show fracturing favorable to vertical fluid transport.

#### 1.2.1 Pre-Cenozoic Basement Geology

The study area is highly anisotropic. Northwest (~N30W), west-northwest (~N60W), and north-south outcrop patterns, structures, and isopachs are common. In some areas, a northeast (~N30E) fabric is also evident (see Figure 1-2). All of these trends probably have a Precambrian origin.

The earliest Precambrian crust formed around 1.7 Ba. At that time, a thick eugeosynclinal package of sediments and volcanic rocks was deformed, metamorphosed, and accreted from the southeast to the edge of the incipient North American craton (Condie, 1982). Suturing, thrusting, and metamorphic transposition within this accreted terrane probably resulted in a northeast-striking fabric.

Partial melting of the crust, between 1.4 and 1.5 Ba, resulted in the emplacement of discordant, potassium-rich granite batholiths (Silver, 1978; Condie and Budding, 1979; Anderson, 1983). These granite bodies comprise a significant fraction of the upper crust and add important radiogenic heat to the crust. Apparently, these granites annealed only a portion of the northeast-trending fabric. Regionally, several large-scale, but some-

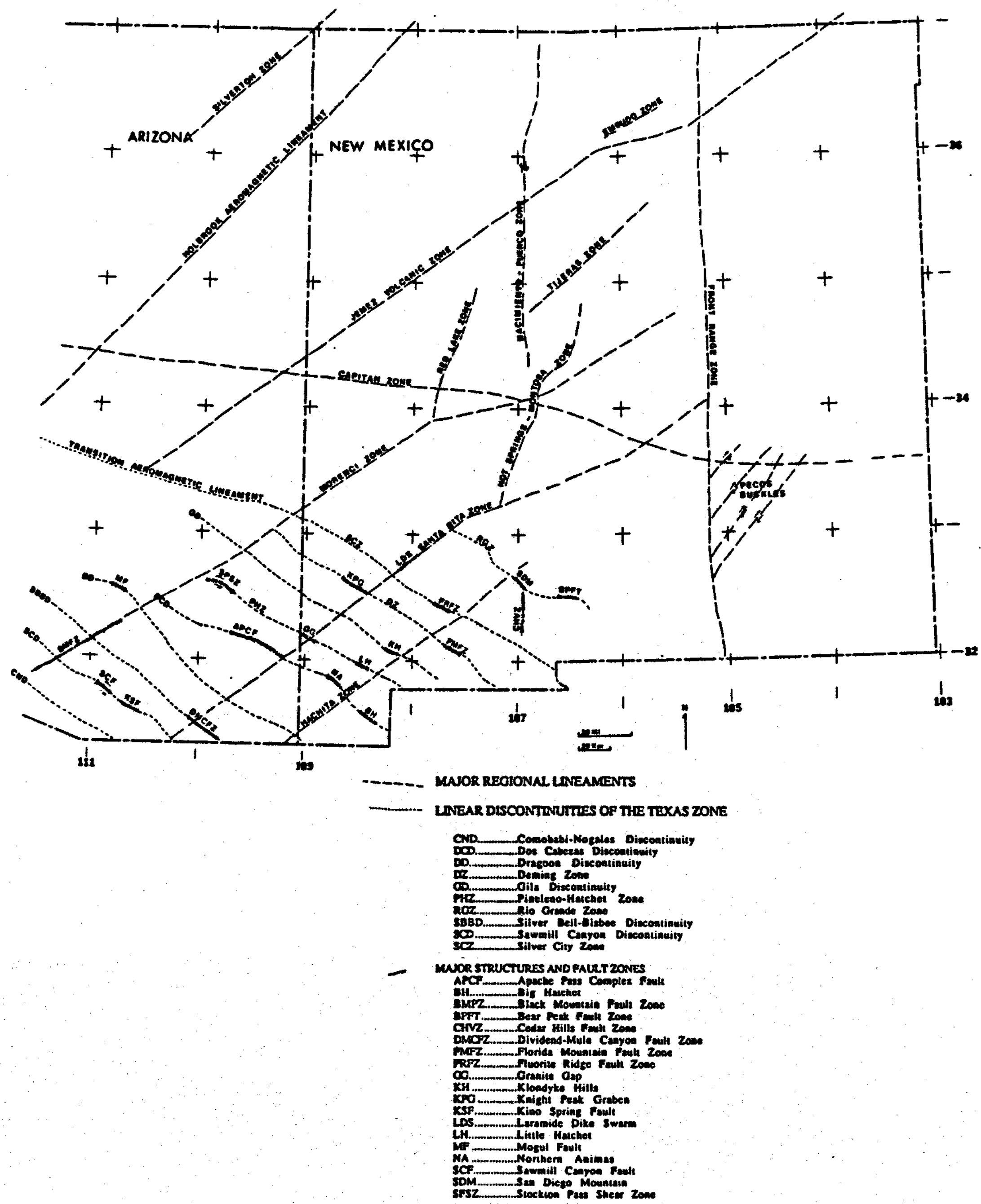



Figure 1-2. Regional lineament map. The identified lineaments are extrapolated from geological and geophysical data taken principally from Chapin and others (1978), Laughlin and others (1979), New Mexico Geological Society (1982), Seager (1983), Titley (1976), Vroman (1976), and Woodward (1984).

what diffuse northeast-striking zones, are the locus of Cenozoic volcanism (Laughlin and others, 1979; Chapin and others, 1978; Woodward, 1984). The geothermally important Jemez volcanic zone (see Figure 1-2) is one example (Laughlin and others, 1979).

Precambrian west-northwest striking shear zones are also very prominent. In Arizona, to the west of the study area, these zones cut 1.4- to 1.5-Ba granite batholiths. In some instances, these shear zones are intruded by 1.1-Ba mafic dikes (Swan, 1982). These west-northwest, vertically-oriented, shear zones also exhibit lateral displacements in addition to vertical offsets.

Large-scale anisotropicity in southwest New Mexico is predominantly north-south or west-northwest in orientation. Late Cenozoic rejuvenation of Precambrian structures provides potentially important fractured volumes in Precambrian crystalline rock for geothermal systems. Deeply penetrating structures developed during the Precambrian may provide avenues for magma intrusion at Socorro (Chapin and others, 1978).

Paleozoic sedimentation patterns generally conform to Precambrian structural trends (see Figure 1-3). Paleozoic isopachs exhibit northwest and northeast lineations. These trends mimic Precambrian structural grains. This sedimentation was typical of a cratonic setting, as only epeiorogenic subsidence and uplift was the rule until Pennsylvanian time (Kottlowski, 1963).

In the study area, south and southwest of Truth or Consequences (see Figure 1-4), a Cambrian to Ordovician, marine sandstone rests nonconformably upon Precambrian crystalline rocks (Kottlowski, 1963). Interbedded marine shales, sandstones, and

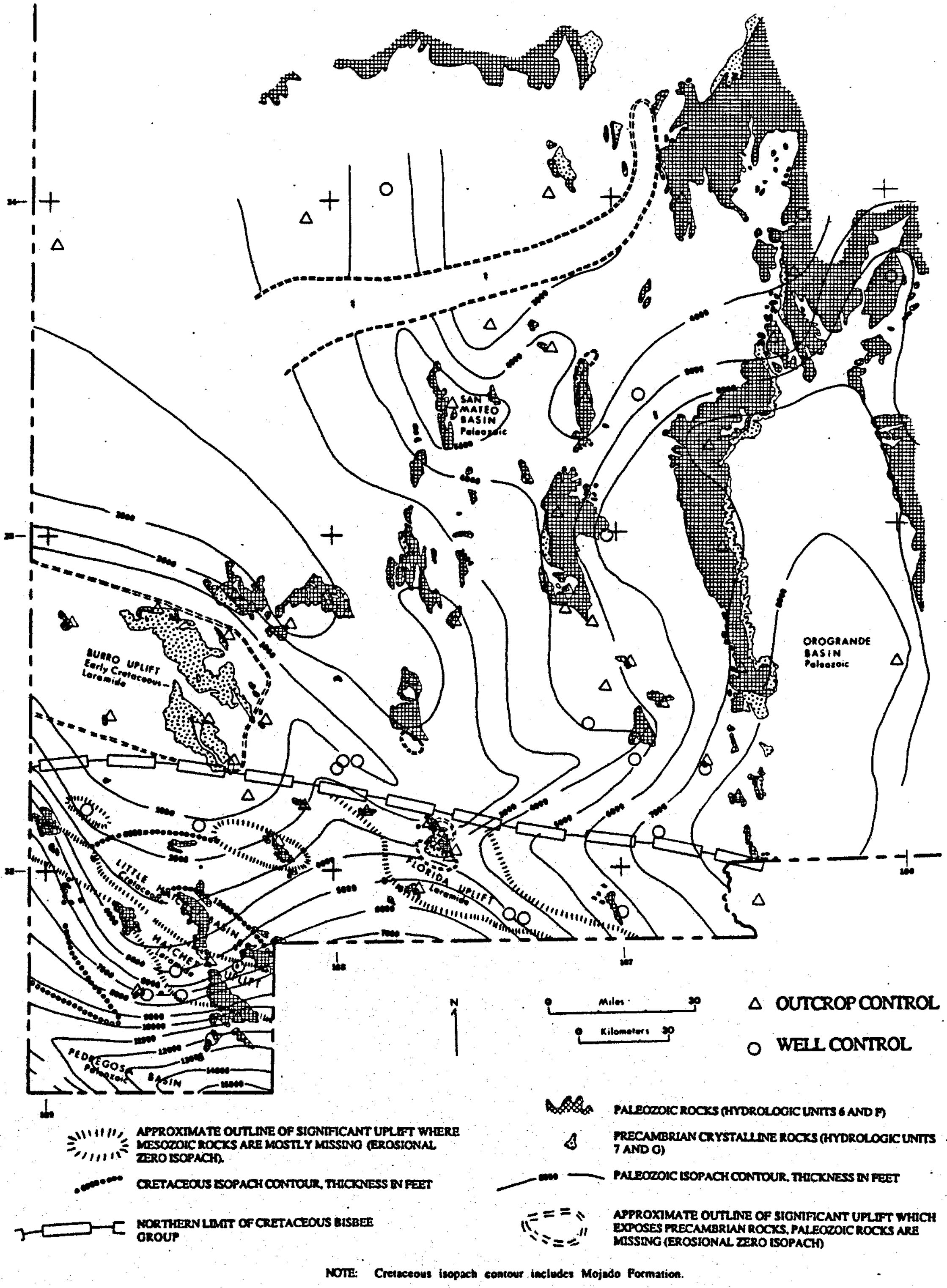



Figure 1-3. Paleozoic and Cretaceous isopach map. The Paleozoic data are from Kottlowski (1963) and Thompson (1982). The Cretaceous data are taken from Thompson (1982).

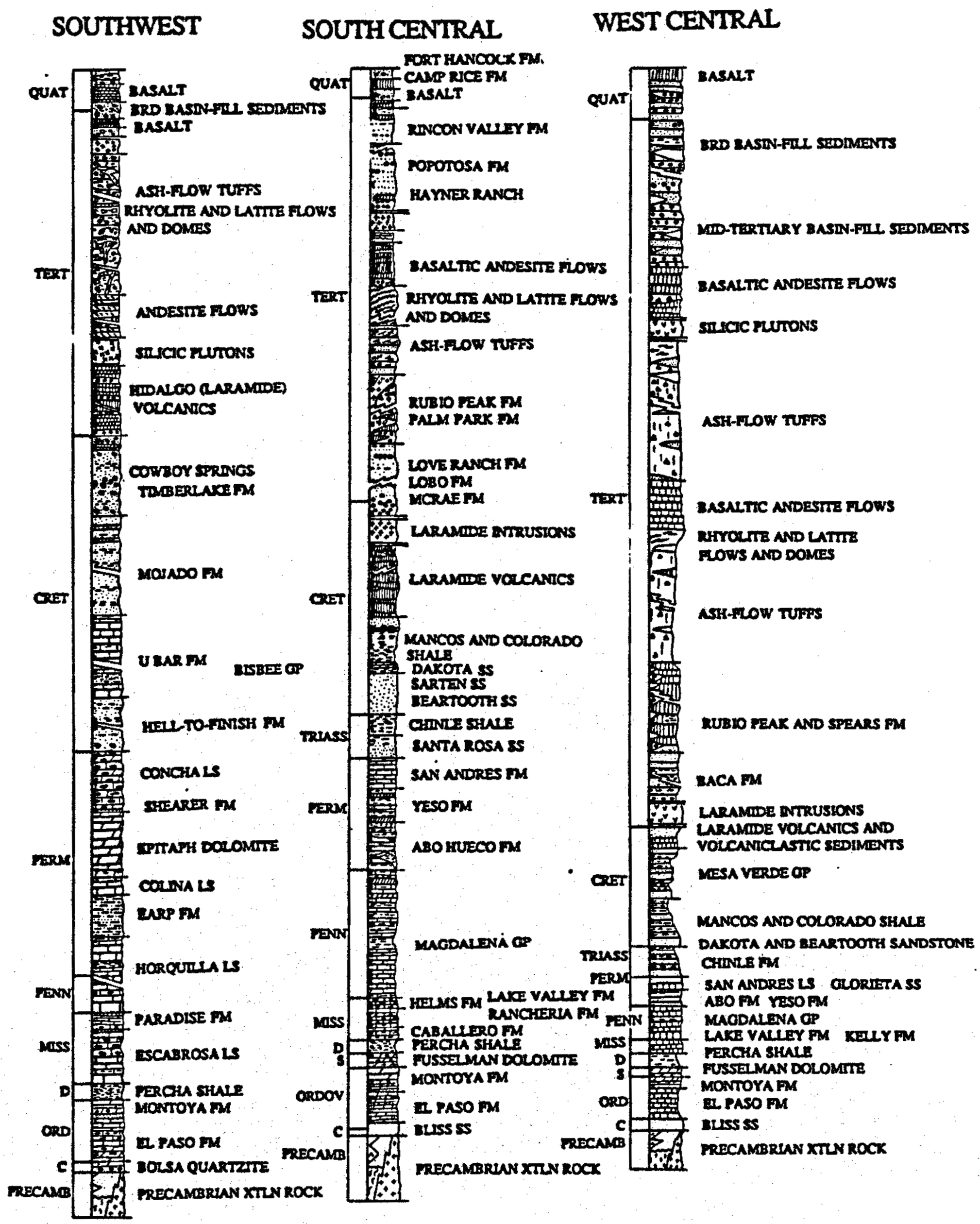



Figure 1-4. Representative stratigraphic sections for southwest, south-central, and west-central New Mexico [After New Mexico Geological Society (1982)].

carbonate rocks overlie the basal Paleozoic sands, while carbonate rocks become dominant higher in the Paleozoic section. Sediments exist for all periods except for the Silurian in extreme western New Mexico, although numerous unconformities are present in lower and mid-Paleozoic sequences. North of Truth or Consequences either Mississippian or Pennsylvanian strata nonconformably overlie Precambrian basement rocks.

In general, the Paleozoic section increases in thickness from north to south. In the Socorro area, Paleozoic strata are less than 1 km in thickness, increasing southward to more than 2 km in the Orogrande basin (see Figures 1-3 and 1-5) in southern New Mexico (Kottlowski, 1975; Jordan, 1975). To the west, more than 3 km of mostly carbonate strata occupy the Pedregosa basin of southwest New Mexico (Greenwood and others, 1977). Between the Pennsylvanian-Permian Orogrande and Pedregosa basins, the section thins or is absent. This prominent west-northwest-striking positive area, known as the Deming axis (see Figure 1-5), traverses the present-day Burro and Florida Mountains (Turner, 1962).

Collisional tectonics of the Quachita-Marathon orogeny apparently reactivated Precambrian structures in-board on the North American craton to form the Pennsylvanian-Permian uplifts and basins (Kluth and Coney, 1981). The north-south grain of the Rio Grande rift may have been enhanced by the Pennsylvanian-Permian deformation (Chapin and Seager, 1975).

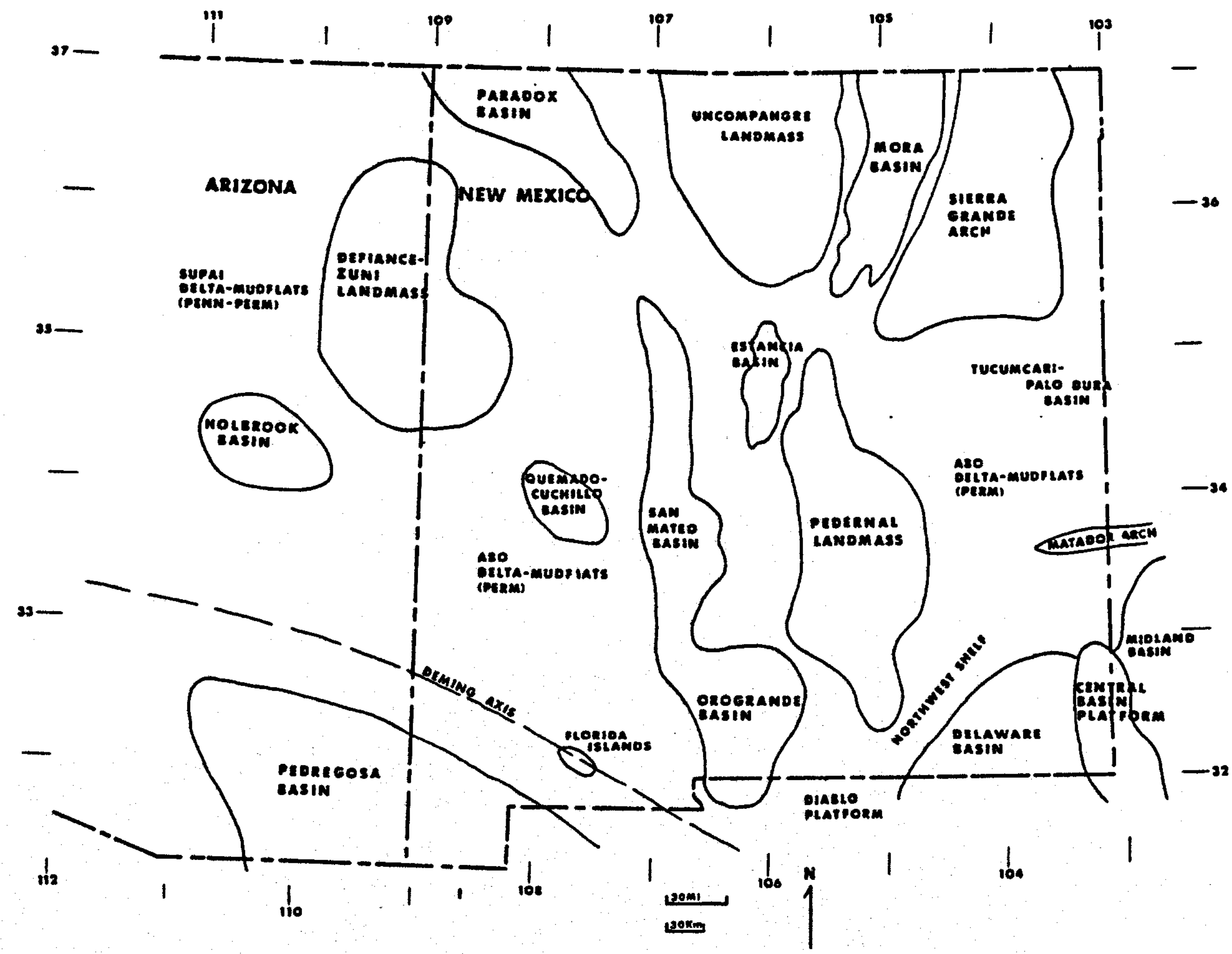



Figure 1-5. Late Paleozoic paleogeography [After Kottlowski (1963); Kottlowski (1969); Turner (1962)].

Paleozoic contributions to present-day geothermal potential are mainly stratigraphic. Several important units provide potential reservoir hosts, especially along major Mesozoic and Cenozoic structures. Paleozoic strata with the best potential to act as geothermal aquifers are the same as those identified as having potential to be oil and gas reservoirs. Potential reservoirs include the Ordovician El Paso Formation and the Montoya Group carbonate sequences, the Silurian Fusselman Dolomite, and the Pennsylvanian-Permian shelf and reef carbonate rocks (Greenwood and others, 1977; Chapin and others, 1978; Thompson, 1982). The Devonian Percha Shale and various clayey units within Mississippian and Pennsylvanian-Permian sequences provide relatively impermeable caps for potential reservoirs.

Triassic and Jurassic rocks are mostly missing in southern New Mexico. However, marine sediments of Jurassic age are known in a deep drill hole near Las Cruces (Thompson and Bieberman, 1975). To the west of the study area, in Arizona, outcrops of Jurassic rocks indicate the presence of a magmatic arc at Bisbee (Titley, 1976; Dickinson, 1981). Other Triassic and Jurassic sequences in southeast Arizona document reactivation of the regional west-northwest structural grain (Titley, 1976). Predominantly vertical tectonism is implied by sedimentation patterns and by the unconformable relationships among Paleozoic and Mesozoic deposits. Similar deformation may extend along structural trends into southwest New Mexico even though stratigraphic evidence is lacking at present.

Strong evidence for tectonism during early Cretaceous, along the west-northwest structural grain, exists in both southwest New Mexico and southeast Arizona. Stratigraphy, unconformable relationships, and provenance of the lower Cretaceous Bisbee Group indicates major vertical tectonism along west-northwest structures (Titley, 1976; Bilodeau, 1982; Mack and others, 1986). Lower Cretaceous carbonate rocks may have potential to act as reservoirs.

1.2.2 Laramide Geology

Upper Cretaceous marine and continental clastic sediments, the Mojado, Colorado Shale, and McRae Formations, crop out at scattered locations throughout the study area. In southwest New Mexico, a 1- to 2-km clastic wedge, the Mojado Formation may record foreland deposition from an initial and advancing Laramide orogen to the west (Mack and others, 1986). The Mojado Formation has only minor potential as a reservoir. The Colorado Shale and McRae Formations are impermeable confining units.

The Laramide orogeny ruptured the study area into west-northwest and north-south structures; however, much discussion and controversy centers on the nature of this deformation. Three general models are currently debated. Corbitt and Woodward (1973), Drewes (1978), and Drewes (1981) argue for large horizontal displacements via thrusting and extend the Cordilleran fold and thrust belt across the southern part of the study area. Jones (1963), Keith and Barrett (1976), Davis (1979), Brown and Clemons (1983), Seager (1983), and Seager and others (1986) present strong evidence for basement block uplifts similar to classic Laramide uplifts of Wyoming and the Colorado Plateau. Drewes (1976), Brown and Clemons (1983), Chapin and Cather (1981), and Seager (1983) present evidence for convergent and divergent strike-slip (transpressional and transtensional) deformation. Keith and Wilt (1986) emphasize mobile and diachronous styles of deformation.

Regardless of the exact kinematics and timing of Laramide deformation, many important features stand out (see Figure 1-6). South of Truth or Consequences (compare Figures 1-1 and 1-6), several large west-northwest trending basement-involved (Precambrian) terranes exhibit 1 to 5 km or more of structural relief (Seager, 1983). North of Truth or Consequences, Laramide uplifts follow a predominant north-south strike. Except for the Hidalgo uplift, west-northwest uplifts have strong asymmetry. A steep northeast face, bounded by northeast vergent faults, monoclinal flexures, and overturned folds, contrasts with a mildly faulted and folded, southwest-dipping, homoclinal slope (Seager, 1983; Seager and others, 1986). Mesozoic and sometimes Paleozoic rocks are missing over uplifts.

Adjacent basins are filled with 1 to 3 km of upper Cretaceous to Eocene clastic sediments such as the Starvation member of the Rubio Peak, Lobo, Love Ranch, Ringbone, and Cowboy Spring-Timberlake Formations (Seager, 1983; Seager and others, 1986). Marginal facies are coarse-grained, sometimes highly-indurated, fan and alluvial deposits. Basinal facies are fine-grained silts, sands, and coal. Neither of these facies makes a good reservoir lithology.

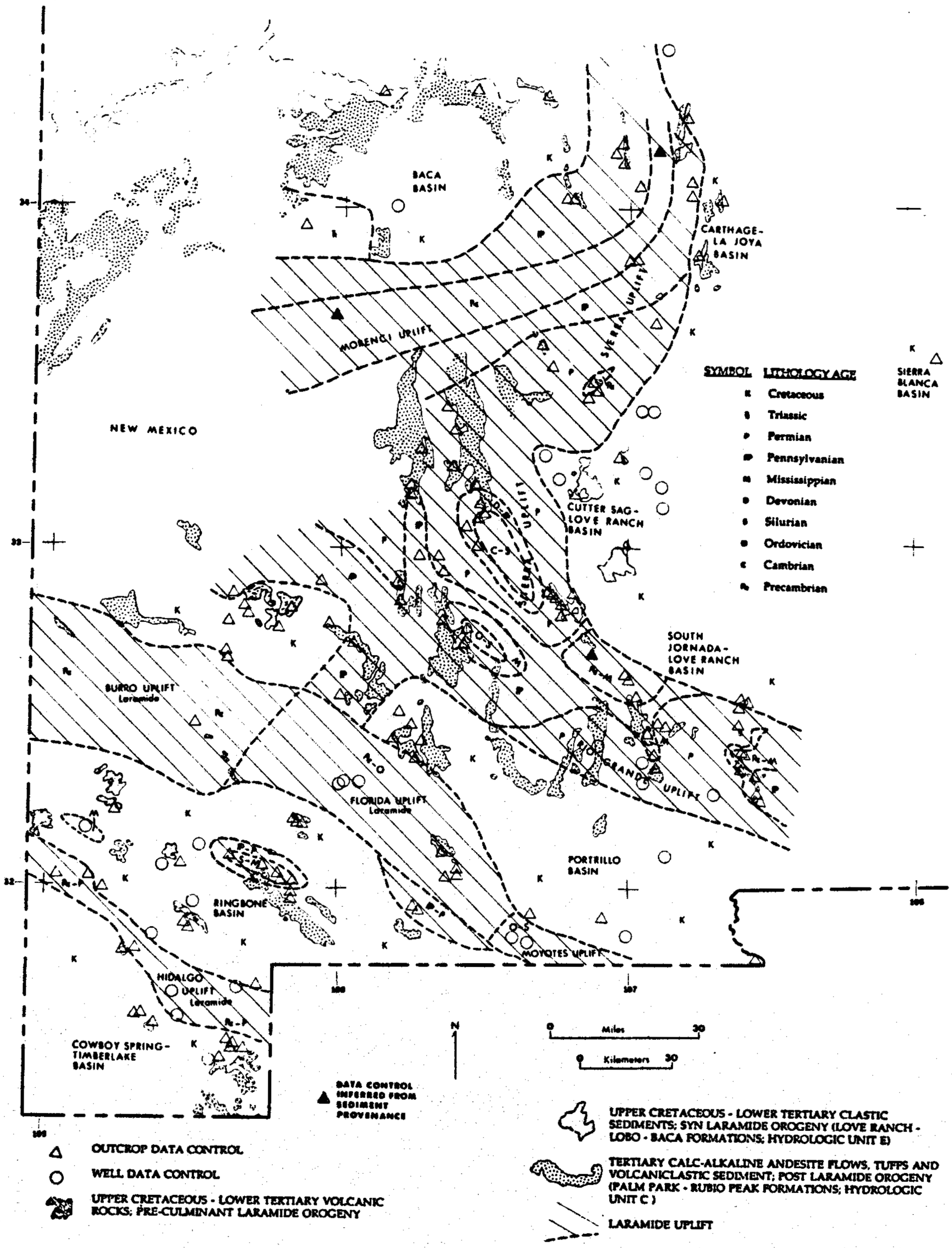



Figure 1-6. Tertiary subcrop map. The principal data sources are Brown and Clemons (1983), Cather and Johnson (1984), Corbitt and others (1978), Dane and Bachman (1965), Foster (1978), New Mexico Geological Society (1982), Seager (1983, 1975), Seager and others (1986), Thompson (1982), and Zeller (1975).

Due to abundant limestone and granite clasts, cemented by calcite, the thermal conductivity of basin-margin sequences is probably moderate to high. Higher clay contents and low quartz contents will give the basinal sequences generally low thermal conductivities (Mack, 1987).

Geologic relationships at San Diego Mountain illustrate the important structural control that Laramide features can have for geothermal systems. A west-northwest-striking Laramide thrust fault, dipping 35 degrees southwest, displaces Precambrian granite over pervasively silicified Paleozoic rocks (Seager and others, 1971; Seager and others, 1986). Footwall silicification and barite-fluorite mineralization in the hanging wall attest to Tertiary hydrothermal systems in this zone. Perhaps more importantly, an apron of silicified Pleistocene Camp Rice deposits covers the area east of San Diego Mountain (Seager and others, 1971). A geothermal system at this location prior to entrenchment of the Rio Grande may account for the silicified Camp Rice deposits. Geothermal fluids discharging from a moderate-to-high temperature (i.e., >100°C) reservoir can precipitate significant silica (Bird and Elders, 1975).

The Tertiary subcrop map (see Figure 1-6) shows Laramide uplifts and basins for geothermal investigation and rock types beneath the early Tertiary (Paleocene to Eocene) rocks. This map represents a powerful tool for interpreting early Tertiary paleogeography and for delineating major Laramide uplifts and basins. This approach is necessary because Laramide features are mostly covered by mid-Tertiary volcanic sequences and by mid- and upper

Tertiary clastic sediments. Only on late Tertiary fault-block ranges are Laramide faults and folds observed at the surface. Deep well lithologies provide important subsurface data.

Laramide (late Cretaceous to early Eocene) orogeny uplifts have a distinctive signature. A major unconformity between lower or mid-Tertiary rock units and older lithology occurs on uplifts. Erosion over Laramide uplifts has removed Mesozoic and sometimes Paleozoic rocks prior to deposition of Tertiary rocks. As a result, lower Tertiary and mid-Tertiary rock units overlie Paleozoic and Precambrian rocks. Laramide basins appear where Tertiary rocks overlie upper Cretaceous rocks, indicating depositional continuity.

The ages of the rock units unconformably underlying the Tertiary rocks are plotted in Figure 1-6, along with outcrops of Laramide volcanic rocks and syntectonic clastic sequences, and subduction related mid-Tertiary (Eocene to Oligocene) volcanic rock outcrops, such as the Palm Park Formation or equivalent. These volcanic and clastic rocks are important aquitards confining permeable units unroofed during Laramide deformation.

### 1.2.3 Mid-Tertiary Geology

Post-Laramide geologic structures and thermal events have a major influence on present-day geothermal phenomena. The crust retains a component of heat from mid-Tertiary thermal disturbance. Elston and others (1983) have observed that the Lightning Dock geothermal system in the Animas Valley overlies the ring-fracture zone of the mid-Tertiary Muir Cauldron. The ring-fracture zone may provide important vertical plumbing for the Lightning Dock system. Fractured mid-Tertiary volcanic rocks also act as shallow (i.e., <300 feet in depth) reservoir rocks for the Lightning Dock, Gila Hot Springs, and Radium Springs geothermal systems. Other mid-Tertiary volcanic and volcaniclastic rocks are important impermeable cap rocks. The Eocene-Oligocene Palm Park Formation is an important example. At Radium Springs, the Palm Park caps a deep geothermal system and vertical discharge is allowed only along a fractured and discordant rhyolite intrusion.

At the end of the Laramide orogeny about 40 to 45 Ma, a profound thermal perturbation affected the lithosphere beneath the southwestern United States. This thermal disturbance accompanied extensive volcanism which covered all but the extreme eastern portion of the study area under a blanket, an average of 1 km in thickness. Locally, volcanic piles, up to 5 km in thickness, fill circular cauldron subsidence features 10 to 50 km in diameter such as the Bursum cauldron (Ratte and others, 1984), large long-lived (i.e., 10 to 15 Ma) elongated depressions greater than 30 by 70 km such as the Blue Creek basin (Wahl, 1980), and the Goodsight-Cedar Hills depression (Seager, 1973). These features are shown in Figure 1-7.

Volcanism began 40 to 43 Ma with the eruption of andesite from scattered stratovolcanoes (Elston and others, 1976). Andesite flows, lahars, breccias, tuffs, and volcaniclastic sediments of the Rubio Peak, Spears, and Palm Park Formations are representative of this initial arc-related calc-alkalic phase of mid-Tertiary volcanism. With time, these andesites became progres-

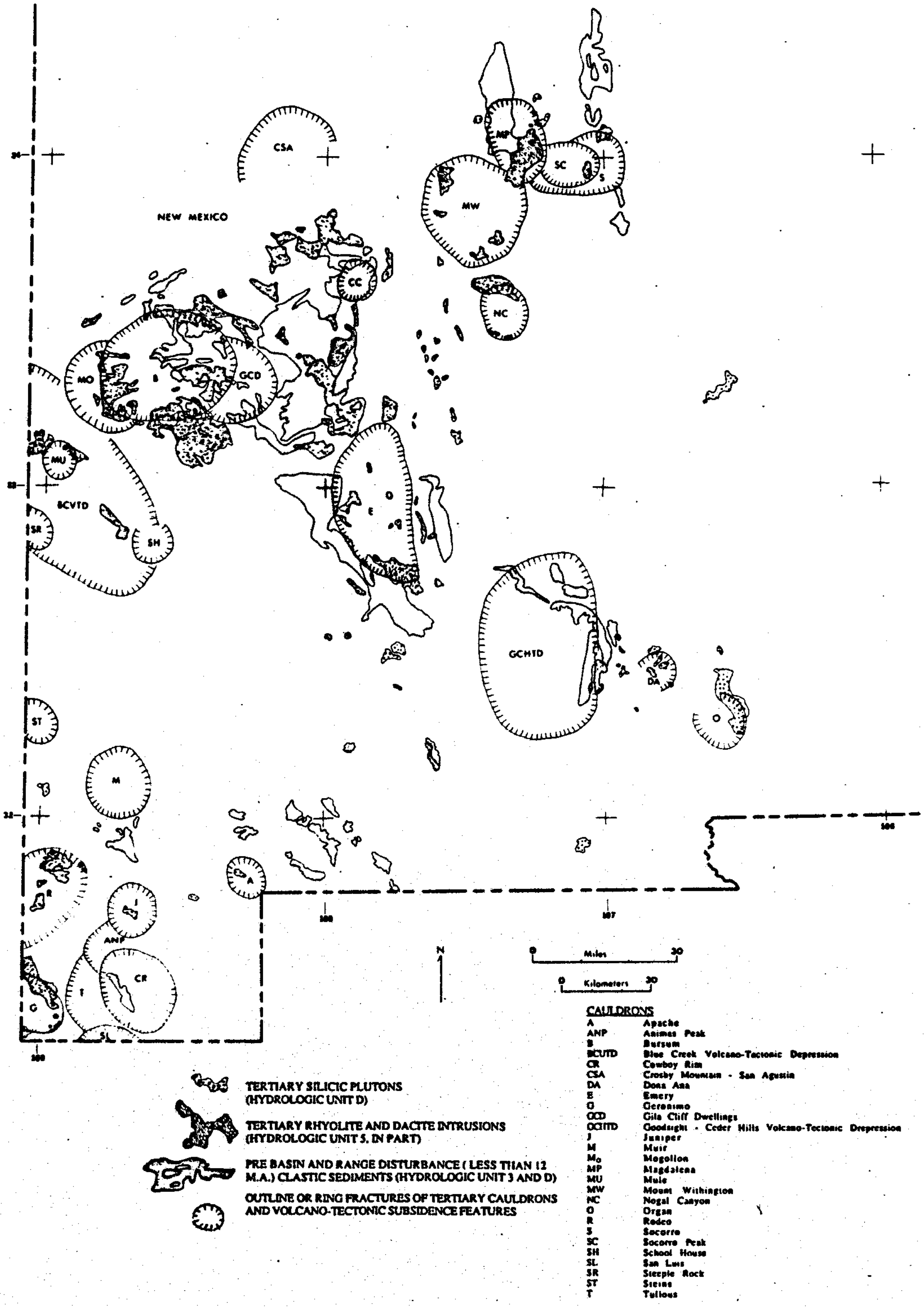



Figure 1-7. Mid-Tertiary tectonic map [After Elston (1984); New Mexico Geological Society (1982); Ratte and others (1984); Seager (1973); Wahl (1980)].

sively richer in iron and poorer in hydrated ferromagnesium minerals as the result of increasing lithosphere temperature (Elston, 1984).

At about 35 to 36 Ma, a main pulse of calc-alkalic volcanism ensued. Coney (1976) appropriately used the phrase, ignimbrite flareup, for this 24- to 36-Ma volcanism. Concurrent with continuing andesite volcanism, colossal rhyolite and rhyodacite ash-flow tuff effusions exploded from collapsing cauldrons. In a 1.7-million-year interval between 27 and 29 Ma, nine cauldrons are known to have erupted more than 6,000 cubic kilometers of ignimbrite (McIntosh and others, 1986). Based on isotopic, major and trace element chemistry, Bornhorst (1980) concluded that the siliceous ignimbrite magmas equilibrated with lower-crust granulite at depths of 20 to 40 km. In accordance with the model of Bornhorst (1980), a corollary has the lower crust attaining an unprecedented peak in temperature in the mid-Tertiary. A large amount of this heat was convected to the surface by magma, but the crust, with a thermal diffusivity of $10^{-6}$ $m^2/s$, is sufficiently thick (i.e., >25 km) that a significant amount of this heat is still conducting to the surface.

Beginning about 29 Ma, the shallow crust began to break under northeast-southwest directed, extensional stress (Chapin and Seager, 1975; Seager and others, 1984; Chamberlin and Osburn, 1986). This occurrence closely corresponds with the very intense phase of ignimbrite volcanism from 27 to 29 Ma. Andesitic volcanism, accompanying the ignimbrite event, also changed character. At about 29 Ma, the andesites became less siliceous

(Seager and Morgan, 1979) and display a narrow range of strontium isotope ratios (Stinnett and Steuber, 1976). These calc-alkalic basaltic andesites became volumetrically dominant between 27 and 30 Ma and capped the siliceous ash-flow tuff cauldron sequences. In addition, silicic cauldron related rocks are lower in calcium and higher in silica after 29 Ma (Elston, 1984). Strontium isotope ratios in the post 29-Ma silicic lavas range from 0.705 to 0.730 (Elston and others, 1976; Bikerman, 1976; Stinnett and Steubmer, 1976). Higher strontium isotope ratios indicate significant crustal-melt contamination of these arc-related magmas.

Major extensional deformation was proposed by Elston (1984) in order to allow room for passive emplacement of large silicic magma bodies. Large shallow magma chambers were required to feed the voluminous ignimbrite volcanism. Morgan and others (1986) highlight the apparent temporal and spatial association of intensely extended terrances with volcanism and plutonism. Morgan and others (1986) also relate changing styles and intensity of extension with increasing crustal temperatures.

Chamberlin (1983) and Chamberlin and Osburn (1986) point out that late Oligocene to mid-Miocene thin-skinned extension in the Socorro region is highly variable and may be divided into domains, which are distinguished by fault dips and attitudes of complementary rotated fault blocks. These domains are separated by high-angle oblique or scissors faults. Extension percentages, inferred from fault and stratal dips, define three classes of domains: (1) severe, 100 to 200 percent extension, 50 to 70 degree stratal dips; (2) moderate, 20 to 100 percent extension, 20 to 50 degree stratal dips; and (3) weak, 2 to 20 percent extension, 0 to 20 degree stratal dips (Chamberlin and Osburn, 1986). Studies by Seager (1981) and Seager and Mack (1986) indicate that additional domains of moderate to severely extended terrance exist in the Las Cruces area.

Chamberlin and Osburn (1986) break out two orders of normal fault spacings. First-order fault spacing shows a 5- to 20-km separation, while the second-order spacing is 0.5 to 1 km. Second order spacing is prominent in high-to-moderate extended domains. In these domains, reservoir potential is enhanced due to extensive fracturing. This potential is dramatically illustrated by intense oxidative potassium metasomatism in highly faulted substrata of these mid-Tertiary extensional domains (Chapin and Lindley, 1986).

Low topographic relief in the mid-Tertiary allowed individual ash-flow sheets to cover thousands of square kilometers. Extensional strain either created low amplitude (i.e., <50 m) or long wavelength (i.e., >100 km) topography. Chamberlin (1983) proposed domino-style rotation on planar, closed-spaced, normal faults for mid-Tertiary deformation near Socorro. Domino-style faulting was first proposed by Proffett (1977) and Morton and Black (1975) for other regions of intense extension outside New Mexico. The domino-style normal faulting hypothesis is consistent with paleotopography inferences.

Thick, up to 1.9 km, clastic sequences are intercalated or immediately overlie upper Oligocene to lower Miocene basaltic andesite flows (Seager and others, 1984). These sediments fill west-northwest oriented basins, are usually tectonically rotated 5 to 50 degrees, and may have anomalous depositional setting and provenance with respect to present-day uplifts (see Figure 1-7). Oligocene to mid-Miocene sediments, such as the Popotosa, Rincon Valley, and Hayner Ranch Formations are generally poor reservoir hosts due to high cementation and advanced diagenesis.

### 1.2.4 Basin and Range Geology

Present physiography of the study area began to develop 9 to 12 Ma (Seager and others, 1984; Seager, 1975; Morgan and others 1986). Scarborough and Peirce (1978) name the tectonism that created the current topography the Basin and Range Disturbance (BRD). This tectonic designation conforms to widespread and correlative geologic relationships described with deep bore-hole and seismic data by Eberly and Stanley (1978). In contrast to close-spaced faults in the mid-Tertiary, BRD faults are generally spaced 5 to 20 km or more apart and result in very little (i.e., $<15^{o}$) fault-block rotation (see Figure 1-8). Basins or grabens produced by this faulting are much narrower than earlier extensional basins, and asymmetric half-graben structures are common. Extensional strain is about 5 to 25 percent (Morgan and others, 1986). A roughly east-to-west oriented minimum stress regime prevailed (Aldrich and others, 1986).

The BRD extension was rather uniform as opposed to the highly variable strain in the mid-Tertiary (Morgan and others, 1986). Rugged topography and large structural relief over 1 to 3

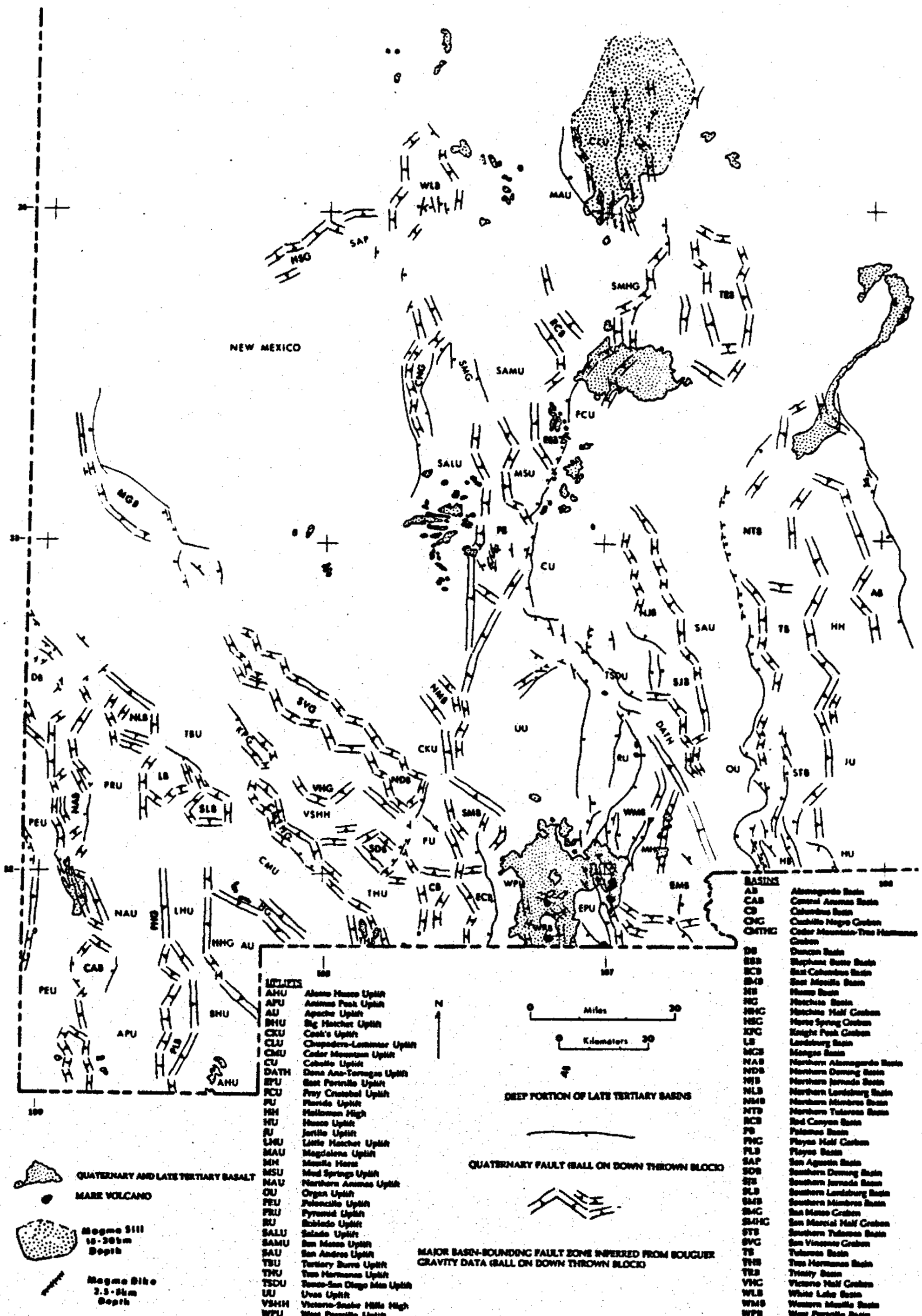



Figure 1-8. Basin and Range Disturbance tectonic map. The principal data sources are Callender and others (1983), Chapin and Seager (1975), Drewes and others (1985), Keller and Cordell (1983), New Mexico Geological Society (1982), Olson and others (1982), Rinehart and others (1979), and Seager and others (1982).

km attest to significant vertical strain over short distances (i.e., <10 km). This strain is usually accompanied on just one or two basin-bounding fault zones. In fact, north-trending BRD horst blocks frequently pierce the middle of broad, earlier developed, northwest-trending, mid-Tertiary basins.

Many BRD features were largely blocked out by 5 Ma (Seager and others, 1984). The Robledo Mountain horst block, also known as the Robledo uplift, is a well documented example. Between 7.1 and 9.6 Ma, the Robledo Mountain horst block had at least 0.6 to 0.7 km of uplift, but this block has had only about 0.1 km of uplift since 7.1 Ma (Seager and others, 1984). Main phase uplift and erosion of the Robledo horst block was concurrent with the eruption of the Seldon basalts on the uplift and in adjacent basins. Quaternary fault scarps in the region (see Figure 1-8) indicate that BRD extension has continued to the present (Seager and others, 1984; Callender and others, 1983). However, vertical strain rates associated with this faulting are only tens of meters per million years as compared to hundreds of meters per million years during main phase faulting from 4 to 10 Ma. In addition to local movements, regional uplift of more than 1 km in the last 10 million years is indicated by studies of Axelrod and Bailey (1976), Scott (1975), Kelley and Duncan (1984), and Eaton (1986).

The BRD structures have major control on current geothermal systems and associated geohydrology. Structural relief created by this tectonism has juxtaposed lithologies with very different hydrologic properties and has produced major topography changes.

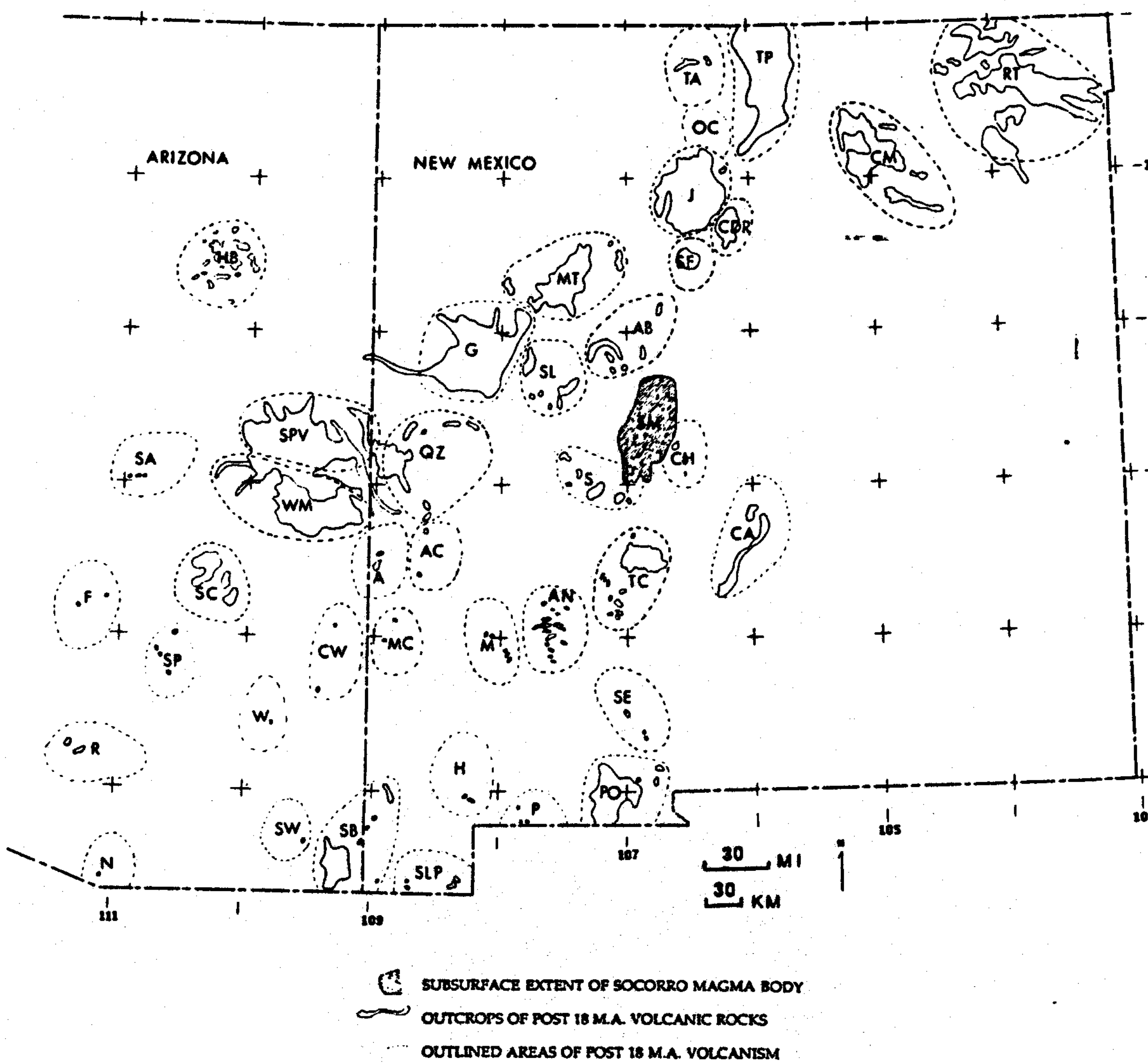
Abrupt changes in permeability can create pressure differences favorable to force vertical movement of groundwater. Vertical water flow transports heat. When flow is forced upward from great depth, heat is concentrated at shallow depths. Mountain ranges formed by the BRD receive sufficient precipitation to constitute runoff sources for recharge of some of the groundwater systems in the study area. Grabens formed by this tectonism are filled with up to 3 km of clastic sediment. In many basin fills, clay comprises a significant clast fraction and quartz content is minor, resulting in low thermal conductivity values.

Quaternary faults may have created new fracture permeability or opened older mineral-sealed fractures. These faults are especially important at crossings of older fractured structures. In these areas, important vertical permeability zones are possible, allowing recharge or discharge to and from deep geothermal aquifers.

The BRD tectonism in the study area was accompanied by alkali and tholeiitic basalt (i.e., <40 percent $SiO_2$) volcanism that is distinctly different than earlier mid-Tertiary calc-alkalic (i.e., >53 to 57 percent $SiO_2$) volcanism. Volumetrically, this volcanism is insignificant compared to earlier mid-Tertiary arc- (and possibly back-arc) related volcanism. Except for the Glenwood-Mogollon and Socorro areas, this volcanism did not appear until about 9 to 13 Ma ago, ending a magma gap or cessation of volcanism that began between 18 and 24 Ma at the end of mid-Tertiary calc-alkalic volcanism. Initiation of alkali basalt volcanism was concurrent with the beginning of the BRD high-angle faulting or rifting. Basaltic volcanism in the study area occurs in ephemeral volcanic fields. These fields are characterized by low-volume, single-eruption central vents (see Figure 1-9).

Volcanism in the Socorro and Glenwood-Mogollon areas is anomalous. In these two areas, bimodal alkali-tholeiitic basalt and high-potassium, high-silica rhyolite volcanism began as early as 21 Ma (Ratte and others, 1984). The last high-potassium, high-silica rhyolite volcanism occurred in the Socorro area about 11 Ma (Bobrow and others, 1983). Also, the Socorro area (see Figure 1-9) is presently underlain at 19 km by a magma body less than 1 km in thickness (Sanford and others, 1973; Sanford and others, 1977). This magma is spatially associated with significant seismic energy release that is only matched by seismicity in the Mogollon region (Taggart and Baldwin, 1982). Judging from historical seismicity of the region, the Socorro magma body may be highly anomalous. Both the anomalous Socorro and Glenwood-Mogollon areas are astride the northeast-trending Morenci lineament (Chapin and others, 1978).

Elsewhere in the study area, the presence of unaltered mantle and lower-crust zenoliths enclosed in post 10-Ma basalts indicate rapid transport to the surface from 235 to 70 km depths (Padovani and Carter, 1977). Due to the low volume (i.e., <3 $km^3$) of individual eruptive events and the probable dike-like morphology of basalt intrusions at mid- to upper crustal levels, these features cannot act as large, sustained heat sources that are required for high-temperature hydrothermal systems.




A..........Alma
AB........Albuquerque Basin
AC........Apache Creek
AN........Animas
CA........Carrizozo
CDR......Cerro Del Rio
CH........Chupadera
CM........Cimmaron
CW........Clifton-Whitlock
F...........Florence
G...........Grants
H...........Hatchet
HB........Hopi Buttes
J............Jemez
M...........Mimbres
MC........Mule Creek
MT........Mount Taylor
N...........Nogales
OC........Ojo Caliente
P...........Palomas
PO........Portrillo
QZ.........Quemado - Zuni Salt Lake
R............Roskruge
RT..........Raton
S.............Socorro
SA..........Sierra Ancha
SB...........San Bernadino
SC...........San Carlos
SE...........Seldon
SF...........San Felipe
SL...........Sierro Lucero
SLP.........San Luis Pass
SM.........Socorro Magma Body
SP...........San Pedro
SPV.........Springerville
SW..........Swisshelm
TA...........Tierra Amarilla
TC...........Truth or Consequences
TP...........Taos Plateau
W............Willcox
WM........White Mountain

Figure 1-9. Areas of post 18-Ma basaltic volcanism. The principal data sources are Aldrich and Laughlin (1981), Bachman and Mehnert (1978), Baldridge and others (1980), Bobrow and others (1983), Johnson and Scarborough (1984), Luedke and Smith (1978), New Mexico Geological Society (1982), Seager and others (1984), and Scarborough (1985).

Magmatic heat sources in the study area are only probable along the Morenci lineament where young, undiscovered bimodal basalt-rhyolite systems may be inferred. The depth and apparent youth makes the Socorro magma body an unlikely heat source for present-day hydrothermal systems.

## 1.3 Geohydrologic Setting

The geology and water-table configuration have a strong influence on groundwater flow systems in the study area. Several hydrologic units may be identified in the geologic framework. These units are either aquifers or aquitards. Units are distinguishable on the basis of water well production, lithology, degree of cementation, amount of deformation, and tectonic setting. Figure 1-10 shows general relationships of these units.

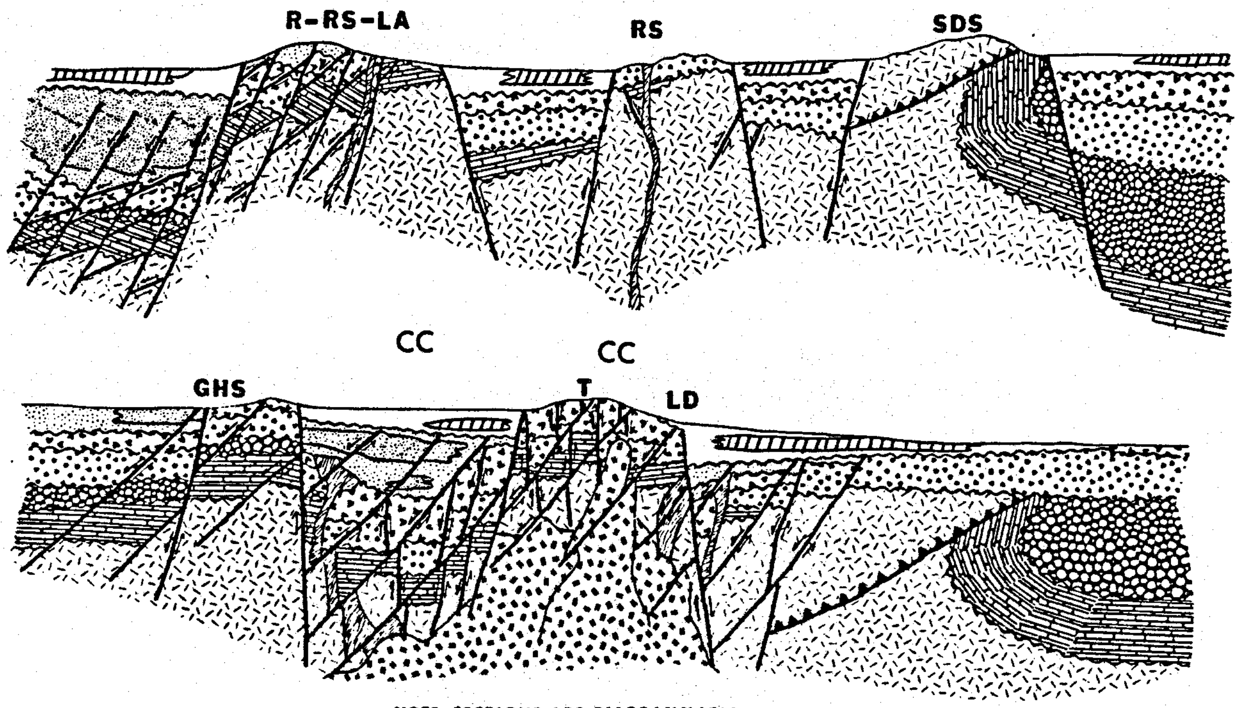
### 1.3.1 Aquifers

Important aquifers, listed in order of increasing age, include:

Unit 1: Recent to Pleistocene; unconsolidated alluvium; fluvial and alluvial fan deposits of present-day flood plains, undeformed; up to 30 m thick; highly permeable; not a geothermal aquifer; Rio Grande flood plain deposits.

Unit 2: Pleistocene to upper Miocene; mostly unconsolidated fluvial and alluvial fan deposits; sediments deposited in BRD basins by through flowing Rio Grande or as marginal fans; undeformed; 0 to 300 m thick; very permeable; not a geothermal aquifer; Camp Rice Formation.

Unit 3: Lower Miocene to middle Miocene; moderately to highly indurated clastic sediments; sediments fill mid-Tertiary proto Basin and Range depressions; faulted and tectonically rotated; up to 1,000 m thick; low permeability except where highly deformed; not an important geothermal aquifer; unit




**NOTE: SECTIONS ARE DIAGRAMMATIC, STRUCTURES AND UNIT THICKNESSES NOT DRAWN TO SCALE.**

**AQUIFERS**

- Unit 1 Recent to Pleistocence; unconsolidated alluvium Included in Unit 2
- Unit 2 Pleistocene-to-upper Miocene; fluvial and alluvial fan deposits
- Unit 3 Lower Miocene-to middle Miocene; fluvial and alluvial fan deposits, indurated and variously deformed
- Unit 4 Oligocene-to-lower Miocene; basaltic flows and rhyolitic ash-flow tuff
- Unit 5 Oligocene-to-lower Miocene, discordant rhyolite and dacite intrusions
- Unit 6 Cretaceous-to-Paleozoic, carbonate rocks
- Unit 7 Precambrian, fractured plutonic and metamorphic rocks

**AQUITARDS**

- Unit A Pleistocene-to-lower Miocene; playa and basinal facies deposits
- Unit B Upper Miocene-to-Oligocene, playa and basinal facies deposits, indurated and variously deformed
- Unit C Lower Miocence-to-Eocene; tuffaceous volcaniclastic sediments, mudflows and altered andesite flows
- Unit D Lower Miocene-to-Eocene; unfractured plutonic intrusive rocks
- Unit E Upper Cretaceous-to-Eocene, indurated clastic sediments
- Unit F Cretaceous-to-Paleozoic; shale
- Unit G Precambrian; unfractured crystalline rock

| | |
|---|---|
| CC | Faulted and extended cauldron complex |
| GHS | Gila Hot Springs |
| LD | Lightning Dock |
| R-RS-LA | Rincon-Radium Springs-Las Alturas |
| RS | Radium Springs |
| SDS | San Diego Mountain |
| T | Tortugas Mountain |

thrust or reverse fault, barbs on upthrown side

contact

normal fault

Figure 1-10. **Generalized cross section of hydrogeologic units. Letter codes above the cross sections identify representative geologic settings diagrammatically for selected southwest New Mexico geothermal systems.**

is mainly an aquitard; Hayner Ranch and Popotosa Formations.

Unit 4: Oligocene to lower Miocene; basaltic flows and ash-flow tuff; mostly secondary fracture permeability; thickest in mid-Tertiary volcano-tectonic depressions, faulted and sometimes rotated; ranges in thickness from 500 m to 3,000 m; may be highly permeable in faulted zones; very important geothermal aquifer; Bloodgood Canyon Tuff at Gila Hot Springs (Elston, 1981).

Unit 5: Oligocene to lower Miocene; discordant rhyolite and dacite intrusions; may be highly fractured and permeable; very important geothermal aquifer; rhyolite dikes at Radium Springs.

Unit 6: Cretaceous to Paleozoic; several carbonate units; important fracture and solution permeability, especially along structural trends; individual units 20 to 150 m thick; very important geothermal aquifer; Penn-Permian carbonate reservoirs for Truth or Consequences, Faywood Hot Springs, and Las Alturas geothermal systems (Gross and Icerman, 1983).

Unit 7: Precambrian; highly fractured plutonic and metamorphic rocks are potentially important geothermal aquifers along major structural trends.

Geologic units 4, 5, and 6 provide the parent aquifers for all identified convective geothermal systems in southern New Mexico. The structural setting and temperature of many systems suggests that flow through fractured Precambrian granite (i.e., unit 7) probably also occurs.

1.3.2 Aquitards

Aquitards in the study area, listed in order of increasing age, are:

Unit A: Pleistocene to lower Miocene; fine-grained playa and basinal facies of BRD graben-filling sediments; less than 300 m thick; Fort Hancock Formation.

Unit B: Upper Miocene to Oligocene; fine-grained playa and basinal facies of clastic packages filling mid-Tertiary proto Basin and Range depressions; frequently faulted and rotated; 150 to 300 m thick; Popotosa Formation.

Unit C: Lower Miocene to Eocene; altered tuffaceous volcaniclastic sediments and mudflows; up to 1,000 m thick; Palm Park Formation.

Unit D: Lower Miocene to Eocene; unfractured plutonic rocks; Organ Batholith.

Unit E: Upper Cretaceous to Eocene; highly indurated clastic sediments filling Laramide basins; 20 to 2,000 m thick; Love Ranch Formation.

Unit F: Cretaceous to Paleozoic; various indurated clastic strata and shales; 10 to 50 m thick; Percha Shale.

Unit G: Precambrian; unfractured plutonic and metamorphic rocks.

Laramide age intrusive and extrusive rocks may act as aquifers or aquitards, depending upon the nature and degree of alteration. In any case, these formations are frequently highly fractured.

The position of aquitards with respect to aquifers is as important as is the existence of the aquifers. Clayey aquitards allow high conductive temperature gradients to occur, confine deep flow systems, and may store large volumes of water due to high porosity. Also, when the hydraulic head is sufficient, aquitards act to refract significant groundwater flow vertically.

### 1.3.3 Basin Classification

Physiographic information allows broad hydrogeologic classification of southern New Mexico basins. Two basic types of hydrologic settings occur in the Basin and Range Province (Snyder, 1962). Open basins have surface drainage exits, while closed basins have interior surface drainage toward a playa. Some closed basins allow discharge only by evapotranspiration from playas. Other closed basins allow groundwater discharge as underflow to adjacent basins. All open basins have at least some underflow in addition to surface outflow by streams. Recharge for closed and open basins may occur from mountain front recharge, stream infiltration, and by subsurface inflow from adjacent higher basins (Rantz and Eakin, 1971).

In the study area, open basins occur along the Gila-San Francisco, Mimbres, and Rio Grande drainages. Closed basins are found elsewhere in southwest New Mexico such as the Tularosa, Playas, and Animas basins.

Nearly all geothermal systems in the study area occur in open-basin hydrologic settings. The Lightning Dock and Hueco Tanks systems are exceptions. These two systems occur on a closed-basin margin where the water table is elevated relative to the basin interior. This fact suggests that these occurrences may not be controlled by the hydrology of the host closed basin. However, basin-bounding faults may act as master conduits to allow interbasin recharge and local flow approximately parallel to large-scale, water-table contours.

A water-table elevation map (see Figure 1-11) and a depth-to-water table map (see Figure 1-12) facilitate interpretation of the geohydrology of the study area. Individual physiographic basins comprise local groundwater flow systems. Water-table contours are widespaced within these basins and are underlain by very permeable aquifers, units 1 and 2. The local groundwater flow systems are bound mostly by aquitards, units B, C, and E.

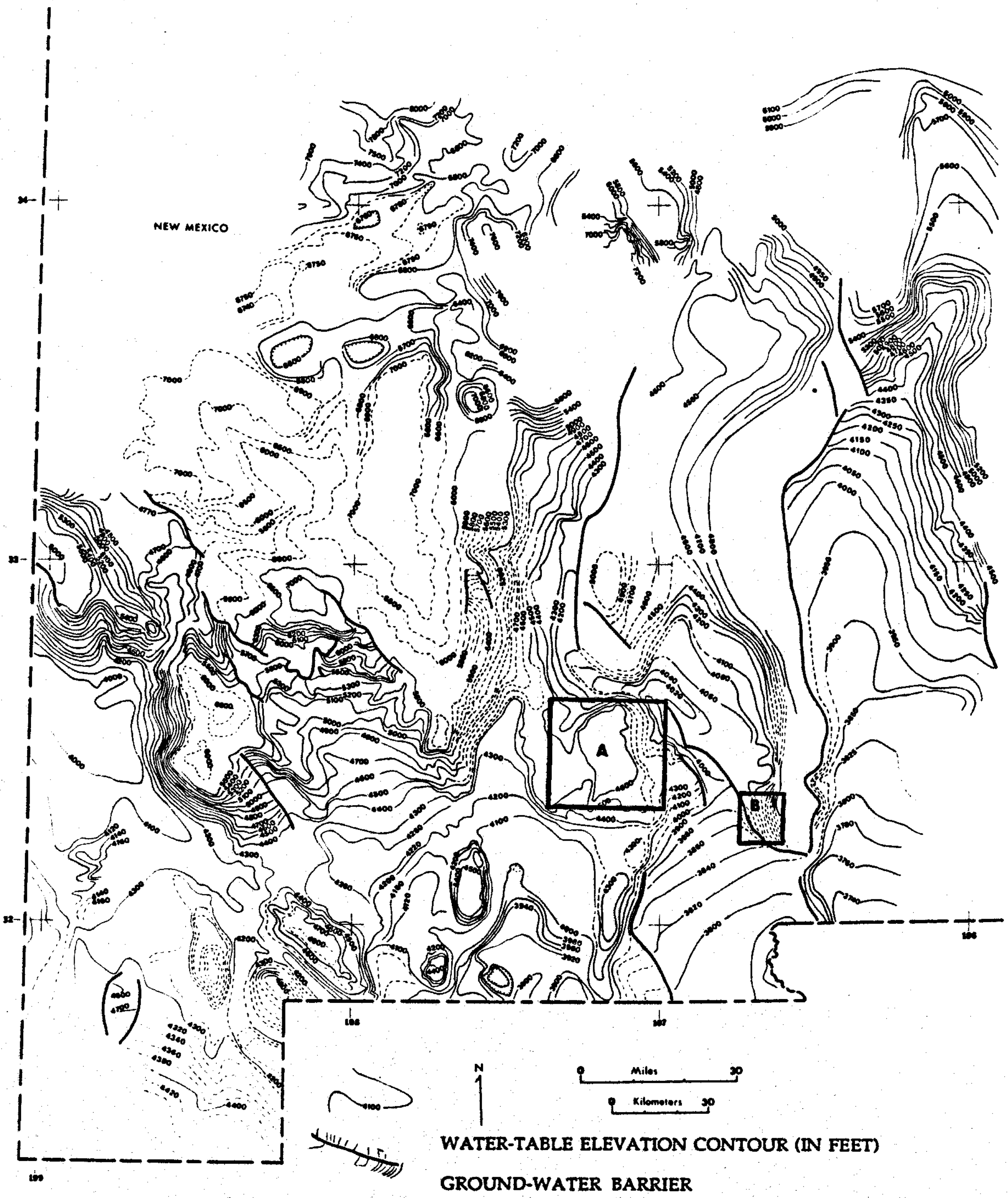



Figure 1-11. Water-table elevation map. The Sierra de Las Uvas area (A) and the western pediment of the Organ Mountains (B) are shown. Locations of geothermal systems are shown in Figure 1-14. The principal data sources are Brady and others (1984), Bushman and Valentine (1954), Clark and Summers (1968), McLean (1970, 1977), O'Brien and Stone (1981), Reeder (1957), Trauger (1972), Wilson and others (1981), and Wright (1980).

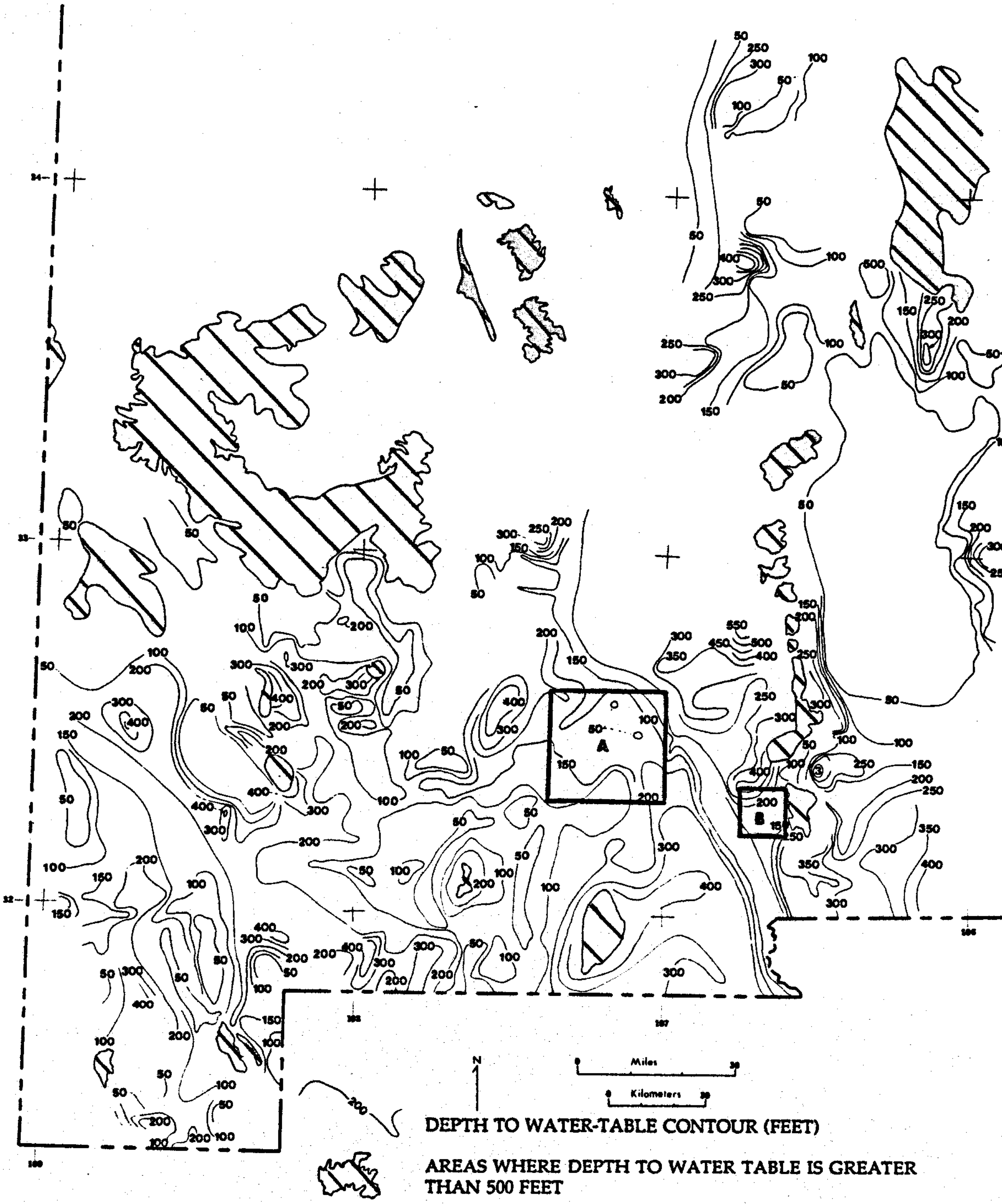



Figure 1-12. Depth to water table map. The Sierra de Las Uvas area (A) and the western pediment of the Organ Mountains (B) are shown. Locations of geothermal systems are shown in Figure 1-14. The principal data sources are Brady and others (1984), Bushman and Valentine (1954), Clark and Summers (1968), McLean (1970, 1977), O'Brien and Stone (1981), Reeder (1957), Trauger (1972), Wilson and others (1981), and Wright (1980).

These local systems may have limited hydrologic connection at depth with aquifers, units 4, 5, 6, and 7. From a geothermal perspective, these local systems are unimportant because deeply reaching (i.e., >1 km) flow paths probably do not exist. High-permeability and vertically inhomogenous basin fill, coupled with flat water tables indicate very strong horizontal flow paths in the basins. In larger basins, where significant differences in hydraulic head occur, some vertical flow may be forced through aquitards, units B, C and E, to charge underlying aquifers, units 4, 5, 6, and 7.

Steep water-table gradients are observed along the pediments of many mountain ranges, while depths to the water table are shallow and show little variation. The western pediment of the Organ Mountains east of Las Cruces is an example (compare Figures 1-1 and 1-11). Here, groundwater in alluvial fans is apparently perched over low-permeability volcanic rocks. This water flows laterally downhill in alluvial fan sediments rather than flowing downward into and through the volcanic bedrock. On other pediments and mountain ranges in the study area, low water-table gradients coincide with relatively deep water tables. The Sierra de Las Uvas, northwest of Las Cruces, which is apparently a recharge area, is an example (compare Figures 1-1 and 1-11).

Sometimes steep water-table gradients coincide with major changes in water depth across areas with little topographic relief. A decrease in the ability of subsurface lithology to laterally transmit water is indicated. Discharge zones for many geothermal systems occur adjacent to these groundwater barriers. Hydraulic heads associated with groundwater barriers increase the penetration depth and intensity of local flow systems causing interactions with hot, deep flows associated with regional systems.

Discharge from deep, regional groundwater flow systems frequently occurs along major perennial drainage where base flow is maintained by groundwater (Hitchon, 1969). This phenomena may help explain the preponderance of geothermal systems in open basins of the study area. The geothermal systems at Truth or Consequences, Gila Hot Springs, Radium Springs, and Lower Frisco Hot Springs are examples. However, drainage has entrenched canyons in these areas to create significant topographic relief. This relief and possible attendant water-table variations will also increase local flow system interaction with deep systems.

Details of flow regimes in and around major fault zones are not seen at the scale used to compile the water-table elevation and depth to water-table maps given in Figures 1-11 and 1-12. Flow systems caused by buried, highly permeable aquifers also may go undetected.

## 1.4 Thermal Regime

Numerous studies have addressed the thermal regime of the study area. Prior to the past 20 years, nearly all investigations focused on gathering basic temperature-gradient and heat-flow information or modeling regional- and crustal-scale aspects of the thermal regime. During the 1970s, many efforts were initiated to explore and characterize the geothermal resources in the study area, resulting in the collection of a large amount of thermal data.

Chemical geothermometry of thermal and nonthermal waters provide much valuable information on subsurfaces temperatures (Swanberg, 1979; Swanberg, 1983). Swanberg and Morgan (1978) used silica geothermometry to investigate terrestrial heat flow.

Studies by Warren and others (1969), Sass and others (1971a), Decker and Smithson (1975), Reiter and others (1975), Reiter and others (1978b), Sanford and others (1979), Decker (1969), Daggett (1982), Reiter and others (1986), Snyder (1986), and Witcher (1988a) have greatly expanded the heat-flow data base for the study area. Regional thermal regime modeling by Lachenbruch and Sass (1978) and Cook and others (1978) investigated the processes affecting the large-scale temperature distribution in the crust. Transient and steady-state models have been presented. Temperature-gradient studies by Morgan and others (1979), Lohse (1982), Icerman and Lohse (1983), and Lohse and Schoenmackers (1985) have provided the detail necessary to observe shallow and local thermal regimes associated with low-to-moderate temperature geothermal systems in Dona Ana County.

Swanberg and Snyder (1984), Snyder (1986), and Witcher (1988b) described and presented a large, industry heat-flow and temperature-gradient data base. Thermal-regime modeling of geothermal systems and small-scale convective and refraction effects are presented and discussed by Blackwell and Chapman (1977), Mansure and Reiter (1979), Morgan and others (1981), Snyder (1986), and Witcher (1988a).

The areal coverage of site-specific studies of heat flow and temperature gradients within the study area is shown in Figure

1-13. Additional site-specific geothermal information for southern New Mexico is compiled in Appendix B.

1.4.1 Compilation of Thermal Data

Three classes of thermal data were compiled for the study area: (1) spring discharge temperatures, (2) water-well depths and production temperatures, and (3) temperature-gradient and heat-flow information. Determination of the temperatures which distinguish thermal springs from nonthermal springs is linked to local mean annual air temperature (MAT) because the local MAT approximates the surface boundary temperature of the conductive thermal regime of the earth. For example, in Montana, where a 5°C MAT may exist, a spring issuing at 20°C is abnormally warm or thermal. A spring discharging 20°C water in southern New Mexico, where the MAT is 17°C (Morris and others, 1985) is considered nonthermal.

The spring discharge temperatures for 85 springs in southern New Mexico exceed the MAT by a mean of $6.7 \pm 9.6$°C. Based on these statistics, an anomalously warm spring is defined as one with a discharge temperature that exceeds the local MAT by the mean temperature difference plus one standard deviation or approximately 16°C (see Table 1-1).

Definitions of thermal wells are based on the thermal gradient, the rate at which temperature increases with depth. Determining a normal or background temperature gradient is not straightforward because the gradient is dependent upon terrestrial heat flow and the thermal conductivity of rock, both of which are functions of location.

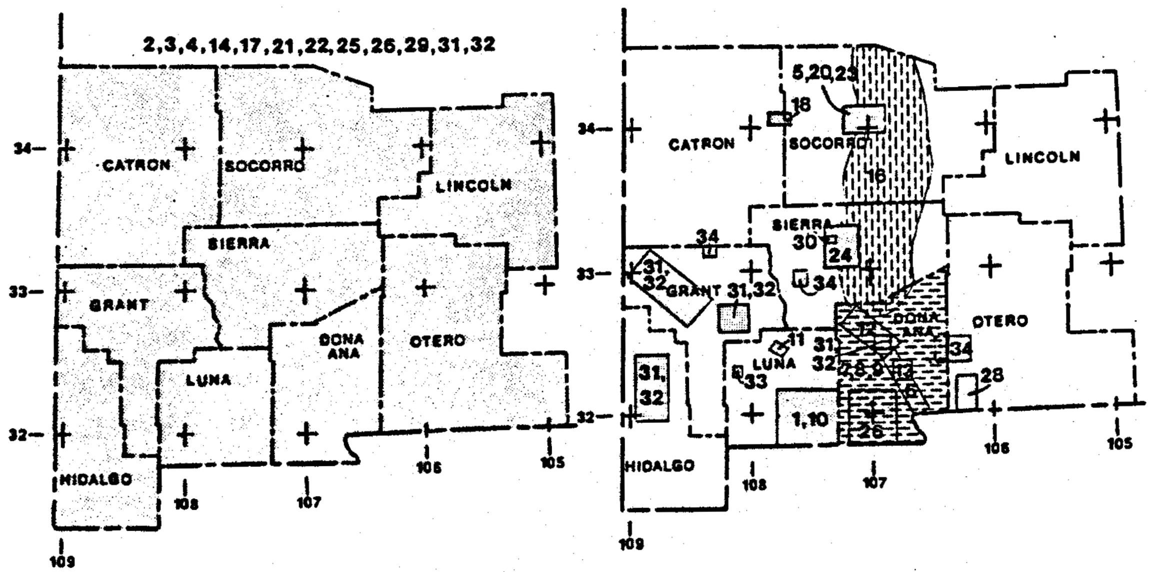



Figure 1-13. Selected site-specific sources of heat-flow and temperature-gradient information. The numbers on the maps identify the following studies: (1) Daggett, 1982; (2) Decker, 1969; (3) Decker and Birch, 1974; (4) Decker and Smithson, 1975; (5) Hawkins and Stephens, 1981; (6) Icerman and Lohse, 1983; (7) Lohse and others, 1980a; (8) Lohse and others, 1980b; (9) Lohse and others, 1981a; (10) Lohse and others, 1981b; (11) Lohse, 1982; (12) Lohse and Schoenmackers, 1985; (13) Morgan and others, 1979; (14) Reiter and others, 1975; (15) Reiter and others, 1978a; (16) Reiter and others, 1986; (17) Reiter and others, 1979; (18) Reiter and others, 1976; (19) Reiter and others, 1978b; (20) Reiter and Smith, 1977; (21) Roy and others, 1968a; (22) Roy and others, 1968b; (23) Sanford, 1978; (24) Sanford and others, 1979; (25) Sass and others, 1971b; (26) Shearer and Reiter, 1978; (27) Snyder, 1986; (28) Taylor, 1981; (29) Warren and others, 1969; (30) Wells and Granzow, 1981; (31) Witcher, 1988a; (32) Witcher, 1988b; (33) Zielinski and DeCoursey, 1983; and (34) unpublished data.

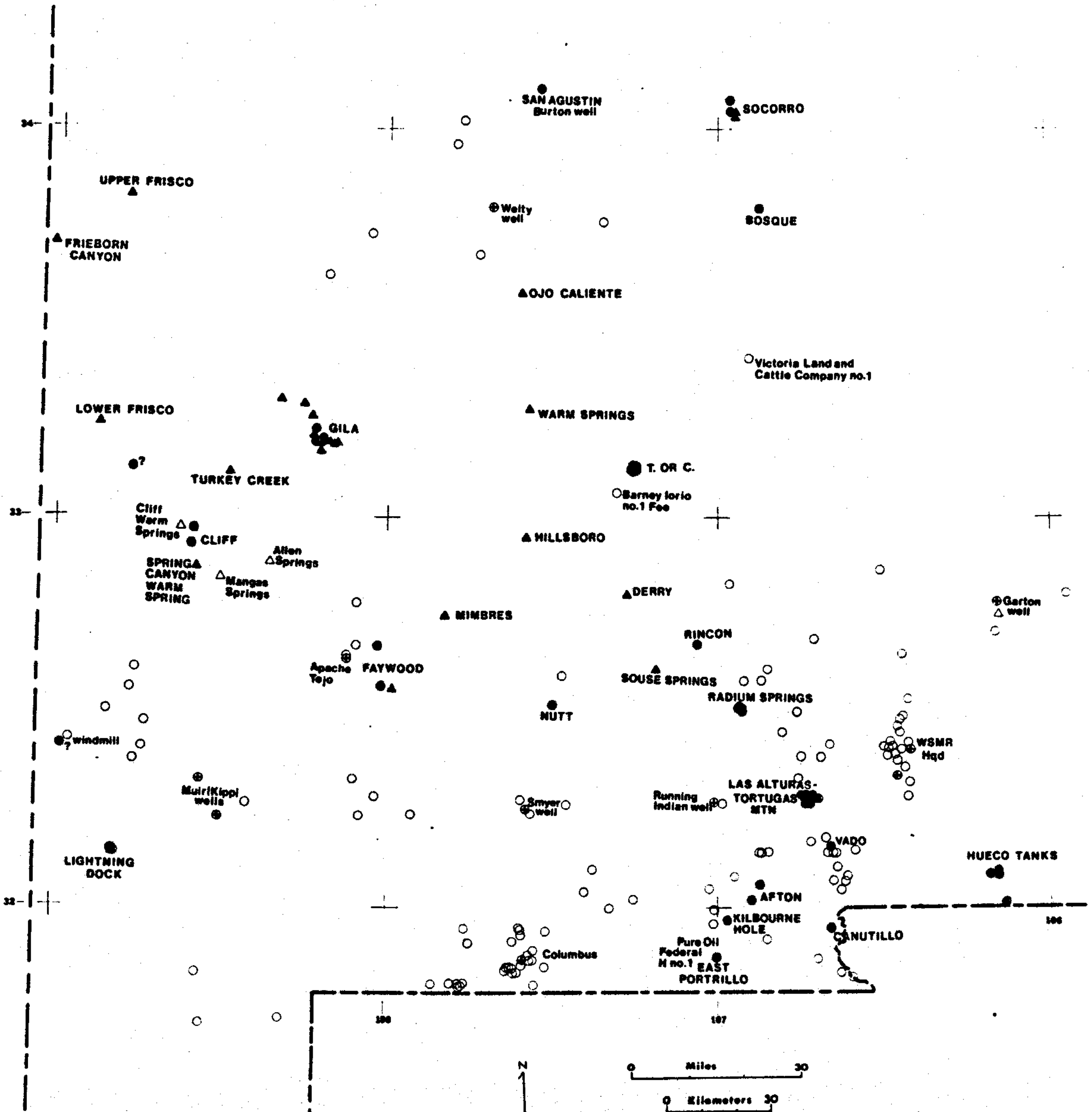
Table 1-1. Anomalously warm springs in the study area. The principal data sources are McLean (1970), Summers (1976), Swanberg (1980), Theis and others (1941), and Trauger (1972).

| Location | Temperature (°C) |
|---|---|
| 3S.1W.22.113 | 33.0 |
| 3S.1W.22.131 | 33.5 |
| 3S.1W.22.31 | 32.2 |
| 12S.14W.1.33 | 64.8 |
| 13S.4W.33.4331 | 39.4 |
| 13S.4W.33.4341 | 41.1 |
| 13S.13W.5.241 | 64.0 |
| 13S.13W.10.121 | 52.0 |
| 13S.13W.17.32 | 43.6 |
| 14S.16W.3.34 | 74.0 |
| 16S.7W.5.2412 | 34.5 |
| 16S.17W.34.21 | 31.0 |
| 17S.4W.29.340 | 33.3 |
| 18S.10W.13.111 | 58.0 |
| 19S.3W.31.34 | 31.0 |
| 20S.11W.20.243 | 53.3 |

Based on statistical analyses of southern New Mexico well data, a mean temperature gradient for 66 water wells greater than 800 feet (244 m) in depth is 34 $\pm$ 17.5$^{o}$C/km. Therefore, a water well whose discharge temperature exceeds the MAT by 16$^{o}$C and has a temperature gradient of at least 52$^{o}$C/km, the mean gradient plus one standard deviation, is classified as a thermal well. Figure 1-14 shows currently known thermal wells and springs in the study area. Other wells and springs with production and discharge temperatures greater than 26$^{o}$C are also shown even though this temperature is not considered anomalous.

Temperature-depth data was compiled for 1,482 water wells from 18 sources. Temperature-gradient estimates were calculated for these wells using the local elevation to estimate the mean annual temperature and assuming that the origin of the produced water is the bottom section of the well. Sixty-two of these wells are classified as thermal wells (see Table 1-2).

Heat-flow information, compiled from 34 published and unpublished sources, was divided into two categories. The first category, measured heat-flow values, includes 110 published values, calculated from temperature-depth data and measurements of bulk thermal conductivity and formation porosity, plus 143 industry values, based on temperature-depth data, measured bulk thermal conductivities, and formation porosity estimates. Category two, estimated heat-flow values, includes 280 industry values and 250 published and unpublished values, based on temperature-depth data and estimated values for thermal conductivity and formation porosity. Thus, 783 heat-flow values were avail-




| | |
|---|---|
| o | Well with discharge temperature greater than 26°C. |
| △ | Spring with discharge temperature greater than 26°C. |
| • | Thermal well with discharge temperature greater than 26°C and 16°C greater than the MAT. Well has an average estimated temperature gradient greater than 50°C/km but less than 75°C/km |
| ● | Thermal well with discharge temperature greater than 26°C and 16°C greater than the MAT. Well has an average estimated temperature gradient equal to or greater than 75°C/km. |
| ▲ | Thermal spring with discharge temperature greater than 26°C and 16°C greater than the MAT. |

Figure 1-14. Thermal wells and springs in the study area.

Table 1-2. Thermal wells in the study area. The principal data sources are Icerman and Lohse (1983), McLean (1977), McLean (1970), Reeder (1957), Summers (1976), Theis and others (1941), Trauger (1972), U.S. Geological Survey WATSTORE Files (1975, 1986), Wilson and Myers (1981), and Wilson and others (1981).

| Location | Depth (ft) | Temperature (°C) | Location | Depth (ft) | Temperature (°C) |
|---|---|---|---|---|---|
| 13S.4W.33.3442 | 125 | 41.6 | 21S.1W.10.2111 | 280 | 76.1 |
| 13S.4W.33.3444 | 105 | 45.6 | 21S.6W.6.1133 | 271 | 38.0 |
| 13S.4W.33.4331 | 162 | 41.1 | 22S.21W.3.312 | 445 | 35.0 |
| 13S.4W.33.4332 | 165 | 41.0 | 23S.2W.35.411 | 1,050 | 36.0 |
| 13S.4W.33.4332 | 158 | 37.0 | 24S.7W.5.1331 | 1,110 | 36.2 |
| 13S.4W.33.4333 | 125 | 41.6 | 24S.7W.5.1331 | 1,110 | 39.0 |
| 13S.4W.33.4334 | 27 | 44.6 | 25S.19W.7.143 | 32 | 36.7 |
| 13S.4W.33.4333 | 55 | 43.0 | 25S.19W.7.234 | 95 | 98.9 |
| 13S.4W.33.4334 | 101 | 44.7 | 25S.19W.7.234 | 83 | 104.4 |
| 13S.4W.33.4343 | 258 | 44.0 | 26S.1W.25.414 | 563 | 33.0 |
| 13S.4W.33.4344 | 125 | 43.8 | 28S.7W.9.4114 | 1,000 | 31.0 |
| 13S.4W.33.4433 | 100 | 44.0 | 28S.7W.19.2211 | 653 | 32.0 |
| 13S.13W.5.2323 | 455 | 74.0 | 28S.7W.26.4222 | 700 | 31.0 |
| 13S.13W.5.2141 | 238 | 74.0 | 28S.8W.25.3111 | 605 | 30.4 |
| 13S.19W.35.133 | 370 | 50.0 | 29S.10W.9.3111 | 468 | 31.0 |
| 14S.4W.4.1211 | 212 | 45.0 | 23S.2E.24.1132 | 1,315 | 65.6 |
| 14S.4W.4.1223 | 165 | 42.0 | 23S.2E.25.3213 | 645 | 68.3 |
| 14S.4W.4.1224 | 205 | 42.2 | 23S.2E.34.231 | 311 | 34.5 |
| 14S.4W.4.2111 | 105 | 46.7 | 23S.2E.34.233 | 330 | 36.8 |
| 14S.4W.4.2112 | 125 | 44.4 | 23S.2E.34.234 | 348 | 42.5 |
| 14S.4W.4.2114 | 186 | 45.0 | 23S.2E.34.214 | 212 | 43.0 |
| 14S.4W.4.2121 | 125 | 44.1 | 23S.2E.34.412 | 485 | 36.5 |
| 14S.4W.4.2124 | 185 | 38.9 | 23S.5E.5.321 | 894 | 32.0 |
| 14S.4W.4.2124 | 14 | 43.0 | 25S.3E.8.214 | 250 | 31.5 |
| 14S.4W.4.2124 | 6 | 43.9 | 25S.3E.17.111 | 710 | 31.0 |
| 14S.4W.4.2124 | 15 | 43.3 | 25S.8E.32.333 | 745 | 61.1 |
| 14S.4W.4.2142 | 176 | 42.5 | 26S.1E.18.222 | 430 | 33.5 |
| 15S.17W.27.111 | 300 | 33.0 | 26S.3E.11.111 | 501 | 31.0 |
| 16S.17W.9.242 | 36 | 30.0 | 26S.7E.1.241 | 504 | 50.0 |
| 19S.12W.19.132 | 881 | 31.0 | 26S.8E.5.332 | 452 | 71.1 |
| 19S.12W.30.411 | 1,208 | 32.5 | 27S.3E.20.432 | 706 | 33.6 |

able for construction of heat-flow maps (see Figures 1-15 and 1-16), of which approximately 32 percent are based on measured thermal conductivity values.

1.4.2 Heat-Flow Domain and Temperature-Gradient Maps

Heat-flow variation in the study area has great complexity. Four thermal domains are interpreted from a histogram of relevant heat-flow data (Witcher, 1988a). Two heat-flow contours at 65 and 105 $mWm^{-2}$ define the areal extent of these domains (see Figure 1-17). Domain 1 shows a heat-flow distribution between 50 and 60 $mWm^{-2}$. Domain 2 has the most measurements and is, therefore, taken to be the regional or background domain. Heat flow in domain 2 has a peak distribution between 80 and 100 $mWm^{-2}$. Domain 3 shows a flux ranging between 110 and 130 $mWm^{-2}$. Domain 4 has exceedingly variable heat flow greater than 145 $mWm^{-2}$. Domains 1, 3, and 4 are local in extent and are superimposed over the larger regional and widespread domain 2.

Local heat-flow domains appear to have characteristic size, shape, and sharpness. Domain 1 causes equidimensional to moderately elongated areas. A considerable size range is also typical of domain 1. Domain 3 covers narrow and elongated areas less than 10 to 20 km across. Length-to-width ratios of 5 to 1 or more are common. The geothermal systems in the study area are always associated with domain 4. Data spacing in most regions is too wide to adequately define the extent of domain 4. However, where data spacing is sufficient, domain 4 is much less extensive than the surrounding domain 3. Domains 3 and 4 are combined in Figure 1-17. These domains result from upward seepage of groundwater.

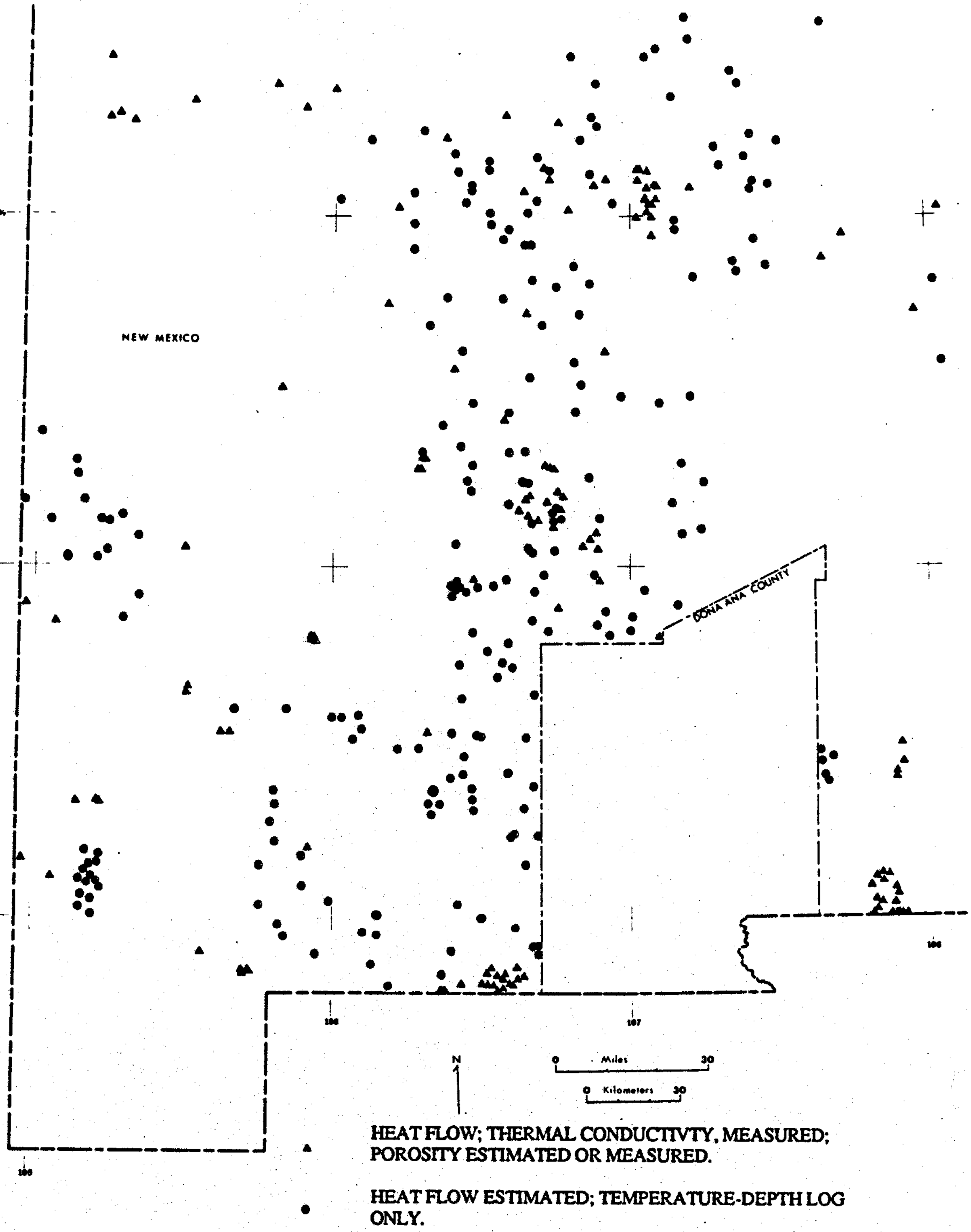



Figure 1-15. Sites of heat-flow information in the study area. All sites have measured temperature-depth data. Heat-flow information for Dona Ana County is shown in Figure 1-16. The principal data sources are given in Figure 1-13.

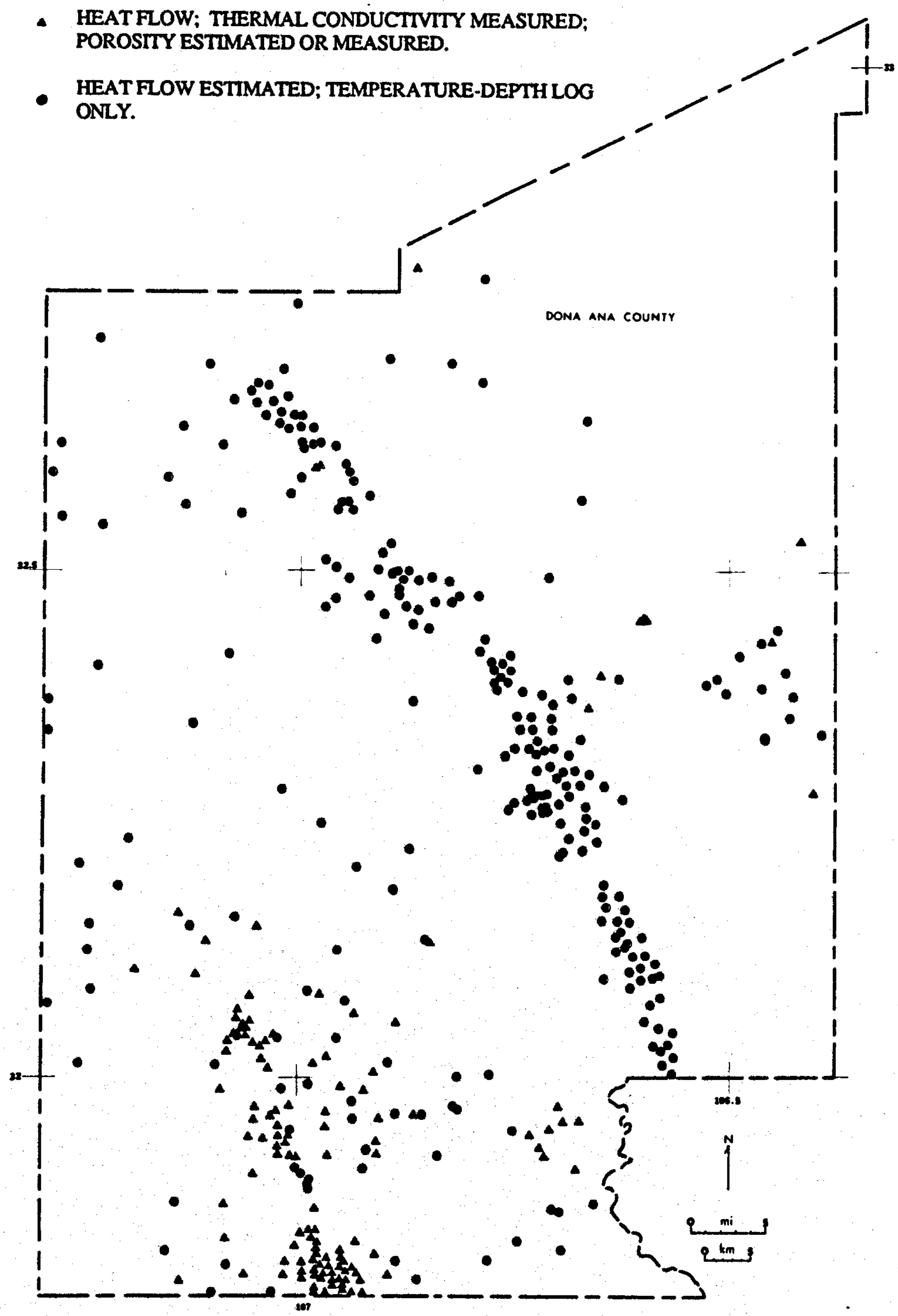



Figure 1-16. Sites of heat-flow information in Dona Ana County. All sites have measured temperature-depth data. The principal data sources are given in Figure 1-13.

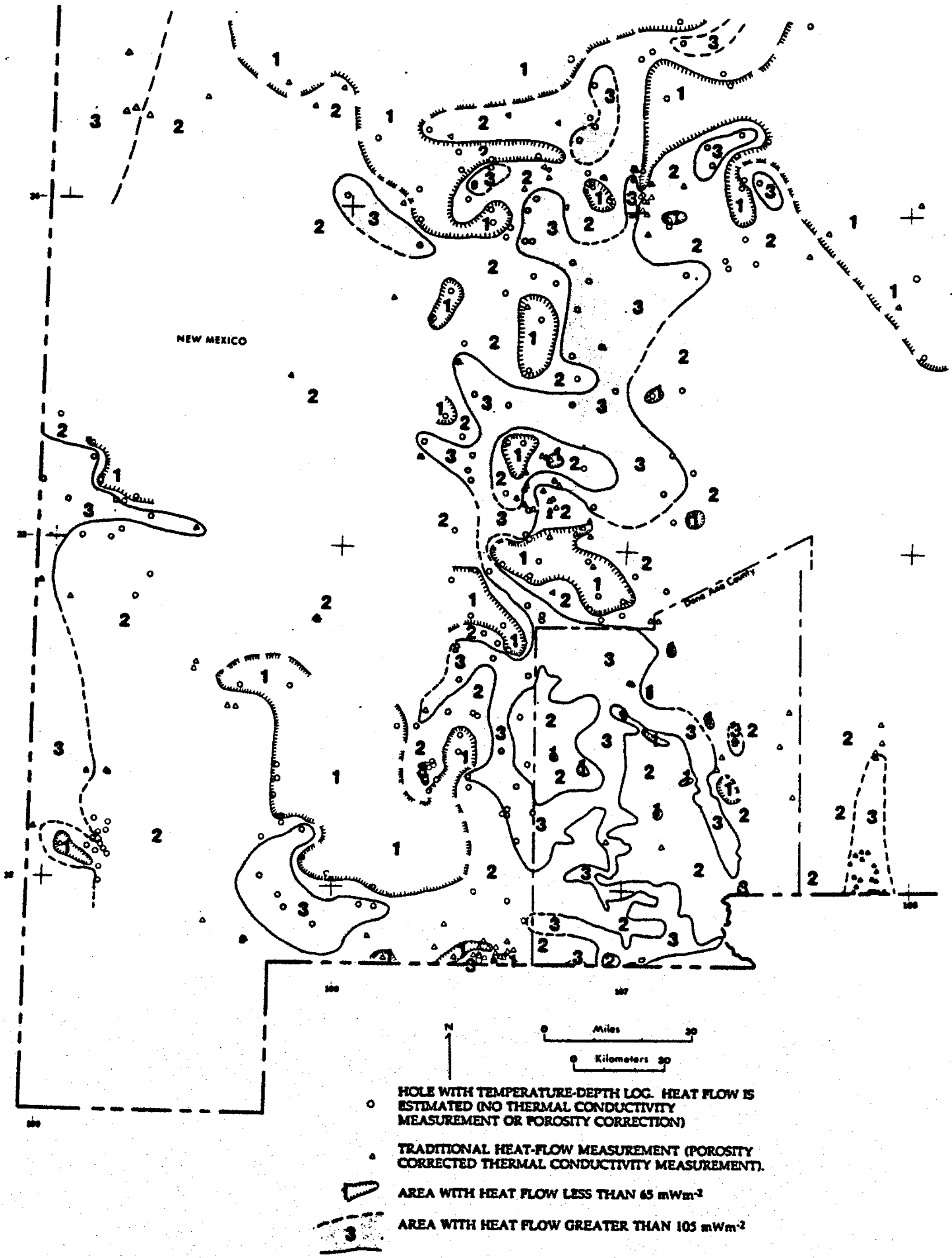



Figure 1-17. Heat-flow domain map. Domain 1: heat-flow values (in units of $mWm^{-2}$) < 65; domain 2: $65 \leq$ heat-flow values $\leq 105$; domain 3: 105 < heat-flow values < 145; domain 4: heat-flow values $\geq 145$. Domain 4 areas are not indicated because the well-characterized areas become single points at this scale. Depth-control data for heat-flow information in Dona Ana County are too dense to be shown. The principal data sources are given in Figure 1-13.

Comparison of the water-table elevation map (see Figure 1-11) and the heat-flow domain map (see Figure 1-17) reveals that areas with steep water-table gradients are frequently characterized by domain 3 heat flow. The region surrounding the Sierra de Las Uvas is a good example (compare Figures 1-1, 1-11, and 1-17). In this area, the domain 3 heat flow and steep water-table gradients correspond to major BRD fault zones inferred from gravity data (Keller and Cordell, 1983). Domain 3 heat flow is very extensive in areas with through-flowing drainage, such as the Rio Grande Valley and its tributaries and may indicate upward seepage, resulting from groundwater flow system discharge. In any case, geothermal potential exists for domain 3 areas. Potential is greatest within domain 3 where conductive temperature gradients exceed 75$^{\circ}$ C/km (see Figures 1-18 and 1-19).

### 1.4.3 Geothermal System Models

Harder and others (1980) and Morgan and others (1981) present strong arguments for forced convection of groundwater through late Cenozoic basins of the Rio Grande rift and suggest geothermal resources will be manifested at basin constrictions or outlets. Elston (1981), Elston and others (1983), and Chapin and others (1978) point out that several geothermal systems in southwest New Mexico occur in association with the ring-fracture zones of mid-Tertiary cauldrons. Late Tertiary faults, which bound Basin and Range uplifts, also may control geothermal systems (Swanberg, 1975; Jiracek and Smith, 1976; Elston and others, 1983).

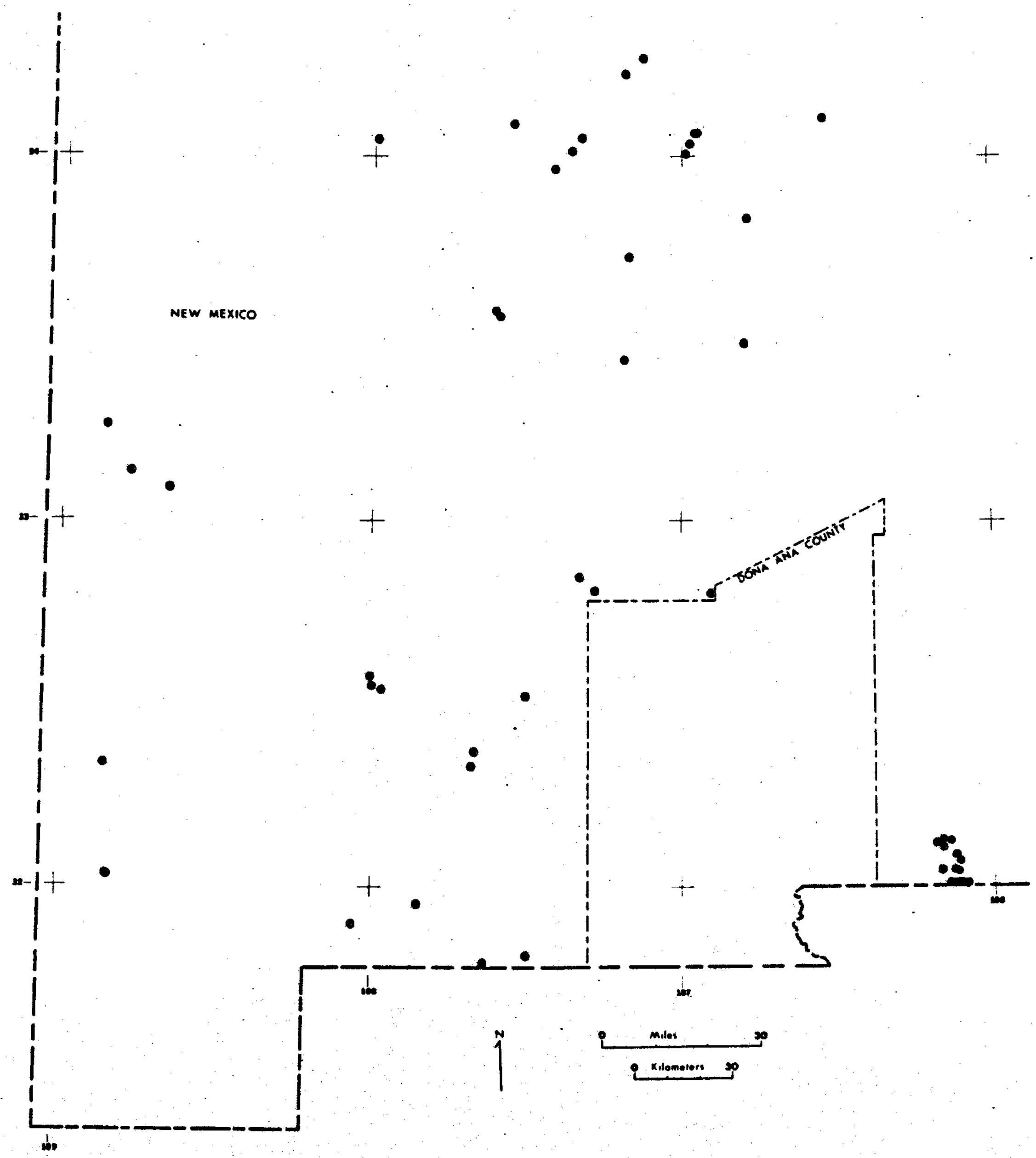



Figure 1-18. Temperature-gradient map for the study area. The dots depict sites where the measured temperature gradient exceeds 75°C/km. All holes have one or more intervals with a least-squares-fit gradient in excess of 75°C/km. Temperature-gradient data for Dona Ana County are shown in Figure 1-19. The principal data sources are given in Figure 1-13.

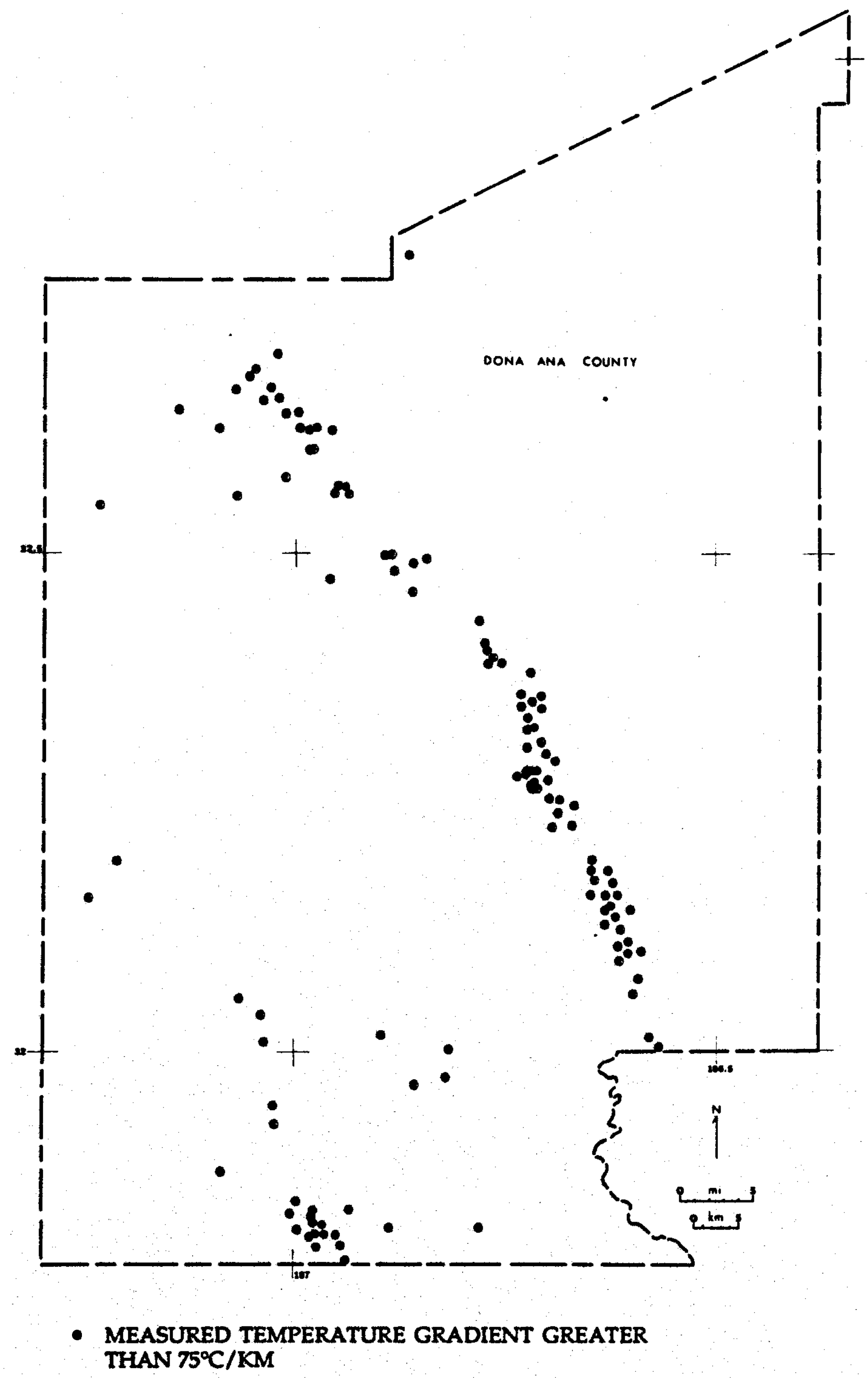



Figure 1-19. Temperature-gradient map for Dona Ana County. The dots depict sites where the measured temperature gradient exceeds 75 °C/km. All holes have one or more intervals with a least-squares-fit gradient in excess of 75 °C/km. The principal data sources are given in Figure 1-13.

Analysis of regional geology, geohydrology, and thermal regimes shows that not all basin outlets or constrictions have associated geothermal anomalies. Conversely, not all identified geothermal systems are associated with constrictions. Examples include the Hueco Tanks, Lightning Dock, Las Alturas-Tortugas Mountain, Faywood Hot Springs, Gila Hot Springs, East Portrillo, Turkey Creek Hot Springs, and Upper Frisco Hot Springs systems. Likewise, not all cauldron ring-fracture zones have geothermal anomalies. Late Tertiary horst-bounding faults appear to be very important on a large scale. In fact, areas containing faults with evidence for Quaternary slip seem to show more geothermal anomalies. However, not all late Tertiary faults have geothermal systems. Clearly, basin constrictions, cauldron ring-fracture zones, and Basin and Range faults are important exploration guides.

All convective geothermal systems in the study area have parent reservoirs in mid-Tertiary volcanic rocks or Paleozoic carbonate rocks. Fractured Precambrian crystalline rocks may also be important reservoirs for some systems. Most geothermal systems in the study area occur over Laramide uplifts. The only apparent exceptions are the Gila Hot Springs, Upper and Lower Frisco Hot Springs, and Turkey Creek Hot Springs. However, these areas may overlie uplifts which have been deeply buried by thick volcanic sequences.

Almost all convective systems in the study area discharge in open basins adjacent to through-flowing perennial drainages (see Figure 1-20). The Lightning Dock, Hueco Tanks, Socorro, and Faywood systems are exceptions.

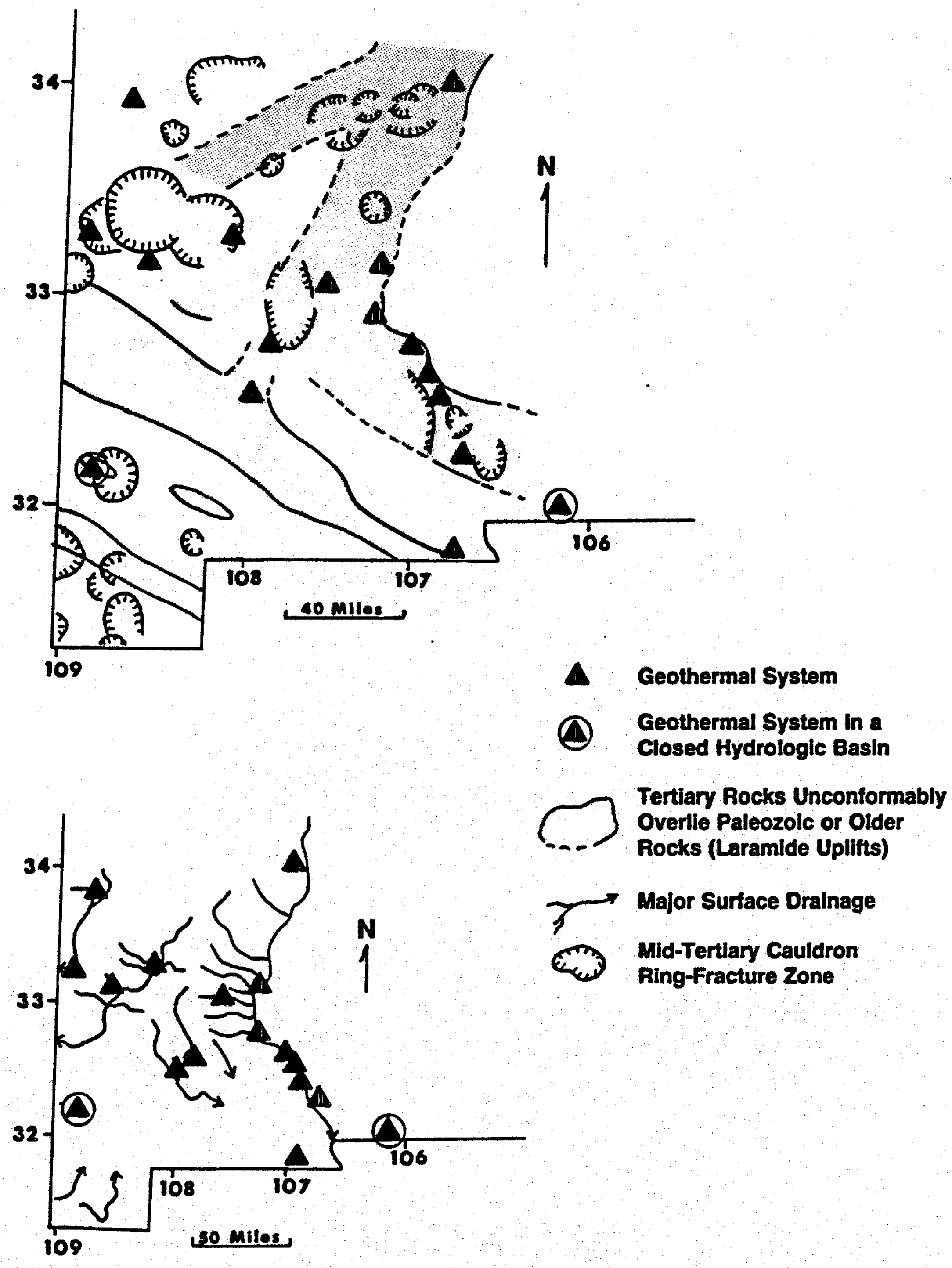



Figure 1-20. Location of convective geothermal systems with respect to Laramide uplifts and regional drainage.

Buried and low-relief horst blocks are favorable sites for systems, especially those horsts which slice Laramide uplifts and mid-Tertiary cauldron ring-fracture zones. In these areas, confining units tend to be missing or thin. Sometimes confining units are pierced by fractured intrusions allowing vertical discharge. Radium Springs is an example.

## 1.5 Concluding Remarks

Occurrence of convective systems in topographically low areas adjacent to through-flowing drainage indicates that these systems probably represent discharge from forced, regional groundwater flow systems in accordance with the models of Freeze and Witherspoon (1967) and Hitchon (1969). Fractured bedrock-reservoir lithologies for these systems indicates that deep circulation in late Tertiary basins with discharge at basin constrictions is not required. The actual discharge control for geothermal systems in the study area is the occurrence of structurally-high windows of permeable bedrock at low elevations. These discharge windows protrude through Tertiary confining units to allow outflow of geothermal waters.

## 1.6 Acknowledgments

Helpful discussions of the Tertiary subcrop map were held with W.R. Seager. Unpublished data from wells in the Plains of San Agustin were kindly provided by R.G. Myers.

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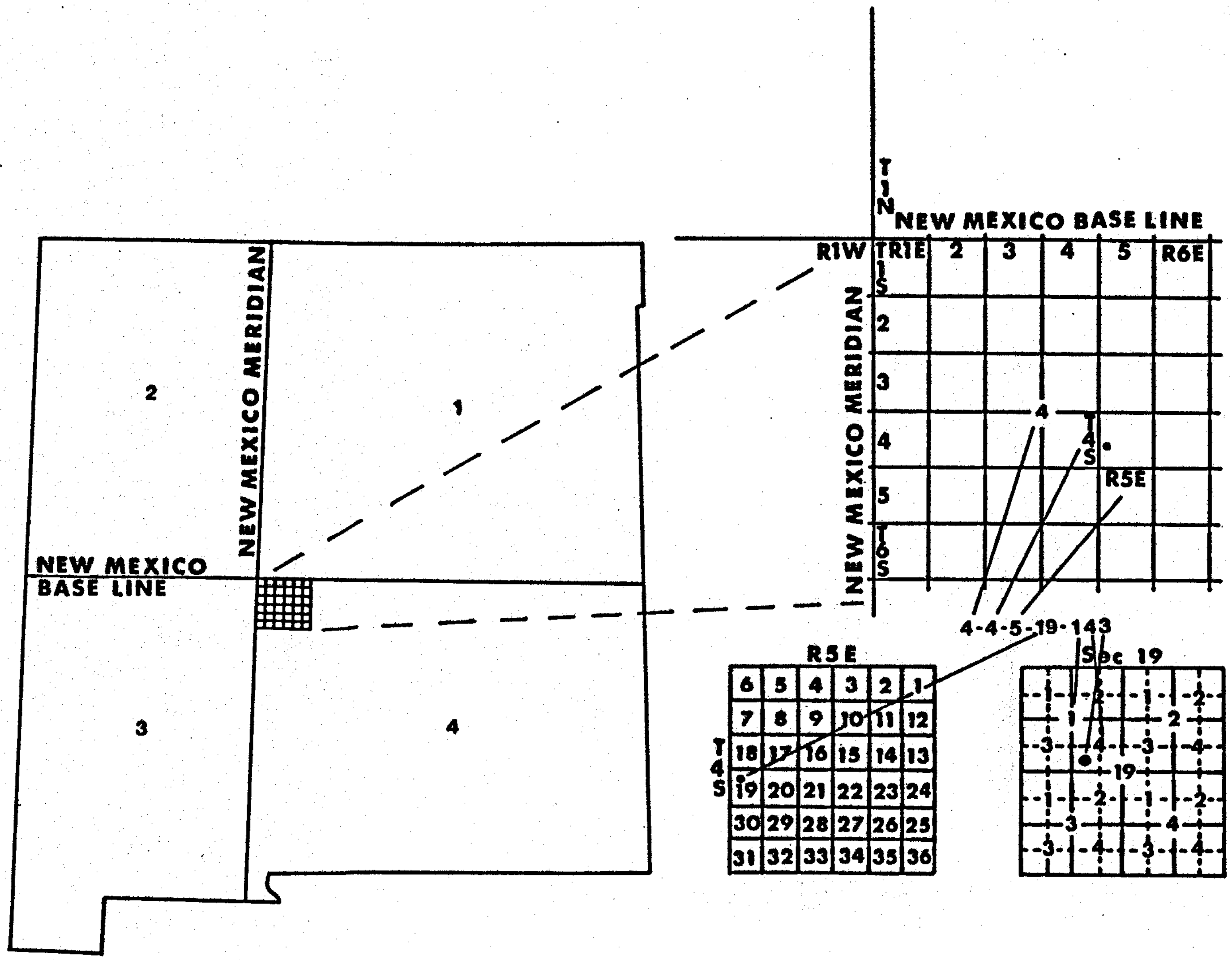
# APPENDIX A

## Coordinate System for Locating Springs and Wells in New Mexico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# APPENDIX B

## Annotated Bibliography for Geoscience Studies in Southern New Mexico

Note: This appendix is divided into three parts. Part I contains a comprehensive bibliography of geoscience studies in southern New Mexico with 421 listings arranged in alphabetical order and numbered sequentially. Part II contains a reference map of geothermal areas located within the study area labeled by county. Part III provides annotations to the bibliography arranged in alphabetical order by county for each of the geothermal areas subdivided by the major scientific category of the study such as geology, geophysical surveys, geochemical studies, hydrogeology, and other.

## Part I

## Comprehensive Bibliography of Geoscience Studies

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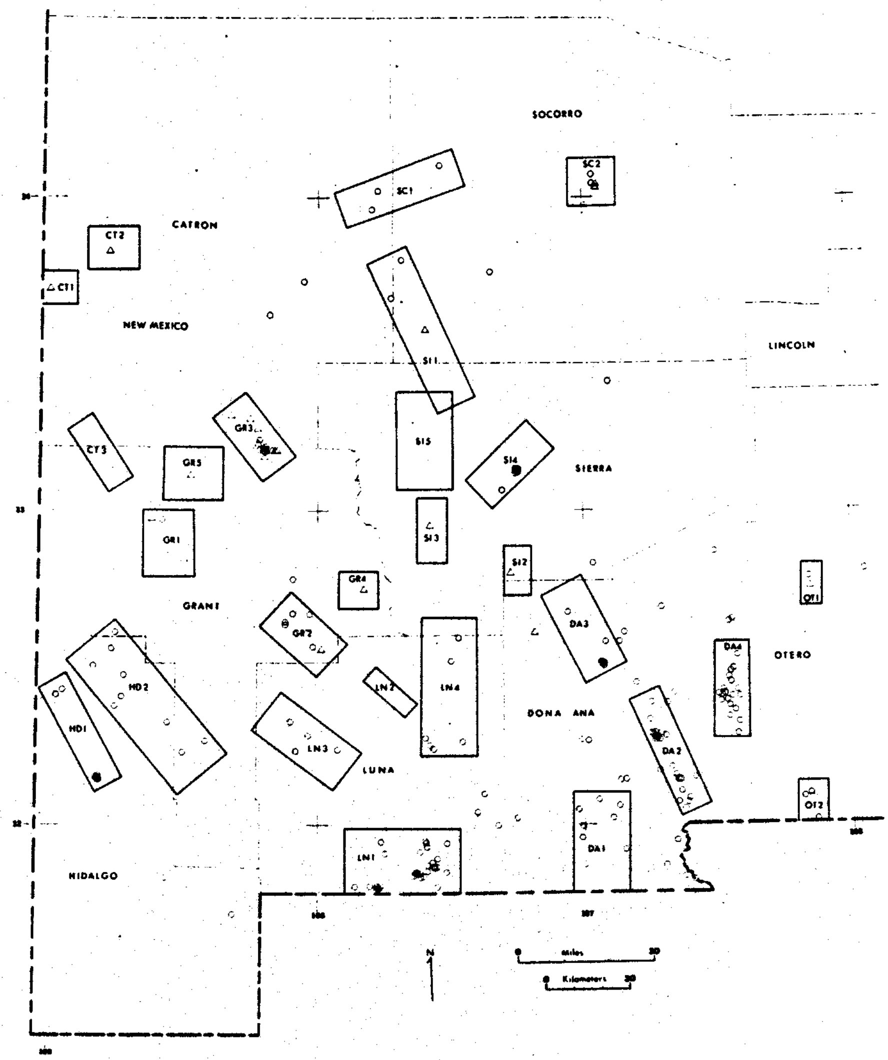
# Part II

## Reference Map of Geothermal Areas




○ Well with discharge temperature greater than 26°C.

△ Spring with discharge temperature greater than 26°C.

**CATRON**
- CT 1 Frieborn Canyon Warm Spring
- CT 2 Lower Frisco Hot Spring/Glenwood
- CT 3 Upper Frisco Hot Springs

**DONA ANA**
- DA 1 East Portillo Mountains/Kilbourne Hole
- DA 2 Las Alturas/Las Cruces East Mesa
- DA 3 Radium Springs/Rincon/San Diego Mountain
- DA 4 Tularosa Basin/White Sands Missile Range

**GRANT**
- GR 1 Cliff Area
- GR 2 Faywood Hot Springs
- GR 3 Gila Hot Springs Region
- GR 4 Mimbres Hot Springs
- GR 5 Turkey Creek

**HIDALGO**
- HD 1 Lightning Dock/Animas Valley
- HG 2 Lordsburg Basin

**LUNA**
- LN 1 Columbus Area
- LN 2 Fluorite Ridge
- LN 3 Victorio Mountains Area
- LN 4 Northern Mimbres Basin

**OTERO**
- OT 1 Garton Well/Tularosa Basin
- OT 2 Hueco Tanks/Hueco Basin

**SIERRA**
- SI 1 Cuchillo/Ojo Caliente
- SI 2 Derry
- SI 3 Hillsboro
- SI 4 Truth or Consequences
- SI 5 Warms Springs/Winston

**SOCORRO**
- SC 1 San Agustin Plain
- SC 2 Socorro

# Part III

## Bibliographic Annotations by Major Scientific Category

COUNTY - Catron
AREA NAME - CT1 - Frieborn Canyon Warm Spring

REFERENCE NUMBERS

CATEGORY

GEOLOGY
- GEOLOGIC STUDIES/MAPS - N/A
- STRUCTURE/TECTONICS - N/A
- RADIOMETRIC AGE DATES - 3, 14, 20,5 254
- IGNEOUS PETROLOGY - 20,254

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - N/A
- HEAT FLOW - N/A
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - N/A
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - N/A
- AQUEOUS GEOTHERMOMETRY - N/A
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 13, 347
- NON-THERMAL WATER CHEMISTRY - N/A
- DEPTH TO WATER - N/A
- AQUIFER CHARACTERISTICS - N/A
- HYDROLOGIC BUDGETS - N/A

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Catron
AREA NAME - CT2 - Lower Frisco Hot Spring/Glenwood

REFERENCE NUMBERS

CATEGORY

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 29, 254, 255, 256, 79, 185
- STRUCTURE/TECTONICS - 29, 254, 255, 256, 185
- RADIOMETRIC AGE DATES - 14, 205, 208, 255, 321
- IGNEOUS PETROLOGY - 20, 208, 255

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - 178
- HEAT FLOW - N/A
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - 203
- SEISMIC - N/A
- GRAVITY - 83
- MAGNETIC - N/A
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 16, 82, 85, 180, 207, 347, 369, 380
- AQUEOUS GEOTHERMOMETRY - 369
- STABLE ISOTOPES - 180

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 16, 207, 256, 347, 369, 380
- NON-THERMAL WATER CHEMISTRY - 369
- DEPTH TO WATER - 22
- AQUIFER CHARACTERISTICS - N/A
- HYDROLOGIC BUDGETS - N/A

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - 394
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Catron
AREA NAME - CT3 - Upper Frisco Hot Springs

REFERENCE NUMBERS

CATEGORY

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 255, 254
- STRUCTURE/TECTONICS - 255, 256
- RADIOMETRIC AGE DATES - 3
- IGNEOUS PETROLOGY - 20

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - 188
- HEAT FLOW - N/A
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - N/A
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY- 16, 188, 207, 347, 380
- AQUEOUS GEOTHERMOMETRY- 207, 380
- STABLE ISOTOPES - 207

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 16, 188, 207, 347, 380
- NON-THERMAL WATER CHEMISTRY - 188, 380
- DEPTH TO WATER - N/A
- AQUIFER CHARACTERISTICS- N/A
- HYDROLOGIC BUDGETS- N/A

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC- N/A
- APPLICATIONS- N/A
- BIBLIOGRAPHIES- N/A

COUNTY- Dona Ana
AREA NAME- DA1 - East Portrillo Mountains/Kilbourne Hole

REFERENCE NUMBERS

CATEGORY

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 71, 72, 73, 117, 129, 130, 131, 133, 135, 184, 243, 258, 259
- STRUCTURE/TECTONICS- 5, 30, 31, 71, 72, 73, 114, 129, 130, 133, 135, 243, 258, 259, 321, 393, 405
- RADIOMETRIC AGE DATES - 2, 3, 31, 116, 129, 130, 135, 176, 205, 321
- IGNEOUS PETROLOGY - 8, 71, 129, 130, 135, 240, 241, 242, 260

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - 201, 201
- HEAT FLOW - 200, 201, 325, 335
- ELECTRICAL RESISTIVITY - 146, 147, 419
- ELECTROMAGNETIC - 139, 236, 391
- SEISMIC - 160
- GRAVITY - 58, 365
- MAGNETIC - 58, 365
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 220, 369
- AQUEOUS GEOTHERMOMETRY - 359, 362, 369, 373, 376, 378, 379, 382
- STABLE ISOTOPES- N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS
- NON-THERMAL WATER CHEMISTRY - 54, 169, 171, 172
- DEPTH TO WATER - 54, 114, 169, 170, 171, 172
- AQUIFER CHARACTERISTICS - 114, 169, 170, 171, 172, 245
- HYDROLOGIC BUDGETS - 245

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS- N/A
- BIBLIOGRAPHIES- N/A

COUNTY - Dona Ana
AREA NAME - DA2 - Los Alturas/Las Cruces East Mesa/Tortugas Mountain

REFERENCE NUMBERS

CATEGORY

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 117, 168
- STRUCTURE/TECTONICS - 30, 31, 75, 98, 101, 114, 168
- RADIOMETRIC AGE DATES- N/A
- IGNEOUS PETROLOGY- N/A

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - 98, 102, 142, 197, 198, 200, 201, 226, 227, 228
- HEAT FLOW - 100, 197, 198, 201, 201
- ELECTRICAL RESISTIVITY - 93, 136, 147, 153, 332, 333, 414, 416
- ELECTROMAGNETIC - N/A
- SEISMIC - 75
- GRAVITY - 75, 365
- MAGNETIC75, 163, 365
- REMOTE SENSING - 145, 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 47, 220, 347, 359, 362, 369
- AQUEOUS GEOTHERMOMETRY - 369, 373, 376, 378, 379, 382
- STABLE ISOTOPES- N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - N/A
- NON-THERMAL WATER CHEMISTRY - 47, 54, 98, 99, 169, 171, 172, 407, 409
- DEPTH TO WATER - 43, 44, 54, 98, 114, 169, 171, 172, 278, 385, 407, 408
- AQUIFER CHARACTERISTICS - 43, 44, 54, 98, 114, 169, 171, 172, 245, 407, 409
- HYDROLOGIC BUDGETS - 54, 100, 245, 407, 409

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - 60, 102, 338
- APPLICATIONS - 19, 60, 102, 338
- BIBLIOGRAPHIES - N/A

COUNTY - Dona Ana
AREA NAME - DA3 - Radium Springs/San Diego Mtn./Rincon

REFERENCE NUMBERS

CATEGORY

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 117, 313, 314, 315, 317, 318, 322
- STRUCTURE/TECTONICS - 30, 31, 115, 313, 314, 315, 316, 317, 318, 321, 322, 323
- RADIOMETRIC AGE DATES - 313, 314, 321, 324, 328
- IGNEOUS PETROLOGY - 313, 314, 318

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - 193
- HEAT FLOW - 193, 316, 317, 325
- ELECTRICAL RESISTIVITY - 93, 147, 153, 157, 158, 159, 332, 333, 415
- ELECTROMAGNETIC - N/A
- SEISMIC - 62, 250
- GRAVITY - 62, 365
- MAGNETIC - 365
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 207, 220, 347, 369
- AQUEOUS GEOTHERMOMETRY - 207, 359, 362, 369, 373, 376, 378, 379, 382
- STABLE ISOTOPES - 207

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 347, 368, 369
- NON-THERMAL WATER CHEMISTRY - 54
- DEPTH TO WATER - 54
- AQUIFER CHARACTERISTICS - 54
- HYDROLOGIC BUDGETS - 54

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - 338
- APPLICATIONS - 338
- BIBLIOGRAPHIES - N/A

COUNTY - Dona Ana
AREA NAME - DA4 - Tularosa Basin/White Sands Missile Range

REFERENCE NUMBERS

CATEGORY

GEOLOGY
- GEOLOGIC STUDIES/MAPS - N/A
- STRUCTURE/TECTONICS - 42, 320
- RADIOMETRIC AGE DATES - N/A
- IGNEOUS PETROLOGY- N/A

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - 61, 194
- HEAT FLOW - 61, 69, 325
- ELECTRICAL RESISTIVITY - 61, 150
- ELECTROMAGNETIC- N/A
- SEISMIC- N/A
- GRAVITY - 61, 69, 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 61, 209
- AQUEOUS GEOTHERMOMETRY - 61, 194
- STABLE ISOTOPES- N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 52, 126, 166, 194, 209, 408
- NON-THERMAL WATER CHEMISTRY - 52, 126, 166, 209, 210, 370, 389, 404, 408
- DEPTH TO WATER - 22, 126, 166, 209, 408
- AQUIFER CHARACTERISTICS - 52, 126, 166, 209, 210, 212, 408
- HYDROLOGIC BUDGETS - 408

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - 61
- APPLICATIONS - 61, 127
- BIBLIOGRAPHIES - N/A

COUNTY - Grant
AREA NAME - GR1 - Cliff Area

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 79, 185, 255, 256
- STRUCTURE/TECTONICS - 79, 185, 255
- RADIOMETRIC AGE DATES - 254, 255
- IGNEOUS PETROLOGY - N/A

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - N/A
- HEAT FLOW - N/A
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - 203, 204
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 347, 369, 380
- AQUEOUS GEOTHERMOMETRY - 369, 371, 380
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 347, 365, 369, 380
- NON-THERMAL WATER CHEMISTRY - 369, 380, 392
- DEPTH TO WATER - 22, 392
- AQUIFER CHARACTERISTICS - 392
- HYDROLOGIC BUDGETS - 392

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - 394
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Grant
AREA NAME - GR2 - Faywood Hot Spring

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 322
- STRUCTURE/TECTONICS - 322
- RADIOMETRIC AGE DATES - N/A
- IGNEOUS PETROLOGY - N/A

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - N/A
- HEAT FLOW - N/A
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 16, 347, 369, 381
- AQUEOUS GEOTHERMOMETRY - 369, 381
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 13, 16, 347, 369, 381
- NON-THERMAL WATER CHEMISTRY - 211
- DEPTH TO WATER - 211, 392
- AQUIFER CHARACTERISTICS - 392
- HYDROLOGIC BUDGETS - 392

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - 394
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Grant
AREA NAME - GR3 - Gila Hot Springs Region

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 254, 255, 256, 392
- STRUCTURE/TECTONICS - 254, 255
- RADIOMETRIC AGE DATES - 255
- IGNEOUS PETROLOGY - 20

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - 345
- HEAT FLOW - N/A
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 345, 347, 369
- AQUEOUS GEOTHERMOMETRY - 369
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 13, 339, 334, 345, 347, 369, 392
- NON-THERMAL WATER CHEMISTRY - 345, 369, 392
- DEPTH TO WATER - 311, 345, 392
- AQUIFER CHARACTERISTICS - 311, 345, 392
- HYDROLOGIC BUDGETS - 311, 345, 392

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Grant
AREA NAME - GR4 - Mimbres Hot Springs

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 80, 322, 392
- STRUCTURE/TECTONICS - 80, 322
- RADIOMETRIC AGE DATES - N/A
- IGNEOUS PETROLOGY - N/A

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - N/A
- HEAT FLOW - N/A
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 347, 369, 392
- AQUEOUS GEOTHERMOMETRY - 369
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 13, 347, 392
- NON-THERMAL WATER CHEMISTRY - 211, 392
- DEPTH TO WATER - 211, 392
- AQUIFER CHARACTERISTICS - 392
- HYDROLOGIC BUDGETS - 392

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - 394
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Grant
AREA NAME - GR5 - Turkey Creek

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 79, 18, 254, 255, 256, 392
- STRUCTURE/TECTONICS - 79, 254, 255, 256
- RADIOMETRIC AGE DATES - N/A
- IGNEOUS PETROLOGY - 20

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - N/A
- HEAT FLOW - N/A
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - 203, 204
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 369, 381
- AQUEOUS GEOTHERMOMETRY - 369, 381
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 369, 381
- NON-THERMAL WATER CHEMISTRY - 369, 381
- DEPTH TO WATER - N/A
- AQUIFER CHARACTERISTICS - N/A
- HYDROLOGIC BUDGETS - N/A

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Hidalgo
AREA NAME - HD1 - Lightning Dock/Animas Valley

REFERENCE NUMBERS

CATEGORY

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 79, 81, 82, 232
- STRUCTURE/TECTONICS - 79, 81, 82
- RADIOMETRIC AGE DATES - 2, 3, 81, 82
- IGNEOUS PETROLOGY - 81

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - 74, 173
- HEAT FLOW - 74, 173
- ELECTRICAL RESISTIVITY - 155, 157, 181
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162, 249
- MAGNETIC - 55, 91
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 74, 81, 180, 191, 257, 286, 355, 381
- AQUEOUS GEOTHERMOMETRY - 74, 81, 180, 191, 192, 377, 380, 381
- STABLE ISOTOPES - 81, 180

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 74, 81, 191, 257
- NON-THERMAL WATER CHEMISTRY - 74, 81, 191, 233, 257
- DEPTH TO WATER - 22, 111, 231, 234, 253, 257, 312
- AQUIFER CHARACTERISTICS - 111, 231, 232, 253, 257, 312, 355
- HYDROLOGIC BUDGETS - 111, 231, 253, 257, 355

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Hidalgo
AREA NAME - HD2 - Lordsburg Basin

REFERENCE NUMBERS

CATEGORY

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 79, 82
- STRUCTURE/TECTONICS - 79
- RADIOMETRIC AGE DATES - N/A
- IGNEOUS PETROLOGY - N/A

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - N/A
- HEAT FLOW - N/A
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - N/A
- AQUEOUS GEOTHERMOMETRY - N/A
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 257, 347
- NON-THERMAL WATER CHEMISTRY - 233
- DEPTH TO WATER - 22, 78, 111, 231, 234, 257, 312
- AQUIFER CHARACTERISTICS - 45, 111, 231, 312
- HYDROLOGIC BUDGETS - 45, 231

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Luna
AREA NAME - LN1 - Columbus Area.

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - N/A
- STRUCTURE/TECTONICS - N/A
- RADIOMETRIC AGE DATES - 2, 3, 321, 324
- IGNEOUS PETROLOGY - N/A

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - 199
- HEAT FLOW - N/A
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 211
- AQUEOUS GEOTHERMOMETRY - 211
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 211
- NON-THERMAL WATER CHEMISTRY - 211
- DEPTH TO WATER - 211
- AQUIFER CHARACTERISTICS - N/A
- HYDROLOGIC BUDGETS - N/A

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Luna
AREA NAME - LN2 - Fluorite Ridge

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - N/A
- STRUCTURE/TECTONICS - N/A
- RADIOMETRIC AGE DATES - N/A
- IGNEOUS PETROLOGY - N/A

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - 196
- HEAT FLOW - 271
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - N/A
- AQUEOUS GEOTHERMOMETRY - N/A
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - N/A
- NON-THERMAL WATER CHEMISTRY - N/A
- DEPTH TO WATER - 27, 76
- AQUIFER CHARACTERISTICS - N/A
- HYDROLOGIC BUDGETS - N/A

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Luna
AREA NAME - LN3 - Victorio Mountains Area

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - N/A
- STRUCTURE/TECTONICS - N/A
- RADIOMETRIC AGE DATES - N/A
- IGNEOUS PETROLOGY - N/A

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - 417
- HEAT FLOW - 417
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 211
- AQUEOUS GEOTHERMOMETRY - N/A
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 211
- NON-THERMAL WATER CHEMISTRY - 211
- DEPTH TO WATER - 22, 211
- AQUIFER CHARACTERISTICS - N/A
- HYDROLOGIC BUDGETS - N/A

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Luna
AREA NAME - LN4 - Northern Mimbres Basin

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - N/A
- STRUCTURE/TECTONICS - N/A
- RADIOMETRIC AGE DATES - N/A
- IGNEOUS PETROLOGY - N/A

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - N/A
- HEAT FLOW - N/A
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 211
- AQUEOUS GEOTHERMOMETRY - N/A
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 211
- NON-THERMAL WATER CHEMISTRY - 211
- DEPTH TO WATER - 22, 211
- AQUIFER CHARACTERISTICS - N/A
- HYDROLOGIC BUDGETS - N/A

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Otero
AREA NAME - OT1 - Garton Well/Tularosa Basin

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 44, 404
- STRUCTURE/TECTONICS - N/A
- RADIOMETRIC AGE DATES - 2, 3, 4
- IGNEOUS PETROLOGY - N/A

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - N/A
- HEAT FLOW - N/A
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 127, 209
- AQUEOUS GEOTHERMOMETRY - N/A
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 127, 209, 337
- NON-THERMAL WATER CHEMISTRY - 53, 89, 127, 138, 209, 210, 337, 404
- DEPTH TO WATER - 11, 22, 53, 89, 126, 138, 209, 337, 404
- AQUIFER CHARACTERISTICS - 11, 53, 89, 126, 138, 209, 210, 337, 404
- HYDROLOGIC BUDGETS - 11, 89, 209

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Otero
AREA NAME - OT2 - Hueco Tanks/Hueco Basin

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 121, 386, 393
- STRUCTURE/TECTONICS - 121, 386, 393
- RADIOMETRIC AGE DATES - N/A
- IGNEOUS PETROLOGY - N/A

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - 386
- HEAT FLOW - 386
- ELECTRICAL RESISTIVITY - 386
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162, 386
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 121, 286
- AQUEOUS GEOTHERMOMETRY - 121, 286
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 121, 286, 386
- NON-THERMAL WATER CHEMISTRY - 121, 209, 386
- DEPTH TO WATER - 22, 126, 209
- AQUIFER CHARACTERISTICS - 126, 209
- HYDROLOGIC BUDGETS - 126, 209

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Sierra
AREA NAME - S11 - Cuchillo/Ojo Caliente

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 21, 128
- STRUCTURE/TECTONICS - 21, 128
- RADIOMETRIC AGE DATES - N/A
- IGNEOUS PETROLOGY - N/A

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - N/A
- HEAT FLOW - N/A
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 347, 369
- AQUEOUS GEOTHERMOMETRY - 369
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 13, 21, 347
- NON-THERMAL WATER CHEMISTRY - 21
- DEPTH TO WATER - 21
- AQUIFER CHARACTERISTICS - 21
- HYDROLOGIC BUDGETS - 21

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Sierra
AREA NAME - S12 - Derry

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 115
- STRUCTURE/TECTONICS - 115
- RADIOMETRIC AGE DATES - N/A
- IGNEOUS PETROLOGY - N/A

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - N/A
- HEAT FLOW - 325
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 347, 369
- AQUEOUS GEOTHERMOMETRY - 369
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 13, 347
- NON-THERMAL WATER CHEMISTRY - 409
- DEPTH TO WATER - 409
- AQUIFER CHARACTERISTICS - 409
- HYDROLOGIC BUDGETS - 409

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Sierra
AREA NAME - S13 - Hillsboro

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 95, 118, 324
- STRUCTURE/TECTONICS - 118
- RADIOMETRIC AGE DATES - 324
- IGNEOUS PETROLOGY - N/A

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - N/A
- HEAT FLOW - 325
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 369
- AQUEOUS GEOTHERMOMETRY - 362, 369
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 13, 369
- NON-THERMAL WATER CHEMISTRY - N/A
- DEPTH TO WATER - 95
- AQUIFER CHARACTERISTICS - 95
- HYDROLOGIC BUDGETS - N/A

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Sierra
AREA NAME - S14 - Truth or Consequences

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 30, 31, 115, 167, 397, 398, 399, 420
- STRUCTURE/TECTONICS - 5, 115, 167, 420
- RADIOMETRIC AGE DATES - 2, 3, 205
- IGNEOUS PETROLOGY - 397, 398, 399

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - 303, 397, 398, 399, 403
- HEAT FLOW - 303, 325, 398, 399
- ELECTRICAL RESISTIVITY - 149
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 214, 347, 387
- AQUEOUS GEOTHERMOMETRY - 369
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 13, 214, 310, 347, 387
- NON-THERMAL WATER CHEMISTRY - 214, 230, 387
- DEPTH TO WATER - 22, 214, 230, 387
- AQUIFER CHARACTERISTICS - 214, 230, 248, 387, 403
- HYDROLOGIC BUDGETS - 214, 230, 248, 387, 403

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Sierra
AREA NAME - S15 Warm Springs/Winston

CATEGORY — REFERENCE NUMBERS

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 322, 324
- STRUCTURE/TECTONICS - 324
- RADIOMETRIC AGE DATES - 324
- IGNEOUS PETROLOGY - 324

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - N/A
- HEAT FLOW - N/A
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - N/A
- AQUEOUS GEOTHERMOMETRY - N/A
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - N/A
- NON-THERMAL WATER CHEMISTRY - N/A
- DEPTH TO WATER - 22, 64
- AQUIFER CHARACTERISTICS - 64, 95
- HYDROLOGIC BUDGETS - 64

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Socorro
AREA NAME - SC1 - San Agustin Plain

REFERENCE NUMBERS

CATEGORY

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 239
- STRUCTURE/TECTONICS - N/A
- RADIOMETRIC AGE DATES - N/A
- IGNEOUS PETROLOGY - 20

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT -1 274, 325
- HEAT FLOW - 274, 225
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - N/A
- SEISMIC - 342
- GRAVITY - 162
- MAGNETIC - 55
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 28, 46, 229
- AQUEOUS GEOTHERMOMETRY - N/A
- STABLE ISOTOPES - N/A

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 28, 46, 229
- NON-THERMAL WATER CHEMISTRY - 17, 28, 46, 229
- DEPTH TO WATER - 17, 22, 28, 46, 229
- AQUIFER CHARACTERISTICS - 17, 229
- HYDROLOGIC BUDGETS - 17, 229

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - N/A
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

COUNTY - Socorro
AREA NAME - SC2- Socorro KGRA

REFERENCE NUMBERS

CATEGORY

GEOLOGY
- GEOLOGIC STUDIES/MAPS - 36, 37, 38, 39, 40, 41, 42, 112, 182, 183, 239, 262, 263, 264, 265, 279, 280, 287, 290, 293
- STRUCTURE/TECTONICS - 25, 33, 182, 183, 262, 263, 264, 265
- RADIOMETRIC AGE DATES - 6, 18, 205
- IGNEOUS PETROLOGY - 18, 20

GEOPHYSICAL SURVEYS
- TEMPERATURE GRADIENT - 112, 272, 294, 325
- HEAT FLOW - 112, 270, 271, 275, 294, 325
- ELECTRICAL RESISTIVITY - N/A
- ELECTROMAGNETIC - 152, 154, 215
- SEISMIC - 23, 25, 33, 34, 86, 87, 279, 281, 282, 288, 289, 291, 292, 295, 296, 297, 298, 299, 301, 301, 302, 326, 327, 342
- GRAVITY - 162
- MAGNETIC - 55, 90
- REMOTE SENSING - 187

GEOCHEMICAL STUDIES
- THERMAL WATER CHEMISTRY - 46, 103, 137, 347
- AQUEOUS GEOTHERMOMETRY - 180, 369
- STABLE ISOTOPES - 97, 180

HYDROGEOLOGY
- THERMAL SPRINGS AND WELLS - 13, 46, 103, 347
- NON-THERMAL WATER CHEMISTRY - 46, 103
- DEPTH TO WATER - 46, 336
- AQUIFER CHARACTERISTICS - 103, 112, 137, 336
- HYDROLOGIC BUDGETS - 97, 112, 137, 336

OTHER
- INSTITUTIONAL/ENVIRONMENTAL/ECONOMIC - 216, 217
- APPLICATIONS - N/A
- BIBLIOGRAPHIES - N/A

CHAPTER 2

# NEW MEXICO STATE UNIVERSITY GEOTHERMAL EXPLORATORY WELL*

## 2.0 Introduction

This chapter discusses the results of the continuation of an exploratory drilling program to confirm a large capacity geothermal reservoir on land owned by New Mexico State University (NMSU). Previous shallow exploration and deep production geothermal well drilling on and nearby the NMSU campus suggested that temperatures higher than the known NMSU resource temperature of 142°F may be obtainable at deeper horizons and that wells completed in shallow bedrock faults may produce much higher yields than the existing NMSU wells completed in alluvium. The exploratory drilling plan objectives were a temperature within ten percent of 170°F and/or a production rate within 10 percent of 500 gallons per minute (gpm) at affordable pumping depths.

## 2.1 Initial Drilling Program

Following substantial geological and geophysical field work, including soil mercury and helium surveys and 10 and 4.5 lineal miles of self-potential and reflection-seismic surveys, respectively (Cunniff, 1986), two drill sites were selected in 1984 at locations believed to overlie intersections of bedrock faults.

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* The principal author of Chapter 2 is Roy A. Cunniff, Senior Engineer, Physical Science Laboratory, New Mexico State University.

The primary site was also believed to represent the shallowest depth to bedrock on the NMSU campus (see Figure 2-1). Drilling commenced on October 19, 1984, on NMSU deep test number three (DT-3). The initial drilling was completed to 963 feet of depth and bottomed in a massive lost circulation zone. When the well was completed, the casing landed at a depth of 974 feet (see Figure 2-2).

## 2.2 Continuation Drilling Program

### 2.2.1 Target Depth and Completion Program

A target depth of 1,500 feet (i.e., approximately 525 feet of continuation drilling) was selected in order to penetrate below the base of the Santa Fe group basin fill estimated to be at a depth of 1,300 to 1,400 feet. If present, andesite sequences would be defined by the 100- to 200-foot penetration into the presumed Paleozoic bedrock. This model of the subsurface was in agreement with the interpretation of a reflection seismic survey conducted by Charles Reynolds and Associates (Cunniff, 1986) and information obtained from nearby wells drilled by Chaffee Geothermal, Ltd. (Gross and Icerman, 1983).

### 2.2.2 Drilling History

The well was re-entered on April 26, 1986, by L&M Drilling, Inc. of Artesia, New Mexico, the selected contract driller. A 8 5/8-inch top casing was threaded into the existing casing at 673 feet to lower the cost of the air drilling procedures and to provide a continuous diameter casing from total depth to the surface.

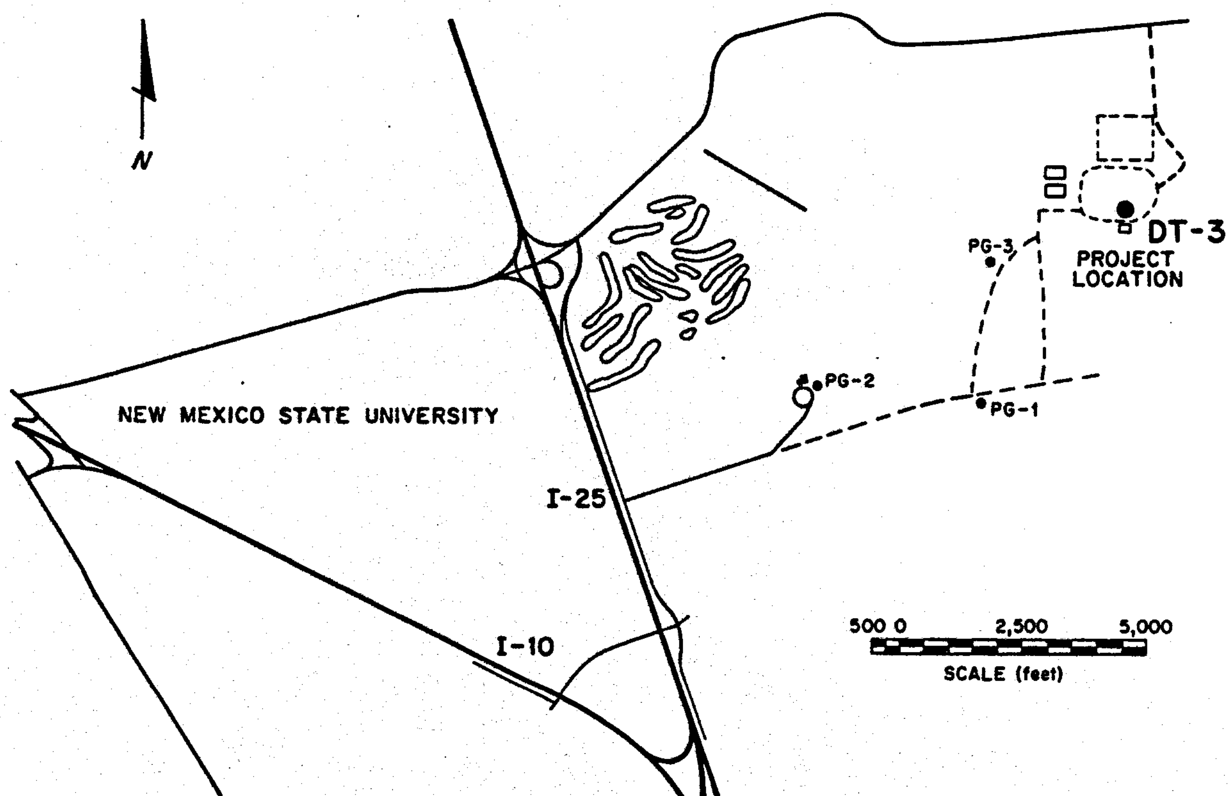



Figure 2-1. Location map for NMSU exploration Well DT-3. Three geothermal production wells are shown as PG-1, PG-2, and PG-3.

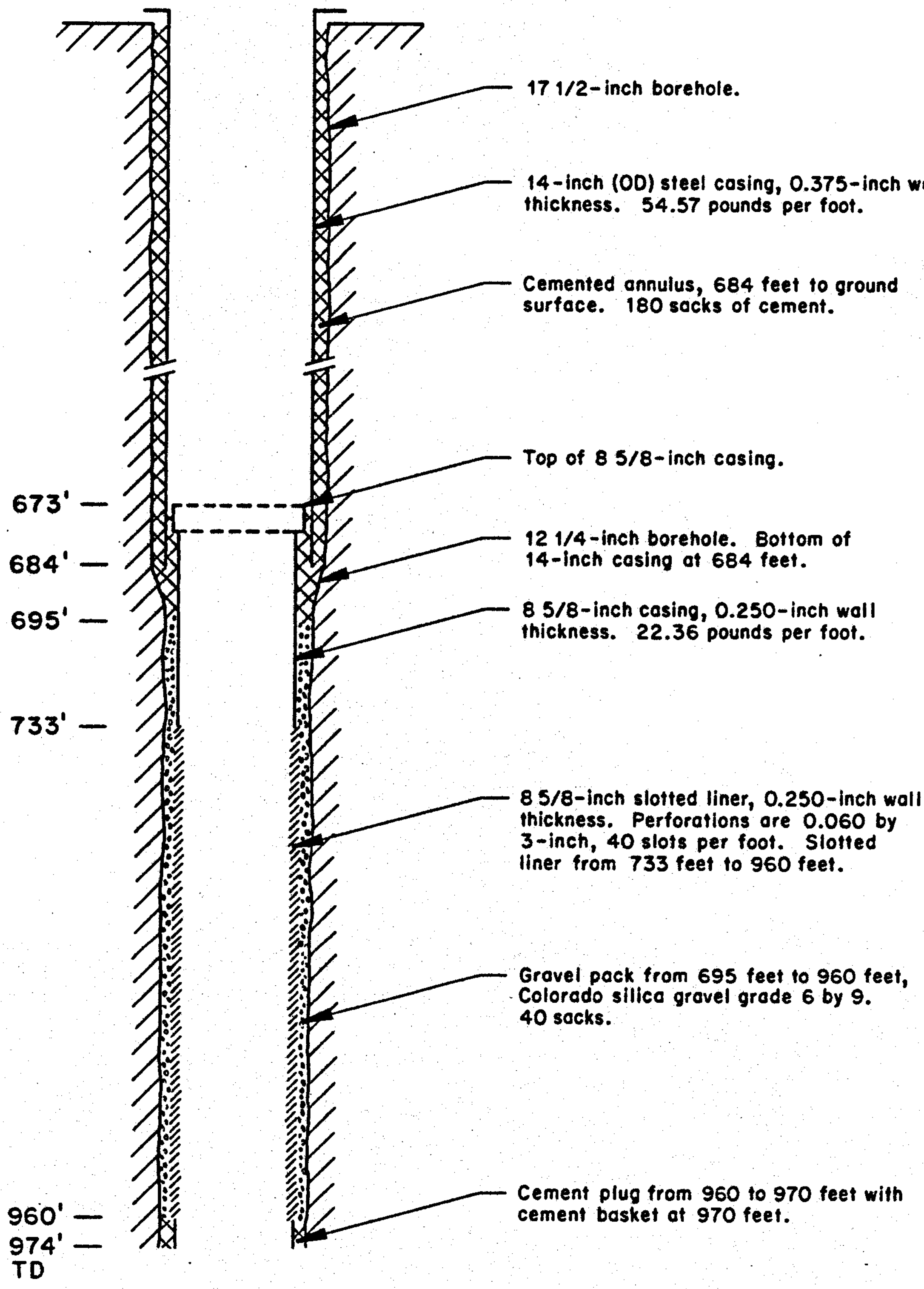



Figure 2-2. Intermediate completion configuration for NMSU exploration Well DT-3. Depths are referenced to the top of the casing.

Drilling commenced following successful cementing of the bottom 13 feet of the top casing assembly. Unknown resistance, believed to be mud and lost circulation material from the initial drilling activities, was encountered at 938 feet, measured from the kelly bushing (KB) of the rig. The hole was circulated and washed to 982 feet KB, which was believed to be approximately the depth of the casing installed in 1984. Cuttings were taken at 985 feet KB. The penetration rate of the 7 7/8-inch drill bit was only 15 feet per hour (fph) using 34,000 pounds of weight until drilling resistance ceased at 987 feet KB and circulation was lost.

Contact was re-established by lowering the drill string to 1,012 feet KB, but circulation could not be re-established with an air flow rate of 2,550 cubic feet per minute (cfm) and 15 gpm of mist pump water. The formation provided a consistent 268 to 270 pounds per square inch gauge (psig) of back pressure, which is equivalent to that of a 630-foot water column, the calculated depth of water in the well bore.

A blind drilling strategy was pursued from 1,012 to 1,015 feet KB at a penetration rate of 30 fph with no returns. Alternate circulating procedures confirmed lost circulation below 987 feet KB with circulation being regained at 986 feet KB. Intervals of circulation suggested that the formation was capable of producing more than 1,000 gpm. No caving or erosion of the zone above 987 feet KB could be detected, suggesting, along with the recorded penetration rate, that this zone was a dense, hard formation.

Options of cementing the zone below 986 feet KB or converting to a mud drilling program were eliminated because of the risk that these intrusive measures could cause severe loss of production. Accordingly, the only realistic options were to use additional air capacity or to continue blind drilling. Following an evaluation of the risks and costs, the decision was made to cease drilling activities and to conduct a drill stem test to evaluate the producing zone. Following completion of a successful drill stem flow test and pressure recovery test, all rig operations, well-completion procedures, and site restoration activities were completed on April 29, 1986 (see Figure 2-3).

## 2.3 Drill Stem Test

A flow test of Well DT-3 was conducted from April 27, to April 28, 1986. The test was designed to obtain physical and chemical data to be used for standard reservoir calculations and for determination of fluid characteristics.

### 2.3.1 Test Methods

An open-end, 6-inch drill stem was inserted in the well to a depth of 745 feet KB, the level of the top of the screen section (see Figure 2-2). The test was designed as an air-lift test for an 8-hour period. Flow rate, surface water temperature, bottom-hole temperature, injection pressure, and downhole pressure buildup were monitored using standard equipment and procedures. Water samples were taken periodically throughout the test.

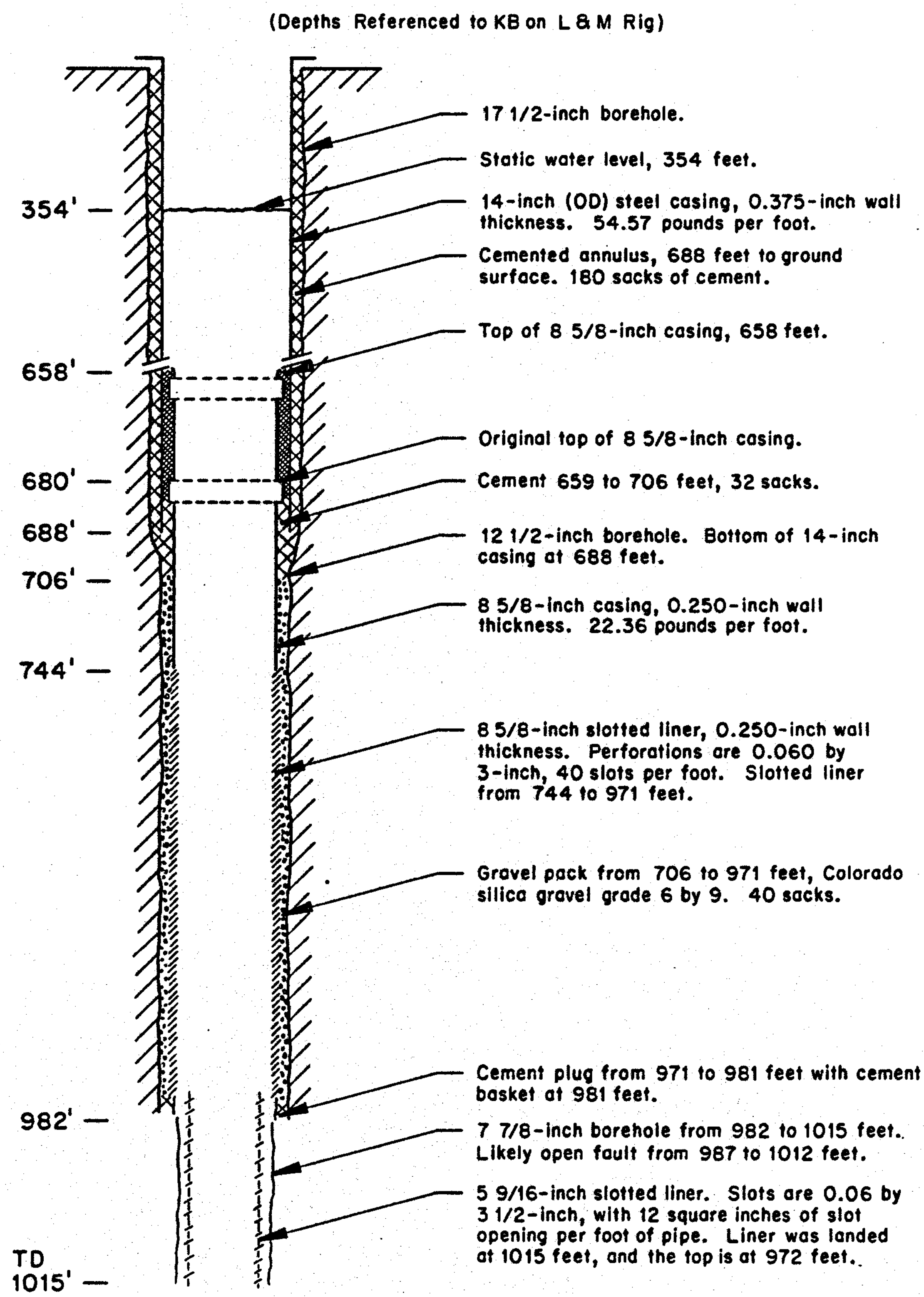



Figure 2-3. Final completion configuration for NMSU exploration Well DT-3. Depths are referenced to the kelly bushing of the rig.

### 2.3.2 Test Operations

The flow test was begun at 9:00 pm on April 27, 1986. Initially, all of the on-site air equipment was used, which included three 850-cfm compressors and the 1,500-psi booster. Flow was estimated to be 1,050 gpm. Because such a high flow rate extended over an 8-hour period might have caused the reserve pits to overflow, at the end of the first 30 minutes, one of the compressors was stopped. The resultant flow rate was 700 gpm, which was maintained for the remainder of the test.

### 2.3.3 Test Results

Surface water temperature data are given in Table 2-1. Water-quality data are given in Table 2-2. During the test, a thick residue of calcium carbonate was deposited on the surface piping and values suggesting that the fluid in Well DT-3 is carbon dioxide enriched and, perhaps, contains a higher concentration of calcium than measured by the water analyses. The relatively high pH, compared to pumped samples from nearby wells, represents the effects of carbon dioxide release. At atmospheric equilibrium, the pH value is approximately 8.4. A copy of the Schlumberger test report is included in Appendix A.

### 2.3.4 Reservoir Hydrology Parameters

Reservoir hydrology parameters were computed from the test data using the methods developed by Earlaugher (1977) adapted for water-well terminology. The computed reservoir parameters are summarized in Table 2-3.

Table 2-1. Surface water temperature for Well DT-3. The temperatures were recorded during a drill stem test.

| Time | Temperature (°F) |
|---|---|
| 9:01 pm | 73 |
| 9:02 | 90 |
| 9:03 | 96 |
| 9:04 | 103 |
| 9:05 | 117 |
| 9:06 | 124 |
| 9:07 | 128 |
| 9:08 | 131 |
| 9:09 | 132 |
| 9:10 | 133 |
| 9:11 | 134 |
| 9:12 | 135 |
| 9:13 | 135 |
| 9:14 | 136 |
| 9:15 | 137 |
| 9:16 | 137 |
| 9:17 | 138 |
| 9:18 | 139 |
| 9:19 | 140 |
| 9:20 | 140 |
| 9:20 - 12:00 | 140 |
| 12:00 - 5:00 am | 140 to 134 |

Notes:
1. Air flow started at 9:01 pm.
2. Water appeared at the surface at 9:04 pm.
3. Gradual warming of the surface piping occurred until 9:20 pm.
4. Water temperature was stable from 9:20 pm until 12:00 pm.
5. Water temperature declined from 12:00 pm to 5:00 am as the result of a 20-mph wind cooling the wet exposed surface piping as the ambient air temperature dropped from 65 to 45°F. Bottom-hole temperature remained effectively constant during this period.

Table 2-2. Water-chemistry analysis of Well DT-3.

| Parameter | Chemical Concentration* (mg/l) |
|---|---|
| Na | 440 |
| K | 53.9 |
| Ca | 105.1 |
| Mg | 32.0 |
| Cl | 528.3 |
| $HCO_3$ | 476.0 |
| $SO_4$ | 236 |
| As | 0.007 |
| Ba | 0.07 |
| Fe | 0.05 |
| B | 0.48 |
| F | 2.04 |
| $SiO_2$ | 47.7 |
| TDS | 1,775 |
| Hardness ($CaCO_3$) | 383 |
| Alkalinity ($CaCO_3$) | 401 |
| Specific conductance (µmhos) | 2,775 |
| pH | 7.63 |

* The values represent the mean of water samples taken during an air-lift test.

Table 2-3. Computed reservoir hydrology parameters for Well DT-3.

| Parameter | Value |
|---|---|
| Permeability | 13.5 darcy |
| Transmissibility | 2,025,968 md-ft |
| Skin factor | negligible |
| Radius of influence | 2,625 ft |
| Reservoir volume | 10,774 acre-ft |
| Productivity | 100 gpm/ft of drawdown |

### 2.3.5 Test Interpretations

Based on these computed values, the reservoir has excellent permeability and should be able to safely produce flow rates in excess of 2,000 gpm. Since no reservoir boundaries were detected during the pressure buildup test, the actual radius of influence and reservoir volume are likely to be higher than the calculated values. Because the bottom-hole pressure increased slightly (i.e., ~ 0.6 psia) during the flow test, the reservoir was apparently recharging at a rate above the extraction rate of 700 gpm. The reservoir also recovered initial pressure within 30 seconds of terminating the air-lift test suggesting that the productivity of the reservoir is higher than the computed value.

The reservoir appears to be separated from cooler groundwater, which could have been drawn into the production zone, because the bottom-hole temperature increased approximately 1$^{o}$F during the test. Based on thermal balance calculations, the wellhead temperature produced by mechanical pumping should be at least 147$^{o}$F.

## 2.4 Temperature Data

Following the completion of the drill stem test, a temperature survey was attempted inside of the well casing from 960 feet to the surface using the temperature sensor in the Schlumberger pressure tool. This survey was abandoned because of increasing rig standby costs when thermal equilibrium was not reached at the bottom of the hole within two hours.

Sixteen hours after the completion of the air-lift test, a temperature survey was collected using a Spafford probe (see Table 2-4 and Figure 2-4). Peak bottom-hole temperature was 147.6°F. The well may have been still experiencing thermal rebound. Because a positive gradient existed from 345 to 970 feet of depth, a strong possibility exists that the measured temperature of 147.6°F would increase slightly, perhaps to 149°F, during high-volume production using a mechanical pump. Several zones of varying gradient exist at 670, 710, 790 to 810, 840 to 860, and 930 to 940 feet. Based on electric logs collected in 1984, these intervals appear to be gravel zones, which might produce some component of the total flow.

## 2.5 Lithologic Data

The interval from 905 to 965 feet KB is essentially a gravel composed of 70 to 75% volcanic rock fragments of dark gray, brown, and red colors; dense, very finely crystalline to amorphous in texture; chiefly basalt, rhyolite, chert, and possible obsidian. The remainder is limestone; light gray, light tan, and gray in color; dense to finely crystalline, some of which appears to be finely oolitic. Destructive solution of this carbonate leaves a residue of very fine rounded quartz sand grains, clear to white in color, and minor amounts of gray silt. No cuttings are available from 965 to 982 feet KB due to lost circulation problems in the original drilling.

The stratigraphy from surface down to at least 960 feet KB is essentially the volcanic gravels of the Santa Fe Group. At

Table 2-4. Temperature-depth data for Well DT-3.

| Depth* (ft) | Temperature (°F) | Depth* (ft) | Temperature (°F) |
|---|---|---|---|
| 355 | 133.2 | 720 | 145.3 |
| 360 | 133.4 | 730 | 145.4 |
| 370 | 133.6 | 740 | 145.6 |
| 380 | 134.2 | 750 | 145.8 |
| 390 | 134.6 | 760 | 145.9 |
| 400 | 135.0 | 770 | 146.0 |
| 410 | 135.5 | 780 | 146.1 |
| 420 | 136.0 | 790 | 146.3 |
| 430 | 136.4 | 800 | 146.3 |
| 440 | 136.9 | 810 | 146.3 |
| 450 | 137.5 | 820 | 146.4 |
| 460 | 137.7 | 830 | 146.5 |
| 470 | 138.0 | 840 | 146.6 |
| 480 | 138.7 | 850 | 146.6 |
| 490 | 139.8 | 860 | 146.7 |
| 500 | 139.9 | 870 | 146.7 |
| 510 | 140.1 | 880 | 146.8 |
| 520 | 140.4 | 890 | 146.9 |
| 530 | 140.7 | 900 | 147.0 |
| 540 | 141.1 | 910 | 147.2 |
| 550 | 141.5 | 920 | 147.3 |
| 560 | 141.9 | 930 | 147.4 |
| 570 | 142.2 | 940 | 147.4 |
| 580 | 142.3 | 950 | 147.5 |
| 590 | 142.4 | 960 | 147.5 |
| 600 | 142.5 | 970 | 147.6 |
| 610 | 142.7 | | |
| 620 | 142.8 | | |
| 630 | 143.3 | | |
| 640 | 144.1 | | |
| 650 | 144.6 | | |
| 660 | 144.8 | | |
| 670 | 144.7 | | |
| 680 | 144.8 | | |
| 690 | 145.0 | | |
| 700 | 145.1 | | |
| 710 | 145.3 | | |

* The depth data are referenced to the rig kelly bushing. The depth to water in the well was approximately 355 ft. Measurements were taken with a Spafford probe approximately 16 hours after an 8-hour air-lift test.

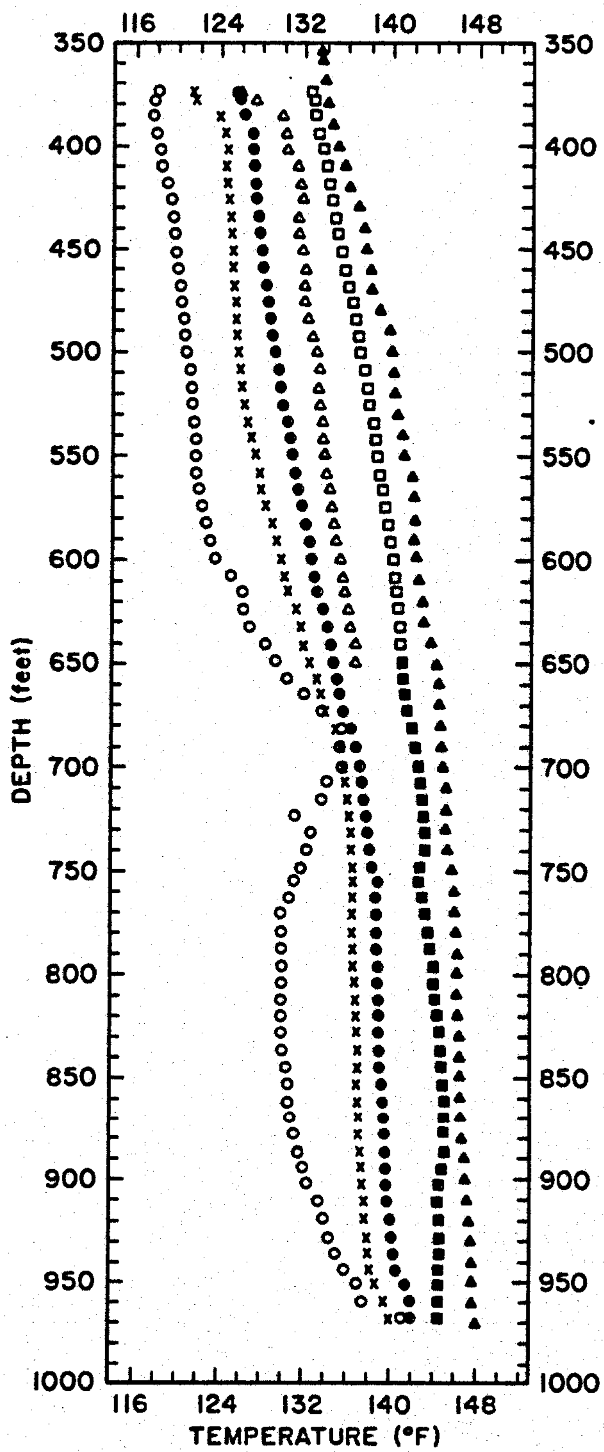



Figure 2-4. Temperature-depth curves for Well DT-3. Six logs are shown: mud-filled hole, 10/26/84 (Δ); open hole, 10/30/84 (o); open hole, 10/31/84 (x); open hole, 11/1/84 (●); cased well 12/4/84 (□); cased well, 12/7/84 (■); cased well, 4/28/86 (▲).

that depth, large fractures occur, which explains the lost circulation problems that led to termination of drilling in 1984. At 982 feet KB, a 3-foot deposit of detrital material, carried into the well by drilling fluids, rested upon a thin, 2-foot thick wedge or block of limestone or andesite. Immediately below this dense, hard rock at 987 feet KB, a high-angle fault with an exceedingly porous and permeable gouge or breccia zone was intersected. At 1,012 feet KB, firm unbroken Hueco carbonate appears to total depth of 1,015 feet KB.

## 2.6 Cost Summary

The total cost associated with NMSU Well DT-3 is $251,103, divided approximately into surface geological and geophysical work during 1982 and 1983 (32%), initial well drilling in 1984 (41%), and continuation drilling in 1986 (27%). The drilling and testing costs were approximately $169/foot. This cost falls in the range of costs experienced by Chaffee Geothermal when drilling three nearby wells during 1981 and 1982 (Icerman and Lohse, 1983) and is approximately 25% lower than the cost of the most directly comparable Chaffee well.

## 2.7 Concluding Remarks

Based on the lithologic data, water-chemistry data, and the hydrological evaluation of the drill stem test for Well DT-3, the zone encountered at 987 feet KB is postulated to be a basement fault in fractured limestone. Possibly, the base of the Santa Fe Group is located at approximately 960 feet of depth where the initial drilling program in 1984 encountered a lost circulation zone. Production from a well completed in this zone is expected to exceed the drilling objectives with respect to yield but fall as much as 15% below the target temperature of 170°F.

## 2.8 References


Cunniff, R.A., 1986, New Mexico State University geothermal exploratory well, DT-3, final completion report: Physical Science Laboratory report, 246 p.

Earlaugher, R.C., 1977, Advances in well test analysis: Society of Petroleum Engineers, Henry L. Doherty Series Monograph 5, 264 p.

Gross, J., and Icerman, L., 1983, Subsurface investigations for the area surrounding Tortugas Mountain, Dona Ana County, New Mexico: New Mexico Energy Research and Development Institute Report 2-68-2238(2), 70 p.

Icerman, L., and Lohse, R.L., 1983, Geothermal low-temperature reservoir assessment in Dona Ana County, New Mexico: New Mexico Energy Research and Development Institute Report 2-69-2202, 188 p.

# APPENDIX A

## Schlumberger Test Report for the Drill Stem Test of NMSU Well DT-3

| REPORT NO. 80297F | WELL PERFORMANCE TESTING™ REPORT | FLOPETROL JOHNSTON |
|---|---|---|
| PAGE NO. 1 | A Production System Analysis (NODAL™) | Schlumberger |
| TEST DATE: 27-APR-1986 | Based On Model Verified™ Interpretation | |

**Company:** NEW MEXICO STATE UNIVERSITY

**Well:** GEOTHERMAL WELL #DT-3

## TEST IDENTIFICATION

| | |
|---|---|
| Test Type | SPRO SUSPENDED |
| Test No. | ONE |
| Formation | HOT WATER |
| Test Interval (ft) | 980 TO 1015 |

## WELL LOCATION

| | |
|---|---|
| Field | GEOTHERMAL |
| County | DONA ANA |
| State | NEW MEXICO |
| Sec/Twn/Rng | NA |

## COMPLETION CONFIGURATION

| | |
|---|---|
| Total Depth (MD/TVD) (ft) | 1015 |
| Casing/Liner I.D. (in) | 8.625-SLOTTED |
| Hole Size (in) | 7.875 |
| Perforated Interval (ft) | SLOTTED 780-980 |
| Shot Density (shots/ft) | NA |
| Perforation Diameter (in) | -- |
| Net Pay (ft) | 25 |

## TEST STRING CONFIGURATION

| | |
|---|---|
| Tubing Length (ft)/I.D. (in) | 745/3.826 |
| Tubing Length (ft)/I.D. (in) | |
| Packer Depth (ft) | NONE |
| Gauge Depth (ft)/Type | 730/DPTT |
| Downhole Valve (Y/N)/Type | NONE |

## TEST CONDITION

| | |
|---|---|
| Tbg/Wellhead Pressure (psi) | 235 (MAX. INJ.) |
| Separator Pressure (psi) | -- |

## INTERPRETATION RESULTS

| | |
|---|---|
| Model of Behavior | HOMOGENEOUS |
| Fluid Type Used For Analysis | WATER |
| Reservoir Pressure (psi) | 280 (APPROX.) |
| Transmissibility (md.ft/cp) | -- |
| Effective Permeability (md) | -- |
| Skin Factor | -- |
| Storativity Ratio | -- |
| Interporosity Flow Coeff. | -- |
| Distance to an Anomaly (ft) | -- |
| Radius of Investigation (ft) | -- |

## ROCK/FLUID/WELLBORE PROPERTIES

| | |
|---|---|
| Oil Density (deg. API) | NA |
| Basic Solids (%) | -- |
| Gas Gravity | -- |
| GOR (scf/STB) | -- |
| Water Cut (%) | 100 |
| Viscosity (cp) | -- |
| Total Compressibility (1/psi) | -- |
| Porosity (%) | -- |
| Reservoir Temperature (F) | 146 |
| Form.Vol.Factor (bbl/STB) | -- |

**MAXIMUM PRODUCTION RATE DURING TEST: 1000 GPM**

## TEST OBJECTIVES:

The objectives were to monitor surface and downhole pressure while injecting air to produce a geothermal well that would not flow to surface.

## COMMENTS:

The well produced approx. 1000 GPM with three pumps and 700 GPM with two pumps, and did not drop the reservoir pressure while producing. After the air injection ceased, the well recovered to full pressure within one minute. The static water column rose to approx. 360 feet below ground level, and exhibited isothermal properties with an averag temperature of 146 degrees Fahrenheit.

**************************
* WELL TEST DATA PRINTOUT *
**************************

FIELD REPORT # : 00297F

INSTRUMENT # : 80138
CAPACITY (PSI) : 10000.
DEPTH (FT) : 730.0
PORT OPENING : OUTSIDE

COMPANY : NM STATE UNIV.
WELL : GEOTHERMAL WELL DT-3

## LABEL POINT INFORMATION

| # | TIME OF DAY HH:MM:SS | DATE DD-MM | EXPLANATION | ELAPSED TIME,MIN | BOT HOLE PRESSURE PSIA | SURFACE PRESSURE PSIG | BOT HOL TEMP. DEG F |
|---|---|---|---|---|---|---|---|
| 1 | 20:47:31 | 27-AP | HYDROSTATIC MUD | 71.92 | 158.43 | 0.00 | 145.0 |
| 2 | 21: 0: 6 | 27-AP | START FLOW | 84.50 | 163.24 | 200.49 | 144.8 |
| 3 | 21: 4: 1 | 27-AP | PUMP PRESSURE @ MAXIMUM | 88.42 | 165.41 | 233.65 | 144.8 |
| 4 | 21:31:36 | 27-AP | PUMP PRESSURE W/ 2 PUMPS-START | 116.00 | 164.73 | 230.44 | 145.6 |
| 5 | 4:58:41 | 28-AP | END FLOW | 563.08 | 165.02 | 205.29 | 146.0 |
| 6 | 4:59: 1 | 28-AP | START SHUT-IN | 563.42 | 155.71 | 48.82 | 146.0 |
| 7 | 5:53:41 | 28-AP | END SHUT-IN | 618.08 | 159.01 | 0.00 | 146.1 |

## SUMMARY OF FLOW PERIODS

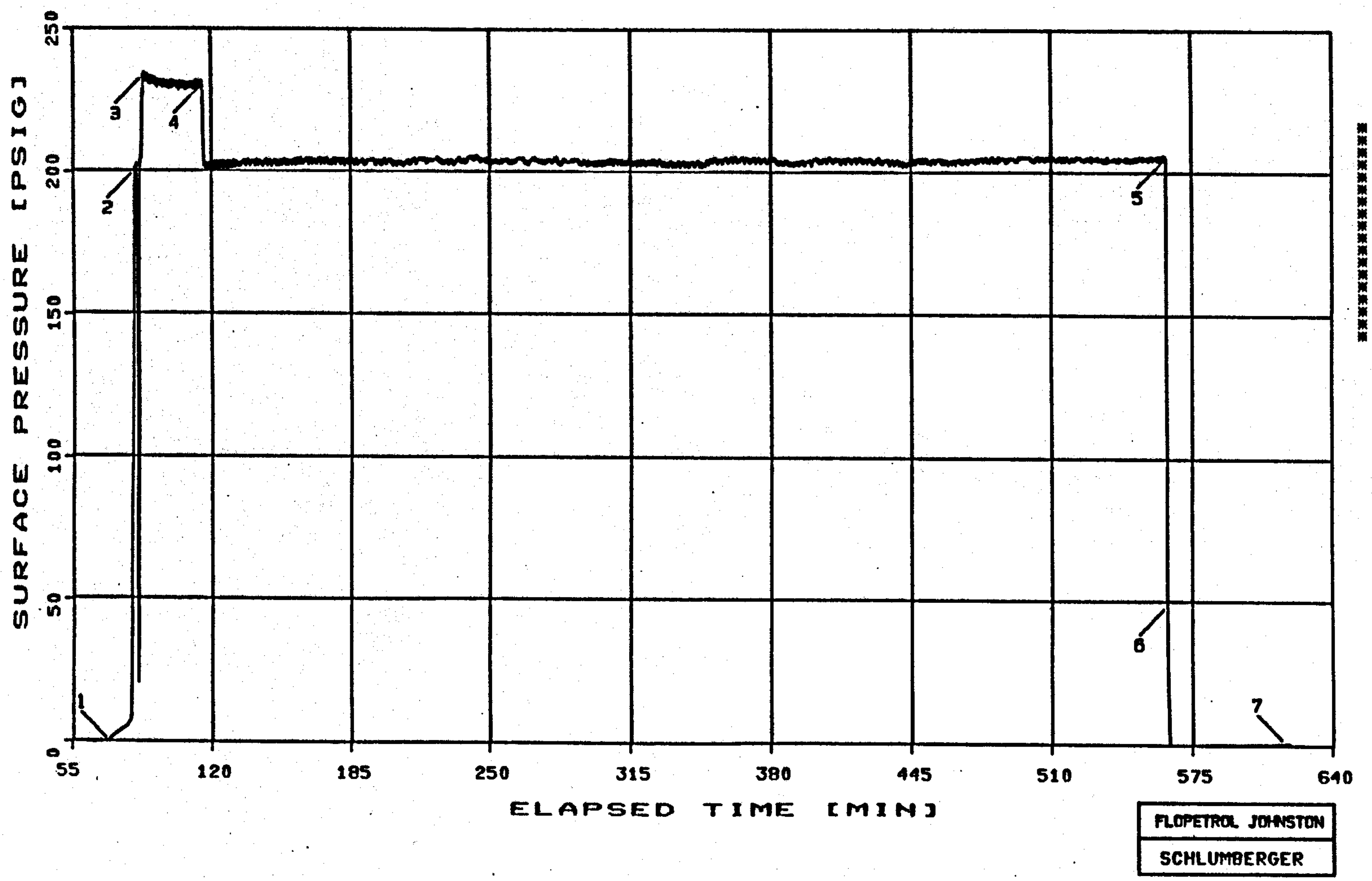
| PERIOD | START ELAPSED TIME,MIN | END ELAPSED TIME,MIN | DURATION MIN | START PRESSURE PSIA | END PRESSURE PSIA |
|---|---|---|---|---|---|
| 1 | 84.50 | 563.08 | 478.58 | 163.24 | 165.02 |

## SUMMARY OF SHUTIN PERIODS

| PERIOD | START ELAPSED TIME,MIN | END ELAPSED TIME,MIN | DURATION MIN | START PRESSURE PSIA | END PRESSURE PSIA | FINAL FLOW PRESSURE PSIA | PRODUCING TIME, MIN |
|---|---|---|---|---|---|---|---|
| 1 | 563.42 | 618.08 | 54.66 | 155.71 | 159.01 | 165.02 | 478.58 |

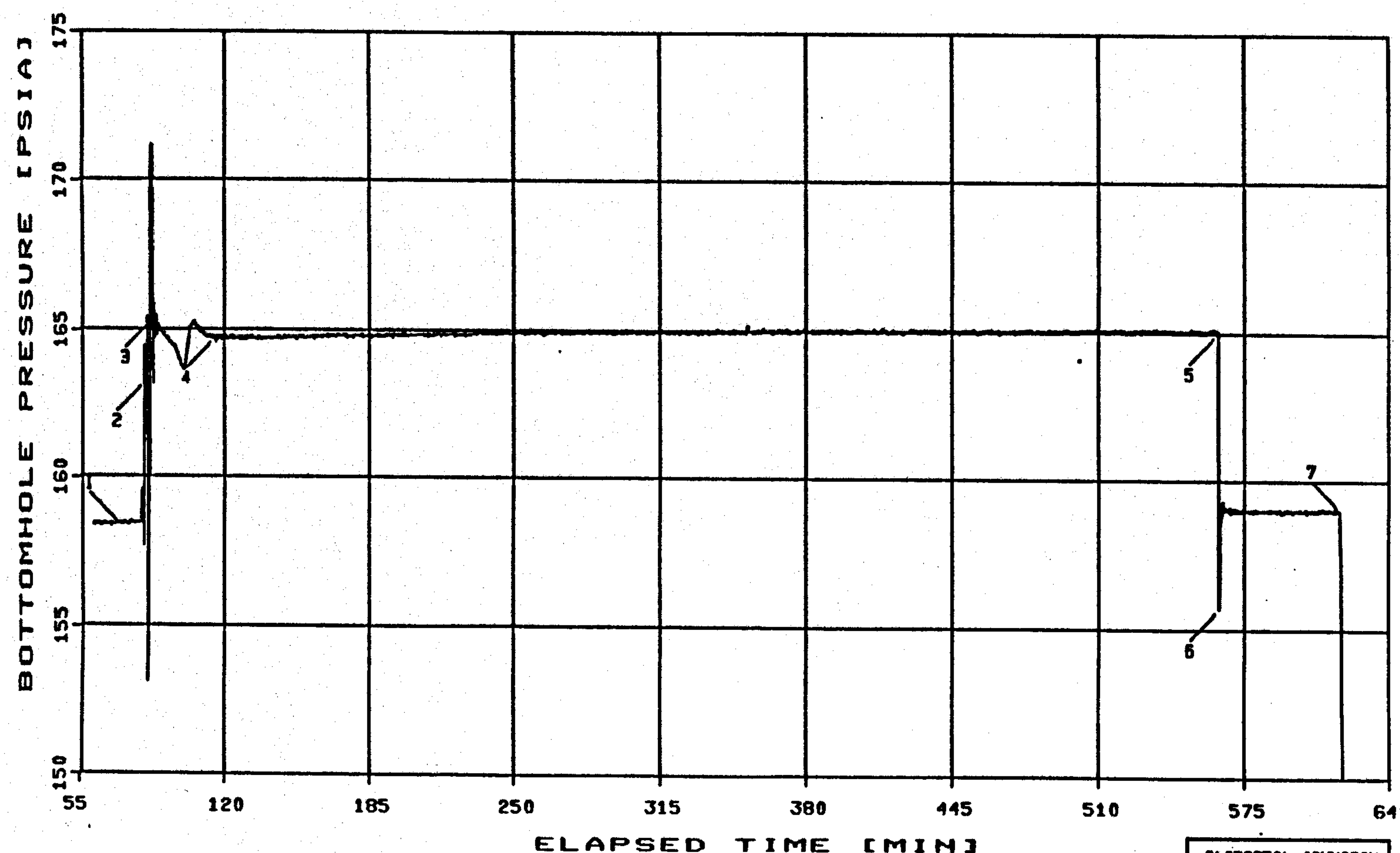
## SURFACE PRESSURE LOG

FIELD REPORT NO. 00297F    COMPANY : NM STATE UNIV.
WELL : GEOTHERMAL WELL DT-3



# BOTTOMHOLE PRESSURE LOG

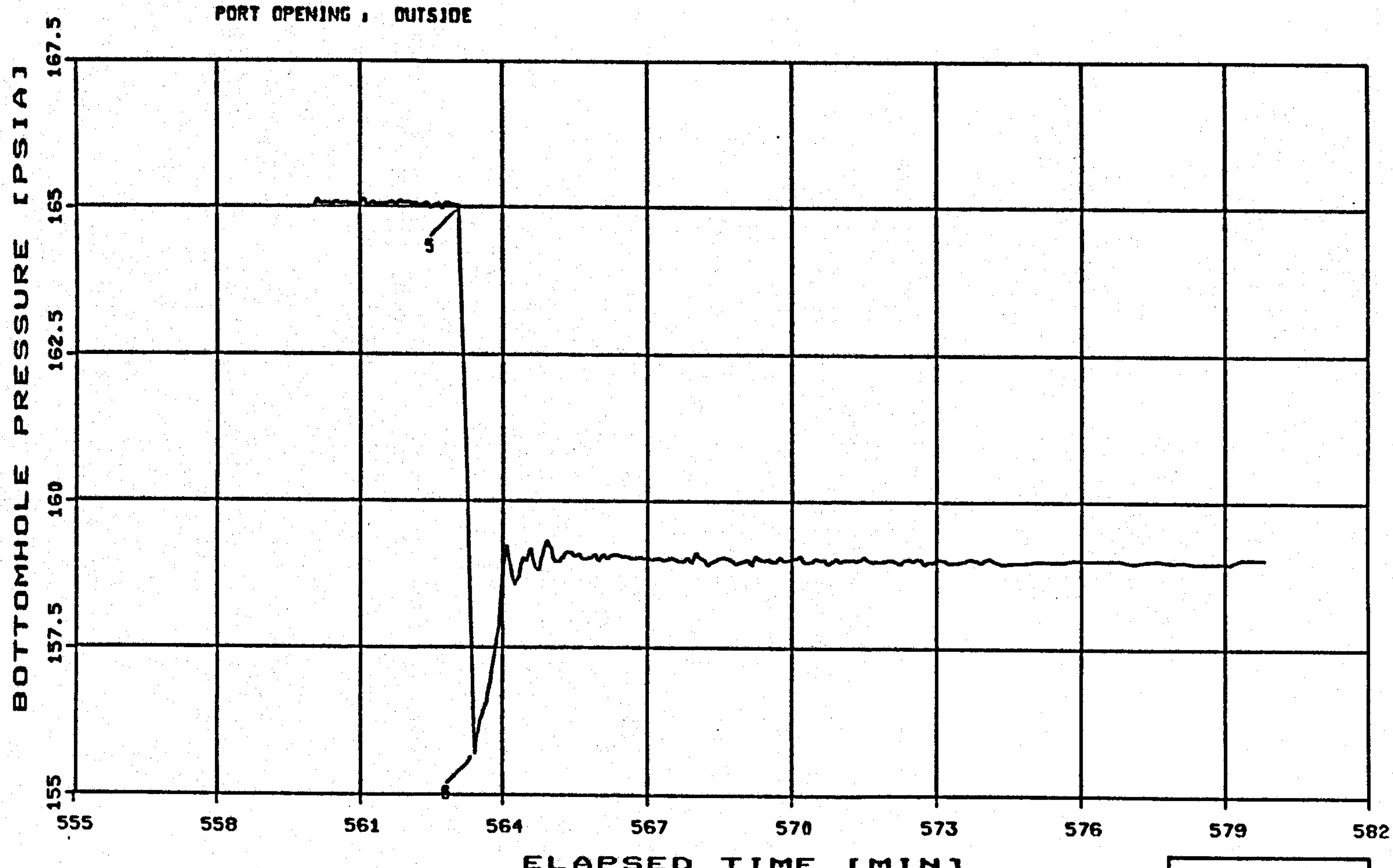
FIELD REPORT NO. 88297F COMPANY : NM STATE UNIV.
INSTRUMENT NO. 88138 WELL : GEOTHERMAL WELL OT-3
DEPTH : 738 FT
CAPACITY : 10000 PSI
PORT OPENING : OUTSIDE




FLOPETROL JOHNSTON
SCHLUMBERGER

## BOTTOMHOLE PRESSURE LOG

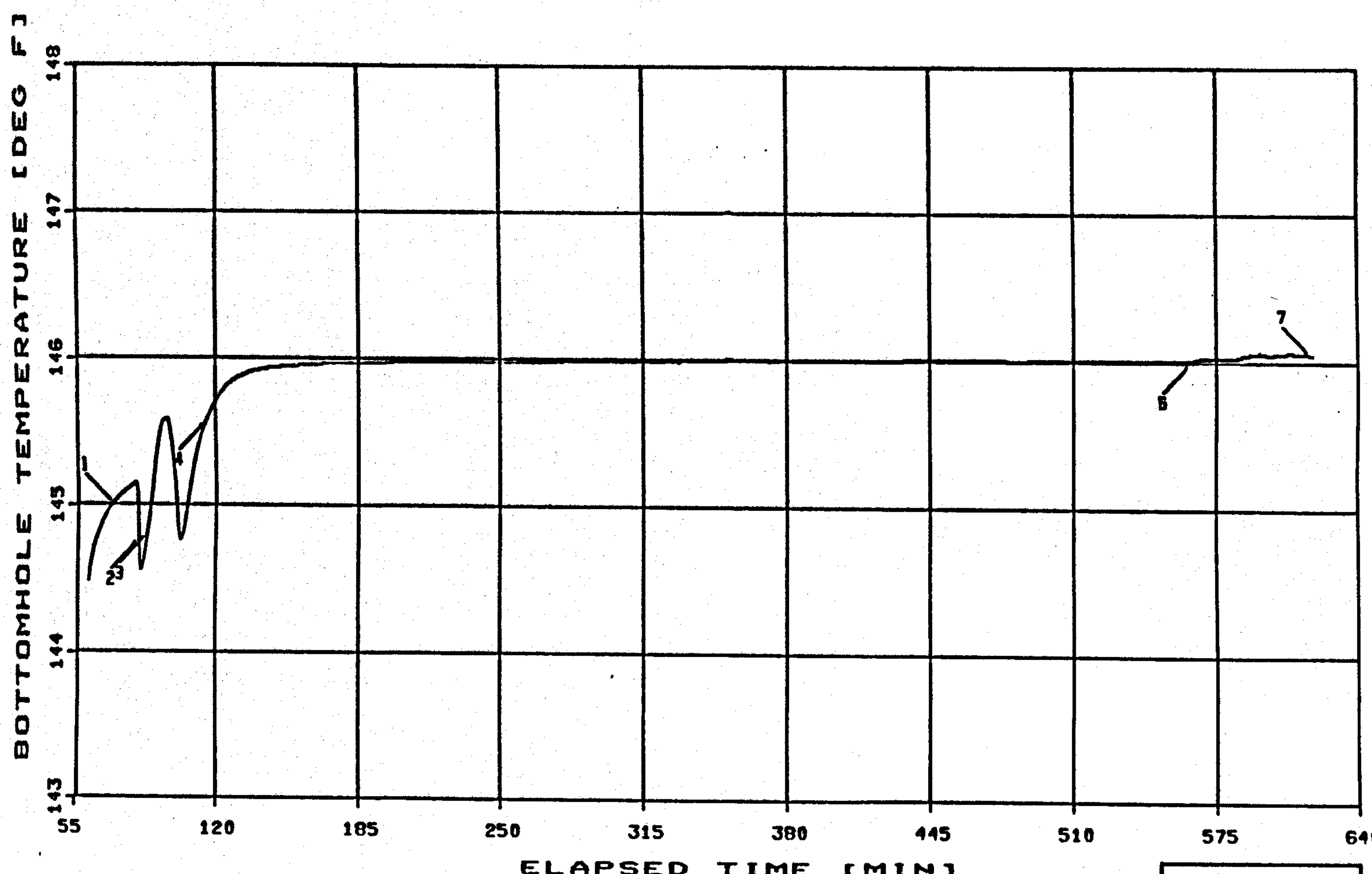
FIELD REPORT NO. 80297F COMPANY : NM STATE UNIV.
INSTRUMENT NO. 80130 WELL : GEOTHERMAL WELL DT-3
DEPTH : 730 FT
CAPACITY : 10000 PSI
PORT OPENING : OUTSIDE




FLOPETROL JOHNSTON
SCHLUMBERGER

# BOTTOMHOLE TEMPERATURE LOG

FIELD REPORT NO. 88297F COMPANY : NM STATE UNIV.
INSTRUMENT NO. 88138 WELL : GEOTHERMAL WELL DT-3
DEPTH : 738 FT




FLOPETROL JOHNSTON
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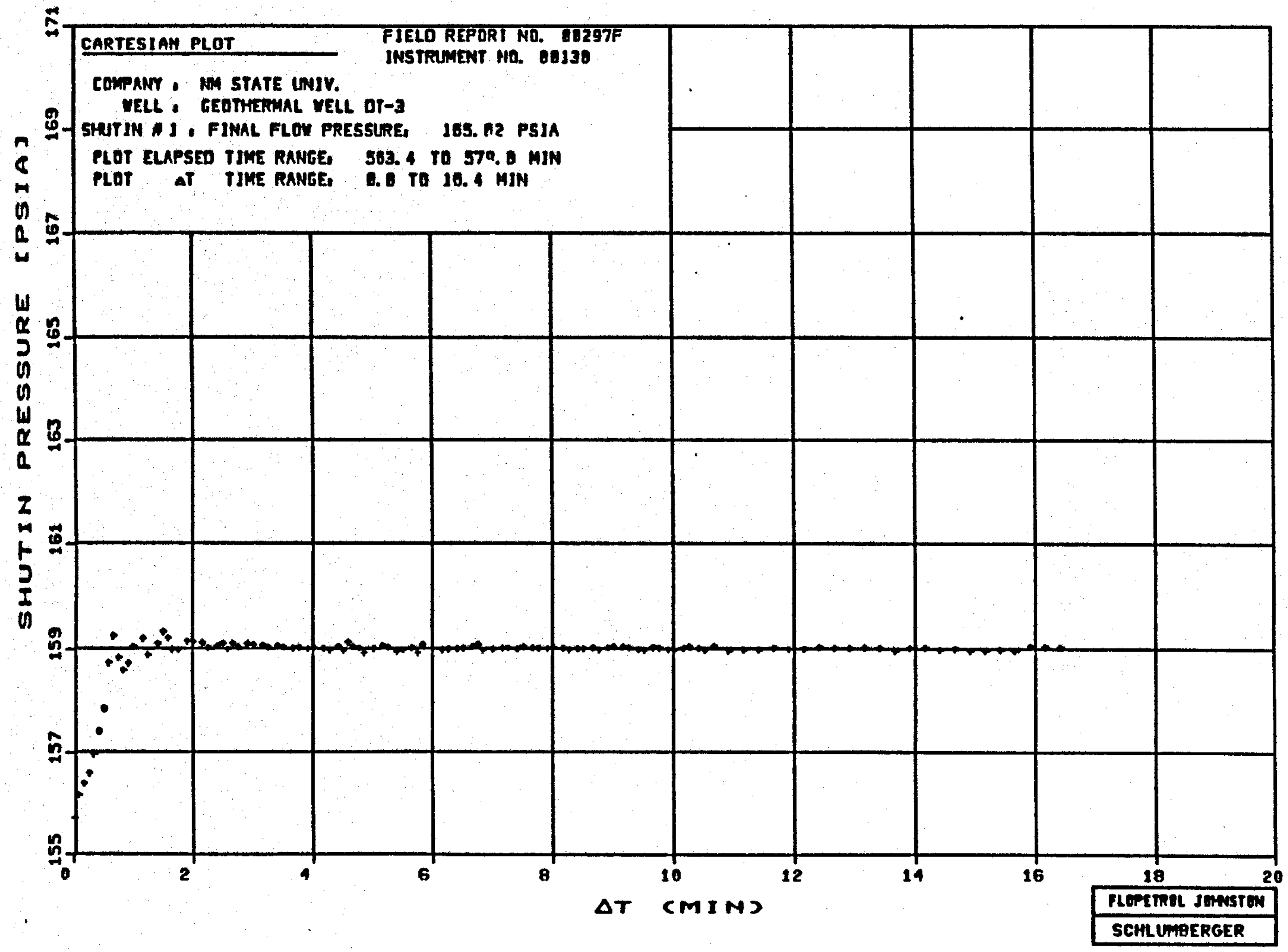
CARTESIAN PLOT
FIELD REPORT NO. 00297F
INSTRUMENT NO. 00130
COMPANY : NM STATE UNIV.
WELL : GEOTHERMAL WELL DT-3
SHUTIN # 1 : FINAL FLOW PRESSURE: 165.02 PSIA
PLOT ELAPSED TIME RANGE: 563.4 TO 579.8 MIN
PLOT ΔT TIME RANGE: 0.0 TO 16.4 MIN
SHUTIN PRESSURE [PSIA]
155
157
159
161
163
165
167
169
171
0
2
4
6
8
10
12
14
16
18
20
ΔT (MIN)
FLOPETROL JOHNSTON
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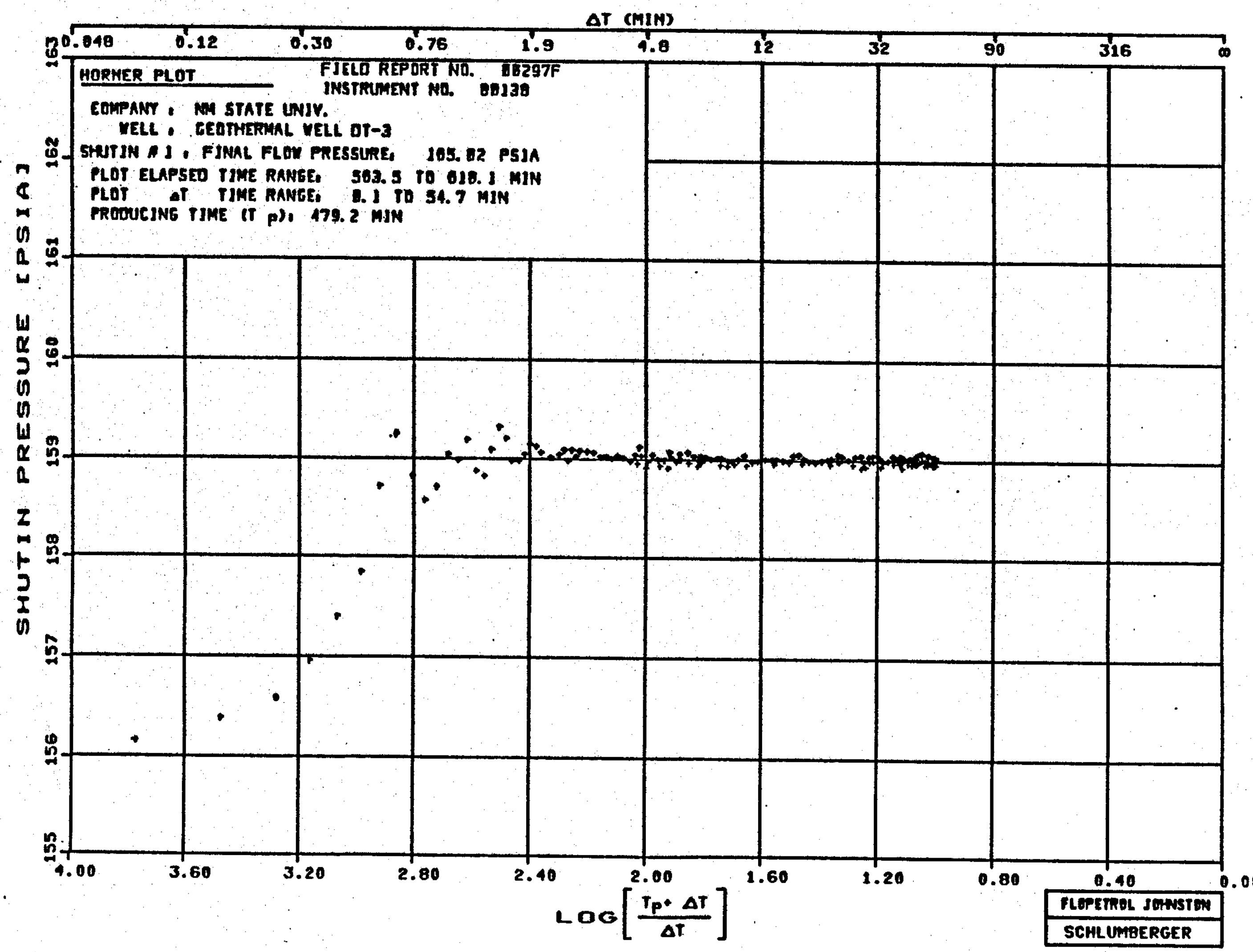
ΔT (MIN)
0.048
0.12
0.30
0.76
1.9
4.8
12
32
90
316
∞
HORNER PLOT
FIELD REPORT NO. 08297F
INSTRUMENT NO. 00138
COMPANY : NM STATE UNIV.
WELL : GEOTHERMAL WELL DT-3
SHUTIN # 1 , FINAL FLOW PRESSURE, 165.02 PSIA
PLOT ELAPSED TIME RANGE, 503.5 TO 618.1 MIN
PLOT ΔT TIME RANGE, 0.1 TO 54.7 MIN
PRODUCING TIME (T p): 479.2 MIN
SHUTIN PRESSURE [PSIA]
163
162
161
160
159
158
157
156
155
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00
LOG [(Tp+ ΔT)/ΔT]
FLOPETROL JOHNSTON
SCHLUMBERGER

CHAPTER 3

# TEMPERATURE, WATER-CHEMISTRY, AND LITHOLOGICAL DATA FOR THE LIGHTNING DOCK KNOWN GEOTHERMAL RESOURCES AREA, ANIMAS VALLEY, NEW MEXICO*

## 3.0 Introduction

The Animas Valley is located in Hidalgo County in extreme southwestern New Mexico. A well-known geothermal resource area lies on the eastern side of the valley at the foot of the Pyramid Mountains. This area was designated a Known Geothermal Resources Area (KGRA) by the U.S. Geological Survey on February 1, 1974 (see Figure 3-1). The KGRA was named Lightning Dock after a prominent peak in the Pyramid Mountains.

Probably because there are no surface manifestations, the geothermal anomaly, which is centered in Section 7, Township 25 South, Range 19 West, was not discovered until 1948. Since that time, many investigators have conducted regional, local, and anomaly-specific studies. Much of this work has been summarized by Elston and others (1983).

Several proprietary geothermal studies were conducted in Animas Valley during the period 1974 through 1978 by, among others, AMAX Exploration, Inc., Aminoil, Chevron Resources, Phillips Petroleum, and Sun Oil Company. AMAX completed a number

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* The principal authors of Chapter 3 are Roy A. Cunniff, President, and Roger L. Bowers, Vice President, Lightning Dock Geothermal, Inc.

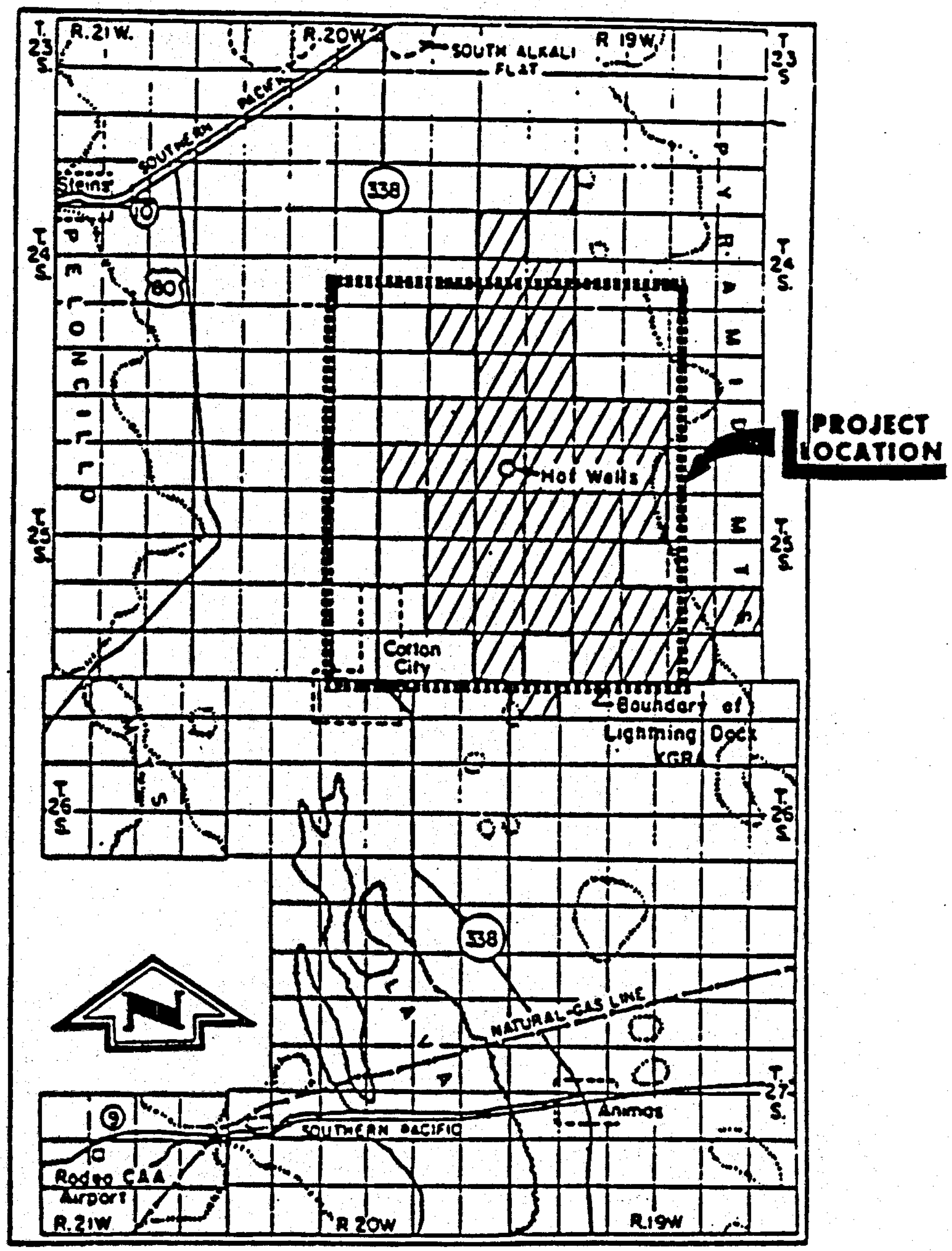


Figure 3-1. Location map for the Lightning Dock KGRA in the Animas Valley, New Mexico. The cross-hatched area defines the Lightning Dock KGRA, with Section 7, T25S, R19W, containing the hot wells.

of geological, geophysical, and geochemical surveys through 1976. This work was summarized and released by Dellechaie (1977). Activities by AMAX ceased until late 1980 when field work was undertaken leading to the drilling of a deep test hole in late 1984.

In 1986, Lightning Dock Geothermal, Inc., acquired the lease previously held by AMAX and a wholly-owned subsidiary, Steam Reserve Corporation. As a result, this chapter provides temperature, water chemistry, and lithological data previously held as proprietary.

## 3.1 Temperature Studies

### 3.1.1 Shallow Drilling

During 1975 and 1976, AMAX drilled 53 shallow temperature-gradient holes throughout the Animas Valley, 10 of which were drilled near the hot wells (see Figure 3-2). These 10 holes ranged in depth from 45 to 158.5 m and recorded bottom-hole temperatures from 21.2 to 58.5°C (see Table 3-1). Most of these holes have conductive temperature-gradient profiles below a depth of 10 m (see Appendix A).

### 3.1.2 Deep Drilling

In 1980, four deep temperature-observation holes were drilled by AMAX (see Figure 3-2). These holes ranged in depth from about 275 to 305 m and recorded bottom-hole temperatures from 40.9 to 127.7°C (see Table 3-2). Hole 672-227, located less than 0.5 km southwest of the hot wells, encountered boiling temperatures at 32 m and reached a temperature of 113°C at 65 m.

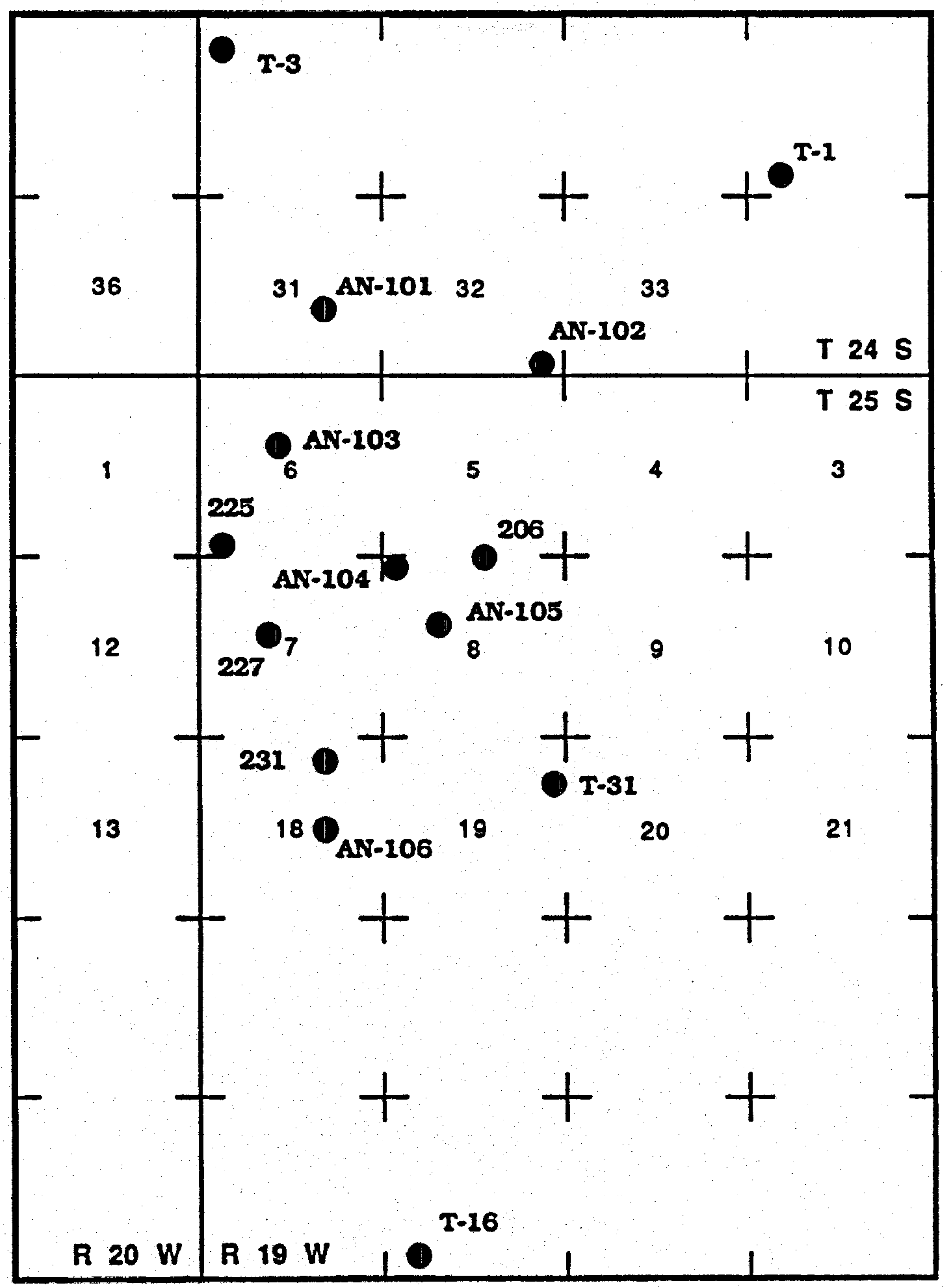


Figure 3-2. Locations of shallow and deep temperature-gradient holes in the Animas Valley, New Mexico. The deep holes are labeled with only the last three digits of the hole number.

Table 3-1. Shallow temperature-gradient holes in the Animas Valley, New Mexico.

| Hole | Latitude | Longitude | Depth (m) | Bottom-Hole Temperature (°C) |
|---|---|---|---|---|
| AN-101 | 32°10.4' | 108°50.1' | 50.0 | 37.5 |
| AN-102 | 32°10.1' | 108°48.7' | 50.0 | 22.2 |
| AN-103 | 32°09.6' | 108°50.1' | 49.4 | 46.6 |
| AN-104 | 32°09.1' | 108°49.6' | 158.5 | 58.5 |
| AN-105 | 32°08.7' | 108°49.2' | 54.0 | 23.3 |
| AN-106 | 32°07.8' | 108°50.1' | 45.7 | 22.7 |
| T-1 | 32°10.9' | 108°47.5' | 49.0 | 21.2 |
| T-3 | 32°11.3' | 108°50.5' | 50.0 | 22.5 |
| T-16 | 32°05.7' | 108°49.6' | 45.0 | 23.9 |
| T-31 | 32°08.1' | 108°48.7' | 53.0 | 22.5 |

Table 3-2. Deep temperature-gradient holes in the Animas Valley, New Mexico.

| Hole | Latitude | Longitude | Depth (m) | Bottom-Hole Temperature (°C) |
|---|---|---|---|---|
| 672-206 | 32°09.1' | 108°49.0' | 284.1 | 40.9 |
| 672-225 | 32°09.2' | 108°50.3' | 305.1 | 68.7 |
| 672-227 | 32°08.6' | 108°50.1' | 250.1 | 127.7 |
| 672-231 | 32°08.0' | 108°49.9' | 275.1 | 43.3 |

Below 65 m, the temperature profile reversed and became essentially isothermal to 120 m. A conductive thermal gradient of about 100°C/km was measured from 120 m to total depth (see Figure 3-3).

3.1.3 <u>Interpretation of the Thermal Data</u>

Shallow temperature-gradient holes help delineate the thermal anomaly on the north, east, and south. Because no holes were drilled west of the hot wells, and only limited temperature data are available from water wells, the western limits and nature of the anomaly are undefined. Temperature contours at a depth of 30 m are shown in Figure 3-4.

The shallow thermal anomaly is centered around the hot wells and Hole 672-227, where boiling temperatures are generally encountered within 40 m of the surface. Bottom-hole temperatures and temperature gradients decrease to the north of the hot wells. This trend could be the result of a significant change in the depth to bedrock to the north of the hot wells. The temperature data suggest a sharp, probably fault controlled, boundary for the thermal anomaly to the east. A high conductive gradient in Hole AN-104 suggests that this hole is located near the controlling fault zone, believed to be the Animas Valley Fault.

Holes 672-231 and AN-106 are due south of the hot wells and show a disturbed thermal regime and a conductive thermal gradient of approximately twice the regional value, respectively. Hole AN-106 showed no indication of the high-temperature anomaly measured elsewhere. To the contrary, the data from this hole suggest the existence of a widespread, relatively low temper-

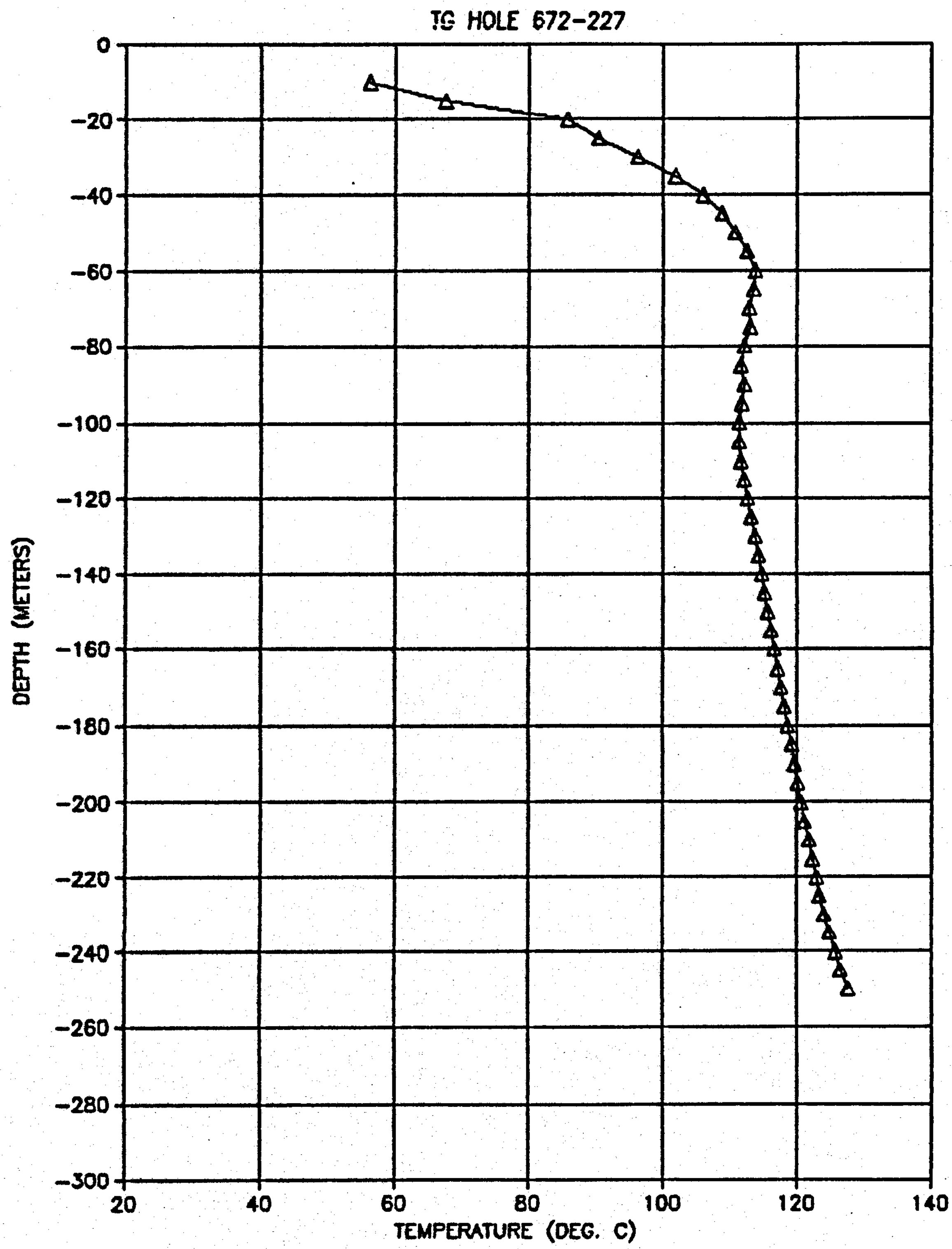


Figure 3-3. Temperature-depth profile for deep temperature-gradient Hole 672-227. This hole is believed to be colocated with the site for a deep test, Well 55-7.

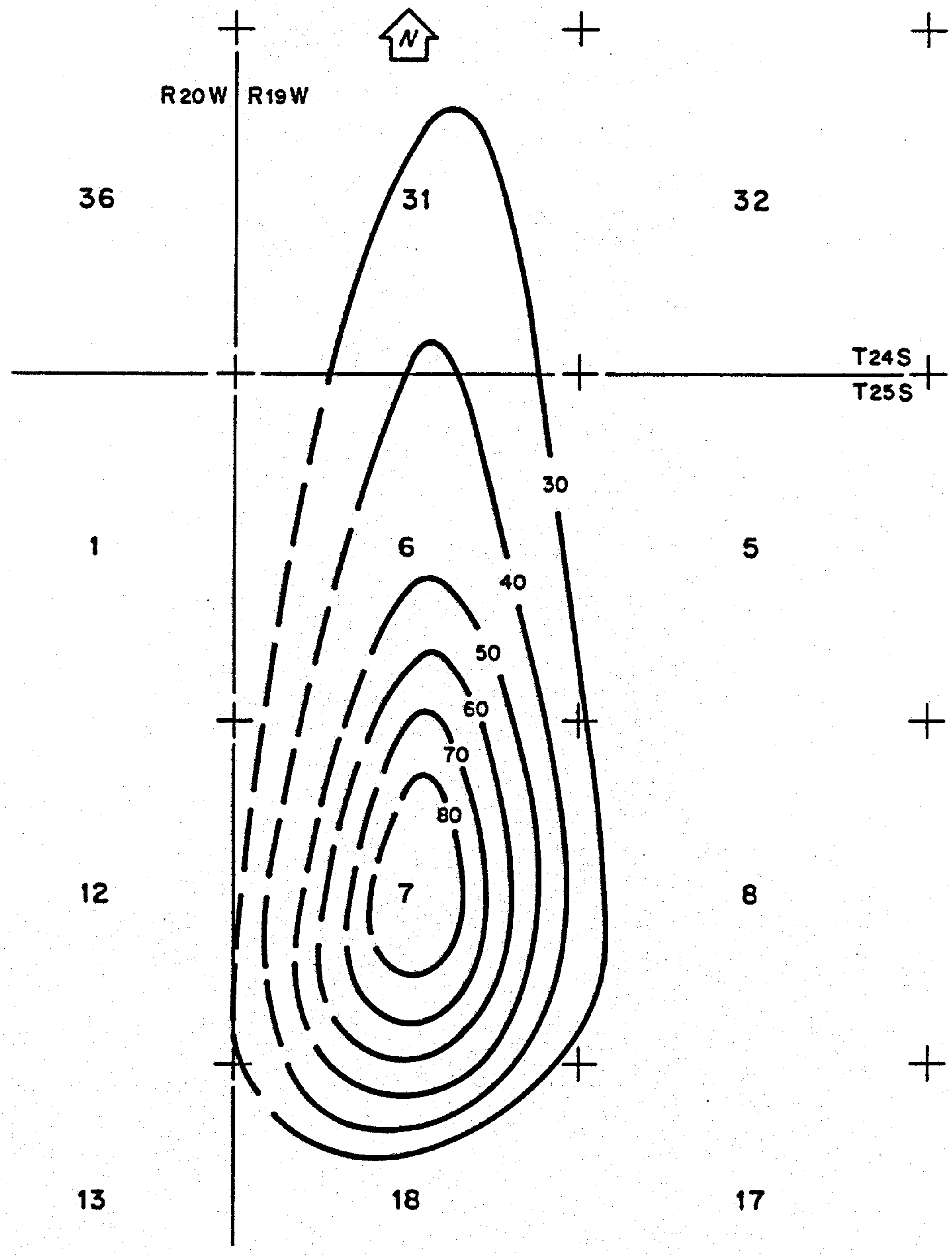


Figure 3-4. Temperature (°C) contours at a depth of 30 meters. The west side of the anomaly (dashed contour lines) is interpreted based on sparse water-well data.

ature thermal anomaly. Other holes drilled by AMAX more than 2 km from the hot wells had non-anomalous thermal gradients of 30 to 50°C/km.

### 3.2 Water-Chemistry Data

Many water samples have been collected, analyses performed, and interpretations made for the Animas Valley during the past thirty years. Water chemistry data have been used to define structural control, postulate fault locations, develop regional hydrology and recharge models, investigate the local thermal regime, and compute reservoir temperatures by geothermometry. Examples of these studies include: Reeder (1957), Dellechaie (1975), Summers (1976), Logsdon (1981), Klein (1981), Swanberg (1981), Hawkins and Stephens (1982), Norman and Bernhart (1982), O'Brien and Stone (1981), and Oil Conservation Division (1986). To complement these data compilations and studies, Tables 3-3 and 3-4 reproduce data made available by AMAX which had not previously been published.

Including the data of Table 3-4, 115 water analyses are reported in the literature for wells in the 60-square-mile study area (see Figure 3-1). Kline (1981) used a one-stage mixing model to develop geothermometry estimates of the reservoir temperature of 165 to 170°C. By using a two-stage mixing model, based on silica/enthalpy relationships to account for the occurrence of boiling and re-equilibration, Kline (1981) concluded that the deeper reservoir has a potential for temperatures in the range of 174 to 210°C.

Table 3-3. Selected water sample locations in the Animas Valley, New Mexico. The data are taken from Dellechaie (1975).

| Sample | Latitude | Longitude |
|---|---|---|
| AMAX-1 | $32^\circ 14.1'$ | $108^\circ 50.7'$ |
| AMAX-2 | $32^\circ 13.3'$ | $108^\circ 52.0'$ |
| AMAX-3 | $32^\circ 12.1'$ | $108^\circ 48.7'$ |
| AMAX-4 | $32^\circ 10.7'$ | $108^\circ 52.0'$ |
| AMAX-5 | $32^\circ 10.1'$ | $108^\circ 52.8'$ |
| AMAX-6 | $32^\circ 08.9'$ | $108^\circ 51.4'$ |
| AMAX-7 | $32^\circ 08.5'$ | $108^\circ 50.1'$ |
| AMAX-8 | $32^\circ 08.9'$ | $108^\circ 49.9'$ |
| AMAX-9 | $32^\circ 08.7'$ | $108^\circ 50.0'$ |
| AMAX-10 | $32^\circ 08.7'$ | $108^\circ 47.6'$ |
| AMAX-11* | $32^\circ$ | $108^\circ$ |
| AMAX-12* | $32^\circ$ | $108^\circ$ |
| AMAX-13 | $32^\circ 06.5'$ | $108^\circ 54.8'$ |
| AMAX-14 | $32^\circ 05.7'$ | $108^\circ 53.2'$ |
| AMAX-15 | $32^\circ 06.3'$ | $108^\circ 50.8'$ |
| AMAX-16 | $32^\circ 04.8'$ | $108^\circ 52.3'$ |
| AMAX-17 | $32^\circ 04.0'$ | $108^\circ 52.3'$ |
| AMAX-18 | $32^\circ 08.7'$ | $108^\circ 50.0'$ |
| AMAX-19 | $32^\circ 17.5'$ | $108^\circ 45.9'$ |

* The precise locations of these samples are not known.

Table 3-4. Water-chemistry analyses for selected samples from the Animas Valley, New Mexico. The data are taken from Dellechaie (1975). The locations for these samples are given in Table 3-3.

| Sample | Na | K | Ca | Mg | $HCO_3$ | $SO_4$ | Cl | B | F | Li | $SiO_2$ | pH | TDS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AMAX-1 | 110 | 2.7 | 10 | 2.0 | 167 | 60 | 14 | 0.0 | 5.4 | 0.1 | 58 | 8.2 | 419 |
| AMAX-2 | 58 | 4.6 | 33 | 3.0 | 133 | 40 | 10 | 0.0 | 4.4 | 0.1 | 77 | 7.9 | 363 |
| AMAX-3 | 120 | 1.5 | 20 | 2.0 | 212 | 44 | 27 | 0.0 | 1.3 | 0.0 | 33 | 8.2 | 461 |
| AMAX-4 | 83 | 2.4 | 48 | 4.0 | 144 | 90 | 42 | 0.0 | 1.1 | 0.1 | 44 | 7.7 | 459 |
| AMAX-5 | 61 | 2.1 | 36 | 3.0 | 138 | 42 | 16 | 0.0 | 1.2 | 0.0 | 48 | 7.8 | 347 |
| AMAX-6 | 74 | 2.4 | 44 | 4.0 | 153 | 115 | 21 | 0.0 | 1.5 | 0.0 | 42 | 7.5 | 457 |
| AMAX-7 | 420 | 26.0 | 70 | 5.0 | 93 | 700 | 130 | 0.0 | 7.8 | 0.8 | 99 | 7.0 | 457 |
| AMAX-8 | 30 | 19.0 | 21 | 0.1 | 80 | 460 | 98 | 0.0 | 13.0 | 0.4 | 130 | 8.1 | 1,132 |
| AMAX-9 | 340 | 20.0 | 20 | 0.3 | 90 | 400 | 112 | 0.4 | 15.0 | 0.5 | 145 | 7.8 | 1,143 |
| AMAX-10 | 62 | 1.8 | 28 | 8.0 | 141 | 500 | 22 | 0.0 | 0.5 | 0.0 | 30 | 8.0 | 343 |
| AMAX-11 | 190 | 5.8 | 210 | 3.0 | 122 | 420 | 380 | 0.0 | 1.9 | 0.2 | 39 | 7.5 | 1,373 |
| AMAX-12 | 340 | 9.5 | 26 | 43.0 | 182 | 720 | 380 | 0.0 | 3.2 | 0.4 | 43 | 7.4 | 1,747 |
| AMAX-13 | 160 | 4.8 | 170 | 16.0 | 171 | 140 | 103 | 0.0 | 5.2 | 0.2 | 59 | 7.7 | 829 |
| AMAX-14 | 87 | 2.8 | 100 | 8.0 | 150 | 140 | 98 | 0.0 | 1.1 | 0.1 | 39 | 7.8 | 626 |
| AMAX-15 | 120 | 3.4 | 64 | 10.0 | 156 | 160 | 72 | 0.3 | 2.9 | 0.2 | 34 | 7.8 | 623 |
| AMAX-16 | 83 | 1.8 | 12 | 0.6 | 106 | 48 | 10 | 0.0 | 3.2 | 0.1 | 37 | 8.3 | 302 |
| AMAX-17 | 160 | 5.4 | 35 | 5.0 | 197 | 170 | 27 | 0.0 | 3.5 | 0.2 | 35 | 7.8 | 638 |
| AMAX-18 | 310 | 23.0 | 22 | 0.5 | 46 | 510 | 89 | 0.5 | 12.0 | 0.7 | 150 | 9.0 | 1,192 |
| AMAX-19 | 100 | 3.6 | 480 | 21.0 | 119 | 1,100 | 42 | 0.2 | 0.8 | - | 33 | 7.0 | 1,900 |

## 3.3 Deep Exploratory Drilling

### 3.3.1 Drilling History

During late 1984 and early 1985, Steam Reserve Corporation (SRC) drilled a deep test well located in Section 7, Township 25 South, Range 19 West. This well, Test for Discovery (TFD) 55-7, was spudded on December 27, 1984. One objective of the well was to intersect the Animas Valley Fault, believed to be dipping westward and controlling the ascending geothermal fluids. The well was located approximately 800 m west of the surface trace of the fault.

According to the SRC report, the well did not encounter high temperatures or large fluid entry zones. Although several minor drilling breaks and lost circulation zones were encountered, drilling progressed with no major problems (see Figure 3-5). On February 13, 1985, the well reached a total depth of 7,001 feet (2,134 m), after which a number of geophysical logs were run including dual induction, gamma, self potential, borehole compensated sonic, caliper, dip meter, and temperature. After logging was completed, 2 7/8-inch tubing was run in the hole to a depth of 3,018 feet (920 m) for subsequent temperature surveys. Drilling operations ceased and the well was shut in on February 18, 1985. In early March 1985, 2 7/8-inch tubing was run to a depth of 6,919 feet (2,109 m), and, following the collection of a temperature survey, the well was again shut in. The well was plugged with cement and abandoned on December 23, 1985.

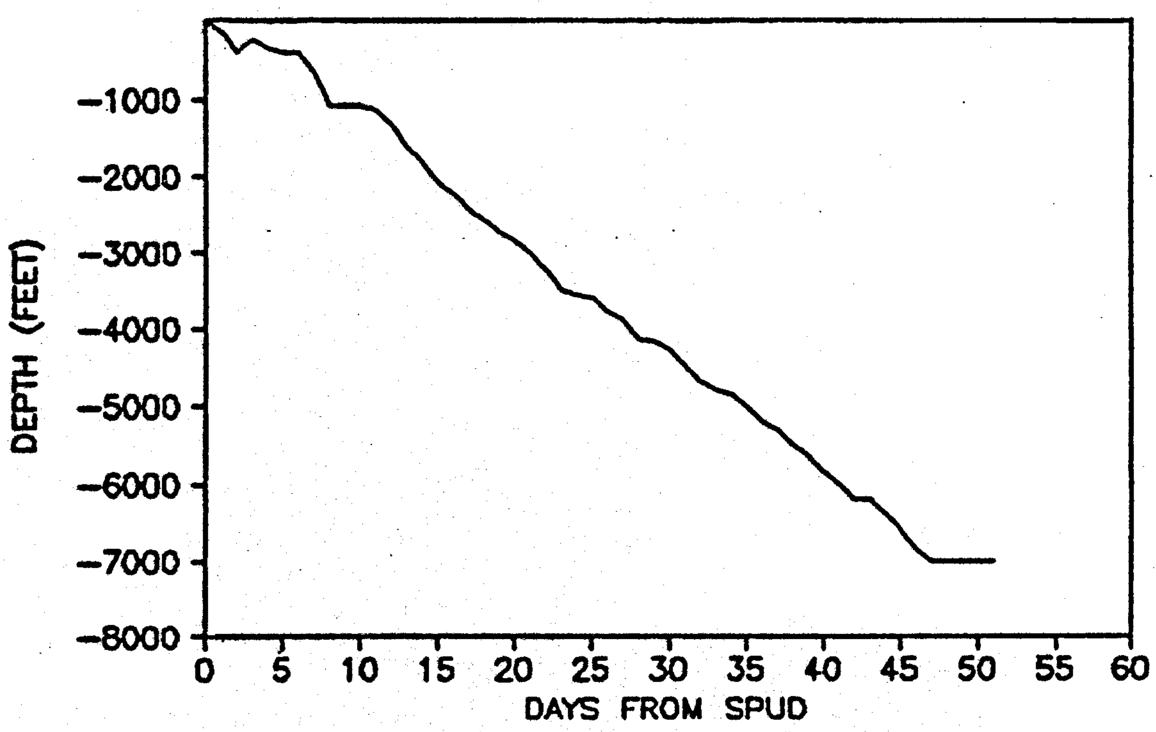


Figure 3-5. Drilling history for Well 55-7. The depth reversal at day 3 corresponds to reaming the pilot hole to 385 feet to set surface casing. On days 8 to 10, 13 3/8-inch intermediate casing was set. Fishing operations occurred at 3,566, 4,167, and 4,839 feet. The data are taken from AMAX Exploration, Inc. (1985).

### 3.3.2 Lithological Data

General descriptions of rock types encountered in Well 55-7 as reported by SRC are as follows:

- Surface to 145 ft: Alluvium - light brown to tan, very poorly sorted, subangular to subrounded, predominantly volcanic clasts (tuffs, ash, and andesite) with a soft weathered clay matrix, locally drusy quartz, some hematite and possibly manganese oxide.

- 145 to 1,460 ft: Rhyolitic lithic tuff - light brown to tan to orange to red, subangular tuff and welded tuff clasts, often brick red due to iron staining, certain zones are extremely silicified, at places contains abundant calcite and clay, common traces of magnetite and/or pyrite.

- 1,460 to 1,990 ft: Interbedded lithic tuffs and solution deposits - white to light gray to dark gray; solution deposits are predominantly calcium carbonate, highly fractured with abundant clear to white calcite veining and locally abundant pyrite veining; tuffs are red to light greenish-brown, commonly silicified with feldspars and micas altering to clay.

- 1,990 to 2,960 ft: Interbedded limestone and siltstone - light to dark-brown to black, sucrosic texture, hard to very hard, locally silty in places, locally highly fractured with abundant calcite veining, commonly contains abundant bioclasts and microfossils, pyritic at places.

- 2,960 to 3,200 ft: Intrusive dike - white to light red, mottled green and white, hard with aphanitic groundmass, with freshly altered plagioclase, biotite, and muscovite, abundant subhedral magnetite, with white to clear calcite veining; biotite and hornblende commonly altered to chlorite, locally contains a trace of pyrite.

- 3,200 to 4,060 ft: Limestone with small intrusive dikes - light to medium brown, dark gray, hard to very hard with sucrosic texture commonly recrystallized, interbedded with siltstone, locally abundant microfossils, commonly abundant white calcite veining with a trace of pyrite; chert zone from 3,400 to 3,480 ft; chloritized intrusive dike from 3,480 to 3,560 ft.

- 4,060 to 4,760 ft: Intrusive dike and limestone - white to pink, very hard, silicified, aplitic, predominately quartz and feldspar, disseminated pyrite, propylitically altered, common to abundant chlorite and magnetite, locally minor biotite, trace of pyrite and kaolin, minor calcite veining; small limestone bed from 4,470 to 4,550 ft - light to dark gray, locally silty, commonly recrystallized, contains fossils, abundant calcite veining with a trace of pyrite.

- 4,760 to 5,780 ft: Limestone - white to light gray to dark gray, hard, brittle, very fine- to fine-grained matrix with abundant intraclasts, locally soft and friable, minor light brown chert, minor calcite veining, visible dolomite rhombs.

- 5,780 to 5,960 ft: Siltstone and shale - siltstone is medium gray brown, moderately hard, well laminated with a fissile appearance, slightly to highly calcic, trace of calcite microveining, rare, very fine-grained pyrite; shale is dark gray to black, very fine grained with calcite cement, dark gray to black organic matter, predominantly blocky with a trace of calcite veining and disseminated pyrite.

- 5,960 to 6,530 ft: Limestone and dolomite - medium to dark gray, white, tan, hard, brittle, locally granular in appearance, cherty with interbedded silica, trace disseminated pyrite, trace microfossils, minor calcite veining; solution deposit from 6,470 to 6,490 ft, tan to white, cryptocrystalline, highly fractured.

- 6,530 to 6,630 ft: Intrusive - light to medium green, hard, fine grained, altered appearance, common to abundant disseminated magnetite, common chlorite, trace epidote, minor calcite, microveining, trace disseminated pyrite.

- 6,630 to 6,800 ft: Dolomite and shale -light gray to gray, moderately hard, recrystallized granular texture, fractured, trace disseminated pyrite; shale is black, soft to moderately hard, slightly fissile.

- 6,800 to 6,860 ft: Sandstone - clear to white with a minor gray-green cast, fine- to medium-grained quartz, subangular to round, moderately well sorted, minor chlorite, trace vein calcite, trace disseminated pyrite; probably the Bliss Sandstone.

- 6,860 to 7,001 ft: Granite - light pink, white to light green, hard, hypidiomorphic texture, moderately fractured with minor kaolin and chlorite fracture fill, trace calcite and hematite, rare pyrite; Precambrian basement.

Formation tops are identified (Thompson, 1986) in Table 3-5. Thompson (1986) identified the Tertiary igneous intrusive between the Horquilla and Escabrosa formations as a granodiorite or monzonite with a possible fault zone at 4,770 feet (1,454 m). Because no other fault zones were apparent below 1,450 feet (442 m), this contact may be very important in determining if the

Table 3-5. Formation tops for Well 55-7. These data are based on Thompson (1986).

| Depth (ft) | Formation | Age |
|---|---|---|
| 0 | Valley fill | Quaternary/Tertiary |
| 290 | Volcanic rocks | Tertiary |
| 1,422 | U-Bar Formation (?) | Late Cretaceous |
| 1,539 | Hell-to-Finish Formation (?) | - |
| 1,842 | Horquilla Formation | Permian-Pennsylvanian |
| 4,075 | Igneous intrusive | Tertiary |
| 4,770 | Escabrosa Formation | Mississippian |
| 5,609 | Percha Shale | Devonian |
| 5,982 | Montoya Formation | Ordovician |
| 6,201 | El Paso Formation | Ordovician |
| 6,781 | Bliss Sandstone | Cambrian/Ordovician |
| 6,858 | Granite | Precambrian |

Animas Valley Fault was intersected as planned. If the contact at 4,770 feet (1,454 m) is the fault, a westward dip of approximately 61 degrees would be indicated, which is a much lower angle than would be expected for the Animas Valley Fault.

### 3.3.3 Temperature Surveys

A temperature survey was run on February 14, 1985, by Schlumberger within 24 hours after reaching total depth (see Figure 3-6). Prior to logging, the well was circulated for about four hours. A temperature peak of about 170°F (77°C) occurred at approximately 1,400 feet (427 m), followed by a temperature reversal and an essentially isothermal zone from 1,800 to 2,600 feet (549 to 792 m). Bottom-hole temperature was 238°F(114.4°C). Below 2,600 feet (792 m), the thermal gradient is positive with marked increases at about 4,600, 6,000, and 6,800 feet (1,402, 1,829, and 2,073 m). The upper part of the hole appears to be warmed and the lower part appears to be cooled relative to a conductive temperature-gradient profile, which is a normal and expected result of drilling operations. The temperature peak and isothermal section indicate fluid entry and movement below the 13 3/8-inch casing set at 1,050 feet (320 m).

A second temperature survey (see Figure 3-6) was run on April 3, 1985, to a depth of 6,919 feet (2,109 m). Reported bottom-hole temperature was 326°F (163.3°C). The upper part of the well, from the surface to approximately 1,300 feet (396 m), exhibits an extremely high thermal gradient to a peak temperature of almost 300°F (149 °C) before the profile reverses below 1,300 feet (396 m) and becomes isothermal at about 2,500 feet (762 m).

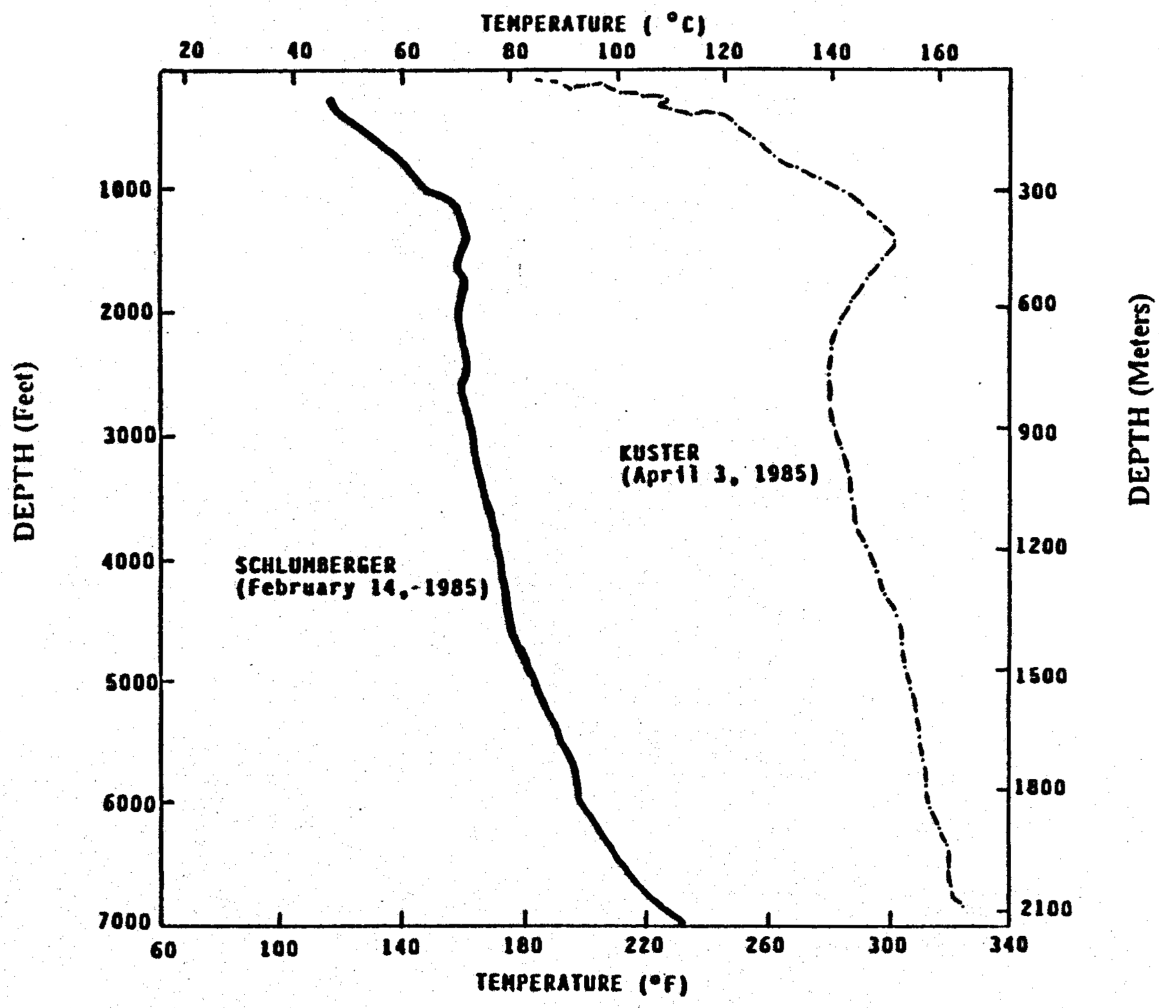


Figure 3-6. Temperature-depth profiles for Well 55-7.

Below 2,500 feet (762 m) to total depth, the temperature-gradient profile appears to be generally conductive with only minor disturbances. Steam Reserve Corporation personnel attributed the temperature peak at 1,200 to 1,300 feet (366 to 396 m) to three small probably water-bearing fracture zones.

### 3.3.4 Geologic Interpretations

The drilling and log records portray Well 55-7 to be a borehole which very likely followed a fault plane intersection from approximately 1,000 to 2,500 feet (305 to 762 m) of depth. The deviation log shows that the drill bit drifted to the south from 1,031 to 1,218 feet (314 to 371 m); drifted to the southeast from 1,218 to roughly 2,000 feet (371 to 610 m); reversed direction to the west-northwest at roughly 2,000 feet (610 m) when a more flexible bottom drilling assemblage was used. The borehole possibly followed the general dip of a fault zone to 2,500 feet (762 m) of depth. Although the stratigraphy and structure are complex, two cross sections have been developed (see Figures 3-7 and 3-8). While these two cross sections serve as one model of the subsurface structure in the vicinity of Well 55-7, many alternative interpretations are possible based on the available data.

Figures 3-7 and 3-8 depict high-angle normal faults and, for a reference datum, depict the depth to the Precambrian granite at the Cockrell Pyramid Federal oil and gas wildcat well drilled approximately 5 km north of Well 55-7. Fault F-2a in Figure 3-7 is shown as a $70^\circ$ normal fault dipping to the west. This fault is the mapped Animas Valley Fault and was modeled by O'Brien

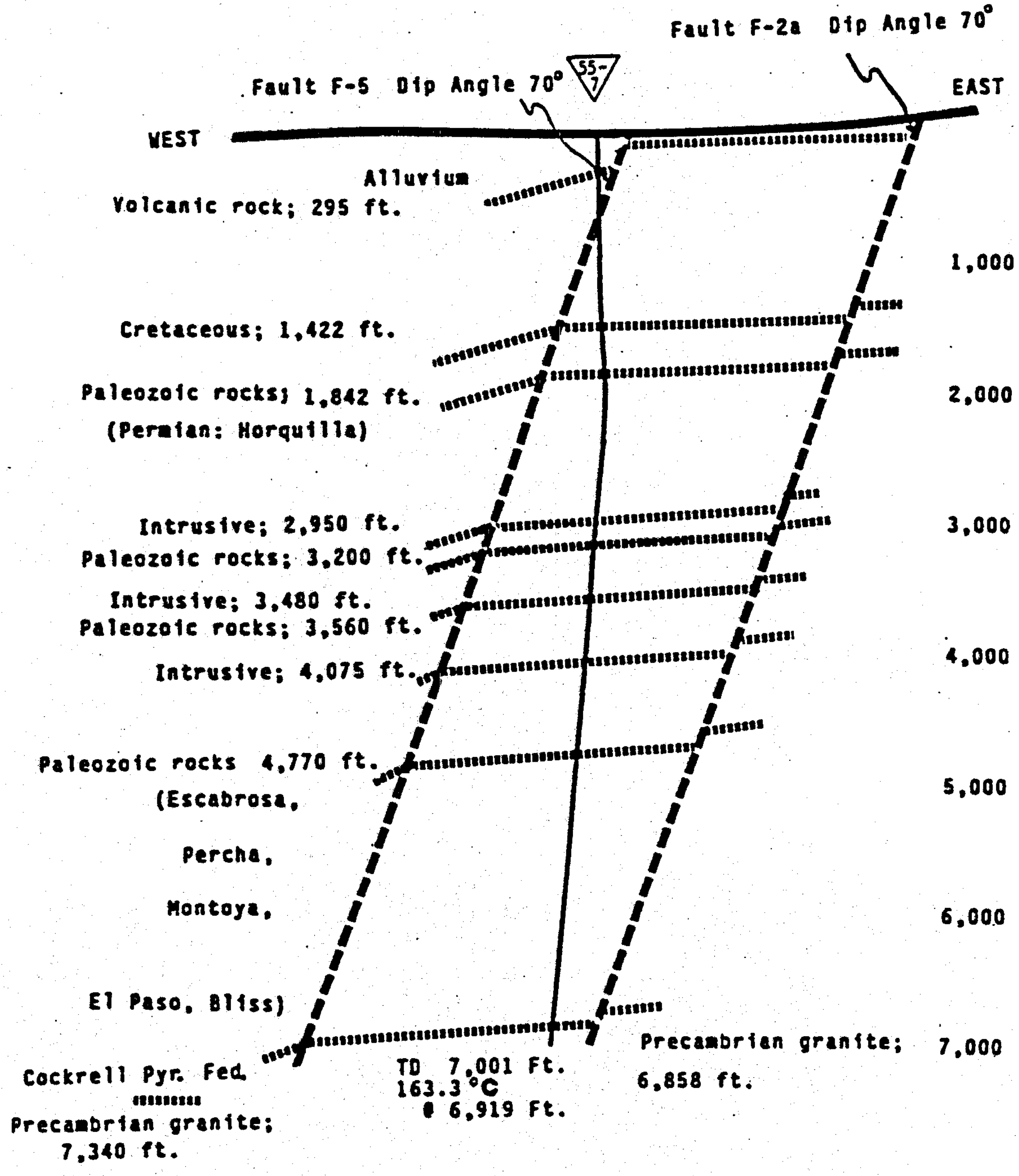


Figure 3-7. East-west cross section through Well 55-7 looking to the north along the trace of the Animas Valley Fault.

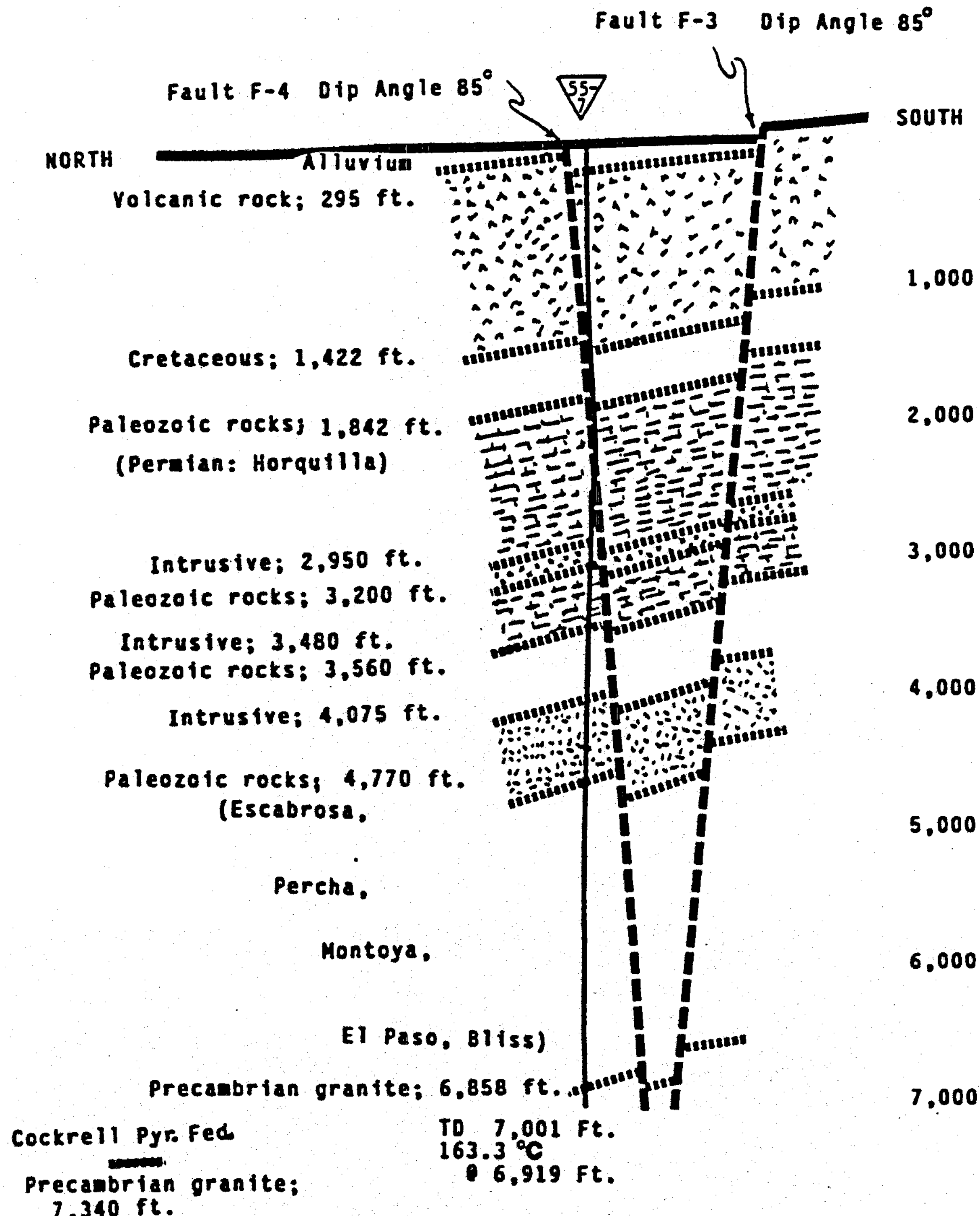


Figure 3-8. North-south cross section through Well 55-7 looking to the east along the strike of inferred northeasterly trending recent faulting.

and Stone (1983). Fault F-5 in Figure 3-7 is an inferred, parallel and an echelon fault, typical of basin-bounding fault systems in deep sedimentary basins of the western U.S.

In Figure 3-8, fault F-3 is an inferred, northeasterly striking fault, which is speculated to be an 85° normal fault dipping to the north. Fault F-5 is inferred to be an 85° normal fault dipping to the south. Both of these faults have been tentatively mapped by Spiegel (Reeder, 1957).

## 3.4 Concluding Remarks

Several estimates have been made for the maximum subsurface temperature in the Lightning Dock KGRA. Dellechaie (1975) first estimated a reservoir temperature of 165°C from initial water chemistry and geothermometry. Later, a maximum temperature of 160°C at depths greater than 4 km was suggested by Dellechaie (1977) based on geochemistry and heat-flow data. Logsdon (1981) concluded that silica geothermometers indicated a shallow reservoir temperature of 165°C and a deep reservoir temperature of 250°C, located 15 km southwest of the hot-well area at a depth of 1.5 km. None of the temperature data from water wells, temperature-gradient holes, or Well 55-7, support this conclusion.

Pilkington (1981) echoed the work of Logsdon (1981), but tempered the reservoir prediction to 220°C at a depth of 2 km. Klein (1981) predicted a minimum reservoir temperature of 160 to 165°C, with a possible mixing with fluids of temperatures up to 210°C, based on reinterpretations of both published and proprietary chemical analyses.

Well TFD 5-7 failed to confirm the existence of the postulated 220°C, high-temperature geothermal reservoir, but did confirm the existence of 165°C temperatures at a depth of slightly more than 2 km. The necessary fracture permeability for production was not found at the depth according to SRC staff. Koening (1974) speculated, based on limited data, that the reservoir could be characterized as a pervasively fractured lithologic unit, with storage or transmissivity increasing locally around major fault intersections, in contrast to a fault plane or the intersection of fault planes. Koenig (1974) also recommended that several detailed geological, geophysical, and geochemical studies be conducted prior to the drilling of a deep test well to identify critical siting parameters. None of these recommended studies were performed to site Well 55-7.

Elston and others (1983) concluded that the geothermal anomaly is structurally controlled by the intersection of the Quaternary Animas Valley Fault with the early Oligocene Muir cauldron. This conclusion is difficult to accept. Based on experience gained from other geothermal systems in the western U.S., even if the old fracture system exists, this fracture system is likely to have little to no control on the modern geothermal system. From theoretical work modeled by Blackwell (1987), the shallow reservoir can be inferred to be very young, probably younger than 10,000 years.

The exploration work conducted by AMAX and SRC delineated a massive relatively low temperature thermal regime, with at least one area of extremely elevated temperature. The shallow geothermal reservoir has been estimated by Callender (1985) to have a volume of at least 0.75 $km^3$ and a total heat content of 0.21 exajoules. Based on the temperature data now available, the shallow reservoir is estimated to have a volume of at least 16.2 $km^3$ and a total heat content of at least 1.6 exajoules. The recoverable heat content from the shallow reservoir is estimated to be 20 to 75 megawatts thermal.

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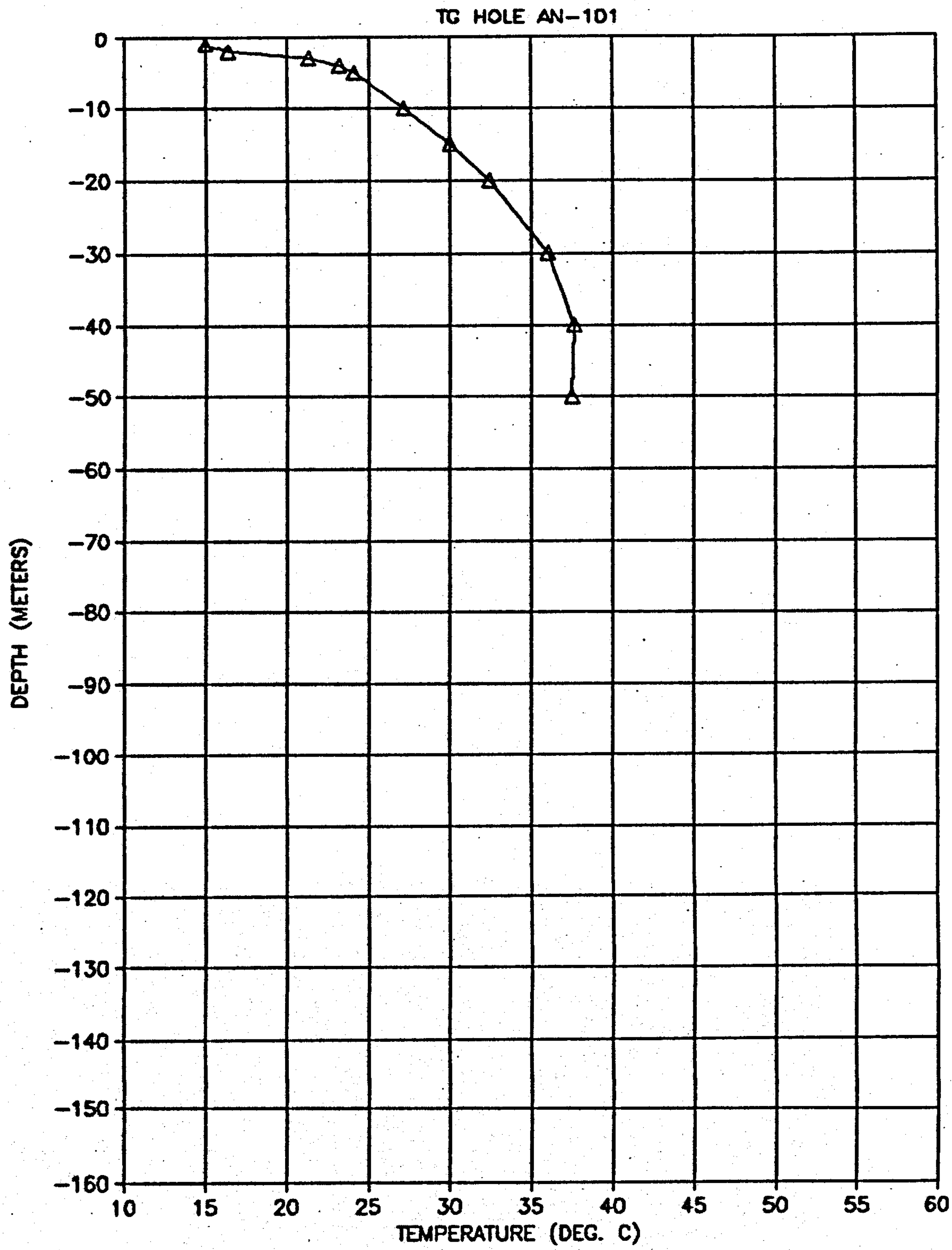
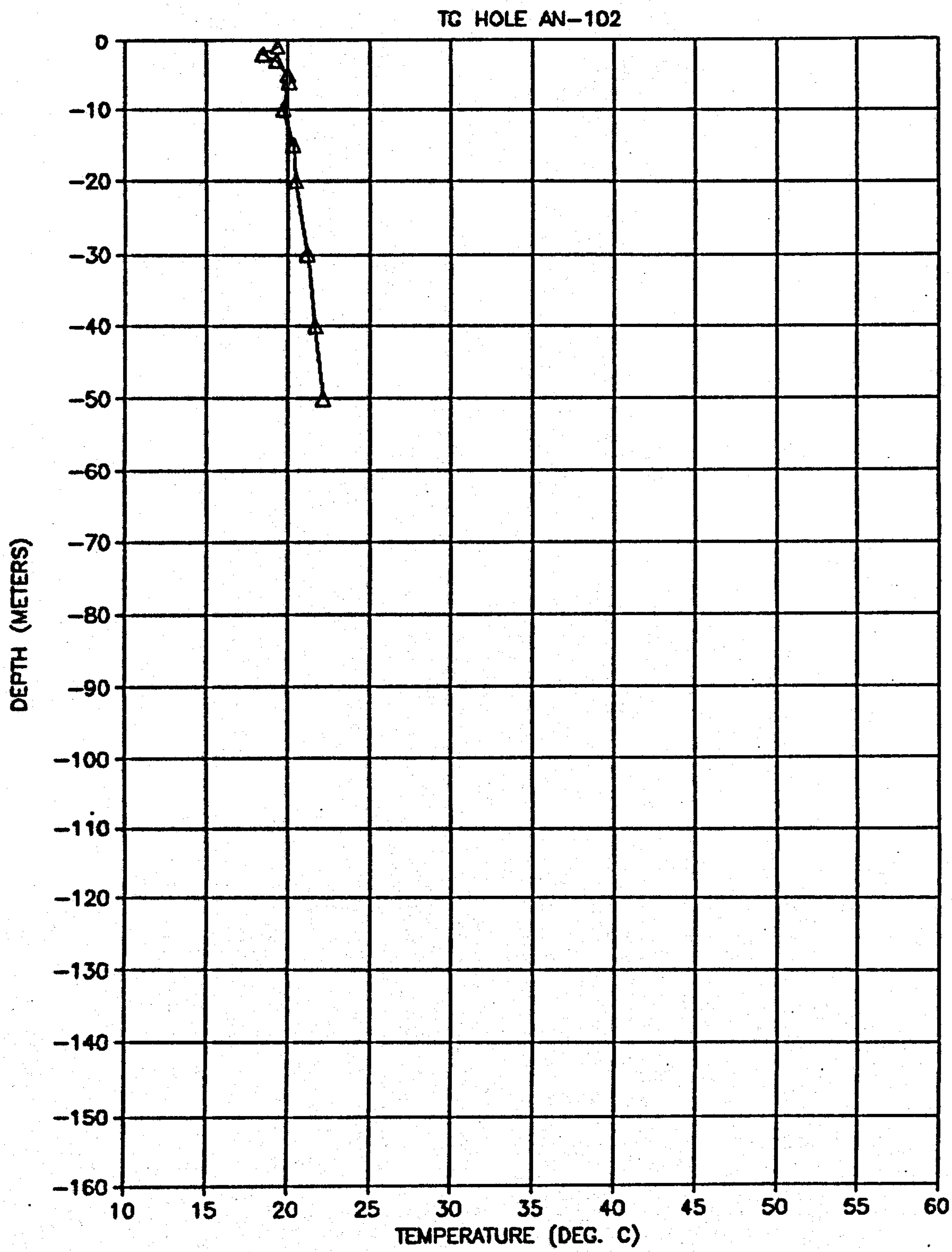
# APPENDIX A

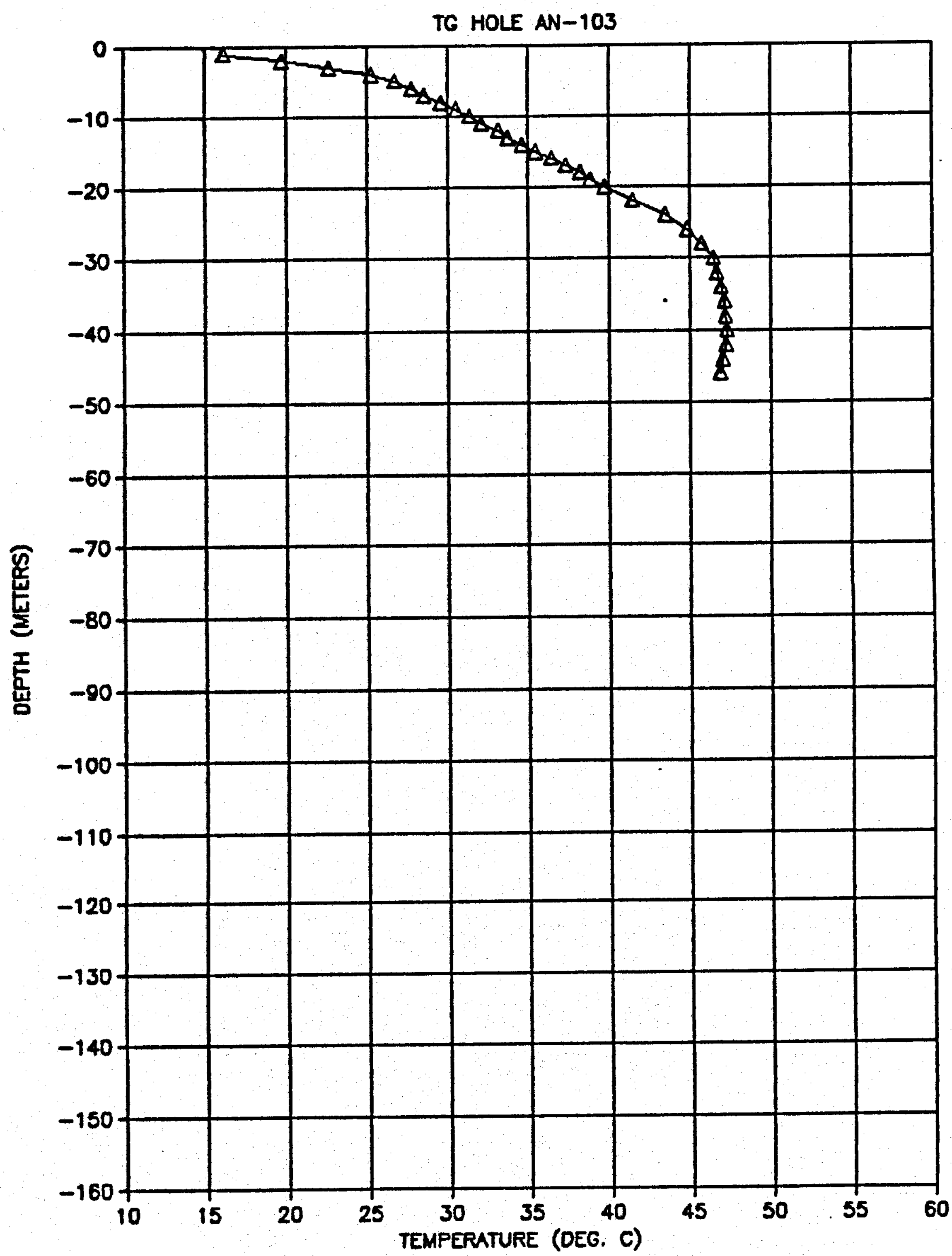
## Temperature-Depth Profiles for Ten Shallow Temperature Gradient Holes

Note: The temperature surveys were performed by Steam Reserve Corporation personnel in 1975 (T-series) and 1976 (AN-series).


TC HOLE AN-101
DEPTH (METERS)
TEMPERATURE (DEG. C)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
10
15
20
25
30
35
40
45
50
55
60



TG HOLE AN-102
DEPTH (METERS)
TEMPERATURE (DEG. C)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
10
15
20
25
30
35
40
45
50
55
60


TG HOLE AN-103
DEPTH (METERS)
TEMPERATURE (DEG. C)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
10
15
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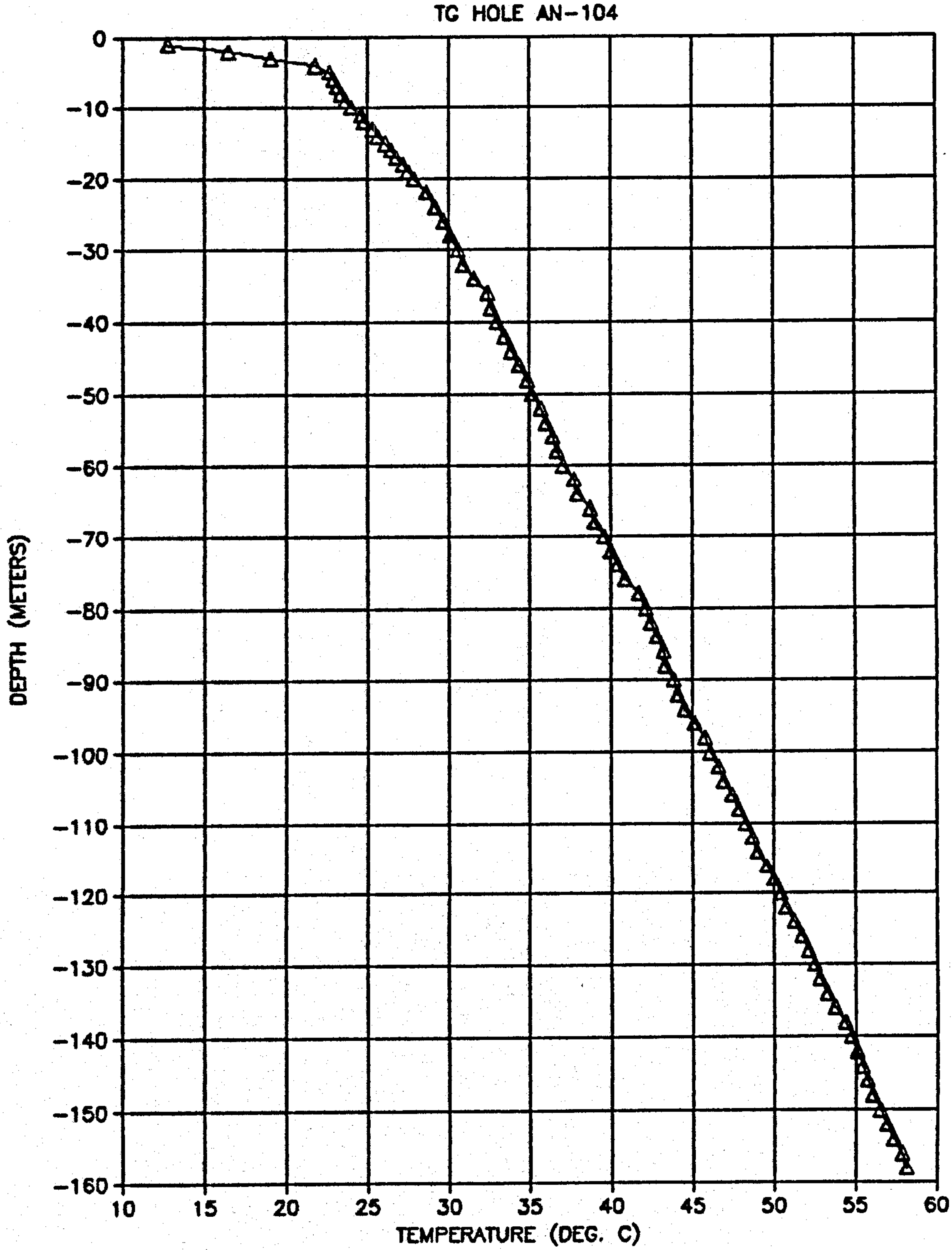
25
30
35
40
45
50
55
60



TC HOLE AN-104
DEPTH (METERS)
TEMPERATURE (DEG. C)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
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-140
-150
-160
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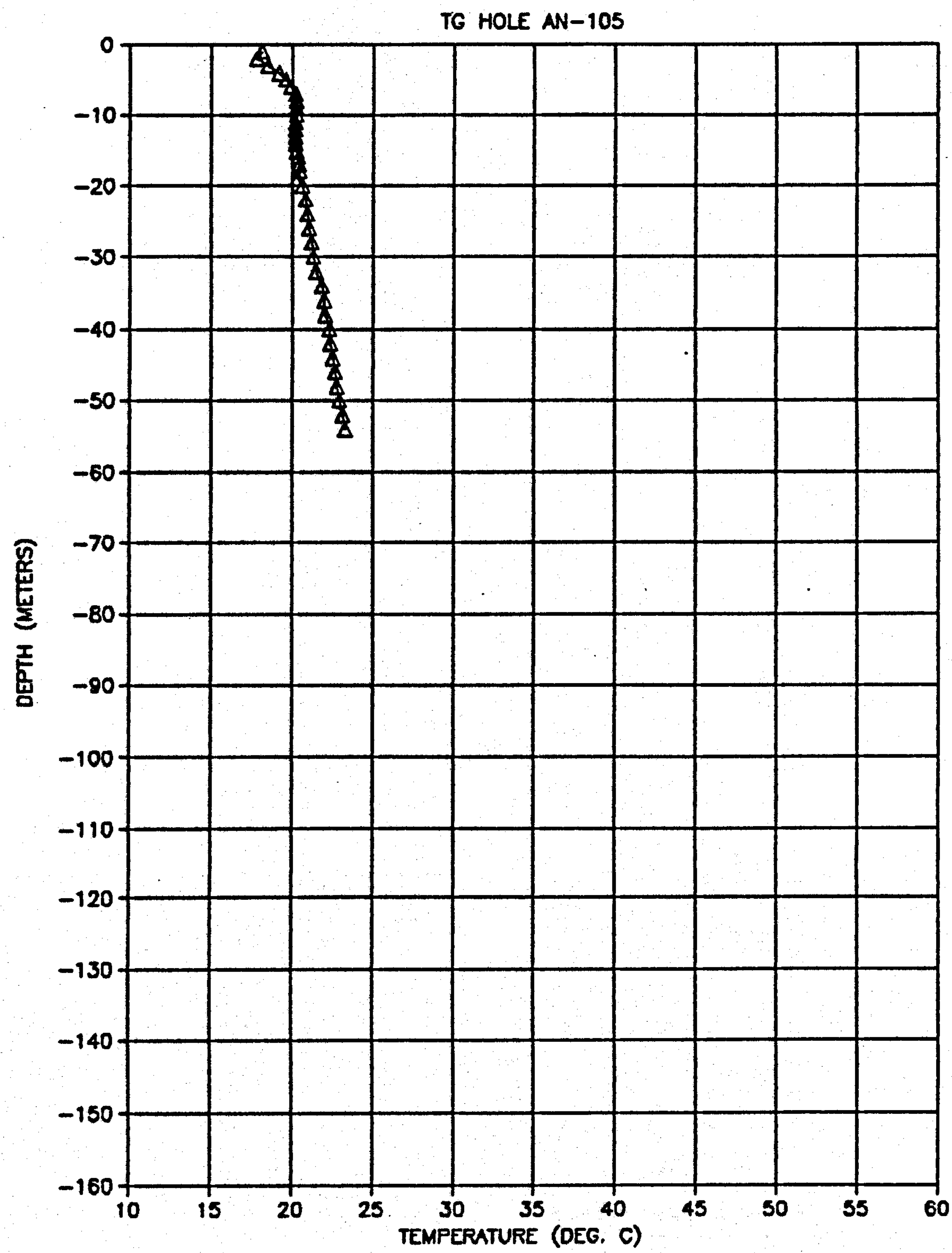
40
45
50
55
60



TG HOLE AN-105
DEPTH (METERS)
TEMPERATURE (DEG. C)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
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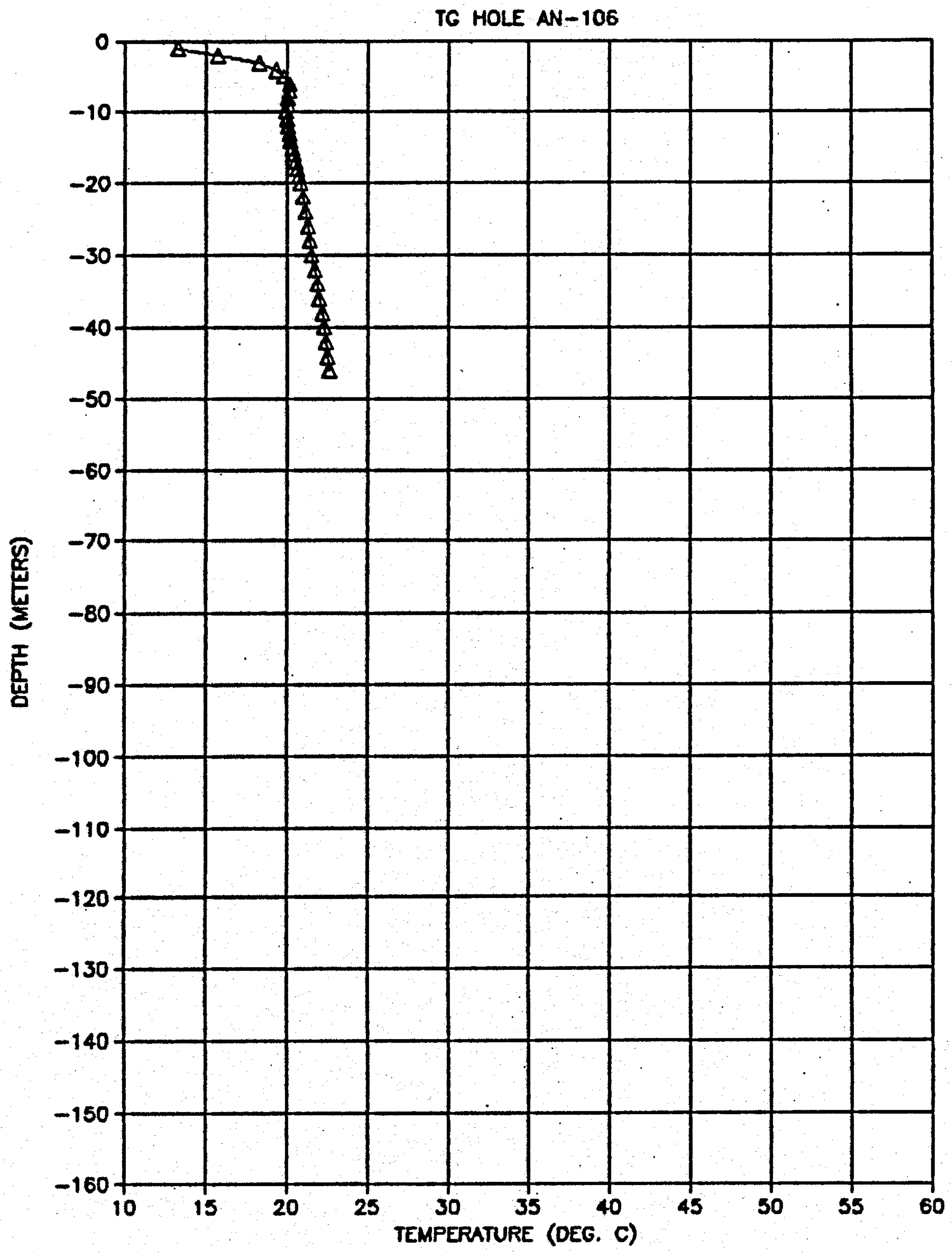
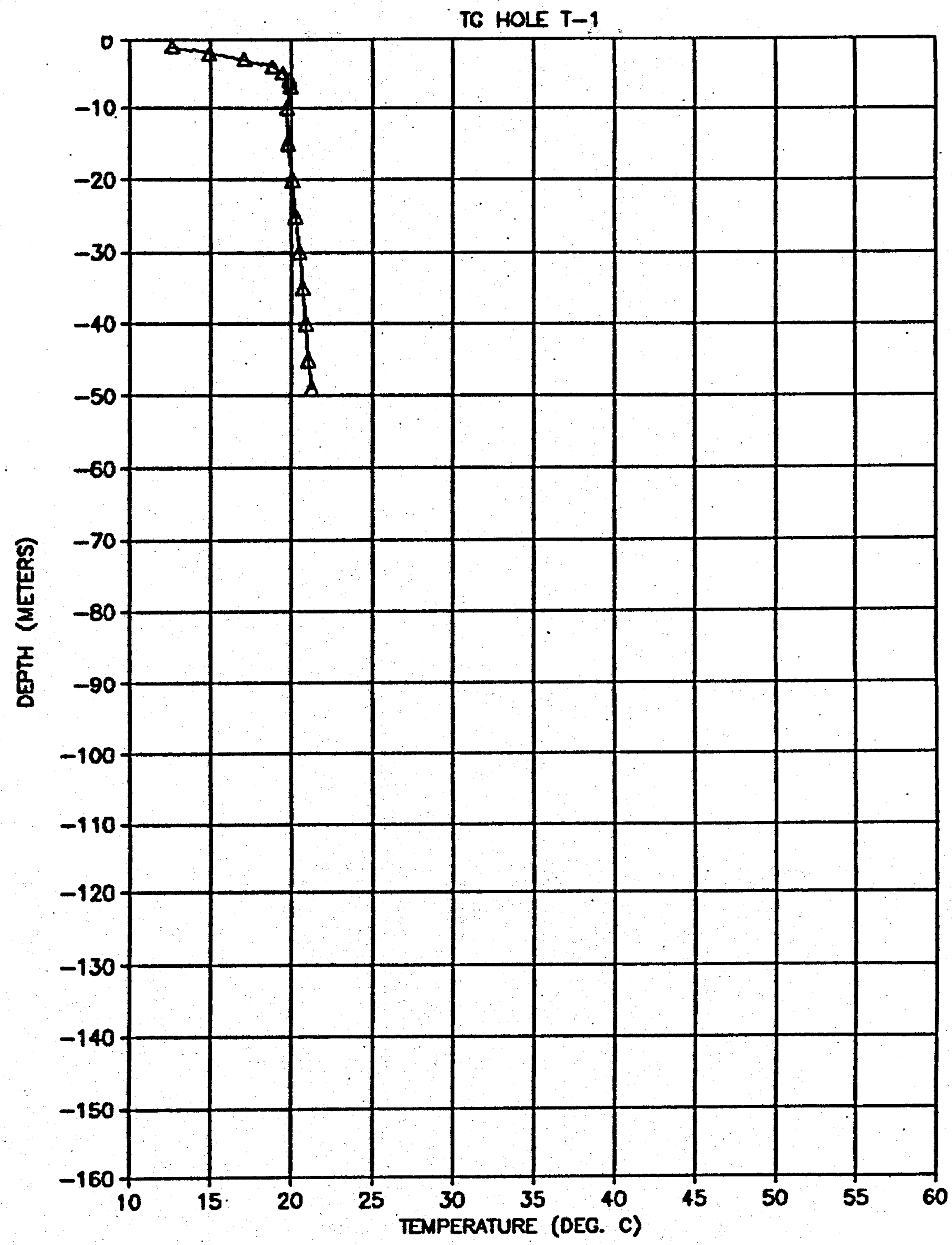
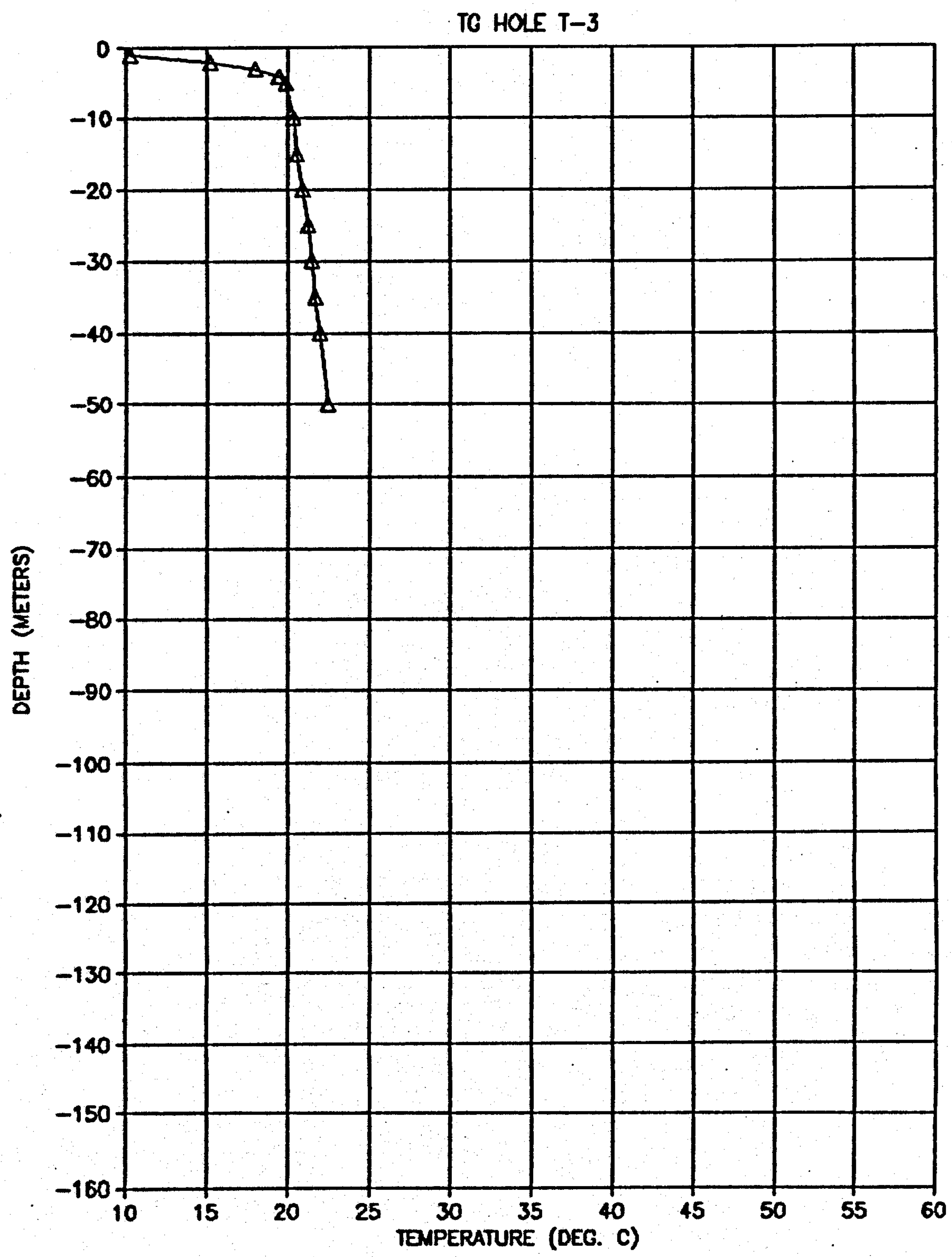
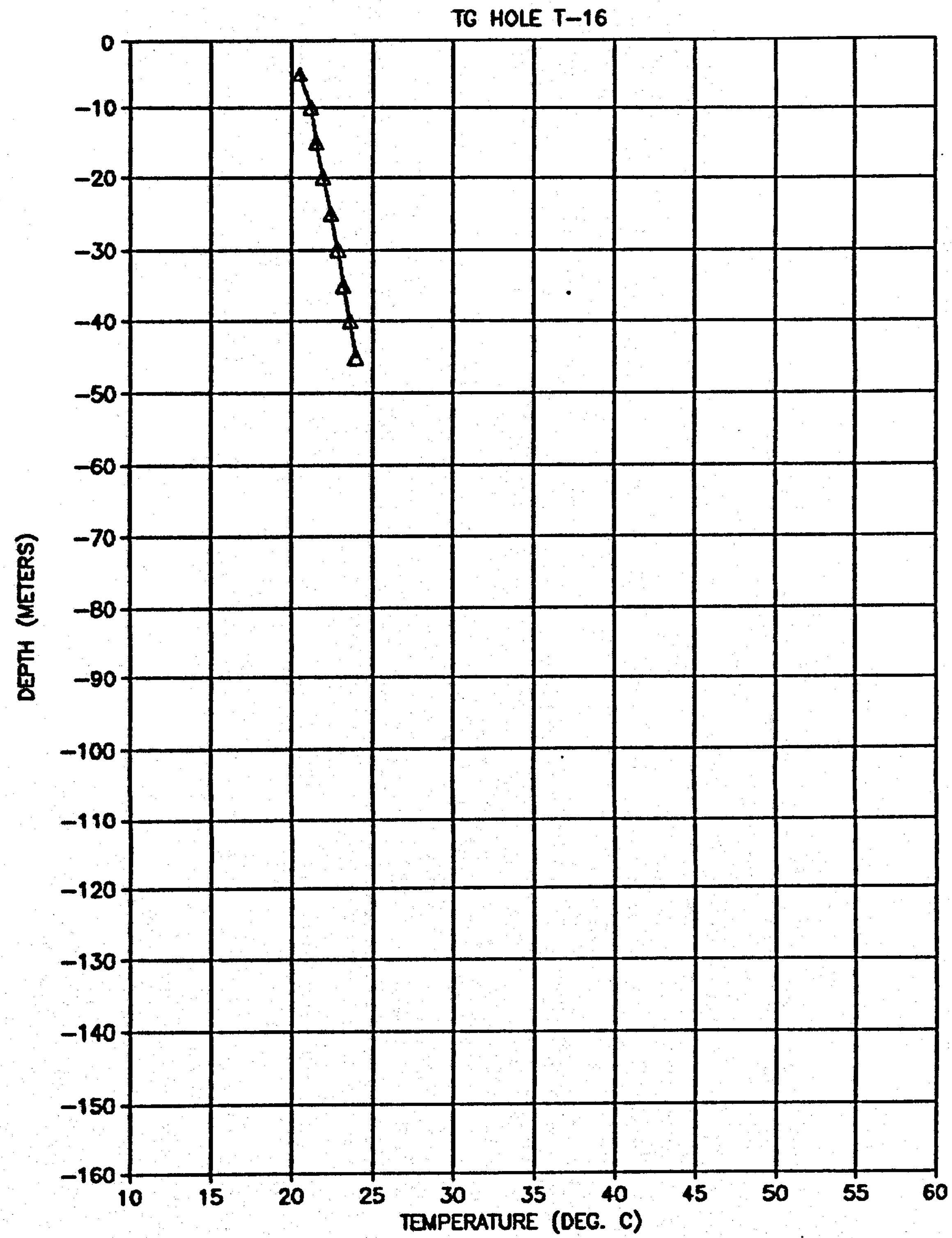
40
45
50
55
60



TG HOLE AN-106
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
DEPTH (METERS)
10
15
20
25
30
35
40
45
50
55
60
TEMPERATURE (DEG. C)


TG HOLE T-1
DEPTH (METERS)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
10
15
20
25
30
35
40
45
50
55
60
TEMPERATURE (DEG. C)


TG HOLE T-3
DEPTH (METERS)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
10
15
20
25
30
35
40
45
50
55
60
TEMPERATURE (DEG. C)


TG HOLE T-16
DEPTH (METERS)
TEMPERATURE (DEG. C)
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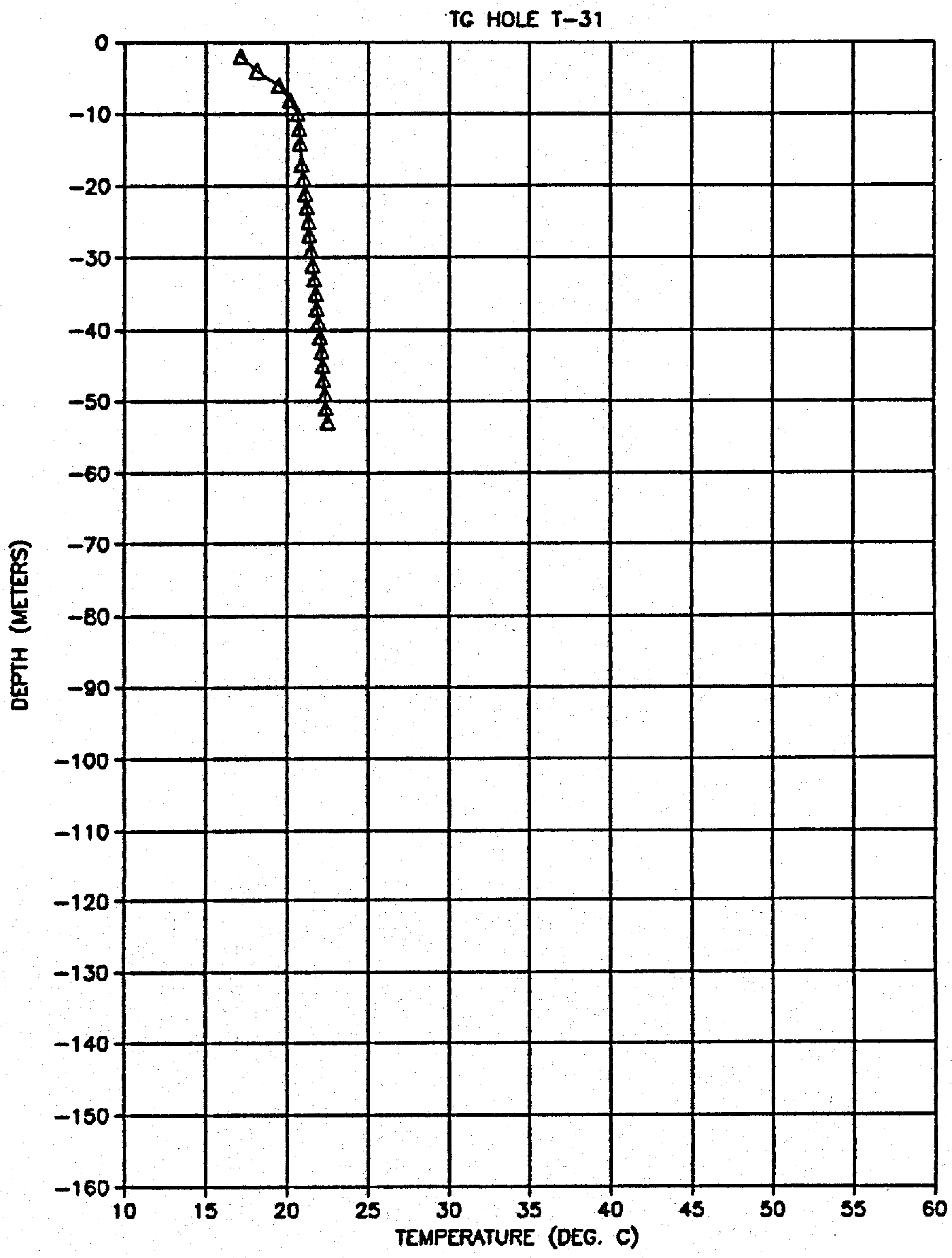
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
10
15
20
25
30
35
40
45
50
55
60



TG HOLE T-31
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
DEPTH (METERS)
10
15
20
25
30
35
40
45
50
55
60
TEMPERATURE (DEG. C)

CHAPTER 4

# PRELIMINARY GEOTHERMAL RESOURCE ASSESSMENT OF THE OROGRANDE, NEW MEXICO, AREA*

## 4.0 Introduction

This chapter contains a preliminary geothermal resource assessment of the area near Orogrande, New Mexico, located at the southern extent of the Tularosa Basin, which is part of the Basin and Range Province. This area lies on the eastern boundary of the southern Rio Grande rift and has been under continuous control of the U.S. Army for more than 40 years. Accordingly, to date very limited data have been collected from which the geothermal resource potential may be assessed. The data for this assessment were obtained from the drilling and testing program for an exploratory water well for use during construction of the Ground-Based Free Electron Laser Technology Integration Experiment (GBFEL-TIE) near Orogrande, New Mexico (see Figure 4-1).

The well was drilled by Salazar Drilling Company under subcontract to Fluor Constructors, Inc. Technical supervision for the drilling operations was provided by the U.S. Army Corps of Engineers, Fort Worth, Texas, District. Related geophysical work was being conducted by the U.S. Army Corps of Engineers, Huntsville, Alabama, District. Assistance, site access, and co-

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* The principal authors of Chapter 4 are Roy A. Cunniff, President, and Roger L. Bowers, Vice President, Lightning Dock Geothermal, Inc.

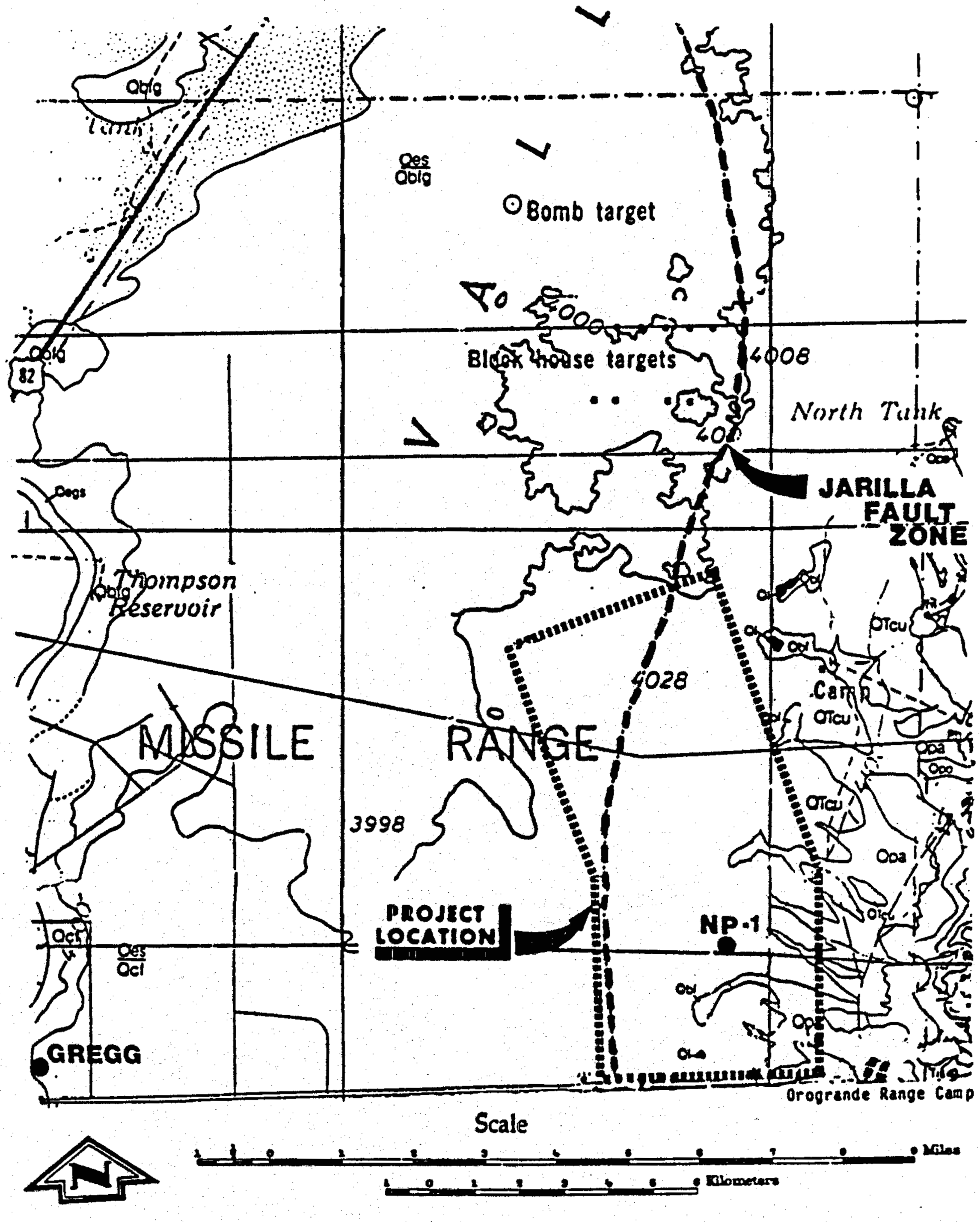


Figure 4-1. Location map for the study area and Well NP-1.

ordination were provided by the U.S. Army Corps of Engineers and the GBFEL-TIE Project Office at White Sands Missile Range.

## 4.1 Drilling History

Well NP-1 was drilled as an exploratory well at a location on the GBFEL-TIE construction site (see Figure 4-1). Target depth selected by the U.S. Army Corps of Engineers was 1,200 feet, with expectations that bedrock might be encountered at a depth as shallow as 850 feet. The well was spudded on July 10, 1987, and a 6 1/4-inch hole was drilled to a total depth of 1,176 feet. Above 600 feet of depth, drilling was relatively slow, and penetration rates including connection time averaged 30 feet per hour (fph). Below 600 feet, the penetration rate averaged almost 60 fph, with peak rates as high as 160 fph (see Figure 4-2). A continuous record of drilling mud return temperatures and drill cuttings at 10-foot intervals were collected.

Subsequent to drilling the slim hole to total depth, a suite of geophysical logs was acquired. Under supervision of U.S. Geological Survey personnel, an attempt was made to obtain air-jetted water samples from five potential water-bearing zones selected by the U.S. Geologic Survey personnel based on a review of drill cuttings and geophysical logs. A water sample was obtained from the deepest zone at 1,030 feet. Unsuccessful attempts were made to jet water from zones at 970 and 723 feet of depth. Because these latter attempts failed, no attempt was made to jet water from the potential water-bearing zones at 452 and 310 feet.

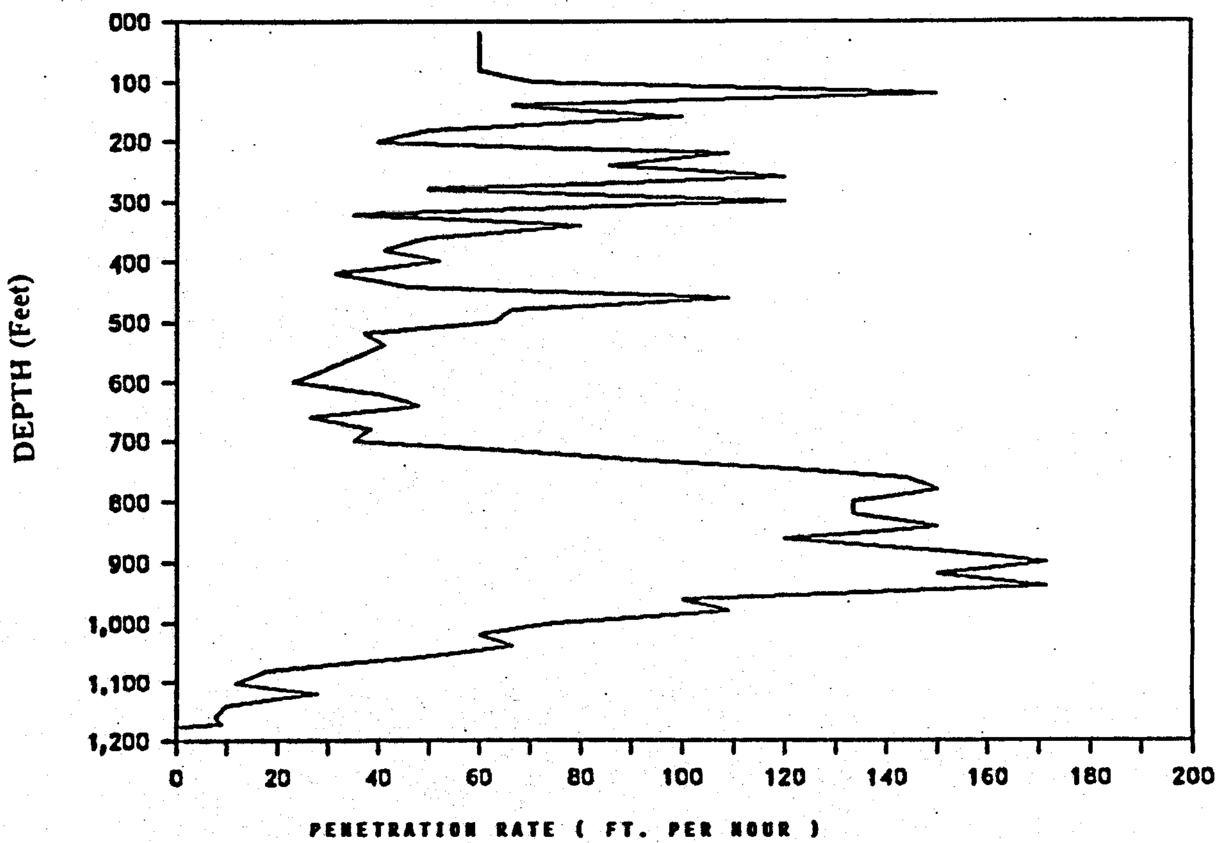


Figure 4-2. Drilling history for Well NP-1.

The well was completed as a water well on July 27, 1987, followed by well development activities, which were completed on July 30, 1987. Initially, a 20-inch surface casing was cemented into a 24-inch diameter borehole to a depth of 38 feet. The pilot hole was reamed to an 18-inch diameter to 1,071 feet of depth in a two-pass operation. A total of 1,054.5 feet of 12-inch casing and screen were landed in the enlarged borehole, with screen consisting of 12-inch stainless steel wire-wound sections at 407.5 to 467.5 feet, 653.5 to 683.5 feet, and 923.5 to 1,033.5 feet of depth (see Figure 4-3).

After the casing and screen were landed, the annulus was filled with graded Colorado silica gravel from total depth to the ground surface. The gravel pack consisted of 10-20 silica gravel, with an effective size of 0.901 mm and a uniformity coefficient of roundness of 1.57.

4.1.1 Test Operations

A Worley 4-inch submersible pump, with a 75-horsepower motor, was set at 832 feet in order conduct a series of controlled pump tests to evaluate well hydraulics and aquifer characteristics. These tests served to help develop the well and to develop information for computing formation productivity. Water-level measurements were obtained by using a standard conductivity probe inserted into a 1-inch monitoring pipe positioned alongside the pump column.

Initially, the well was alternatively pumped and surged for a 6.5-hour period at flow rates ranging from zero to 300 gallons per minute (gpm), with the well being allowed to recover for ap-

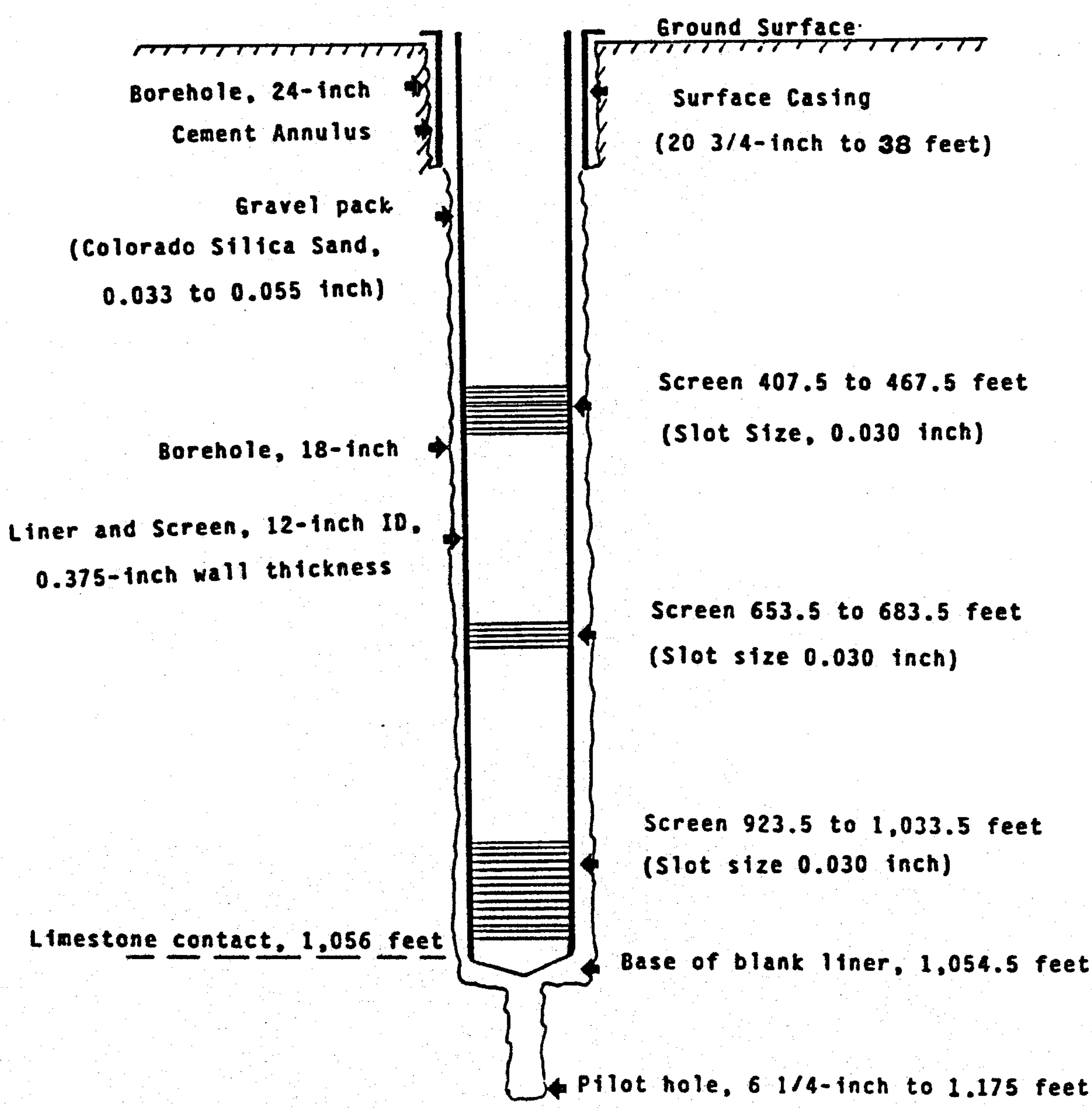


Figure 4-3. Completion configuration for Well NP-1 [After U.S. Army Corps of Engineers (1987)].

proximately 1 hour between each of the three flow periods. Flow rates were measured with a standard irrigation water meter. After the well had recovered from the surging operations, a three-step drawdown test was conducted by pumping the well at rates of 120, 230, and 310 gpm in 4-hour increments. The specific capacity of the well was determined to be 21, 14.8, and 6.8 gpm per foot of drawdown for the respective flow rates (U.S. Army Corps of Engineers, 1987).

A constant flow rate (i.e., 315 gpm) test, initially scheduled for 48 hours, was terminated at 37 hours because equipment problems made the maintenance of a constant flow rate difficult. Recovery measurements were made at the end of the 37-hour test. Transmissibility calculations for the pumping and recovery periods yielded values from 52,300 to 55,800 gpm per foot of aquifer saturated thickness. The aquifer was characterized as a leaky, confined aquifer (U.S. Army Corps of Engineers, 1987).

Pumped water temperature was measured at 87.8°F (31°C) for each flow rate of the step drawdown test and during the 37-hour constant flow rate test. This temperature is lower than the peak temperature measured under static conditions and suggests that mixed flow is produced from several different water-bearing strata.

Based on temperature and water-quality data, most of the production is from the lowest water bearing zone between about 915 and 1,030 feet. This zone, which was depicted on the caliper log to be enlarged from the 6 1/4-inch bit size to 7 to 9 inches, is completed with 110 feet of screen, with 77 square inches of opening per lineal foot. At an average flow rate of about 315 gpm, the screen inlet velocity would be about 0.01 feet per second if all of the production is from this zone, which is only 10 percent of the industry suggested maximum velocity. Accordingly, Well NP-1 should be able to produce safely at least 500 gpm.

#### 4.1.2 Lithology

Cuttings were acquired at 10-foot intervals, and a suite of electrical and geophysical logs were run to total depth. Well NP-1 was completed in basin fill with the characteristics of a playa deposition. A total of 1,056 feet of basin fill was penetrated prior to bedrock contact. Subsurface formations consisted of alternating clay and sand/gravel horizons, with clays constituting the bulk of the formations.

From ground surface to the water table, identified by electric logs to be at 250 feet of depth, clays comprise 46 percent of the formation. Five distinct clay layers were intersected, with the thickest being 75 feet from 70 to 145 feet of depth.

Below the water table, drilling encountered 32 separately defined clay strata. Thick sequences are at 612 to 670 feet and from 702 to 763 feet. From the water table to a depth of 875 feet, clays constitute 70 percent of the formation material.

Below 875 feet of depth, only one clay horizon was noted at 897 to 915 feet. Another possible clay layer was encountered just above bedrock contact, but this layer had a large proportion of gravel and could be clay sloughed from the borehole walls. The lowest 180 feet of basin fill above bedrock contact contained only 15 percent clay. A detailed lithology, based on a review of the cuttings and well logs (U.S. Corps of Engineers, 1987), is reproduced in Appendix A.

4.1.3 Temperature Surveys

Three temperature surveys were conducted in addition to a record of the drilling mud return temperature (see Figure 4-4). Two of the surveys were completed in the pilot hole. The first survey was conducted 1 hour after drilling was completed and depicted a thermal regime strongly affected by the sun-warmed mud pit resulting in effectively isothermal subsurface temperatures of about 85°F, the mud pit temperature.

A second temperature survey was made 23 hours after drilling stopped, approximately 12 hours after completion of the other logging operations. By this time, the mud level in the borehole had dropped to a level of 450 feet so temperature data were only collected from 450 to 1,175 feet (see Figure 4-5). This survey depicted a temperature increase of 8°F in the interval 450 feet to total depth for an average gradient of 1.1°F per 100 feet of depth. This gradient is much lower than the average gradient of 1.8°F/100-ft found in the southern Rio Grande rift.

A final temperature survey of the completed well was conducted on August 20, 1987, 18 days after the conclusion of well testing operations. By this time, the subsurface conditions should have reached thermal equilibrium. Measured bottom-hole temperature was 91.9°F (33.3°C) at 1,050 feet of depth. Although not remarkably elevated, this temperature is a good indicator of a possibly warmer geothermal source temperature. The well had a

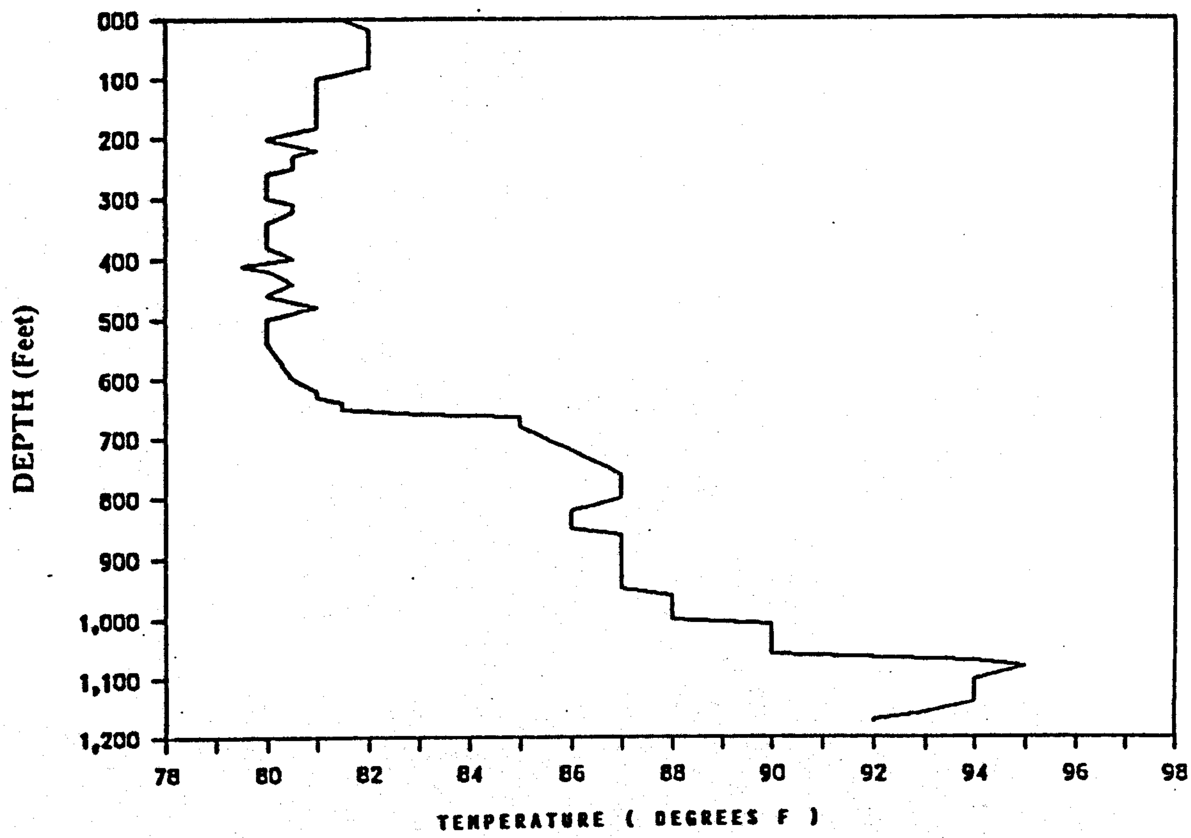


Figure 4-4. Drilling mud return temperature for Well NP-1.

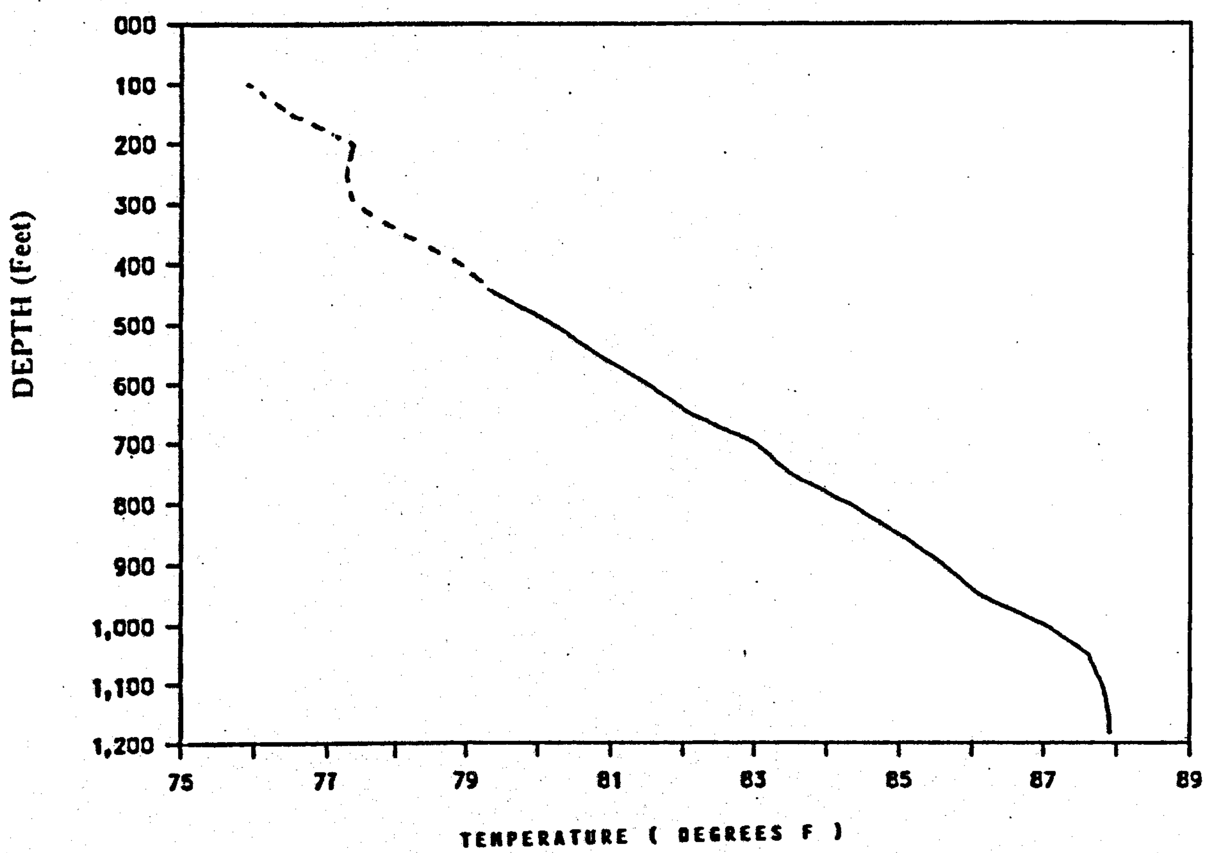


Figure 4-5. Temperature-depth profile for Well NP-1. These data were collected from the mud-filled open hole prior to the well being completed.

positive temperature gradient from the ground surface to total depth (see Table 4-1 and Figure 4-6).

From the measured water surface at 315 feet to a depth of 1,000 feet, the average temperature gradient is 2.15$^{o}$F/100-ft, which is slightly above normal. Below 1,000 feet, the gradient increased sharply to a range of 11.5 to 16$^{o}$F/100-ft, suggesting a convective source may exist near bedrock contact.

4.1.4 Heat-Flow Data

Drill cuttings were grouped into ten representative zones for an evaluation of thermal conductivity. Using a quartering method, samples extracted from the grouped cuttings were measured for thermal conductivity at Southern Methodist University (see Table 4-2).

The thermal conductivity, temperature-gradient, and, thus, the computed heat-flow values are relatively low in the interval from 50 to 280 meters (164 to 918 ft). This interval contains 70 percent clays, alternating with sand layers.

From 280 meters (920 ft) to bedrock contact (i.e., ~ 322 m), the formation consists of 85 percent sand and well-sorted and graded gravel. Thermal-conductivity values generally are higher in these zones as are heat-flow values. The limestone bedrock below 322 meters has an unusually low thermal conductivity, which suggests the limestone has been significantly altered. The geophysical logs indicate that this interval contains several thin zones of probable sandy shale, perhaps accounting for the low thermal conductivity.

Table 4-1. Temperature-depth data for Well NP-1.

| Depth* (ft) | Temperature (°F) | Depth* (ft) | Temperature (°F) |
|---|---|---|---|
| 315 | 74.1 | 680 | 79.2 |
| 320 | 74.3 | 690 | 79.2 |
| 330 | 74.3 | 700 | 79.2 |
| 340 | 74.4 | 710 | 79.3 |
| 350 | 74.6 | 720 | 79.3 |
| 360 | 74.7 | 730 | 79.5 |
| 370 | 74.7 | 740 | 79.6 |
| 380 | 74.8 | 750 | 79.7 |
| 390 | 74.9 | 760 | 79.8 |
| 400 | 75.1 | 770 | 79.8 |
| 410 | 75.2 | 780 | 79.9 |
| 420 | 75.3 | 790 | 79.9 |
| 430 | 75.4 | 800 | 80.0 |
| 440 | 75.7 | 810 | 80.1 |
| 450 | 75.9 | 820 | 80.1 |
| 460 | 76.0 | 830 | 80.3 |
| 470 | 76.0 | 840 | 80.3 |
| 480 | 76.1 | 850 | 80.5 |
| 490 | 76.2 | 860 | 80.6 |
| 500 | 76.3 | 870 | 80.9 |
| 510 | 76.5 | 880 | 81.2 |
| 520 | 76.9 | 890 | 81.2 |
| 530 | 76.9 | 900 | 81.2 |
| 540 | 76.9 | 910 | 81.2 |
| 550 | 77.2 | 920 | 81.4 |
| 560 | 77.5 | 930 | 81.4 |
| 570 | 77.8 | 940 | 81.7 |
| 580 | 78.1 | 950 | 82.4 |
| 590 | 77.8 | 960 | 82.8 |
| 600 | 78.0 | 970 | 83.2 |
| 610 | 78.0 | 980 | 83.5 |
| 620 | 78.4 | 990 | 84.1 |
| 630 | 78.6 | 1,000 | 84.8 |
| 640 | 78.7 | 1,010 | 86.3 |
| 650 | 78.9 | 1,020 | 87.6 |
| 660 | 78.9 | 1,030 | 89.2 |
| 670 | 79.1 | 1,040 | 90.8 |
| | | 1,050 | 91.9 |

* The depth data are referenced to the ground surface. The depth to water in the well was approximately 315 ft. Measurements were taken 18 days after the conclusion of a 37-hr flow test.

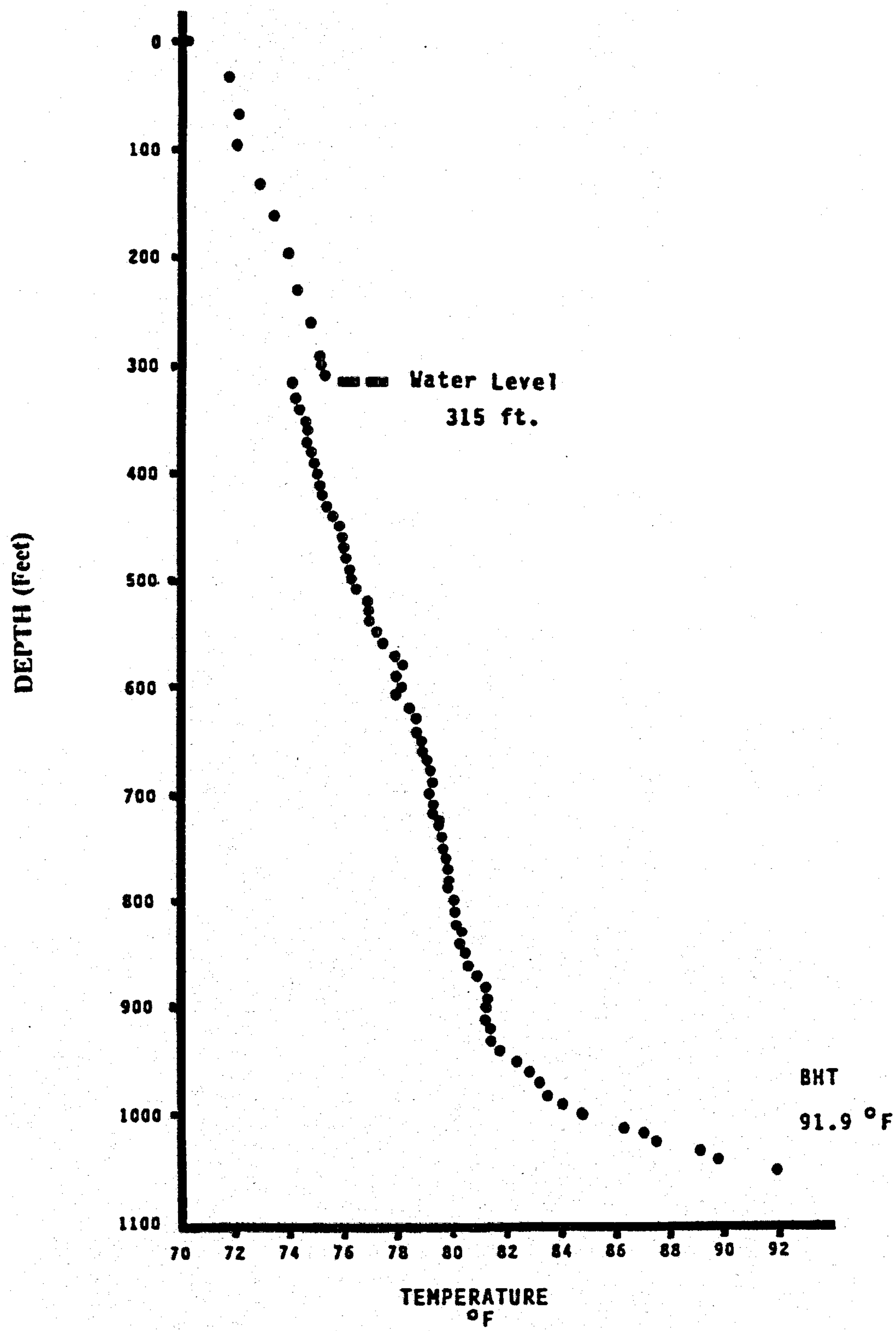


Figure 4-6. Temperature-depth plot for Well NP-1.

Table 4-2. Measured thermal-conductivity, measured temperature-gradient, and computed heat-flow values for Well NP-1.

| Depth Interval (m) | Thermal Conductivity ($W/m-^{o}K$) | Temperature Gradient ($^{o}C/km$) | Heat Flow ($mW/m^2$) | Heat Flow (HFU)* |
|---|---|---|---|---|
| 50 to 60 | 1.87 | 27.8 | 52.0 | 1.2 |
| 96 to 120 | 1.80 | 20.9 | 37.6 | 0.9 |
| 140 to 165 | 2.10 | 20.0 | 42.0 | 1.0 |
| 210 to 225 | 1.92 | 14.8 | 28.4 | 0.7 |
| 230 to 280 | 2.47 | 17.8 | 44.0 | 1.1 |
| 290 to 295** | 2.54 | 77.8 | 197.6 | 4.7 |
| 305 to 317** | 2.57 | 277.8 | 713.9 | 17.1 |
| 325 to 340 | 2.38 | isothermal | — | — |
| 325 to 350 | 2.43 | isothermal | — | — |
| 355 to 358 | 2.32 | isothermal | — | — |

* 1 HFU = 41.8 $mW/m^2$.

** This zone is disturbed, possibly by lateral water movement.

Heat flow in the interval from 290 to 295 meters (950 to 965 ft) is 4.7 HFU, which is in general agreement with the reported average value of 3.1 HFU for 18 drill holes in the Jarilla Mountains (Decker and Smithson, 1975). For the interval from 305 to 317 meters (1,000 to 1,040 ft), heat flow is 17.1 HFU, which is far above the accepted value of 2.0 HFU for conductive heat flow in the Rio Grande rift (Muffler, 1979). This sharply elevated heat flow suggests a highly disturbed zone centered at 311 meters (1,020 ft). This zone is characterized by the nuclear logs as one of lateral water movement. Possibly, the heat-flow values are reflecting a warmer source to the east, rising through a fault conduit, and water movement above the limestone bedrock which probably dips to the west.

#### 4.1.5 Geothermometry

Three water sample analyses were used to estimate potential reservoir temperatures by geothermometry. Computed temperatures for a variety of geothermometers are given in Table 4-3.

Because Well NP-1 as completed contains 110 lineal feet of screened sections allowing water to enter the well bore from many different horizons, the pumped water samples are blended and mixed flows. Furthermore, the zone just above bedrock contact seems to exhibit lateral water movement, suggesting mixing is occurring at depth. Consequently, the geothermometer values are unlikely to be representative of the ultimate reservoir temperature. The elevated calcium and magnesium concentrations make the sodium/potassium geothermometer unreliable. If an accurate mixing ratio could be determined, the silica geothermometer

Table 4-3. Geothermometry data for water samples collected from Well NP-1.

| Geothermometer | Temperature (°F) | | |
|---|---|---|---|
| | Sample A[a] | Sample B[a] | Sample C[a] |
| Conductive quartz[b] | 170.9 | 170.6 | 173.9 |
| Adiabatic quartz[b] | 177.9 | 177.7 | 180.6 |
| Chalcedony[b] | 114.3 | 144.0 | 117.5 |
| Average silica[b] | 108.1 | 107.9 | 111.0 |
| Sodium/potassium[c] | 111.8 | 135.6 | 139.5 |

[a]Sample A was jetted from a depth of 1,030 ft. Samples B and C were taken at the conclusion of the step drawdown and constant flow rate pump tests, respectively.

[b]The source of this geothermometer is Fournier and others (1974).

[c]The source of this geothermometer is Truesdell (1975).

meter should be the most accurate estimate of the reservoir temperature.

#### 4.1.6 Interpretations of the Thermal Data

Although the measured temperature of Well NP-1 was only moderately warm, the temperature was abnormally high relative to that of nearby water wells. The positive temperature gradient is strongly suggestive of a much warmer geothermal source. This conclusion is reinforced by the geothermometry data. The presence of shallow groundwaters, presumably nonthermal, results in a strong cooling tendency in the shallower portions of Well NP-1. Considerable mixing of thermal and nonthermal waters is possible. With a continuous gravel pack in the well annulus, waters are probably entering the well screen at several different strata. Without knowledge of the yield of the various water-bearing strata, precise mixing models cannot be developed.

### 4.2 Water-Quality Data

Water samples were acquired using standard procedures during the jetting operation from the zone at 1,030 feet of depth and at the conclusion of the step drawdown and constant flow rate tests. Chemical analyses of these samples are given in Table 4-4. The two pumped water samples are noticeably less saline than the jetted sample, although Well NP-1 water is in the very saline range of 10,000 to 35,000 milligrams per liter of total dissolved solids. Chloride concentration is somewhat lower, and sodium, calcium, magnesium, and sulfate concentrations are substantially lower, in the pumped samples than the jetted sample.

Table 4-4. Water-chemistry analyses for samples from Well NP-1.

| Parameter | Chemical Concentration (mg/l) Sample A* | Sample B* | Sample C* |
|---|---|---|---|
| Na | 5,776 | 4,420.9 | 4,141.8 |
| K | 25.8 | 28.1 | 27.8 |
| $CaCO_3$ | 4,748 | 2,653 | 2,374 |
| Ca | 1,253.5 | 801.6 | 760.5 |
| Mg | 394.1 | 158.7 | 115.9 |
| Fe | 0.21 | < 0.05 | < 0.05 |
| Mn | 0.45 | 0.43 | 0.44 |
| Cl | 4,486.2 | 4,346.2 | 3,918.1 |
| F | 1.11 | 1.12 | 1.09 |
| $NO_3$ | - | 0.01 | < 0.01 |
| $HCO_3$ | 109.8 | 97.6 | 96.4 |
| $SO_4$ | 9,329 | 5,253 | 5,071 |
| As | 0.014 | 0.08 | 0.086 |
| Ba | 0.02 | 0.01 | < 0.01 |
| Cd | 0.011 | < 0.005 | < 0.005 |
| Cr | < 0.02 | < 0.02 | < 0.02 |
| Pb | 0.009 | < 0.005 | < 0.005 |
| Hg | < 0.0002 | < 0.0002 | < 0.0002 |
| Se | < 0.001 | 0.002 | < 0.001 |
| Ag | < 0.02 | < 0.02 | < 0.02 |
| B | - | 0.74 | 2.13 |
| $SiO_2$ | 28.4 | 28.3 | 29.6 |
| TDS | 21,404 | 15,147 | 14,165 |
| pH | 7.66 | 7.66 | 7.64 |

* Sample A was jetted from a depth of 1,030 ft. Samples B and C were taken at the conclusion of the step drawdown and constant flow rate pump tests, respectively.

## 4.3 Comparisons with Other Wells in the Tularosa Basin

The central and eastern portions of the Tularosa Basin are shown in Figure 4-7, with the locations of selected test and water wells identified. Temperature, water-table depth, and water-chemistry data have been published for many of these wells (Cooper, 1973; Kelly, 1973; Cunniff and Swanberg, 1980). All of these wells were completed in basin fill.

### 4.3.1 Temperature Data

Well NP-1 is significantly warmer than other water wells at White Sands Missile Range (WSMR). At comparable depths, production well waters have an average temperature of 69.5°F. Only a few of the deepest test wells show elevated temperatures. The Gregg test water well had a measured temperature of 78.8°F at a depth comparable to that of Well NP-1. The warmest test well at WSMR was T-14, drilled to a depth of 6,015 feet, with a measured bottom-hole temperature of 196°F. Well T-14 was noticeably cooler at shallower depths; for example, at 3,700 feet, the reported temperature was 84.9°F. Approximately 20 miles north of Well NP-1, several deep oil and gas wildcat wells were drilled to the east of the WSMR boundary. The highest recorded temperature was 240°F in the depth interval from approximately 6,000 feet to total depth of 7,660 feet. Temperature comparisons of the test wells, wildcat wells, and Well NP-1 are given in Table 4-5.

Two shallow test wells, Collins T-1 (T26S, R7E, Section 1) and T-2 (T26S, R8E, Section 2) were drilled in the southern part of the Tularosa Basin, about 5 miles south of Well NP-1. Collins

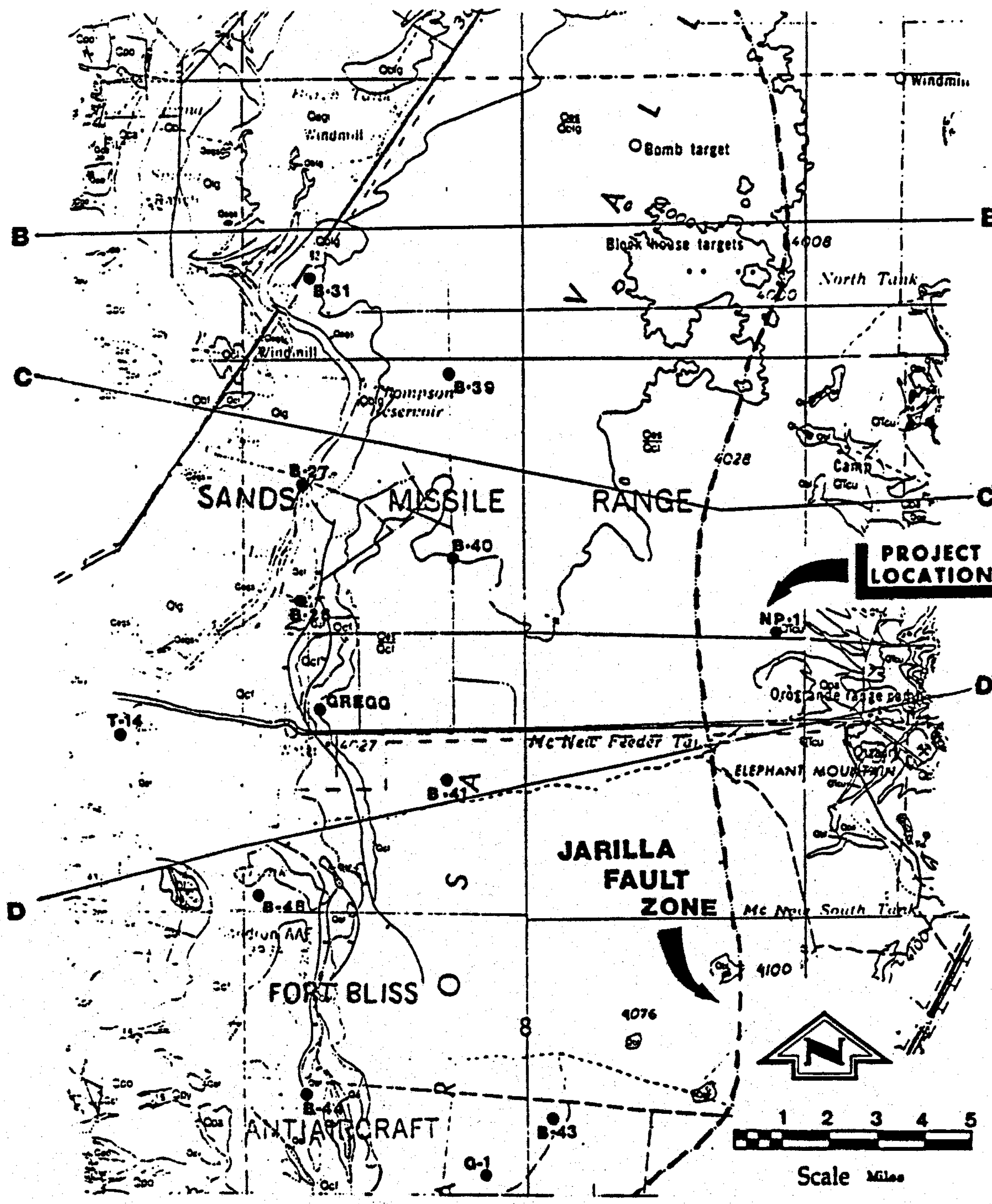


Figure 4-7. Location map for selected production water wells and test wells in the southern Tularosa Basin.

Table 4-5. Temperature comparisons for wells in the Tularosa Basin.

| Well* | Location | Depth (ft) | Peak Temperature (°F) | Basin Fill Thickness (ft) | Bottom Formation |
|---|---|---|---|---|---|
| Gregg | 22S.6E.08.414 | 1,010 | 79 | 1,010 | Basin fill |
| T-14 | 22S.5E.15.221 | 6,015 | 196 | 6,015 | Basil fill |
| Texaco No. 1-G | 18S.8E.33.232 | 7,660 | 240 | 23 | Paleozoic |
| Texaco No. 1-E | 18S.8E.10.330 | 7,785 | 215 | 25 | Paleozoic |
| Garton | 18S.8E.05.431 | 989 | 97 | 783 | Paleozoic |
| NP-1 | 21S.7E.36.344 | 1,176 | 92 | 1,056 | Paleozoic |



* The Gregg and T-14 wells are test wells. The Texaco wells and the Garton well are oil and gas wildcat wells. The sources of the data are as follows: Gregg (Cooper, 1973); T-14 (Doty and Cooper, 1970); and Garton (McLean, 1970). The data for the Texaco wells are extracted from well logs.

T-1 was sited near a surface expression of the Jarilla Fault, while Collins T-2 was drilled about 5 miles to the east on the upthrown side of the fault. Collins T-1 displayed a mud temperature of 128°F at a depth of 507 feet; T-2 was noticeably cooler, with a maximum temperature of 78°F at 731 feet of depth.

Temperature data from the Collins wells and the deep oil and gas wildcat wells suggest that a cooling trend is observed in drill holes completed to the east of the Jarilla Fault Zone. Since Well NP-1 was sited on the eastern or upthrown side of the fault, the somewhat cool temperature could be further evidence of this trend.

4.3.2 Water Chemistry

A Piper diagram of the principal anions and cations from the WSMR Post Headquarters main well field, with values from Well NP-1 included, is given in Figure 4-8. This plot clearly shows that the waters from Well NP-1 are distinct from the Post Headquarters well field. Water-chemistry data for selected wells shown in Figure 4-7 are given in Table 4-6. These wells are 7 miles or more west of Well NP-1.

4.3.3 Groundwater Level

Based on electric logs acquired from Well NP-1, the depth to the water table was determined to be 250 feet. From ground surface to almost 900 feet, the formation material consisted predominantly of clays with thin gravel lenses. This formation is typical of the playas encountered in other WSMR test wells. The playa material is a poor water source. Specific yields are as low as 1 gpm per foot of drawdown, with transmissibilities as

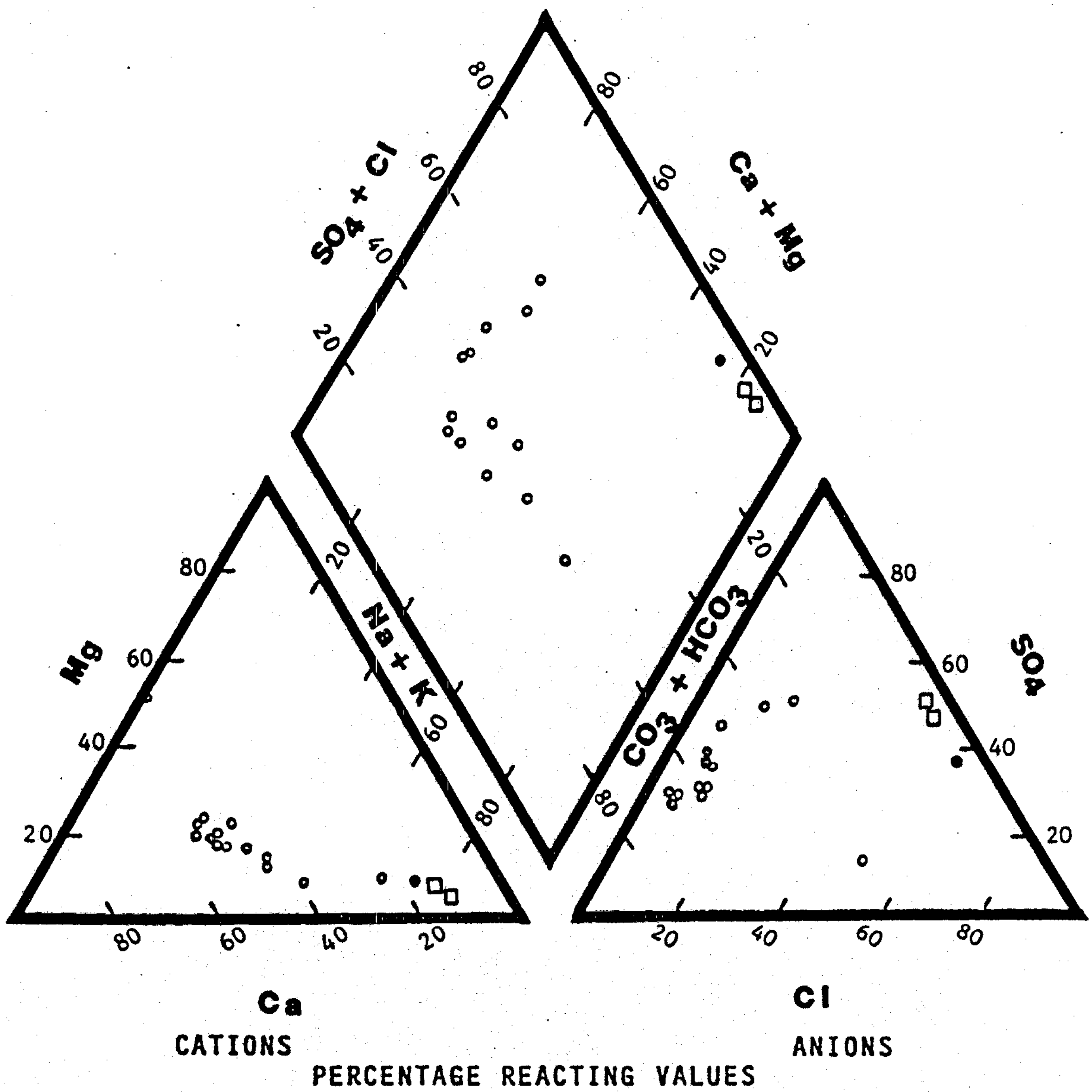


Figure 4-8. Piper diagram for Well NP-1 water [jetted sample (●) and pumped samples (□)] and production wells (o) for the Post Headquarters at White Sands Missile Range. The data for the production wells are taken from Kelly and Hearne (1976).

Table 4-6. Water-chemistry analyses for samples from selected wells in the Tularosa Basin. The locations for these wells are given in Figure 4-7.

| Well* | Chemical Concentration (mg/l) Na & K | Ca | Mg | Cl | $NO_3$ | $SO_4$ | F | $SiO_2$ | TDS | pH | Approximate Sample Depth (ft) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NP-1 | 5,802 | 1,254 | 394 | 4,486 | 0.01 | 9,329 | 1.1 | 28.4 | 21,404 | 7.7 | 1,030 |
| Gregg | 3,340 | 455 | 478 | 708 | 0.3 | 8,730 | 6.4 | 40 | 13,900 | 7.4 | 1,010 |
| T-14 | 41,400 | 1,660 | 792 | 66,000 | 14 | 1,960 | 0.7 | 17 | 112,000 | 6.7 | 3,150 |
| B-26 | 977 | 210 | 120 | 86 | 0.7 | 2,800 | 1.3 | 26 | 4,350 | 7.9 | 180 |
| B-27 | 1,242 | 270 | 150 | 87 | 1.4 | 3,300 | 1.1 | 26 | 5,220 | 8.0 | 165 |
| B-31 | 25,460 | 610 | 8,000 | 29,000 | 0.02 | 30,000 | 1.7 | 20 | 90,500 | 7.6 | 180 |
| B-38 | 2,011 | 560 | 300 | 1,700 | 2.8 | 3,900 | 1.6 | 21 | 8,640 | 7.7 | 190 |
| B-39 | 2,611 | 1,100 | 630 | 5,800 | 5.7 | 2,400 | 0.5 | 21 | 12,800 | 7.5 | 165 |
| B-44 | 147 | 67 | 19 | 53 | 0.46 | 130 | 0.9 | 30 | 664 | 7.9 | 240 |

* The sources of the data are as follows: Gregg (Cooper, 1973); T-14 (Doty and Cooper, 1970); B-26 through B-44 (Cooper, 1973).

low as 1.2 gallons per day per square foot (Henry and Cluck, 1981).

The temperature survey for Well NP-1 indicated a static water level of 315 feet. The fact that the static water level in Well NP-1 is significantly lower than the apparent depth to the water table could imply that vertical permeability is very low and that the potential water-bearing strata centered at about 445 feet of depth, which was screened, is not a good producing zone. The massive clay deposits could have infiltrated the gravel pack blocking communication in the well annulus from the surface to below 800 feet of depth.

Table 4-7 gives the static water level and depth to the water table for the wells shown in Figure 4-7. Comparison of the data in Table 4-7 shows that the groundwater level slopes downward from west to east and from north to south in the basin. For example, between the Gregg well and Well B-40, the groundwater level drops 17.3 feet. Similarly, between Wells B-39 and B-40, the groundwater level drops 15.2 feet.

Perhaps the lower static water level in Well NP-1 merely reflects the normal west to east drop in the groundwater level. The groundwater level possibly should rise as bedrock slopes upward towards the Jarilla Mountains from the central basin. Under this conjecture, the water level in Well NP-1 would be expected to be higher than in Well B-40, located 7 miles to the west. Instead, the water level in Well NP-1 is almost 33 feet lower than in Well B-40.

Table 4-7. Static water level and depth to the water table for selected wells in the Tularosa Basin.

| Well | Location | Static Water Level* (ft) | Depth to the Water Table (ft) |
|---|---|---|---|
| NP-1 | 21S.7E.36.344 | 3,780.5 | 315.0 |
| Gregg | 22S.6E.08.414 | 3.830.7 | 214.3 |
| B-26 | 21S.6E.32.114 | 3,818.3 | 141.3 |
| B-27 | 21S.6E.17.314 | 3,825.9 | 119.9 |
| B-31 | 20S.6E.29.123 | 3,840.6 | 123.4 |
| B-38 | 22S.6E.11.234 | 3.854.2 | 129.9 |
| B-39 | 21S.6E.02.142 | 3,828.6 | 156.4 |
| B-40 | 22S.6E.26.142 | 3.813.4 | 188.6 |
| B-41 | 22S.6E.23.213 | - | dry |
| B-43 | 23S.7E.30.122 | - | dry |
| B-44 | 23S.6E.20.332 | 3,775.5 | 196.5 |
| B-48 | 22S.6E.31.322 | 3,802.4 | 204.6 |
| G-1 | 23S.6E.35.100 | 3,793.2 | 287.5 |

* The static water level is referenced to mean sea level. The sources of the data are as follows: Gregg (Cooper, 1973); B-26 through B-48 (Cooper, 1973); and G-1 (Cruz, 1985).

If the water level in Well NP-1 is anomalously low, this condition could confirm another feature of the Jarilla Fault Zone, namely, that the fault serves as an aquitard. As reported by Henry and Cluck (1981) for wells in the southern part of the Tularosa Basin, the Jarilla Fault serves to separate the basin water from the groundwater to the east, and a distinct water level trough exists on the eastern side of the basin. Groundwater levels to the east, on the upthrown side of the Jarilla Fault, range from 70 to 100 feet lower than the levels to the west.

## 4.4 Geologic Cross Sections

Based on work performed by King and Harder (1982), the eastern basin-bounding feature is believed to be the Jarilla Fault Zone, at least in the middle to southern part of the Tularosa Basin. According to King and Harder (1982), the Otero Platform is a distinct physiographic unit, upthrown and separate from the Tularosa Basin, with the Jarilla Fault Zone serving as the dividing line. In comparison with the large amount of geophysical work undertaken to define the western basin boundary, the eastern boundary is almost completely unmapped. Using early and somewhat sparse gravity data (Seager, 1980), and information from the limited number of deep oil test wells, cross sections of the Tularosa Basin from the Organ Mountains to the Jarilla Fault Zone have been developed (King and Harder, 1982). The consensus is that the Jarilla Fault Zone is a major structural control for the eastern boundary. The temperature data, water-chemistry, and hydrology information compiled as part of the assessment of Well NP-1 also suggest that the Jarilla Fault Zone may control geothermal production.

Possible geologic cross sections of the Tularosa Basin in vicinity of Well NP-1 are shown in Figure 4-9 (Seager and others, 1987). Cross section C-C' depicts the probable bedrock at about 850 feet in the vicinity of Well NP-1. Since bedrock was confirmed at 1,056 feet, these cross sections can be considered only approximations of the likely subsurface structure. The location for the Jarilla Fault is based on an interpretation of gravity data collected at stations one or more miles apart (Seager and others, 1987). The Jarilla Fault Zone is shown as the center of the gravity low so the fault could be located anywhere within one mile of the depicted strike (Seager, 1987).

Well NP-1 is shown on the upthrown side of the likely strike of the Jarilla Fault Zone. Depth to bedrock data from the drilling operations confirm that the major vertical displacement of the fault is located to the west of the well. A well located at or near the fault likely would show more positive geothermal indications.

Overall vertical displacement along the Jarilla Fault could be as much as 6,300 feet (King and Harder, 1982). About 1,000 feet of that displacement possibly can be accounted for by the depth to bed-rock in Well NP-1. Even though there is 1,000 feet of vertical displacement to limestone contact between the Texaco wells and Well NP-1, the true geologic displacement could be

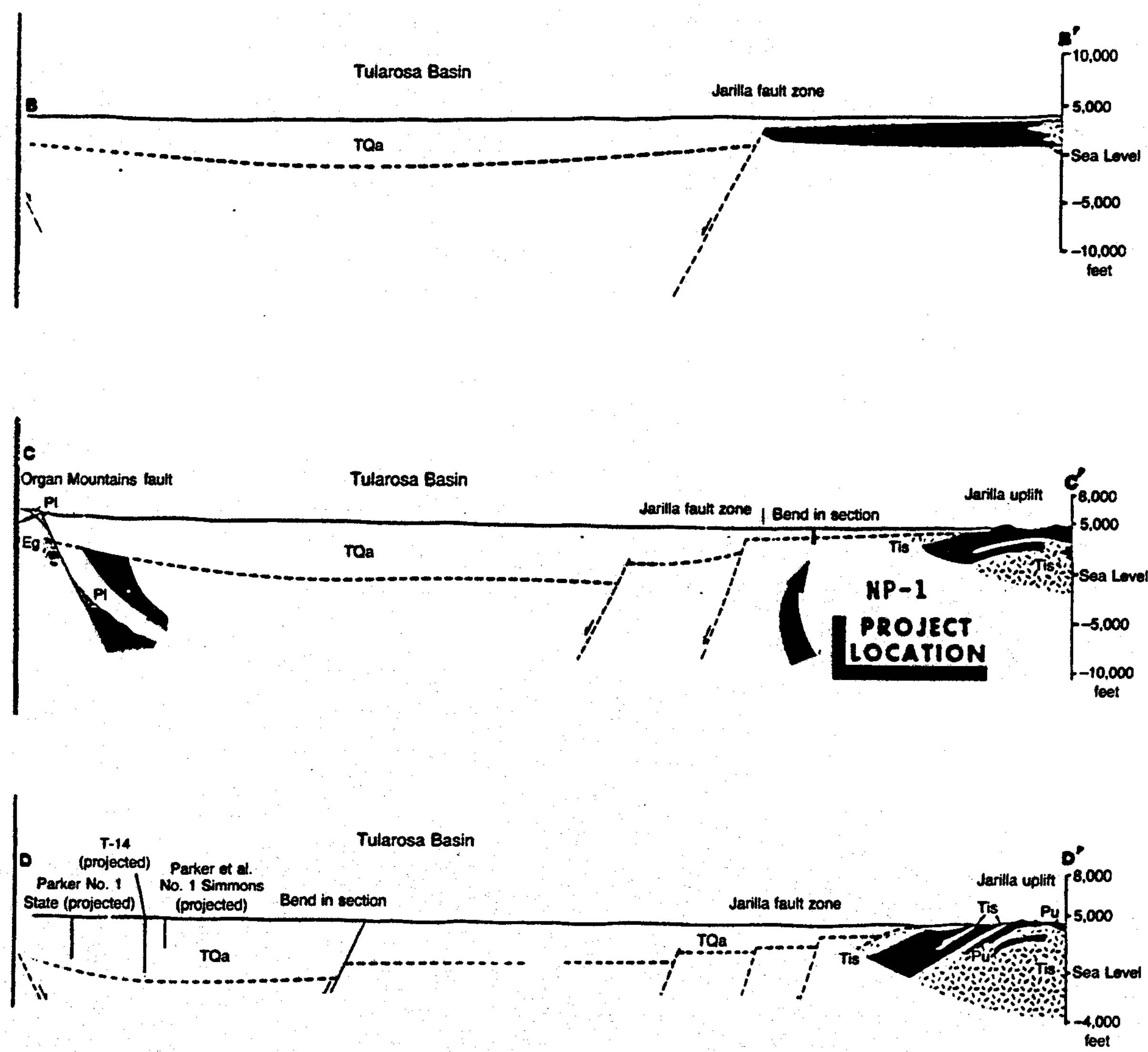


Figure 4-9. Possible geologic cross sections of the Tularosa Basin near Well NP-1. These cross sections are labeled on Figure 4-7. The data are adapted from Seager and others (1987).

vastly different depending on erosion and other factors. However, vertical displacement of at least an additional 5,000 feet exists somewhere to the west of Well NP-1. A single major displacement of 5,000 feet could exist, but the gravity data suggest that en echelon downthrown fault blocks are more likely. The western basin-bounding fault in the vicinity of the WSMR Post Headquarters has been mapped by reflection seismic surveys (Cooper, 1973; Kelly, 1973), which indicate that this fault has an en echelon downthrown structure.

The western basin-bounding fault is active (Seager and others, 1987), with a total vertical displacement of more than 12,000 feet in the vicinity of the Post Headquarters. At least 6,000 feet of this vertical movement was defined by the drilling of test Well T-14, which bottomed at 6,015 feet in basin fill. The remainder of the total displacement is represented by the uplifted Organ Mountain complex adjacent to the Post Headquarters.

Since the western basin-bounding fault is young and active, the Jarilla Fault Zone also might have experienced episodes of relatively recent movement. At the Jarilla Mountains, there is no surface indication of recent activity similar to the faulted fan surfaces at the western margin. Further to the south in the basin, a series of minor antithetic faults and rifts, which are younger Quaternary faults related to the basin-bounding faults, are present near the Texas-New Mexico border (Seager, 1980).

## 4.5 Concluding Remarks

Data from Well NP-1, together with the limited data from other deep exploratory wells, suggest that a very large, low-temperature thermal anomaly exists in the eastern Tularosa Basin. This anomaly possibly is structurally controlled by the Jarilla Fault, but present data do not permit an accurate mapping of the fault. Drilling activities have been so limited that there can be only speculation as to the nature and extent of the potential geothermal resource. Additional geophysical work including gravity and reflection seismic surveys are needed in order to more accurately delineate the Jarilla Fault. Subsequent temperature-gradient holes could then help define the geothermal resource potential.

Coordination with the Huntsville District of the U.S. Army Corps of Engineers suggests that the planned future series of test borings may enable siting of selected test holes and completion of some of the deeper tests as temperature-gradient holes. Two locations along the possible strike of the fault are easy to access by vehicle. The most accessible locale is along a paved road, where gravity data (Seager and others, 1987) suggest the fault is a series of en echelon downthrown blocks. The second area is to the northwest of Well NP-1, where a power line road runs east and west almost orthogonal to the fault.

## 4.6 References

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# APPENDIX A

## Lithology for Well NP-1
## (U.S. Army Corps of Engineers, 1987)

Table A4-1. Lithology of Well NP-1.

| Depth Interval (ft) | Description |
|---|---|
| 0 to 70 | Sand, very fine grained to fine grained with clay, minor silt, and uncemented caliche |
| 70 to 110 | Clay with fine-grained sands and minor uncemented caliche |
| 110 to 145 | Clay, with minor uncemented caliche |
| 145 to 168 | Sand, very fine grained to fine grained with minor clay, silt, and uncemented caliche |
| 168 to 185 | Clay, with fine-grained sands and minor caliche |
| 185 to 189 | Sand, very fine grained to fine grained |
| 189 to 190 | Clay, with fine-grained sands |
| 190 to 202 | Sand, very fine grained to fine grained |
| 202 to 210 | Clay, with very fine-grained sands and minor uncemented caliche |
| 210 to 214 | Sand, very fine grained to fine grained |
| 214 to 228 | Clay, with very fine-grained sands |
| 228 to 259 | Sand, very fine grained to fine grained |
| 259 to 271 | Clay, with minor fine-grained sands |
| 271 to 273 | Sand, fine grained with minor clay and caliche |
| 273 to 276 | Clay, with minor fine-grained sands |
| 276 to 278 | Sand, very fine grained to fine grained with minor clay |
| 278 to 281 | Clay, with minor fine-grained sands |
| 281 to 287 | Sand, very fine grained to fine grained |
| 287 to 291 | Clay, with minor fine-grained sands |
| 291 to 297 | Sand, very fine grained with minor clay and caliche |

Table A4-1. Continued.

| Depth Interval (ft) | Description |
|---|---|
| 297 to 318 | Clay, with minor fine-grained sands and caliche |
| 318 to 321 | Silt, with minor clay and very fine-grained sands |
| 321 to 327 | Clay, with very fine-grained sands |
| 327 to 329 | Sand, very fine grained with minor clay and silt |
| 329 to 334 | Clay, with minor very fine-grained sands |
| 334 to 347 | Sand, very fine grained to fine grained with minor silt |
| 347 to 366 | Clay, with minor silt and uncemented caliche |
| 366 to 367 | Sand, very fine grained to fine grained |
| 367 to 369 | Clay, with very fine-grained sands and minor caliche |
| 369 to 372 | Sand, very fine grained to fine grained with minor caliche |
| 372 to 376 | Clay, with minor very fine-grained sands and caliche |
| 376 to 378 | Sand, very fine grained to fine grained |
| 378 to 380 | Clay, with minor fine-grained sands and caliche |
| 380 to 382 | Sand, very fine grained to fine grained with minor clay |
| 382 to 385 | Clay, with minor fine-grained sands |
| 385 to 388 | Sand, very fine grained to fine grained |
| 388 to 396 | Clay, with minor fine-grained sands |
| 396 to 398 | Sand, fine grained with minor clay |
| 398 to 423 | Clay, with minor fine-grained sands |
| 423 to 452 | Sand, very fine grained to fine grained |

Table A4-1. Continued.

| Depth Interval (ft) | Description |
|---|---|
| 452 to 460 | Clay, with minor very fine-grained sands |
| 460 to 461 | Sand, very fine grained with minor clay |
| 461 to 472 | Clay, with minor fine-grained sands |
| 472 to 488 | Sand, with minor clay |
| 488 to 490 | Clay, with minor fine-grained sands |
| 490 to 492 | Sand, very fine grained with minor clay and uncemented caliche |
| 492 to 502 | Clay, with minor fine-grained sands |
| 502 to 506 | Sand, very fine grained with minor clay and uncemented caliche |
| 506 to 540 | Clay, with minor very fine-grained to fine-grained sands |
| 540 to 552 | Sand, very fine grained with minor clay and caliche |
| 552 to 575 | Clay, with very fine-grained sands and minor silt |
| 575 to 584 | Sand, with minor clays |
| 584 to 595 | Clay, with very fine-grained sands |
| 595 to 602 | Sand, very fine grained to fine grained |
| 602 to 604 | Clay, with minor fine-grained sands and minor uncemented caliche |
| 604 to 605 | Sand, very fine grained to fine grained |
| 605 to 608 | Clay, with minor fine-grained sands and minor uncemented caliche |
| 608 to 612 | Sand, very fine grained to fine grained |
| 612 to 670 | Clay, with very fine-grained to fine-grained sands |
| 670 to 702 | Sand, very fine grained to fine grained, silty |

Table A4-1. Continued.

| Depth Interval (ft) | Description |
|---|---|
| 702 to 710 | Clay, with very fine-grained to fine-grained sands |
| 710 to 763 | Clay, with very fine-grained to fine-grained to medium-grained sands, uncemented caliche |
| 763 to 770 | Sand, very fine grained variable to coarse grained, abundant clay |
| 770 to 783 | Clay, with very fine-grained to fine-grained sands, minor caliche and trace granules |
| 783 to 785 | Sand, very fine grained to fine grained |
| 785 to 787 | Clay, with very fine-grained sands |
| 787 to 797 | Sand, very fine grained to medium grained, trace caliche, lithic cemented sands with trace coarse-grain sands to granules |
| 797 to 818 | Clay, abundant fine-grained to coarse-grained sands, lithic fragments |
| 818 to 823 | Sand, very fine grained to medium grained to some coarse grained, granules to pebbles to 8-mm lithic fragments |
| 823 to 834 | Clay, with very fine-grained sands, some medium- to coarse-grained sands, granules to pebbles |
| 834 to 835 | Sand, very fine grained to coarse grained |
| 835 to 858 | Clay, with fine-grained sands, trace granules to pebbles to 7-mm lithic fragments |
| 858 to 861 | Sand, very fine grained to fine grained to coarse grained |
| 861 to 875 | Clay, with minor fine-grained sands, some coarse-grained sands to pebbles to 6 mm |
| 875 to 893 | Silt, with fine- to medium- to coarse-grained sands, trace pebbles to 6 mm |
| 893 to 897 | Sand, very coarse grained to granules, trace of caliche and caliche cemented sands |

Table A4-1. Continued.

| Depth Interval (ft) | Description |
| --- | --- |
| 897 to 915 | Clay to silt, with minor fine-grained sands, some very coarse-grained sands to granules, trace caliche and caliche cemented sands |
| 915 to 919 | Sand, very coarse grained to granules |
| 919 to 925 | Silt to fine-grained sand, with medium-grained sands to pebbles to 7-mm lithic fragments, minor clay |
| 925 to 926 | Sand, very coarse grained to granules |
| 926 to 927 | Silt to fine-grained sand, with medium-grained sands to pebbles, lithic fragments, minor clay |
| 927 to 928 | Sand, fine grained to medium grained to coarse grained to granules |
| 928 to 942 | Silt to coarse-grained sands to granules, with pebbles to 11 mm |
| 942 to 950 | Sand, very fine grained to coarse grained to granules to pebbles to 6-mm lithic fragments |
| 950 to 954 | Silt to coarse-grained sands to granules, with pebbles to 7 mm |
| 954 to 1,037 | Sand, very coarse grained to granules, lithic fragments to pebbles to 9-mm inferred heavy gravel zones throughout |
| 1,037 to 1,058 | Clay to coarse-grained sands, with some very coarse-grained sands to grandules, trace pebbles to 5 mm |
| 1,058 to 1,175 | Limestone |