GEOTHERMAL RESOURCE POTENTIAL OF THE TUCSON BASIN, ARIZONA

by

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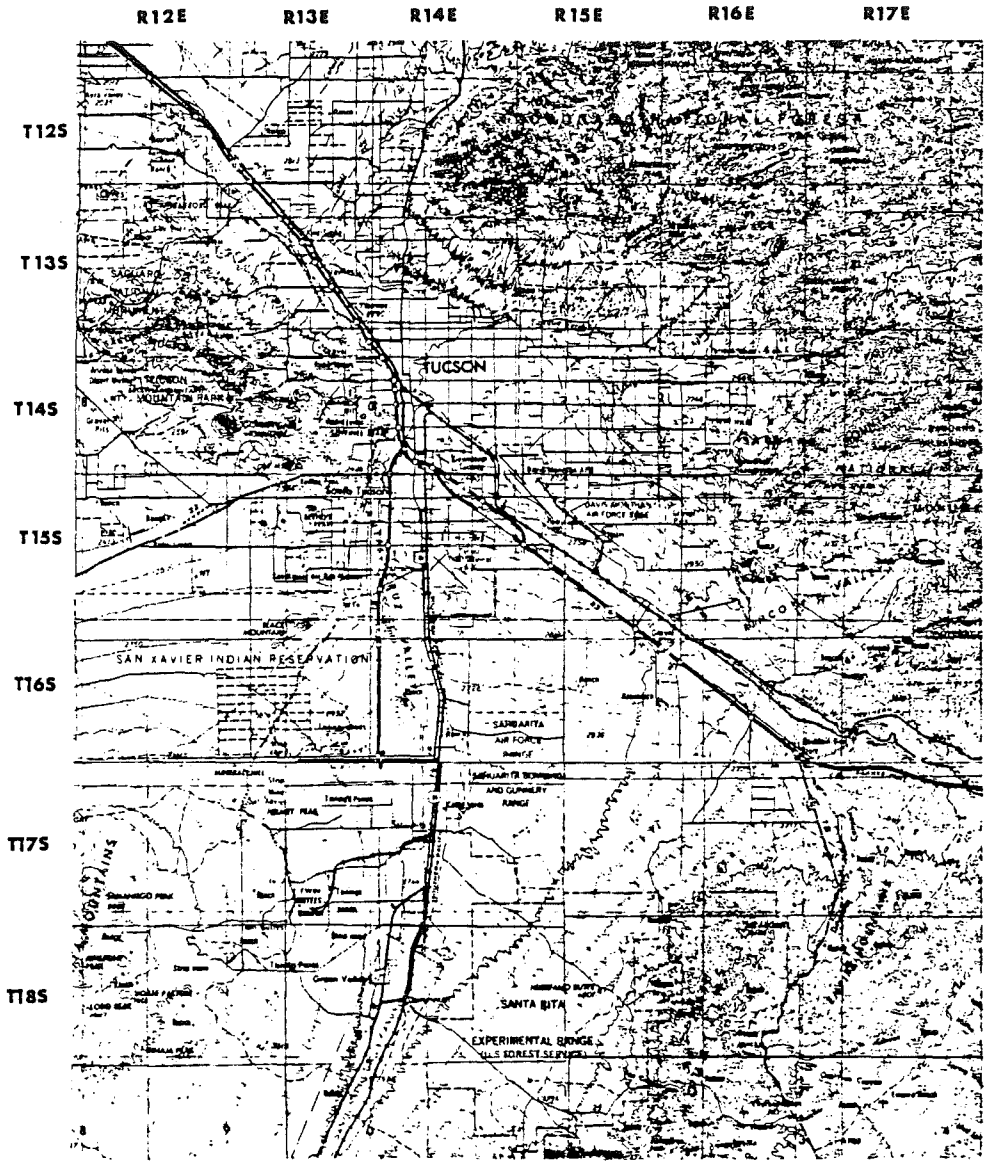
GEOTHERMAL RESOURCE POTENTIAL OF THE TUCSON BASIN

INTRODUCTION. The Tucson basin, located in southeastern Arizona, underlies a rapidly growing metropolitan area. Because of Tucson's rapid growth and because it's economy relies heavily upon the aerospace, agriculture, defense, education, electronics, mining, and tourism industries, significant opportunities exist for direct-heat utilization of geothermal water. Geothermal energy could have economic impact by stabilizing energy costs to resource users.

The purpose of this report is to outline known occurrences of thermal (>30°C) water around Tucson. Identification of the main geologic and geohydrologic features which determine the temperature distribution beneath Tucson provides a basis to formulate geologic models which have use in exploration and evaluation of area resources.

Several factors are required to make geothermal energy economically feasible, the most important of which is the availability of a suitable resource for a desired application. The scope of this study precludes detailed discussion of the economic, engineering, and institutional factors concerning geothermal resource development. This report focuses on potential geothermal resources in a geologic context so that planning and feasibility studies and possible development can proceed. Important questions addressed by this report are: Do potential resources lie beneath land which is favorable for development? What depth is the resource? What production temperatures are likely to be found? What is the probable chemical quality of the geothermal water? What kind of rock acts as the geothermal reservoir? What are the reservoir properties? What are the geologic controls on reservoir permeability and location? What is the geothermal heat source? What is the probable life of the reservoir?



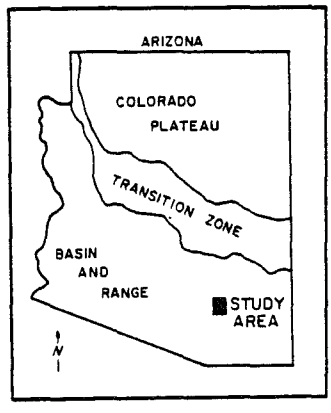


FIGURE 1 Location map of the Tucson basin

Agua Caliente, a thermal (30 to 32°C) spring near Tanque Verde, the discovery of thermal (50 to 57°C) water during water well drilling by Tucson Electric Power (TEP) and a geologically favorable regional setting for geothermal resources target the Tucson basin for geothermal resource investigation.

The Tucson basin, as used in this report, refers to a sediment filled structure. The basin roughly coincides with the Santa Cruz Valley between Green Valley and Rillito. On the surface, the basin is bound by the Tucson, Santa Catalina, Tanque Verde Rincon, Santa Rita, and Sierrita Mountains.

The basin is a three dimensional geologic feature analogous to a "sediment filled and irregularly shaped bathtub." Bedrock, as seen in the surrounding mountains would comprise the "bathtub" walls and bottom. Figure 1 is a location map showing the Tucson basin.

LAND OWNERSHIP. Land ownership in the Tucson basin is predominantly private and state trust land. Private lands predominate in the area north of Interstate 10 and along the Santa Cruz River (fig. 2). State trust land interspersed with private land occurs south of Interstate 10. Both the private and state lands are institutionally suitable for development of geothermal resources by land owners and industry. U.S. National Park land on the basin margins, at the Saquaro National Monuments, is legally exempt from development. Davis Monthan air Force Base is not available for private exploitation of geothermal energy; however, the Department of Defense may have the option to develop this land. Geothermal development on county, municipal, or on the San Xavier Indian Reservation by the private sector may not be institutionally favorable.

PREVIOUS GEOLOGIC STUDIES. Numerous reports are available on the geology and geohydrology of the basin. Studies describing the Cenozoic

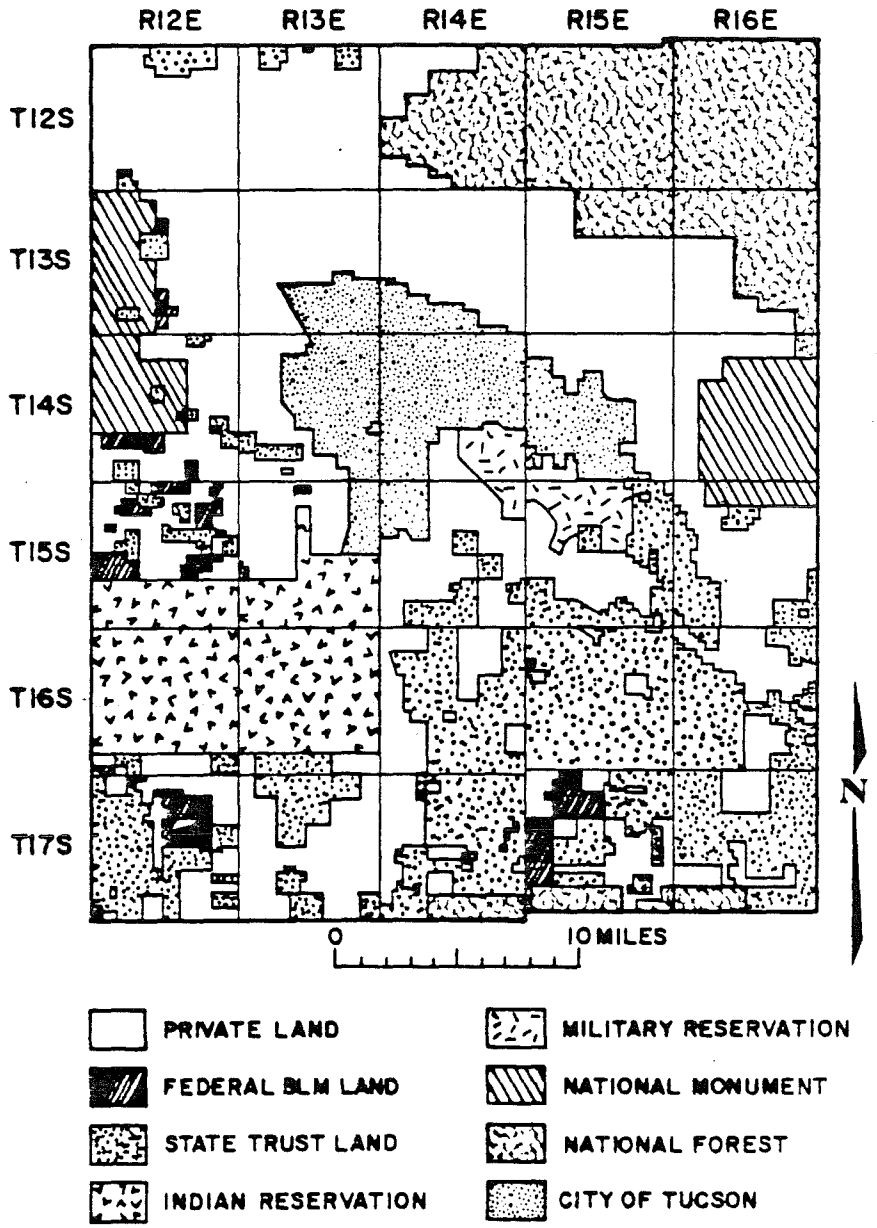


FIGURE 2 Land status map of the Tucson basin

sediments, are of prime importance because these rocks probably have the greatest potential to act as geothermal reservoirs.

Studies in the Tucson basin by Pashley (1966), Davidson (1973), and Gass (1977) provide stratigraphic information on the Cenozoic sediments in the basin. Regional Cenozoic stratigraphy studies by Heindl (1958), Eberly and Stanley (1978), Scarborough and Peirce (1978), and Scarborough and Wilt (1979) point toward a realistic geologic framework from which to interpret the stratigraphy of the Tucson basin.

Geohydrologic study of the Tucson area by Smith (1910) provides baseline data on the area's ground water conditions before development. Schwalen and Shaw (1957), Heindl and White (1965), and Davidson (1973), discuss the geohydrology of the basin and the effects of withdrawal on water-table levels. Geochemical studies by Feldman (1966), Smoor (1967), and Laney (1972) yield additional ensight on the flow paths and define the chemical quality of the shallow ground water in the basin.

Geophysical studies by Davis (1967); Sauck and others (1971), Davis (1971), Vroman (1976), and Parker (1979), define the major structural configuration of the basin's subsurface. Supkow (1971) discusses an interesting application of temperature data to solve ground water problems. Eberly and Stanley (1978) show interpreted seismic reflection profiles of the basin.

Bedrock geology is an important factor in understanding the thermal regime and to identify lithology or basement structure that may act as a geothermal reservoir. Published studies of the surrounding mountain ranges are useful to understand bedrock geology.

Brown (1939), Bikerman and Damon (1966), Mayo (1968), and Damon, Bryant and Mayo (1968) summarize the geology of the Tucson Mountains. Percious (1968) describes the geology south of the Tucson Mountains in the Del Bac Hills. Studies by Cooper (1960), Cooper (1971), Cooper (1973), Shalfiqullah and Langlois (1978), and Jansen (1976) define the structure, stratigraphy and geochronology of the Sierrita Mountains.

Mapping and geologic interpretations by Drewes (1971a), Drewes (1971b), and Drewes (1972) provides a geologic understanding of the Santa Rita Mountains. North of Interstate 10 on the east margin of the basin, mapping by Davis (1975), Drewes (1977), Thorman (1977) defines the geologic terrain in the Rincon and Tanque Verde Mountains.

Recent mapping, combined with detailed structural, petrologic and geochronologic studies, has yielded significant information concerning the geologic nature of the Santa Catalina Mountains. Studies by Damon and others (1963), Davis (1975), Shakel (1974), Budden (1975), Creasey and Theodore (1975), Banks (1976), Creasey and others (1976), Creasey and others (1977), Shakel and others (1977), and Keith and others (1980), covered this range of mountains. The structural morphology of the Santa Catalina Mountains and Rincon Mountains is summarized by Davis and Coney (1979), and Davis (1980).

REGIONAL SETTING. The Tucson basin is situated in the Mexican Highland section of the Basin and Range province near the boundary of the Sonoran section (fig. 1). Major Quaternary basin entrenchment by major drainage is distinctive geomorphic feature in the Mexican Highland section. This entrenchment is suggestive of either uplift of the region relative to the

Sonoran section or acquisition of through flowing status by the Gila River drainage system during Pleistocene or late Pliocene.

A zone of Pleistocene fault scarps has been mapped in detail near the Santa Rita Mountains on the southeast margin of the Tucson basin (Calvo, 1981, pers. comm.). These fault scarps indicate that tectonism is occurring in the region, albeit at a low rate.

Sixteen heat flow measurements within 80 km of Tucson have been done (fig. 3). These measurements were reported by Roy and others (1968), Warren and others (1969), Sass and others (1971), and Shearer and Reiter (1981). The mean heat flow for these measurements is $89 mW/m^2$. Studies by Shearer and Reiter (1981) indicate a mean heat flow of $80 mW/m^2$ in the Arizona Basin and Range and that local variations in heat flow probably result from ground water movement in the vicinity of the measurements. The worldwide mean heat flow is between 59 and 67 mW/m^2 (Sclater and Francheteau, 1970). Thus, the heat flow in the Tucson region is slightly above normal and indicates elevated temperatures in the crust.

No Quaternary of Recent volcanic rocks are known in the area, therefore, magma is tentatively ruled out as a heat source. A shallow mantle (25-30 km depth) and heat generated by decay of anomalously high concentrations of radioactive elements which are dispersed through crustal rocks are the most likely heat sources. Heat generated by crustal strain or faulting is probably insignificant compared to mantle or radiogenic heat.

The crust of southeastern Arizona is highly anisotropic and is dominated by a west-northwest to north-northwest structural grain which is superimposed on an older northeast grain (Swan, 1982 and Silver, 1978). The

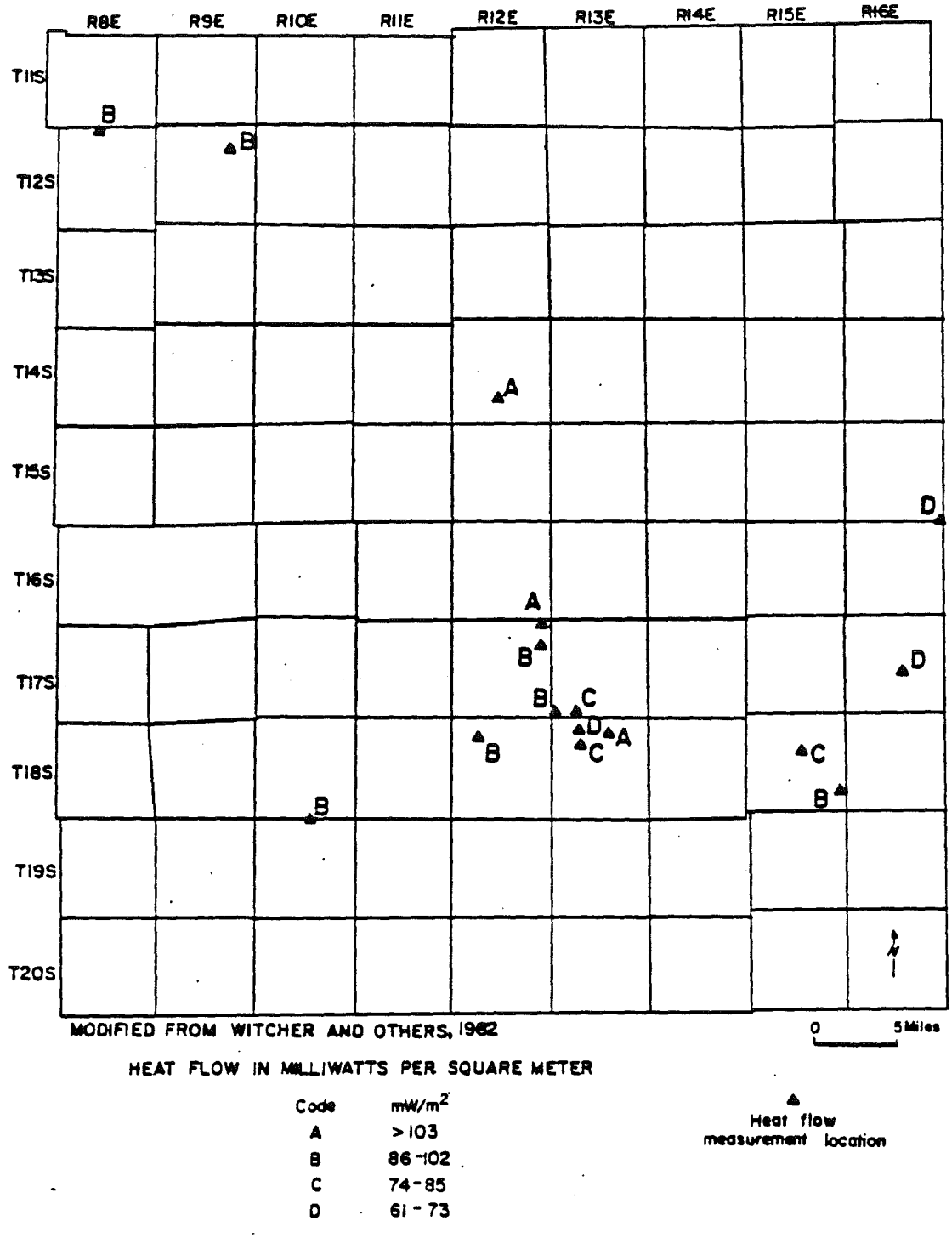


FIGURE 3 Map of Tucson region showing heat flow measurements

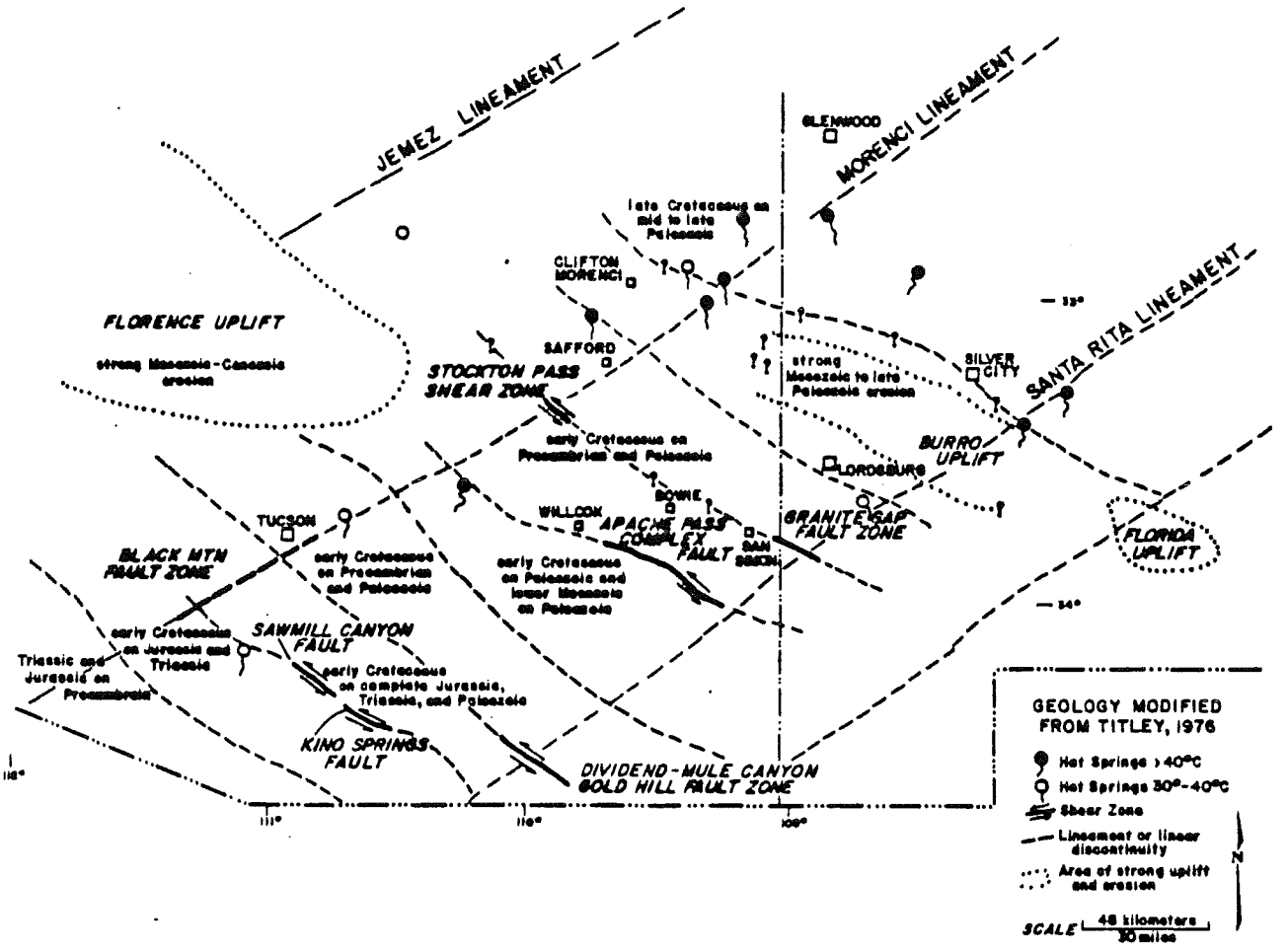


FIGURE 4 Crustal discontinuities and lineaments in southeastern Arizona

dominant grain is defined by west-northwest to west-striking outcrop patterns that are elongated transversely to present day landforms (Titley, 1976). This grain is revealed in at least six linear discontinuities, which border northwest trending blocks of some 30 to 40 km width. Each block shows unique Mesozoic stratigraphic relationships which are distinct from adjoining blocks. Figure 4 reproduces Titley's interpretive maps which show the linear discontinuities and the Mesozoic stratigraphy of the blocks. In a few areas, major west-northwest oriented faults and nearby stratigraphic packages along the discontinuities record differnential uplift and left-lateral strike-slip movement (Lutton, 1958; Titley, 1976; Drewes, 1971; Drewes, 1972; and Swan, 1976). These crustal discontinuities appear to correlate with late Paleozoic and Mesozoic tectonic and sedimentation patterns observed by Elston (1958), McKee (1951), Peirce (1976) and Ross (1973). One of these discontinuities crosses the Tucson basin from Vail to the southern Tucson Mountains (fig. 5). The northern boundary of a deep Bouguer gravity low south of Interstate 10 coincides with this discontinuity. The gravity low indicates a major sediment filled graben structure in the basin (Davis, 1971). Within the Tucson Mountains, the structural grain is parallel and coincident with the discontinuity.

The Morenci lineament, originally defined by Chapin and others (1978) in New Mexico, also crosses the basin. Elsewhere in southeast Arizona, the Morenci lineament is marked by a variety of northeast trending physiographic anomalies and faults; but probably most important, every thermal spring in southeast Arizona with temperature greater than 40°C occurs within 20 km of the lineament trace. In the Tucson basin, Agua

Caliente spring (32°C) is centered on the lineament. A geophysically inferred structural zone crosses the basin coincident with the Morenci lineament. Gravity and resistivity data are interpreted to show a major northeast-trending fault on the north side of the Sierrita Mountains (Vroman, 1976; Davis, 1971). On strike with this fault, several parallel faults are observed along the northeast-trending Del Bac Hills (Percious, 1968). A northeast-striking aeromagnetic anomaly, extends the Del Bac Hills trend into the basin (Sauck and others, 1971).

GEOLOGY AND GEOHYDROLOGY

INTRODUCTION. Before outlining the bearing of geologic history on geothermal resource potential in the Tucson basin, it is necessary to describe the basic nature of a hydrothermal system. All hydrothermal systems have four common elements. These elements are: (1) a heat source (2) a recharge source (3) a circulation framework or storage reservoir and (4) a discharge mechanism.

As discussed earlier, igneous heat sources in this area are tentatively ruled out; therefore, thermal water in the Tucson area, is better explained by deep circulation of water to depths where the geothermal gradient allows high temperatures to exist. In most geothermal systems, permeable rocks containing thermal water are overlain by an impermeable "cap" rock. The "cap" rock prevents discharge from the reservoir except along localized zones, thus conserving heat in the reservoir. Stratigraphic reservoirs may form when impermeable sediments are deposited over permeable sediments. Similar reservoirs may also evolve during volcanism where the style and composition of eruptions change with time. When mud flows and impermeable tuff are deposited on permeable volcanic flows, such as fractured basalt or fractured welded tuffs, a potential reservoir is formed. Also, reservoirs may result where low angle faults juxtapose impermeable rock over the top of permeable rock. Faults and facies changes may provide local vertical permeability to allow aquifer recharge and discharge. Faulting and sedimentation may bury an aquifer at great depth where temperatures may be high due to the geothermal gradient.

The geologic evolution of the Tucson area is discussed within a threefold chronology for purposes of discussing geothermally favorable geologic

environments. Relationship of Pre-Oligocene history to geothermal potential is not well understood. Mid-Tertiary (Oligocene-Miocene) history is important because deformation related to this time interval may have created permeable zones in basement rocks. Post mid-Miocene Basin and Range tectonism also created the favorable setting for geothermal resources.

PRE-OLIGOCENE. The Precambrian Pinal Schist, which crops out in the Catalina and Rincon Mountains, is a thick sequence of metamorphosed sedimentary and volcanic rock. Near Coolidge and Casa Grande, the Pinal Schist acts as a reservoir for thermal water discovered by the Geothermal Kinetics Systems - AMAX Exploration 1 Pima Farms test well drilled in 1974. Production tests of the 2,000 to 2,445 m interval in this hole yielded 1,100 L/min of 82°C water (Dellechaie, 1975).

Approximately 142my BP, large granitic batholiths intruded the Pinal Schist. The Oracle Granite, which crops out in the Catalina Mountains, comprises one of these batholiths. Following emplacement of the batholiths, erosion exposed the Pinal Schist and Oracle Granite. Sandstone, limestone and shale of the Apache Group were then deposited on this eroded surface. Scattered outcrops of Apache Group are found in the Catalina Mountains. Around 1100my BP these Precambrian sediments were intruded by diabase sills. Prior to deposition of the Paleozoic sediments, erosion beveled the Precambrian terrane. The anisotropic nature of the regions crust, which is most evident in the northwest-striking discontinuities and the northeast-striking lineaments, had an origin during Precambrian.

During the Paleozoic 200 to 600my BP, the Tucson area was mostly tectonically stable. A basal arkosic sandstone, the Bolsa Formation, is overlain by interbedded shales and carbonate rocks; the carbonate rocks

become dominate higher in the Paleozoic section. Depositon occurred in all periods of the Paleozoic except for the Silurian. Paleozoic rocks have little geothermal potential as reservoirs except where they are involved in low angle faulting. This potential will be discussed later under mid-Tertiary geologic history.

The Mesozoic was a time of intense and complicated tectonism, plutonism and sedimentation. Two periods of orogeny (mountain building) are recorded by Mesozoic rocks. The first orogeny occurred during Triassic(?) and Jurassic; and the second, called the Laramide orogeny, is late Cretaceous to early Tertiary age. The Tucson areas copper deposits were emplaced during the the Laramide.

Sedimentary and igneous rocks associated with the two Mesozoic periods of mountain building probably have little potential as geothermal reservoirs; however, basement structure that was developed or reactivated during this time may have geothermal importance. Deformation associated with the Mesozoic orogeny reactivated Precambrian zones of crustal weakness which may allow very deep (>2 km) circulation of water.

MID-TERTIARY Erosion during Eocene, preceding the mid-Tertiary tectonism, an event characterized by voluminous eruptions of compositionally diverse lavas (Shafiqullah and others, 1980). In the Tucson Mountains, mid-Tertiary basaltic and siliceous flows (38.5 to 18.8 my BP) are in angular unconformable contact with underlying Laramide 70 to 50 my old volcanic rock (Bikerman and Damon, 1966). Thick sequences of clastic sediments interbedded with volcanic flows accumulated in Oligocene and early Miocene depositional basins, contemporaneous with

mid-Tertiary volcanism. The tilted and indurated gravels and siltstones of the Pantano and Helmet Formations are examples of mid-Tertiary sedimentation. Mid-Tertiary sediments and volcanic flows may have reservoir potential where they are highly fractured by faults associated with metamorphic core complexes.

Metamorphic core complexes such as the Rincon-Santa Catalina-Tortolita complex evolved during mid-Tertiary (Banks, 1977; Davis and Coney, 1979). The metamorphic core complexes formed as a result of regional tectonic strain and profound thermal disturbance, which accompanied mid-Tertiary plutonism and volcanism (Banks, 1977 and Davis and Coney, 1979). Metamorphic core complexes have a distinctive structural morphology (Davis and Coney, 1979); a low angle fault zone of chloritized mylonite breccia overlies mylonitized metamorphic rocks and geniss. Deformed, but unmetamorphosed rock overlie the low angle fault. The low angle Catalina fault zone and overlying deformed "cover rocks" are potential geothermal reservoir rocks. The "cover rocks" are highly fractured and they may be preserved at depth in the Tucson basin.

Gneiss clasts in deformed sediments document erosional unroofing of portions of the Rincon-Santa Catalina-Tortolita metamorphic core complex and they suggest mid to late Miocene arching of this complex. Using clast composition, Voelger (1953) and Pashley (1966) assigned these deformed sediments to three units. Type 1 Rillito Beds, the oldest unit of Pashley (1966), consists of volcanic, pink granite, limestone, quartzite, schist, and very few gneiss clasts. Also, mudstone strata containing massive gypsm beds is observed in a Rillito I outcrop in T. 13S, R. 14E, sec 14, SW 1/4, NE 1/4, SW 1/4 (Pashley, 1966). In addition, several 3 inch thick beds of mudcracked limestone and 6 feet thick beds of white volcanic ash are

observed in these sediments. Mudstone and gypsum, which distinguish the Rillito I from other Rillito units, indicate a low-energy playa environment situated near the center of a closed depositional basin. Today, Rillito I sediments are tilted and lie adjacent to the Santa Catalina-Tanque Verde mountain front.

Red, Type II and lightgray, Type III Rillito beds contain a greater abundance of gneiss clasts and much less limestone than the Rillito I (Pashley, 1966). Type II and Type III Rillito intertongue and contain no mudstone units but, they do have volcanic ash deposits. Rillito III sediments contains more gneiss clasts than the Rillito II and they may be younger; however, the differences in their color and composition may relate more to provenance rather than age. Increased gneiss clasts and an absence of mudstone deposits in Rillito II and III indicates a higher energy depositional environment than the Rillito I, greater exposure of the core complexes, and possibly greater topographic relief of the core complex.

All Rillito units are tilted and cut by normal faults which may merge into the low-angle Catalina fault. In general, strikes and dips of the Rillito beds, measured by Pashley (1966), mimick the fold-like structure of banded gneiss in the Tanque Verde-Santa Catalina Mountains. Exceptions include areas nearest the Catalina fault which are roughly on strike with antiformal axes in the gneiss. Increasing gneiss content, generally conformable bedding with fold-like structure in adjacent metamorphic terrain, faulting, and apparent arching of Catalina fault, may indicate depositon along east-northeast trends contemporaneous with late phases of metamorphic core complex evolution. Volcanic ash deposits, probable

listric normal faulting, may indicate elevated crustal temperatures during mid to late Miocene.

A similar geologic terrain in Idaho dramatically illustrates the reservoir potential of the low angle fault and the allochthonous cover rocks. Geothermal drilling to 2 km depths in the southern Raft River Valley encountered thermal (140°C) water contained in fractured Tertiary sediments which are allochtonous over quartzite and schist (Covington, 1980). Geologic studies of the surrounding Albion-Raft River-Grouse Creek Mountains show a metamorphic core complex (Davis and Coney, 1979, Compton, 1980 and Armstrong, 1968). High angle Pliocene and Pleistocene faults at the surface are shown by Covington (1980) to flatten and merge into a low angle fault zone overlying the schists and quartzites. A geophysically defined basement lineament trending northeast, the Narrows structure, is inferred by Covington (1980) to leak thermal water into deformed sediment overlying the basement low-angle fault. It should be noted that the analogy between Raft River basin and Tucson basin is not perfect. For instance, the Raft river area appears to be more tectonically active and the regional heat flow in that area may be higher. However, the comparison is useful to infer potential reservoir lithology and structure; but, prediction of similar temperatures, depths, and well production rates in the Tucson basin is highly speculative at this point.

Additional insight into geothermal potential of "cover rocks" associated with the Rincon-Santa Catalina-Tortolite complex is gained by inspection of allochonous rocks in the Saguaro National Monument East of Tucson. These rocks overlie the low-angle Catalina fault at the base of Tanque

Verde Mountains. In the Monument, Paleozoic limestones show intense fracturing. These fractures are mostly sealed with carbonate and siliceous filling; however, if similarly deformed rocks are present at depth in the basin, they may have open fractures by virtue of being in a different environment. Provided this is true, the deformed and fractured allochthon rocks may have potential as geothermal reservoirs where they are hydrologically connected with deeply circulating flows of water.

POST MID-MIOCENE. During late Miocene, listric faulting and volcanism waned. Listric normal faulting was replaced by high-angle normal faulting as the crust partially cooled, contracted, and became more brittle. Present day land forms and first order structure of the basin evolved as a result of this high angle faulting, which created horsts and grabens. Eroding horst blocks form present day mountain ranges and piedmonts, while interconnected grabens form the basin. The basin is filled with debris eroded from adjacent horsts.

This post mid to late Miocene high-angle faulting in southern Arizona is called the Basin and Range disturbance (Scarborough and Peirce, 1978). In the Tucson basin, this faulting probably began after 11.6 m.y. BP (Scarborough and Peirce, 1978). The 11.6 m.y. BP age is from a K-Ar date of the uppermost volcanic strata encountered at 2,180 m depth by the Humble State 34-1 drill hole (D-15-14-5C) (Damon and others, unpub. manuscript, Scarborough and Peirce, 1978). Clastic sediments overlie the volcanic rocks.

Basin and Range faulting largely ended by the time major drainage to the Gulf of California integrated between basins. Very few Quaternary

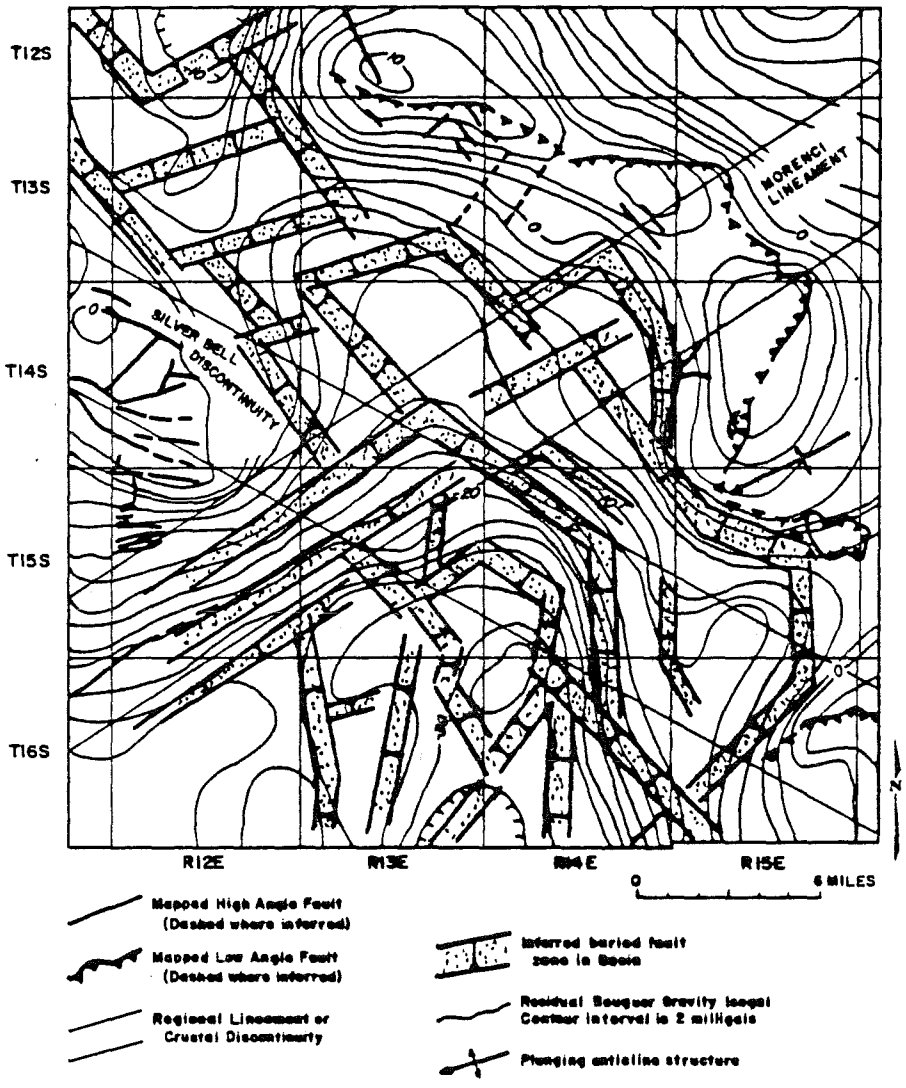


FIGURE 5 Bouguer gravity map of the Tucson area showing major structures and lineaments

fault scarps, development of erosional pediments which were buried by basin fill prior to stream entrenchment, are all evidence of waning Basin and Range faulting before drainage integration. The Gila River drainage system in southeastern Arizona, which includes the Santa Cruz River, obtained through flow status between 5.5 m.y. and 2.2 m.y. (Shafiqullah and others, 1980).

Basin and Range tectonism and sedimentation has played a major role in shaping the geothermal resource potential of the Tucson Basin because: (1) highly deformed and potentially permeable metamorphic core complex cover rocks were deeply buried by basin fill sediment (2) high-angle normal faults, forming grabens may provide vertical zones for deep circulation of water (3) thick, closed-basin deposition of clastic sediment has resulted in important facies variations whose distribution and geometry may have a thermal and geohydrologic character which is favorable for geothermal resources.

Figure 5 is a regional Bouguer gravity map from Aiken and others (1981) showing major structure zones. This structure is interpreted from gravity maps, published by Davis (1967, 1971) and Aiken and others (1981).

Gravity data are useful to show major Basin and Range structure because high angle faulting has disrupted the bedrock into "box like" structures (grabens) which have filled with low density clastic sediment. The density contrast of the sediment and bedrock has resulted in relative mass deficiency over areas underlain by grabens and close-spaced gravity contours may indicate faults. Density variations in bedrock have minor affect on gravity observations compared to the basin-fill sediment and bedrock

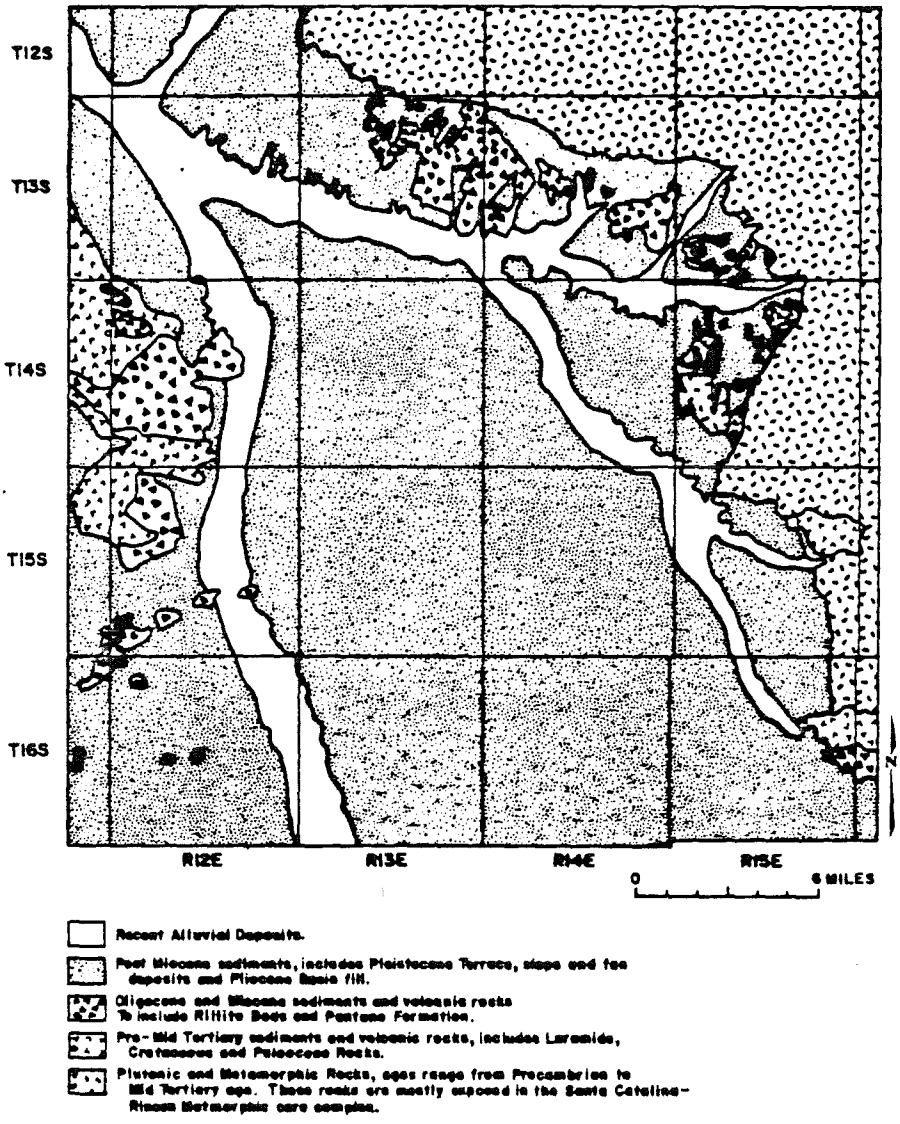


FIGURE 6 Generalized geology of the Tucson basin region

density contrasts.

A complex en-echelon zig-zag pattern of interconnected grabens forms the Tucson basin which is filled with clastic sediment. The deepest grabens occur south of Tucson. The Humble State 32-1 stratigraphic test (D-16-15-5C) encountered more than 2150 meters of clastic sediment, which are presumably basin fill sediments; although the lower sediments immediately overlying the volcanic sequence may in part comprise stratigraphy correlative to the Rillito beds of Pashley (1966). Northeast and northwest-striking faults that bound the north end of the deep graben south of Tucson are coincident with the Morenci lineament and a crustal discontinuity, respectively. A smaller graben structure, north of the Morenci lineament underlies the city. The major grabens are oriented north-northeast; while the minor grabens are oriented northwest. Sediments filling these grabens are generally fine grained over the deepest portions of the basins at depths less than 700 m.

GEOHYDROLOGY. At present time, the Tucson area is one of the largest municipalities in the United States which depends entirely upon a ground water supply source (Wright and Johnson, 1976). More than 200 wells, located in the Tucson basin are operated by the City of Tucson and several water companies (Wright and Johnson, 1976).

The ultimate source of the ground water is from precipitation in mountains surrounding the Santa Cruz River drainage basin (Davidson, 1973). This water enters the Tucson ground water reservoir by infiltration from stream flow, under flow from adjacent basins and by infiltration from runoff near the mountains. Recharge by direct precipitation on valley floors is believed negligible because of high evaporation potential

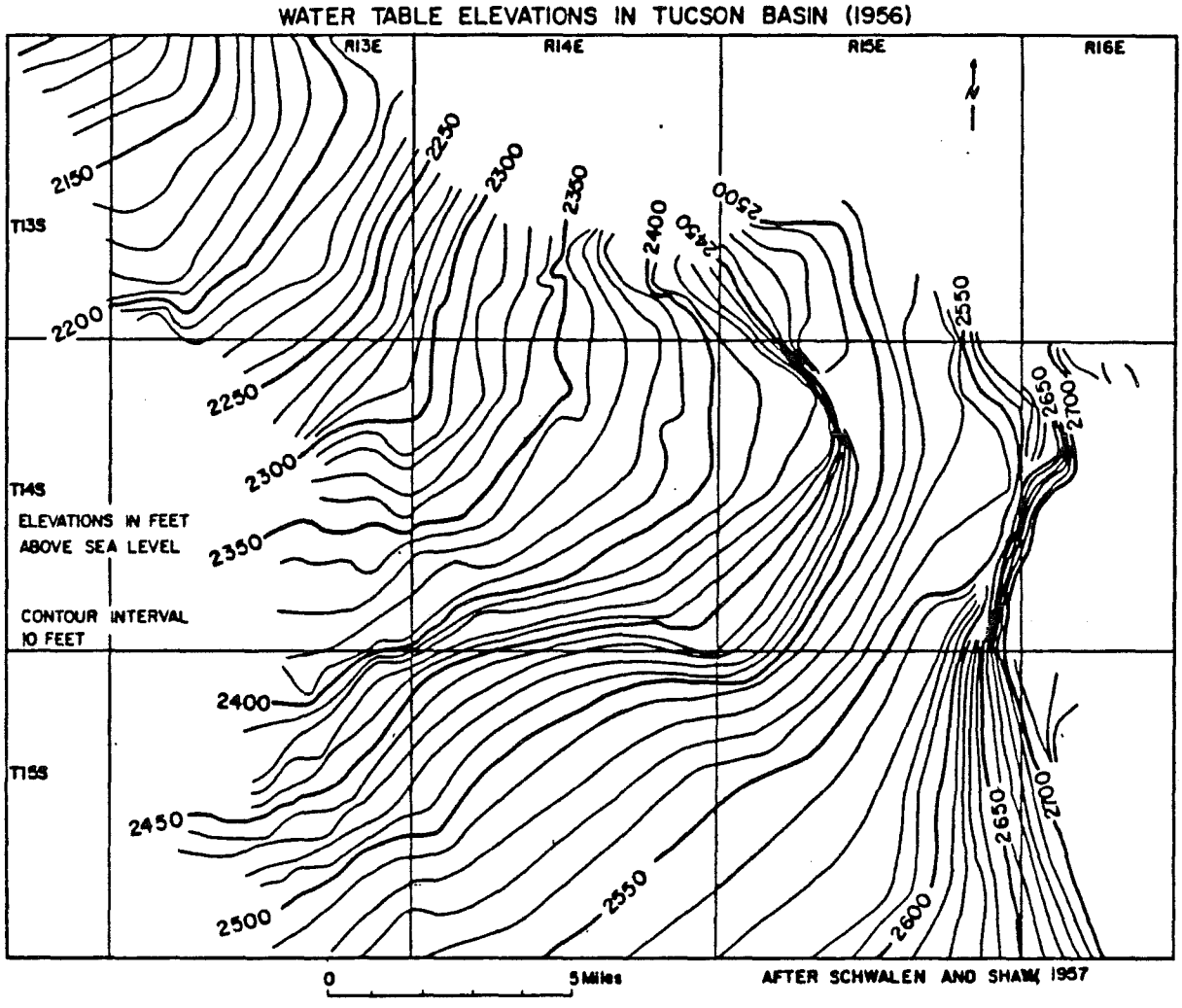


FIGURE 7 Map of water table in Tucson basin in 1956

Davidson, 1973 and Anderson, 1973). Some water is returned to ground water storage by irrigation and sewage effuent that is discharged to the Santa Cruz River.

Ground water in the Tucson basin is stored in and transmitted through unconsolidated to semi-consolidated clay rich sand and gravel. Ground water movement is generally from south to north along the axis of the basin and from the mountains toward the basin axis (fig.7).

Prior to 1940, the geohydrologic system was in approximate equilibrium because recharge was about equal to discharge. While wells existed in the basin prior to 1940, the water pumped from these wells was probably equal to the amount formerly lost through evapotransporation along stream and arroyo courses. Since 1940, the area has experienced population growth that has resulted in accelerated ground water usage. As a result the water table has declined at rates exceeding 8 feet per year at several locations (Wright and Johnson, 1976). These declines show that the amount of water in storage is dropping and that withdrawal is exceeding natural recharge. Continuing growth in the area, coupled with present ground water usage, indicates potential for serious water supply problems in the future. A rapidly lowering water table causes increased potential for subsidence, higher costs because well pumps have to lift water to greater height and drilling depths are greater. In addition large uncertainties exist both in quantity and chemical quality of ground water deep within the basin. Several solutions are being studied and planned. They include both providing and developing additional water (Central Arizona Project) and conserving valuable ground water supplies (Ground Water Management Act).

Development of potential geothermal resources in the Tucson area will have to be accomplished in a manner which will not exasperate current ground water supply problems. Geothermal development has potential to increase ground water problems through additional use of potable ground water or by degrading the quality of existing supplies. However, geothermal development also has potential to help solve the areas water-supply problems while conserving fossil fuels and stabilizing energy costs to potential users. The potential for conservation of ground water through geothermal development is straight forward. Geothermal water can replace potable ground water which is currently used in boilers and heaters. After the geothermal heat is extracted the effluent may be reinjected back into the geothermal reservoir to be reheated and used again; or if the geothermal water is of sufficient quality it is possible to add it to drinking water supplies, or it may be used for other non-drinking uses. Because thermal water is generally found at greater depth in the basin, development will increase the knowledge of ground water supply at depths greater than currently explored. Savings in energy costs, from extracting heat from thermal water before other uses, may help offset pumping costs of deep water supply wells. This multiple use could conserve both energy and water. The benefit and feasibility of using geothermal energy to conserve ground water should receive serious attention by researchers, developers and legislators.

THERMAL REGIME OF THE TUCSON BASIN

INTRODUCTION. Many factors influence the temperature distribution within the upper crust of the earth. Heat flow from the earth's interior is the most important factor. Daily and annual solar heating affects temperatures only a few meters below the surface. Temperature changes caused by pressure increases with depth (adiabatic temperature) are insignificant and of no importance in shallow crustal studies because of the incompressibility of rock.

Subsurface temperature is predominatly influenced by heat conducting from the mantle through crustal rock, thermal conductivity of crustal rock, and by ground water flow. Additional factors are also important, such as radiogenic and chemical heat production in the crust, and by time (i.e., time since emplacement of a magma body, initiation of ground water convection or temperature changes in the mantle). Topography may also influence shallow subsurface temperature distribution.

Conductive heat flow measurements are the easiest and most straightforward method to study the temperature distribution in the crust. Conductive heat flow depends mostly upon the rock thermal conductivity and temperature changes with depth. The equation for vertical conductive heat flow, assuming no radiogenic heat production, ground water convection, or inhomogeneity in crustal rock is:

$$q = K\frac{\partial T}{\partial Z}$$

q = heat flow
K = the rock thermal conductivity

$\frac{\partial T}{\partial Z}$ = the temperature gradient

Temperatures at various depths may be extrapolated in a region of known conductive heat flow if reasonable assumptions about rock thermal conductivity can be made. For this reason, heat flow drill holes are sited in nonpermeable, isotropic rock such as granite when studying regional temperature distribution in the crust. However, the objective of geothermal exploration is to determine local temperature variations which could indicate hydrothermal convection systems, at economically drillable depths. Since convective transport of heat from great to shallow (economic) depths occurs in such convection systems, geothermal studies are concerned with convective heat flow studies in addition to conductive heat flow measurements. Also, convective heat flow measurements contains information concerning the movement of ground water that may be useful for indirect estimation of flow rates, rock permeability, and heat budgets within a geothermal system. The equation for vertical heat flow with convection, but no heat production is:

Equation (2) $$q = K\frac{\partial T}{\partial Z} + pCv\partial T$$

where:

p = the density of water

c = the heat capacity of water,

∂T = change in temperature through interval of the heat flow measurement,

v = the vertical component of water velocity,

other terms same as in Equation (1)

The vertical velocity of convective water flow is dependent upon the pressure or hydraulic head, permeability, and fluid viscosity according to Darcy's Law.

PREVIOUS STUDIES. Conductive heat flow measurements have been accomplished by Roy and others (1968), Warren and others (1969), Sass and others (1971) and Shearer and Reiter (1981) using temperature logs of mineral exploration drill holes where core is available for thermal conductivity determination. Conductive heat flow measurments in area surrounding the Tucson basin have a mean heat flow of 89 mW/m^2 (Fig. 3). Normal heat flow for the southern Basin and Range in Arizona is 80 mW/m^2 (Shearer and Reiter, 1981). The Tucson area overlies a zone of elevated crustal temperatures. Additional evidence is provided by modeling of aeromagnetic data for the depth to Curie temperature (~525°C) (temperature that crustal rocks lose magnetic susceptibility). These studies reveal a shallow Curie temperature depth in the Tucson region (Hong and others 1981, and Carlos Aiken, 1981, pers. comm.).

In another study, Supkow (1971) compared computer simulations of subsurface temperature for several hypothetical ground water flow regimes with measured temperatures of shallow wells in the Tucson basin. Supkow's study illustrated the applicability of temperature surveys to identify zones with downward flow or seepage (recharge) of ground water.

TEMPERATURE AT THE WATER TABLE. Figure (8) is a generalized map of temperatures at the water table in the basin in 1967. This map is modified from the water table temperature map presented by Supkow (1971). Areas with temperatures less than 22°C coincide with the Santa Cruz River Rillito Wash, Tanque Verde Wash and Pantano Wash. Supkow (1971) coincluded that recharge occurs in these areas. Where water has a downward component of movement, heat is transported downward with the water in a direction opposite to upward transfer of heat by conduction. (Equation 2).

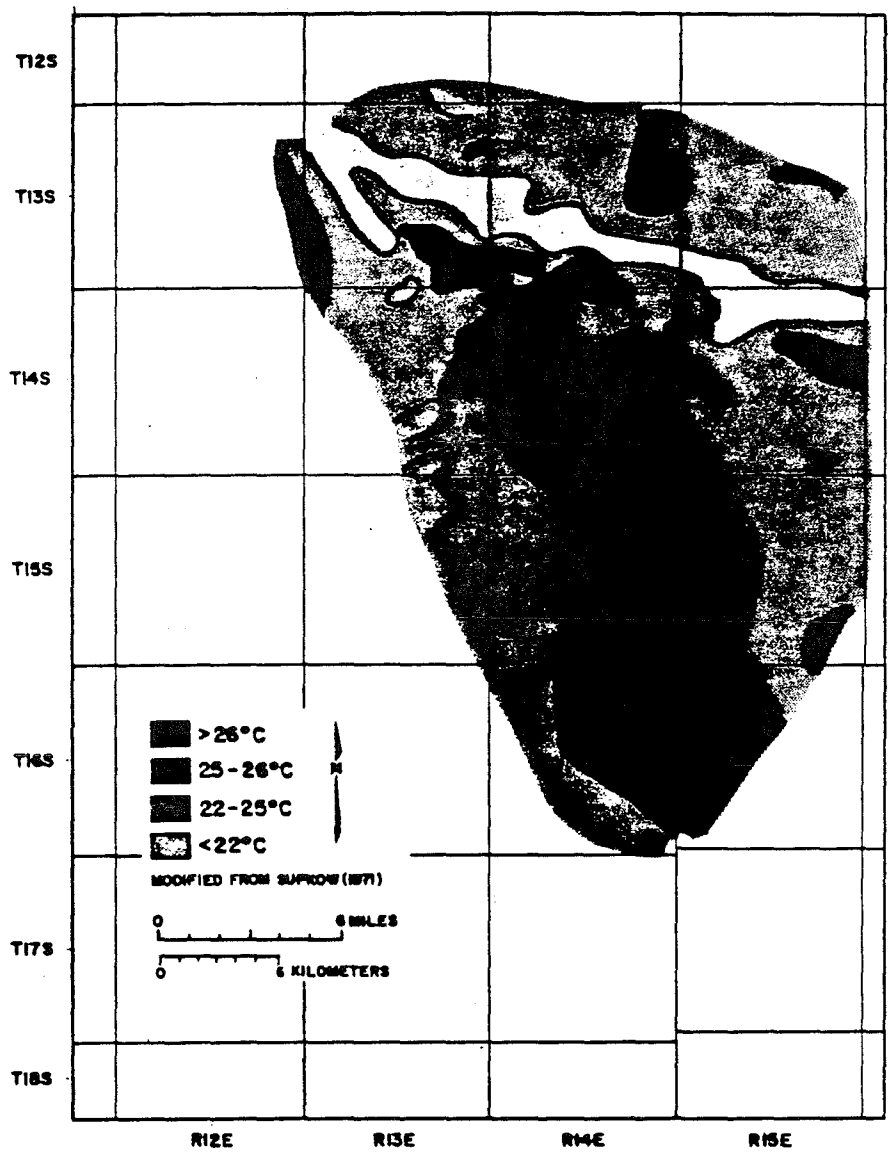


FIGURE 8 Temperature at the water table in the Tucson basin

Thus, temperatures are lower in areas with downward flowing water than in areas with purely conductive heat flow. The opposite temperature distribution occurs with upward moving water.

Supkow (1971) attributed areas with higher water table temperatures to zones where permeability of shallow ground water aquifers is low. This is, in part, correct because these areas will have a large conductive component of heat flow. However, Supkow (1971) failed to account for differences in thermal conductivity, which can vary by a factor of 1.5 in basin fill sediments and by lateral variations of conductive heat flow which may vary locally by a factor of two or more. Local deep convection systems may heat overlying rocks to cause these temperature variations. Also, higher water table temperatures may result from leakage of deep thermal water into shallow ground water. I propose that areas with water table temperatures greater than 26°C occur where the underlying rock has a low thermal conductivity, zones of upward flow of water exists, an underlying anomalous heat source exists, or all three may occur.

TEMPERATURE GRADIENTS. Geothermal systems beneath Tucson may make their presence known by high temperature gradients in shallow aquifers. Average temperature gradients for wells are easily calculated using bottom-hole temperature and well depth. In this study, the surface discharge temperature is assumed to roughly represent bottom-hole temperature. In calculating a gradient, the mean annual temperature (MAT) is subtracted from the well temperature, the difference in degrees Celsius (°C) is divided by well depth in meters (m) and the quotient is multiplied by 1,000. The calculated temperature gradient is in degrees Celsius per kilometer (°C/km).

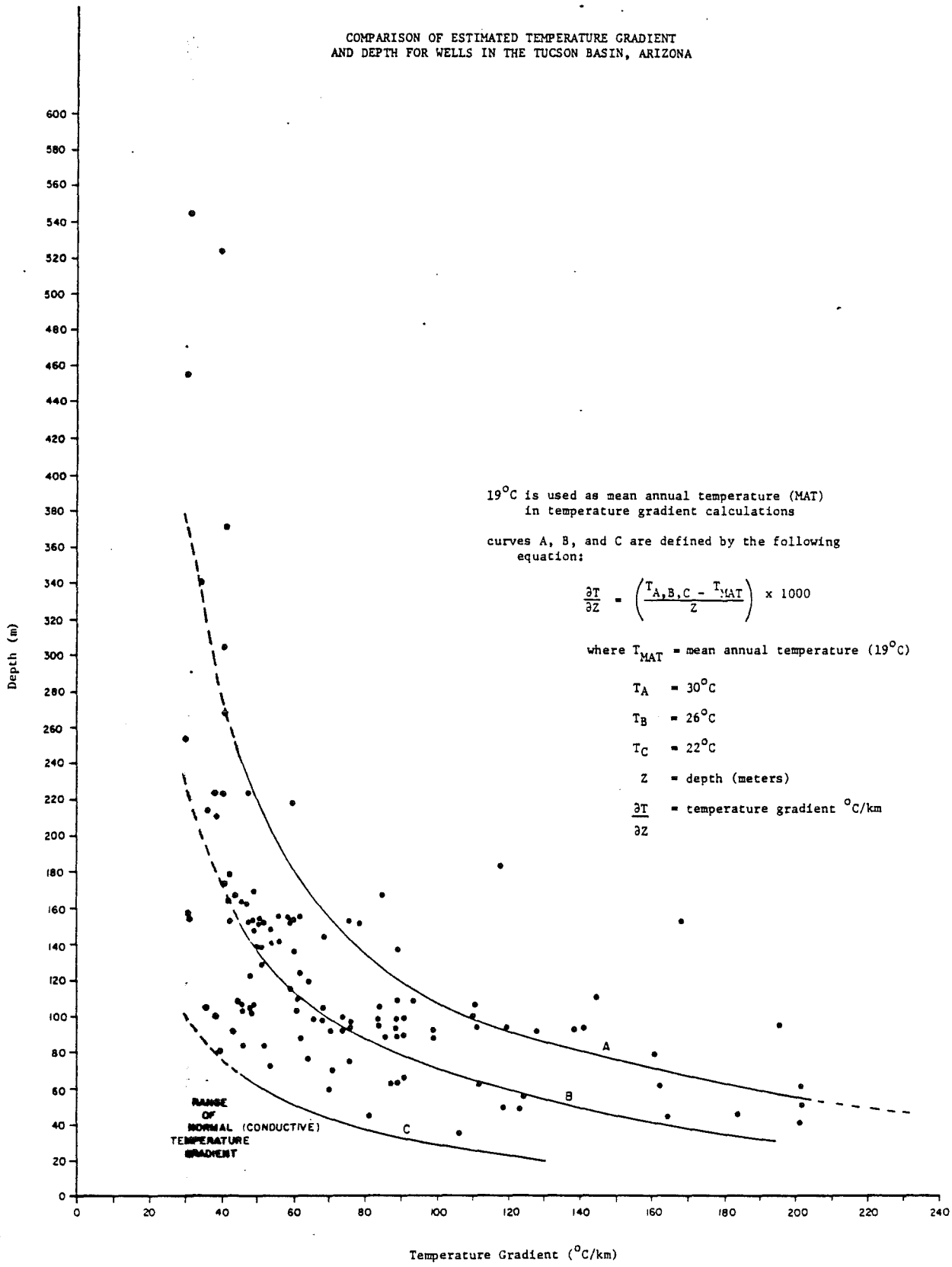


FIGURE 9 Temperature gradient versus depth of wells in the Tucson basin

Figure (9) compares calculated temperature gradients in the Tucson basin with respective well depths. Wells greater than 250 m depth have gradients which range between 30 and 45°C/km. These gradients are considered as background for the Tucson basin.

In Tucson basin wells less than 250 m depth, calculated temperature gradients range 30°C/km to over 200°C/km. Within this interval, Witcher (1979) averaged the temperature gradients over discrete depth intervals and found that gradients systematically decrease with depth and apparently level out at 37°C/km below 250 m. This systematic decrease in temperature gradient is approximated by the following equation:

Equation (3)

$$\frac{T}{z} = \frac{T - Tmat}{z} \times 1000$$

where:

$\frac{T}{z}$ = temperature gradient °C/km

T = well temperature (assumed as bottom-hole) °C

Tmat = mean annual air temperature (MAT) °C

z = depth (m)

Computed temperature gradient versus depth curves using equation (3) are shown in Fig. (9) for well temperatures of 22°C, 26°C and 30°C respectively. In areas where ground water recharge occurs, Supkow (1971) has shown that temperatures at the water table are between 22°C and the mean annual temperature (MAT) (19-20°C). The mean temperature of all wells in the Tucson basin is 26°C; while 30°C is approximately 10°C above the MAT. This later criteria defines thermal springs in southern Arizona (Witcher, 1981). A well whose temperature gradient plots to the right of line A (30°C) is therefore considered geothermally anomalous. The systematically higher

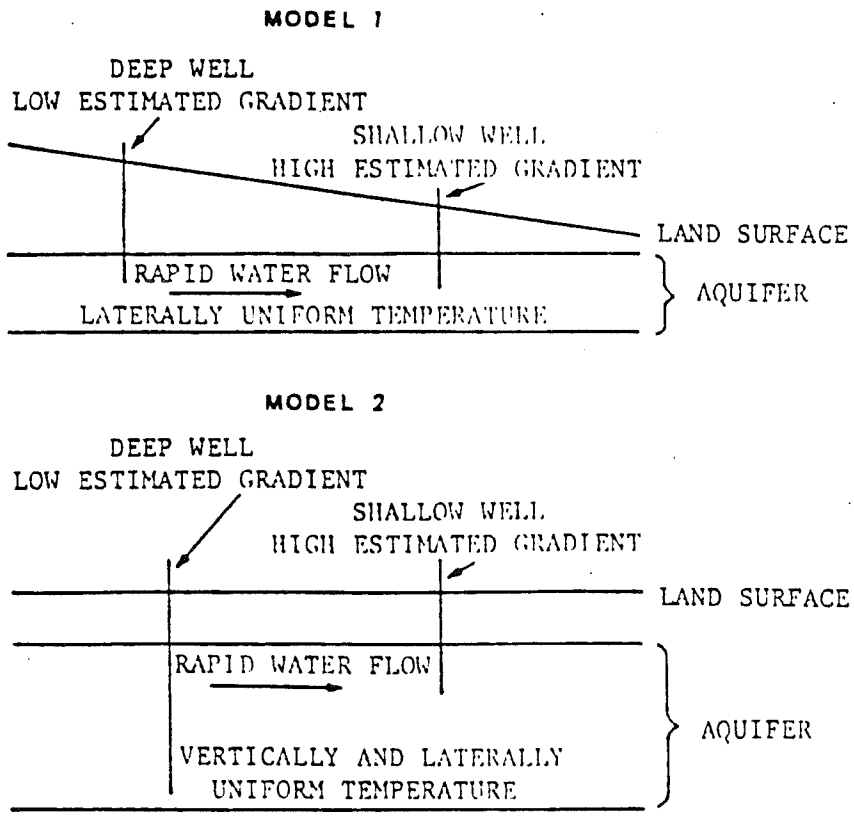


FIGURE 10 Models of temperature and ground-water flow used to explain temperature gradient variation

gradients from shallower holes result from ground water movement and to a lesser extent, lower thermal conductivity sediments at very shallow depth. For instance, systematically increasing gradients may be caused by a land-surface and water-table convergence in the direction of lateral water flow in shallow (<250 m) aquifers (Fig. 10). Secondly, the upper 250 m of the basin may be a continuous aquifer whose temperature from top to bottom generally varies only slightly from 26.0°C as a result of rapid ground flow, induced by either pumping or a sloping water table in an aquifer that has high permeability. With either of these processes, estimated gradients increase systematically with decreasing well depth (Fig.10). A third, but important, mechanism is probably superposed on the two preceding and primary conditions in a few areas and accounts for anomalously high temperatures. Leakage of thermal water into shallow (<250 m) aquifers from underlying confined aquifers may cause temperatures in shallow aquifers to exceed 26°C. In a more complex model, shallow ground water is heated by high conductive heat flow through impermeable rock which underlies the shallow aquifers. This impermeable rock confines a hydrothermal convection system that supplies the heat.

Geothermal exploration in the Tucson area is readily accomplished using the models previously discussed by calculating and plotting on maps residual gradients for wells whose gradients exceed line B (26°C). The residual gradients is a relative measure of the amount of temperature abnormality. It is calculated by subtracting the computed gradient from the gradient predicted by line B at the specified well depth. Figure 11 is a map of residual gradients, which were derived in the same manner. In general, low residual gradients correlate with low temperatures at the water table

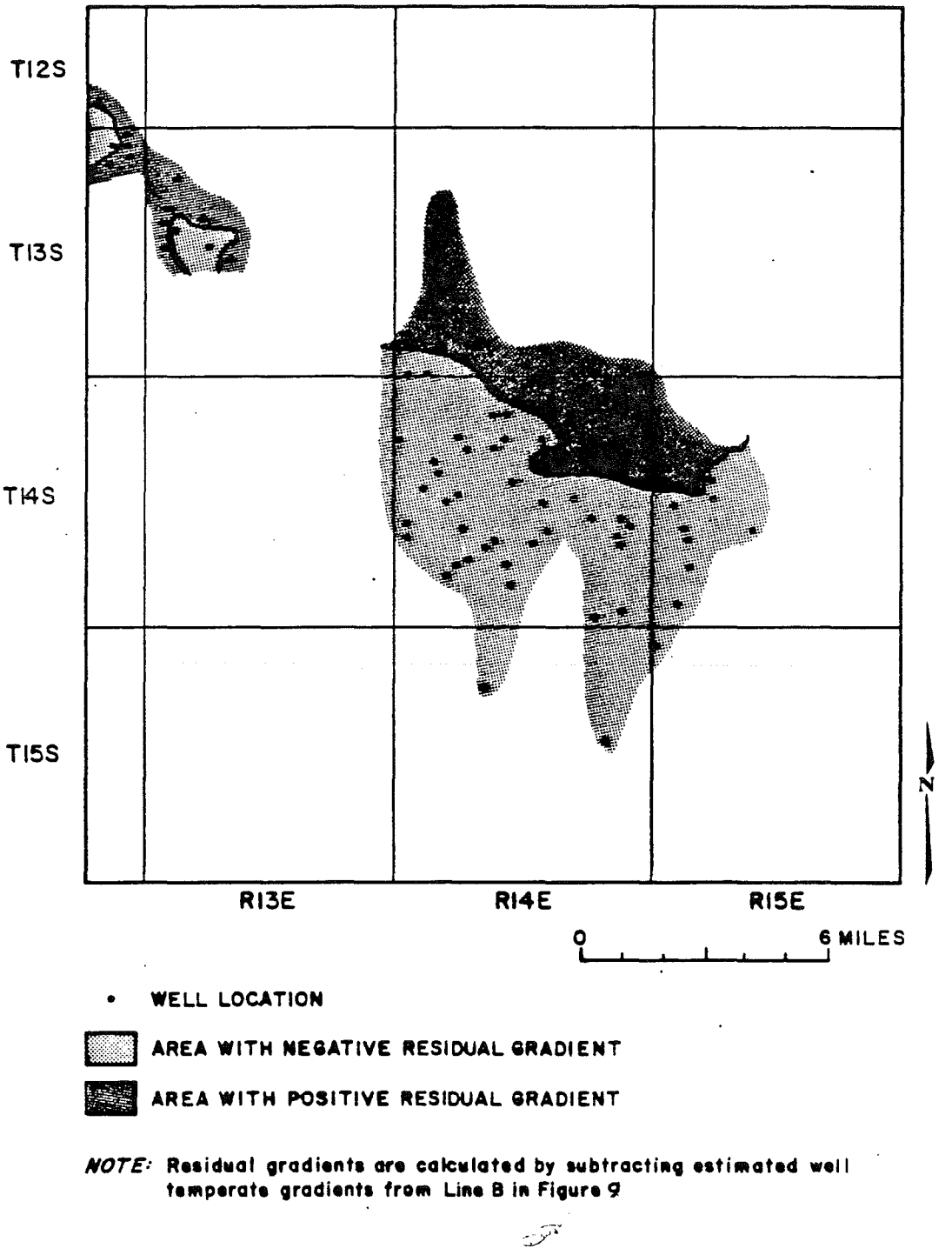


FIGURE 11 Generalized map of residual temperature gradients

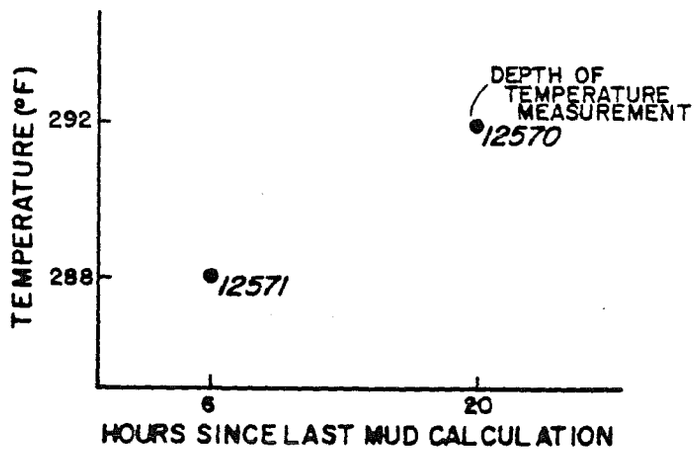


FIGURE 12 Temperature measurements in the deep Exxon (Humble State 32-1) drill hole

measured by Supkow (1971). The high residual temperature gradient anomalies show areas where with shallow (<1 km) geothermal resource potential is probably best.

The only deep (>1.5 km) information on the Tucson basin is from the Humble State 32-1 stratigraphic test drilled in 1972. This hole, 3832 m total depth, had bottom-hole temperatures taken during geophysical logging. Figure 12 shows the bottom-hole temperatures measured in the Humble State 32-1 at various times after mud circulation of the hole was stopped. While the depths vary, the temperature gradient (547°C/km) required to explain the bottom-hole temperature variation as a function of depth is unrealistic. The temperature increase is probably due to bore hole reequilibration with original thermal conditions prior to cooling disturbance from mud circulation. At 3831.3 m, the temperature of the hole was 144.4^{o}C at 20 hours after mud circulation had stopped (files Arizona Oil and Gas Conservation Committee). A calculated average gradient for this hole is 32.7^{o}C/km. This grandient is normal and agrees with gradients predicted from regional heat flow and probable thermal conductivity values.

THERMAL WATER. At least 30 wells are reported to produce thermal (>30°C) water in the Tucson basin (Fig. 13). A thermal spring, Agua Caliente, at the base of the Santa Catalina Mountains east of Tucson discharges 30 to 32°C water from alluvial sediments.

Thermal wells in the basin range from 64 to 959 m depth (Table 1). The deeper thermal wells pump up to 6100 L/min gpm of 57°C water. Thermal water occurrences in the basin are mostly widely scattered. However, a notable concentration of thermal wells does exist in Township 15 south, Range 14 east where the highest temperature thermal water know in the basin

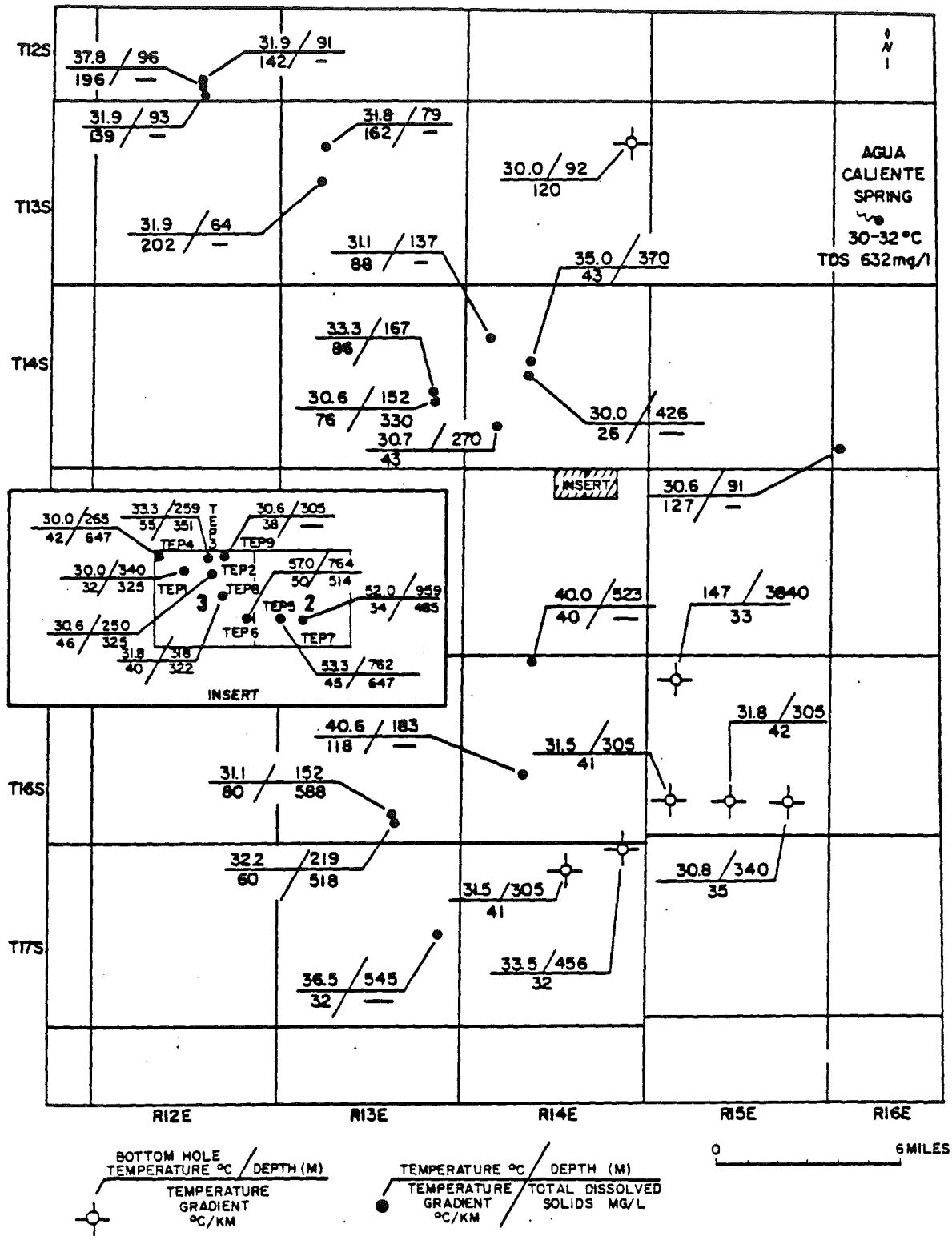


FIGURE 13 Map of thermal wells and springs in the Tucson basin

Table 1 Thermal wells and springs in the Tucson Basin

Location

D-12-12-34dbb

Quadrant/Township/Range/Section/Quarter/Quarter-Quarter

Surface Discharge Temperature (°C) T-bottom hole temperature log G-bottom hole geophysical log

Depth (meters)

Gradient (°C/Km)

Total dissolved solids (TDS) in milligrams per liter (mg/L)

Sources:

(1) Dutt and McCreary (1970)

(2) U.S. Geological Survey

(3) Mburu (1975)

(4) City of Tucson

(5) Supkow (1971)

(6) Giardina and Conley (1978)

(7) Tucson Electric Power

(8) Laney (1972)

(9) Swanberg and others (1977)

TABLE 1 Thermal wells and springs in the Tucson basin

Well	Location	Temperature	Depth	Gradient	TDS
	D-12-12-34dbb	31.9	91	142	
	D-12-12-34dbd	37.8	96	196	
	D-12-12-34dcc	31.9	93	139	
	D-13-13-8bdd	31.8	79	162	
	D-13-13-17caa	31.9	64	202	
	D-14-13-12abc	30.0T	92	120	
	D-14-13-25da$_1$	33.3	167	86	
	D-14-13-25da$_2$	30.6	152	76	330
	D-14-14-7dda	31.1	137	88	
	D-14-14-16cbb	35.0	370	43	
	D-14-14-16ccc	30.0	426	26	
	D-14-14-29cbc	30.7	270	43	
	D-14-16-31bdc	30.6	91	127	
TEP5	D-15-14-2cac	53.3	762	45	647
TEP7	D-15-14-2dbc	52.0	959	34	485
TEP9	D-15-14-3aba	30.6	305	38	
TEP3	D-15-14-3abb	33.3	259	55	351
TEP2	D-15-14-3abc	30.6	250	46	325
TEP8	D-15-14-3acd	31.8	318	40	322
TEP1	D-15-14-3bac	30.0	340	32	325
TEP4	D-15-14-3bbb	30.0	265	42	647
TEP6	D-15-14-3dad	57.0	764	50	514
	D-16-13-34aab	31.1	152	80	588
	D-16-13-34aab	32.2	219	60	518
	D-16-14-4ba	40.0	523	40	
	D-16-14-21ccb	40.6	183	118	
	D-16-15-5ca	147.0G	3840	33	
	D-16-15-26ddd	30.8T	340	35	
	D-16-15-28ddd	31.8T	305	42	
	D-16-15-30ddd	31.5T	305	41	
	D-17-13-13cdd	36.5	545	32	
	D-17-14-1baa	33.5T	456	32	
	D-17-14-3dcc	31.5T	305	41	
Agua Caliente	D-13-16-20cdd	30.4	spring	--	632

Table 2 Selected chemical analyses of thermal water in the Tucson Basin

Location

D-12-12-34dbb

Quadrant/Township/Range/Section/Quarter/Quarter-Quarter

analyses in milligrams per liter (mg/L)

Temperature (^{o}C)

Data Sources:

(1) Dutt and McCreary (1970)

(2) U.S. Geological Survey

(3) Tucson Electric Power

(4) Laney (1972)

(5) Swanberg and others (1977)

TABLE 2 Selected chemical analyses of thermal water in the Tucson basin

Well No.	Location	Temperature	pH	Na	K	Ca	Mg	Cl	SO_4	HCO_3	NO_3	B	F	SiO_2
1	D-12-12-7caa	30.8	7.6	86	2.8	65	10	92	168	268	25	0.13	0.4	34
2	D-12-12-34dbb	31.9	9.2	66	0.8	4	0	60	38	63	6	0.56	1.3	11
3	D-12-12-34dbd	37.8	8.4	108	1.1	5	1	36	22	220	8	0.32	0.7	12
4	D-12-12-34dcc	31.9	8.0	55	2.6	59	9	40	26	278	7	0.12	0.5	35
5	D-13-13-17caa	31.9	7.8	105	3.3	104	12	84	200	220	7	0.07	0.4	12
6	D-14-14-29cbc	30.7	7.8	120	3.6	71	10	104	246	120	2	0.55	1.8	--
7(TEP5)	D-15-14-2cac	52.2	9.1	202	---	4	0.8	49.5	270	69	-	--	9.8	30
8(TEP7)	D-15-14-2dbc	52.0	9.1	155	---	4.3	0.4	31	182	120	1.4	--	5.7	46
9(TEP3)	D-15-14-3abb	33.3	7.9	75	---	48	3.7	10	105	165	-	--	0.7	24
10(TEP2)	D-15-14-3abc	30.6	7.8	74	---	46	5.8	10	115	154	-	--	0.6	22
11(TEP8)	D-15-14-3acd	31.8	7.8	75	---	38	3.3	11.5	133	140	-	--	1.07	32
12(TEP1)	D-15-14-3bac	30.0	7.7	68	---	40	4.6	10.5	130	140	-	--	0.73	30
13(TEP4)	D-15-14-3bbb	30.0	7.9	65	---	48	4.6	13.2	135	146	-	--	0.6	30
14(TEP6)	D-15-14-3dad	57.0	9.1	174	---	3	0.8	40.5	220	89	-	--	4.9	39
15(	D-16-13-34aab	31.1	7.5	53	4.6	87	22	61	210	145	-	0.08	--	38
16	D-16-13-34aab	32.2	7.7	52	4.5	74	21.0	54.0	180	147	-	0.11	--	41
17	D-16-14-21ccb	40.6	7.7	26	2.4	66	11	16	76	210	18	0.06	0.4	25
Agua Caliente Spring	D-13-16-20cdd	30.4	7.8	132.6	5.5	26.4	2.4	25.9	188.3	195.2	-	0.12	7.11	58

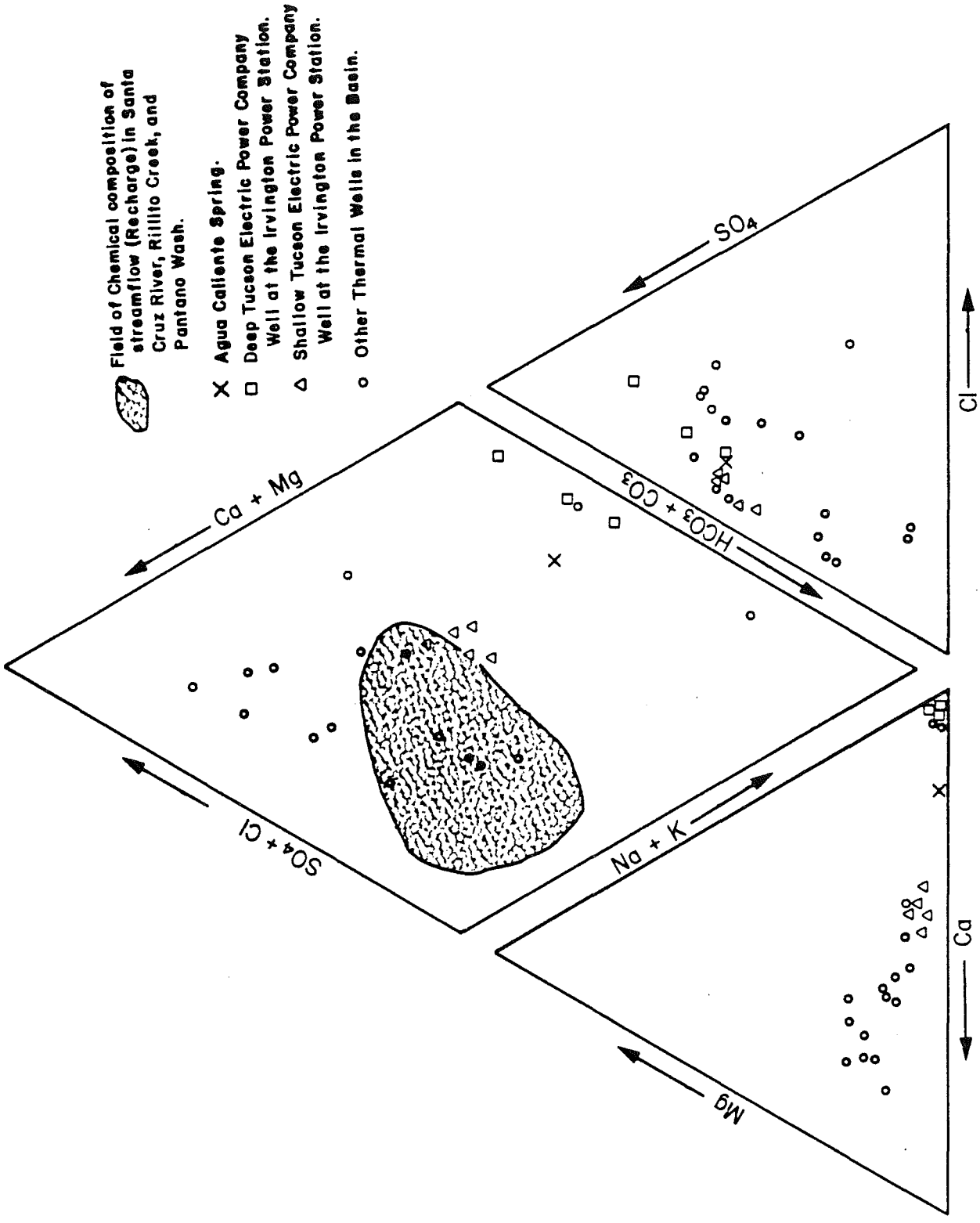


FIGURE 14 Piper diagram showing water chemistry of thermal water in the Tucson basin

occurs.

South of Tucson in Townships 16 and 17 south, Ranges 13, 14, and 15 east, numerous widely scattered thermal wells have been drilled. Distribution of these wells mostly reflects deep water well drilling by the City of Tucson. Exceptions are wells drilled for water supplies at mining operations near Sahuarita, west of the Santa Cruz River.

Northwest of Tucson, thermal water is pumped from two different areas near Cortaro. These wells are relatively shallow (<100 m depth) and have high estimated average temperature gradients. Individual thermal wells on the northside and eastside of Tucson, may have been intersected by thermal water related to the Aqua Caliente spring system.

Chemical quality of thermal water in the basin is generally good and is exceptable for most uses (Table 2). A few wells discharge high fluoride water which is unexceptable to drink by children. Total dissolved solids generally range between 300 and 700 mg/L and two distinct chemical grouping are observed. The highest temperature water is sodium sulfate type; while the majority of the thermal waters in the basin are calcium-sodium bicarbonate to calcium-sodium sulfate composition (Fig. 14). Nonthermal water in the basin is mostly calcium-sodium bicarbonate composition (Fig. 15).

Basin fill sediments (post mid-Miocene rock) act as a reservoir for known thermal water occurrences in the basin.

IRVINGTON ROAD AND I-10 ANOMALY. The first significant indication of a possible geothermal resource in the Tucson basin was described by Schwalen and Shaw (1957); although at the time it was not recognized.

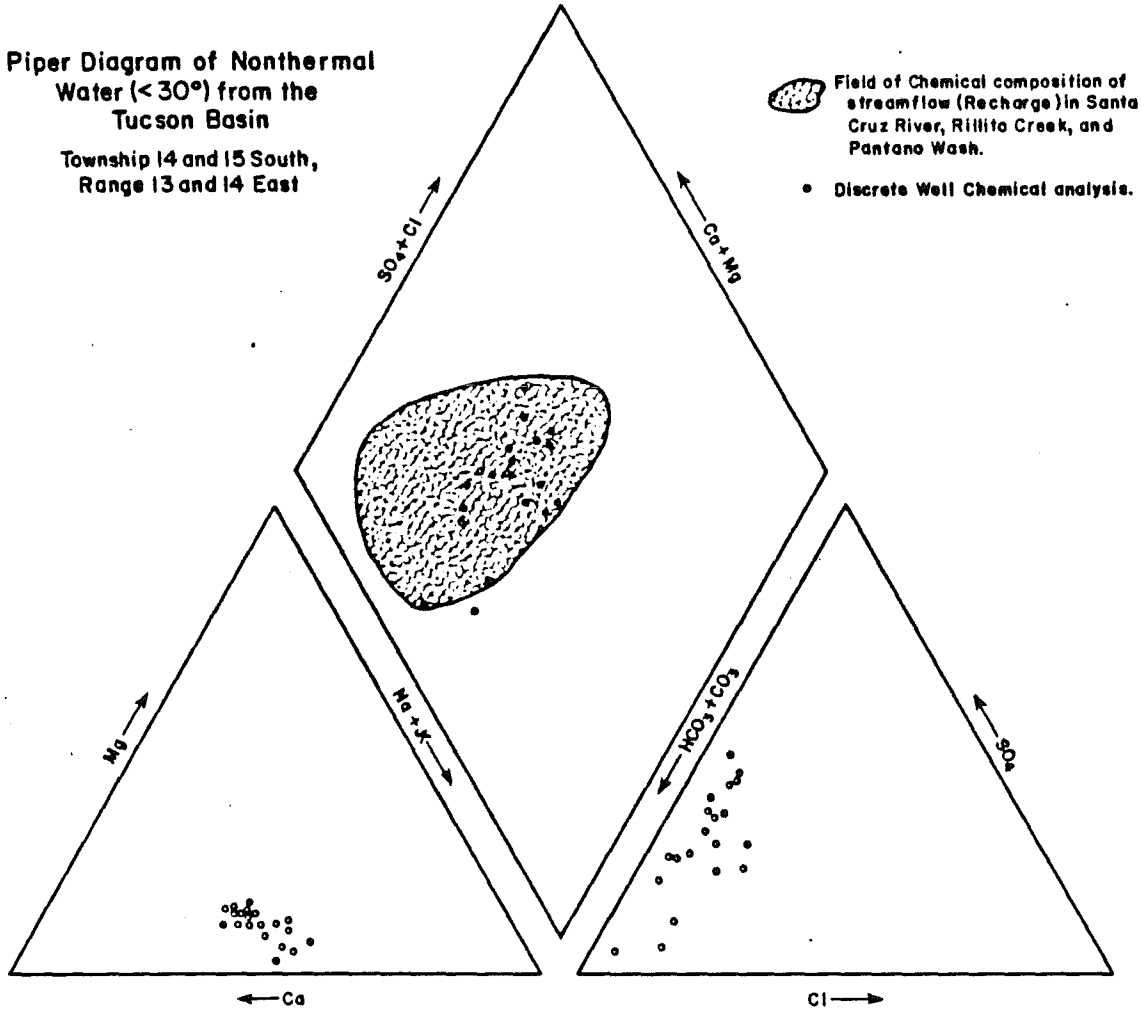


FIGURE 15 Piper diagram showing water chemistry of nonthermal water in the Tucson basin

Hot water encountered in a Tucson Electric Power Well (TEP 1, D-15-14-3bac) at the Irvington Power Station was considered a nuisance and a curiosity. During drilling of this well in 1956, the water temperature changed from 27.8 to 43.3°F; drilling was stopped at 350.5 m and the hole was cemented back to 341.4 m to prevent entry of hot water into the well (Schwalen and Shaw 1957).

Since 1956, eight additional wells have been drilled by TEP in sections 2 and 3 Township 15 south, Range 14 east. These wells range in depth between 250 m and 959 m and have temperatures that range from 30°C to 57°C (Table 1). TEP wells 5, 6, and 7 have depths between 700 and 960 and they pump the hottest known water in the basin (52 to 57°C) from depths below 400 m depth. Greatest production in TEP 5 is from about 563.9 m depth (files, USGS, Tucson).

Other TEP wells, all less than 350 m depth, pump 30 to 33°C water. A temperature log of the upper, unperforated and cased interval of TEP 5 (Fig. 16) indicates that most water production in other nearby wells probably comes from depths less than 200 meters. The concave temperature-depth profile above 200 meters results from downward transport of heat by water movement. The concave interval correlates with permeable sand and gravel deposits. Through this zone, ground water flows laterally down the hydraulic gradient which is caused by nearby pumping wells and a sloping water table. The temperature gradient (57° km) below 200 m is linear and indicates a conductive thermal regime (no water movement). Extrapolation of this gradient up to the surface and down to 564 m depth gives temperatures near the mean annual air temperature (19-20°C) and discharge temperature (52°C) of TEP 5 respectively. These data indicate a conductive

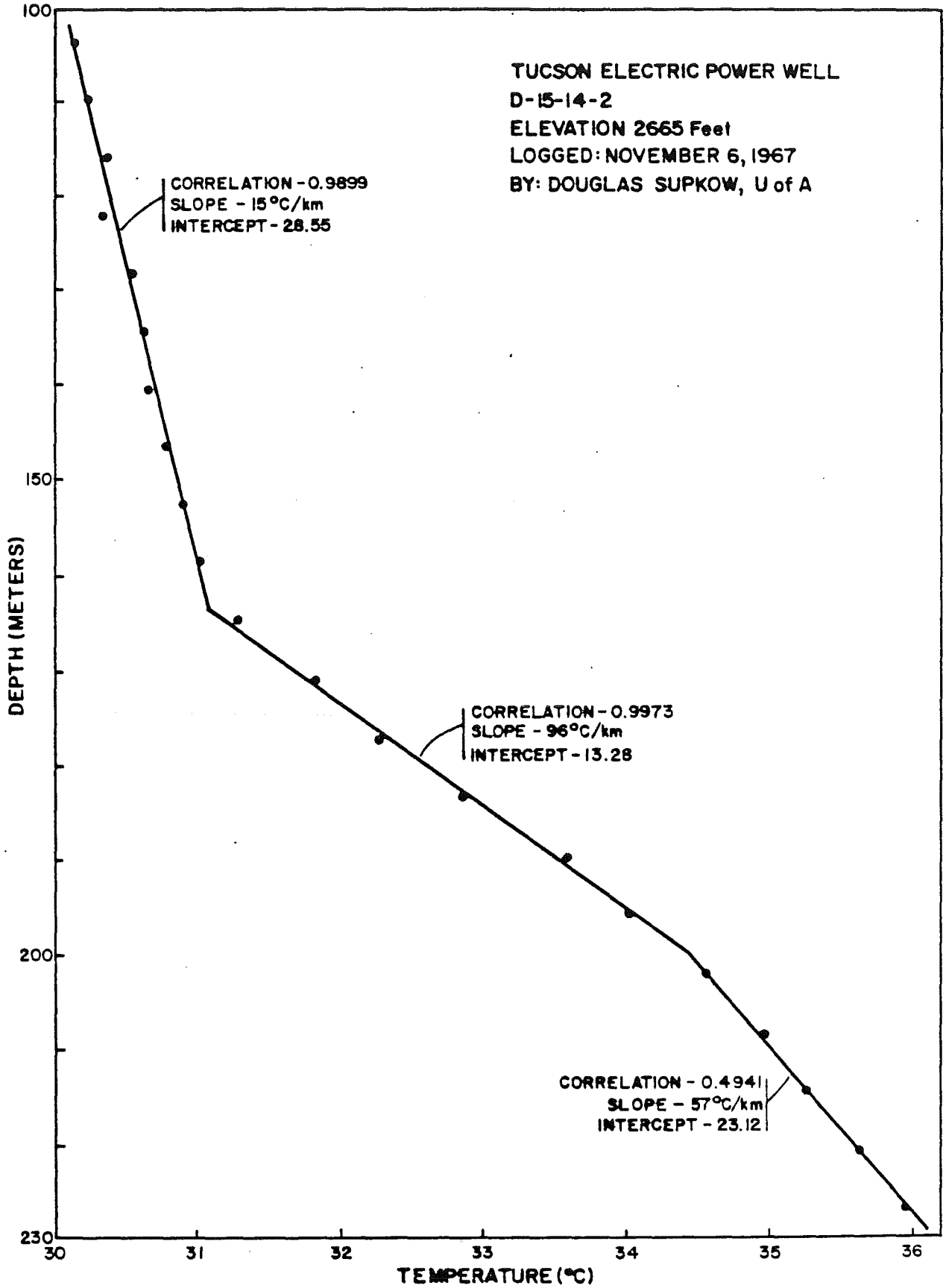


FIGURE 16 Temperature log of well D-15-14-2 cac

thermal regime between 200 m and the underlying thermal aquifers. This 57°C/km conductive gradient is anomalously high compared to normal basin gradient of about 35 to 40°C/km.

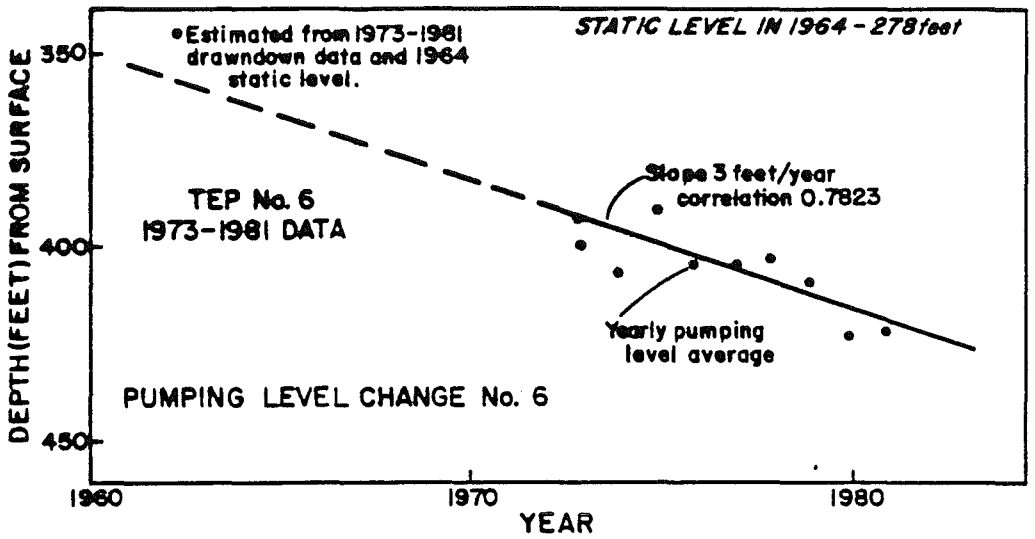
Ground water chemistry of the shallow TEP (<350 m) wells is distinct from the deep (>700 m) wells. The deep water has lower calcium, magnesium and bicarbonate and higher sodium, sulfate, chloride, and fluoride concentrations than the shallow water. The composition of deep geothermal water is sodium sulfate while the water from the shallow TEP wells is calcium-sodium sulfate (Fig. 14). The shallow TEP wells are chemically typical of both shallow ground water in the basin and surface water flow and runoff in local drainage (Fig. 14). Deep geothermal water encountered by wells TEP 5 and 6 has very high pH (>9.0) and relatively low silica concentration (<40 mg/L). Silica concentrations in the deep waters are in approximate equilibrium with quartz at measured temperatures. A correction for silica dissociation at high pH was calculated before estimation of silica geothermometers.

Geohydrology of the Irvington and I-10 area is somewhat complex. During drilling of the TEP 1 well in 1956, water was initially encountered at 44.8 m depth (2,468 feet elevation); however, after the hole was cased and perforated below 73.2 m, the static water level was 57.3 m depth (2,427 feet elevation). This 12.5 m drop in the static water level suggests either confined water below 73 m or a perched water table above 73 m.

The deep geothermal aquifers (>500 m depth) are apparently confined and hydrologically separate from the shallow (<200 m depth) aquifers. Evidence for confined conditions was observed during drilling of TEP 4, a shallow well, and TEP 5, a deep well. In November, 1959, TEP 4 had a static

water level of 57 m (2,413 feet elevation). TEP 4 was perforated at 73 to 261.5 m depth. In January, 1960, TEP 5 was completed to 762 m depth with perforated casing at 310 to 627 m. Static water level in this well was 87.5 m depth (2,378 feet elevation). A difference of 10.7 m in static water level is observed between TEP 4 and TEP 5. Actually the hydraulic head difference between the two wells is much greater because the shallow water table slopes upward from TEP 4 to TEP 5. If the shallow water table were similar to that observed in 1956 (Fig. 12), which is reasonable when considering that 4.27 m separates the TEP 1 (1956) level and the TEP 4 (1959) level (in conformance with the 1956 water table; thus, the total difference in hydraulic head between the deep water and the shallow water may approach 21 m.

Transmissivity values were determined for TEP 5 by the University of Arizona Soils and Water Engineering Department in 1966. Drawdown transmissivity was 670,000 L/day/m (54,000 GPD/FT while the recovery transmissivity was 780,000 L/day/m (63,000 GPD/FT). Prior to the test, the static level was 92.4 m; at the end of the test, the pumping level was 108.8 m. During testing of this well, which is perforated between 310 and 627 m, an approximate 6810 L/min (1,800 gpm) discharge rate was maintained. The deep thermal aquifer is very productive. However, since development of these wells by TEP, significant well pumping level drop has been observed. Figure 17 shows the historical pumping level drawdown. For the last twenty years; TEP 6 pumping level has dropped at .9 m (3 feet/year) while the TEP 5 pumping level has dropped 1.4 m (4.5 feet/year). Both wells have pumped up to 6100 L/min (1,600 gpm) almost continuously during this time. Heavy pumping, well interference, facies changes and possibly nearby



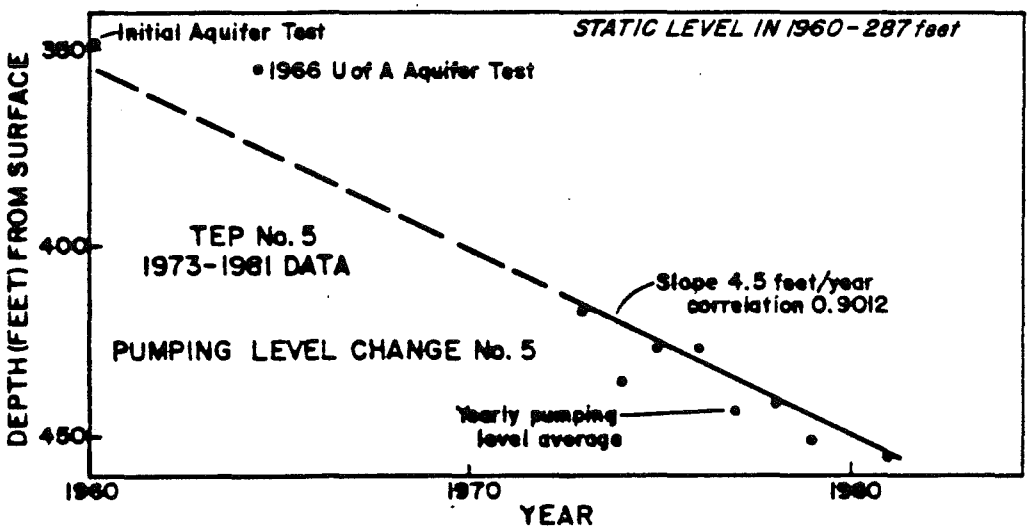


FIGURE 17 Historical pumping level drawndown in wells D-15-14-2cac and D-15-14-3dad

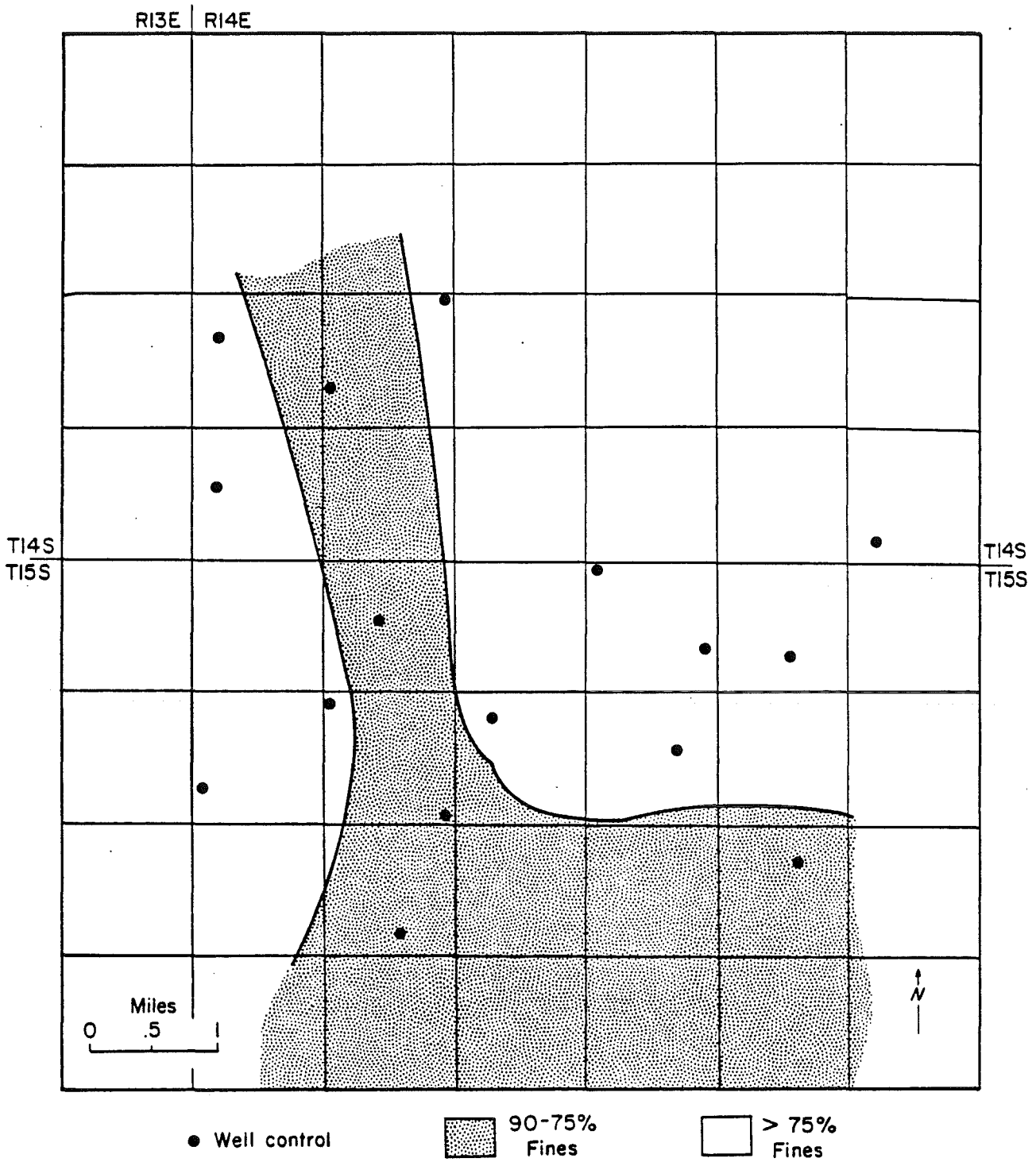


FIGURE 18 Map of percent fines between 122 and 213 m depth

fault zones may all contribute to these drawdowns.

On a regional scale, the anomaly Irvington and I-10 anomaly lies on the intersection of the northeast-trending Morenci lineament and a major northwest-trending crustal discontinuity, while locally, this anomaly occurs on the northern margin of a large complex graben that is indicated from Bouguer gravity Maps (Fig. 5).

Approximately coincidental with the thermal anomaly, a northeast trending ground water fall of uncertain origin is observed in the basin. Possible explanations for the ground water fall include a fault zone or a facies change; or it may simply be the margin of a large ground water depression, caused by heavy pumping in Tucson. Lithology logs of wells from the area around Interstate 10 and Irvington Road show a north-northwest trending zone of mostly mudstone, clay and siltstone. Figure 18 is a generalized map of percent fines (<0.062 mm) between 122 and 213 m depths. The axis of the north-northwest trending zone is characterized by lithology with greater than 90 percent clay.

Figure 19 is a map of dissolved sulfate. Highest sulfate concentrations occur in the north-northwest zone of high percentage of clay and silt. Relatively close-spaced gravity contours parallel both the zone of higher sulfate ground water and the clay and silt zone; they may indicate a major Basin and Range fault zone. The elongated nature of the clay distribution and its correlation with a gravity gradient may be evidence of deposition in a sag pond type environment next to a major fault zone which is now buried. A narrow facies change to sand and gravel west of the clay zone and a more gradual change to sand and gravel east of the zone supports

DISSOLVED SULFATE IN SHALLOW (<300m) IN A PORTION OF THE THE TUCSON BASIN

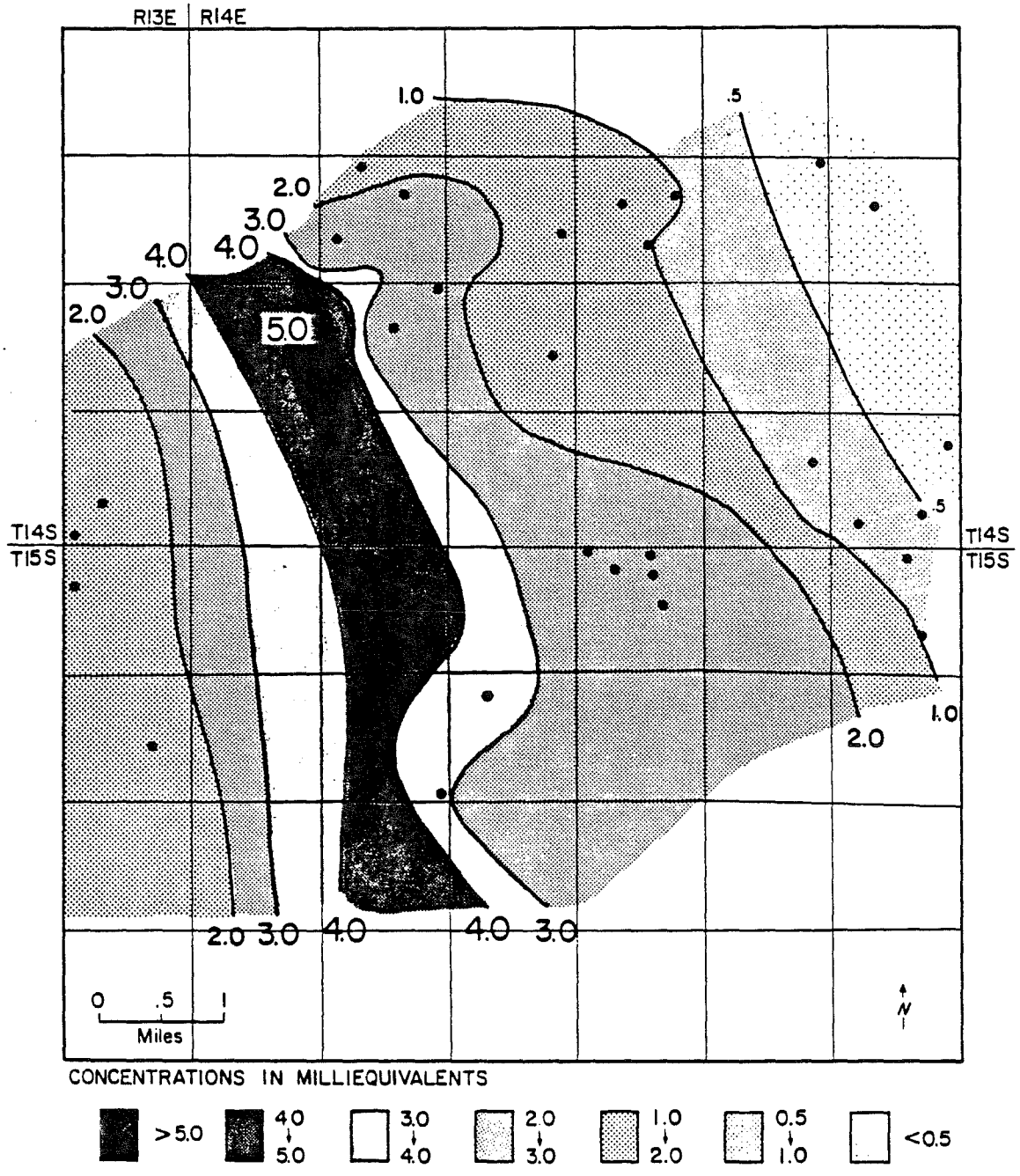


FIGURE 19 Map of sulfate distribution in ground water

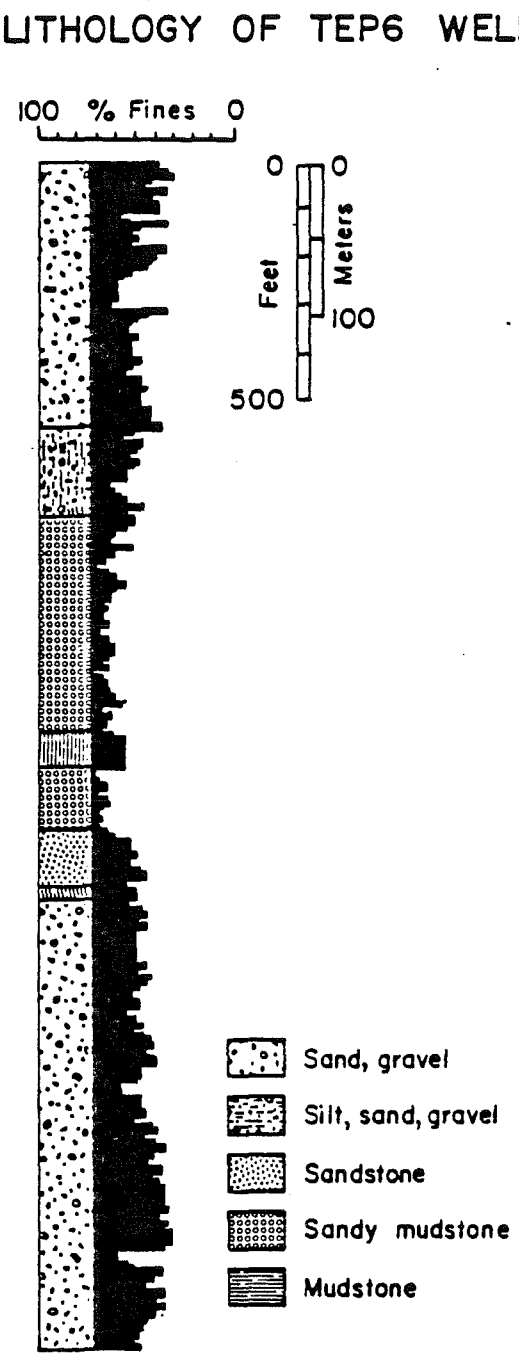


FIGURE 20 Lithology log of Tucson Electric Well 6

this inferrance; however this same distribution of basin fill could have resulted from a westward displacement of the toe of an alluvial fan toward the Tucson Mountains. Such a fan would have derived its detritus from the higher Catalina-Tanque Verde Mountains. The clayey zone thickens and widens to the south in an area that Bouguer gravity data indicates a large deep graben.

Thermal water encountered by TEP wells 5, 6, and 7 is contained in indurated sandstone and conglomerate below 427 m depth. These deep sediments have a more varied composition than overlying finer grained sediments. Figure 20 is a lithology log of TEP 6. Mudstone and sandy mudstone between 229 and 427 m depth separates thermal water from shallow ground water above 305 m depth. This confining mudstone unit apparently thickens and becomes gypsiferous to the south and southwest. Indurated sandstone and conglomerate which contains thermal water may occur at greater depth in these areas below the mudstone.

The Humble State 32-1 Hole (D-16-15-5Ca) was drilled through gypsiferous mudstone from 351 m depth to about 823 m depth. Below 823 m depth this hole encountered sandstone and conglomerate with interbedded siltstone. The temperature of the mud increased noticeably at 1,158 m according to the geologists' log of this hole which is on file at the Arizona Oil and Gas Conservation Commission, Phoenix. This increase may have resulted from thermal water entering the drill hole.

CONCLUSIONS. A large volume of thermal water (40 to 60°C) is inferred to occur in portions of the Tucson basin below 549 m depth. Well producing water from this reservoir were drilled between 762 m and 945 m depth in the

Irvington-Interstate 10 area. This thermal water is chemically distinct and physically separate from shallow ground water currently used for Tucson water supply. The geothermal water is softer than shallow ground water; but, it contains high fluoride. This thermal water is apparently not connected hydrologically in any simple fashion to shallow ground water. While upward leakage may occur, its role in recharge to shallow aquifers is probably insignificant; or otherwise, the shallow water would have a very distinct chemical and temperature affinity with the deeper thermal water.

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