Reconnaissance Assessment of the Geothermal Potential of San Bernardino Valley, Cochise County, Arizona

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by

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Prepared for

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SUMMARY

San Bernardino Valley, Arizona became an area of geothermal interest because of recent volcanic activity (≤ 3 m.y. old), young fault scarps, high geothermometers (to 229°C), and a geophysical anomaly. Geothermal leases were initially acquired in about 1979.

The highest surface discharge temperature in the valley is 32°C, not 40°C as previously reported. This 32°C water occurs at San Bernardino Ranch along the international border. It results from forced convection of deeper ground water as the ground water flows south into Mexico through the constricted basin outlet. The bedrock constriction can be seen on the gravity map. Lateral flow of ground water into this area where the water table is converging with the land surface elevation also contributes to the warm water occurrence. Water that is 27°C at 300 m depth at the northern end of the valley is near the surface at the southern end.

General geology of the valley is that of older basalts (3 m.y.) at higher elevations along the valley margins and presumably in the center of the valley, where they are covered by younger basalts (1 to 0.3 m.y.) and cinder cones. Mountains on both sides of the valley are composed chiefly of Miocene to Late Cretaceous rhyolite flows, ash-flow tuffs, and volcaniclastic sediments. Thicknesses and occurrences of sedimentary and Tertiary volcanic rocks beneath the basaltic rocks in the basin are poorly constrained because few deep holes have been drilled in SBV. Beneath the basalts, mid-Tertiary volcanic rocks most probably unconformably overlie a thick Paleozoic sequence, which in turn rests unconformably on Precambrian basement. The presence of Early Cretaceous Bisbee Group rocks is controversial.

Several regional structural grains in southeastern Arizona have been periodically reactivated during different geologic times, principally along WNW, NW, and NE trends. Basin structure in SBV today is one of north-south to north northeast orientation, faulted or tilted down on the west. The graben is bounded east and west by high-angle normal Basin and Range faults. Faulting and basin subsidence essentially ceased about 1 m.y. ago.

A major geologic structure in the valley is the mid-Tertiary Geronimo Trail cauldron, a collapsed caldera about 22 km in diameter. Intersection of the cauldron ring-fracture zone with a high-angle Basin and Range fault could provide an area of important fracture permeability for deep flows of water. In New Mexico, intersection of the Animas fault with the ring-fracture zone of the Muir cauldron provides structural control for thermal fluids at the Lightening Dock KGRA.

Geologic maps and reports and reconnaissance field checks suggest that

locally bleached, hydrothermally altered volcanic rocks and outcrops of Paleozoic limestone were mistakenly identified as "exposed igneous plugs" of possible Quaternary age during interpretation of an aeromagnetic survey. There is no evidence for an igneous heat source in San Bernardino Valley.

Temperatures were measured in nine holes and gradients are high to normal in all of them. However, only two wells, both at the southern end of the valley, were deep enough to intersect the water table. In these two holes gradients are very high (108 to 85°C/km) above the water table, but fall off to very low (11 to 4°C/km) below the water table. We suspect this condition would be found in all of the holes if they could be measured to some depth below the water table. The temperature-depth curves of the two deep drill holes are characteristic of a forced convection system augmented by lateral flow of ground water. The high gradients above the water table merely reflect the difference between the mean annual surface temperature and the enhanced temperature of ground water at the water table. They do not reflect high heat flow beneath the aquifer.

High geothermometers calculated for San Bernardino waters are unreliable. A review of water chemistry shows that silica and cation contents in ground water are controlled by lithology and acidity (dissolved carbon dioxide) rather than by temperature-dependent reactions. Measured temperatures and qualitative geothermometers are more reliable, but these indicate nonthermal waters in the valley, except possibly at San Bernardino Ranch.

San Bernardino Valley, Arizona has been seismically inactive during historic times, but young fault scarps indicate recent and continuing tectonism, although at a diminished rate. San Bernardino Valley, Sonora experienced a major earthquake (M about 7.2 to 7.4) in 1887, about 55 km south of the international border.

The nearest electrical transmission line is a 69 kV line owned by Arizona Public Service. The line comes down Sulphur Spring Valley (west of SBV) and then east as far as Douglas, which is about 11 km west of the Johnson Windmill prospect. Distribution lines (25 and 7.2 kV) owned by Sulphur Spring Valley Electrical Co-op, Willcox and Columbus Electric Power, Deming provide electricity to ranches at the northern end of the study area. About 800 km^2 at the southern end of the valley are not on electrical distribution lines.

Direct-use applications for low to moderate temperature geothermal energy are extremely limited, as ranching is the only occupation in the valley.

San Bernardino Valley lies in the north northwest extension of the Pedregosa basin, which has been favorably compared with the Permian basin. Oil and gas potential is considered good, but deep oil-and-gas wildcats drilled in the valley have been unsuccessful to date.

CONCLUSIONS

There is no igneous heat source in San Bernardino Valley. High geothermal gradients are caused by forced convection and lateral flow of ground water, and are not related to high heat flow. High geothermometers are caused by nontemperature-dependent chemical reactions and are invalid indicators of high-temperature waters at depth. Measured temperatures and qualitative geothermometers indicate nonthermal water in San Bernardino Valley. A possible exception may exist at San Bernardino Ranch where 40°C water could be encountered at shallow depths. We do not believe water much warmer than 40°C exists in the valley at a reasonable depth.

It is difficult to rank the prospect areas because geothermal potential is not indicated. Nonetheless we suggest Cottonwood Draw has most potential on the basis of measured temperatures; Baker Springs has the second most potential on the basis of known structure. Johnson Windmill appears to have the least potential.

RECOMMENDATIONS

We recommend that the geothermal leases and lease applications held in the Johnson Windmill, Cottonwood Draw, and Baker Springs prospect areas be dropped. Potential for electrical generation is non-existent. Direct-use potential is minimum to non-existent.

INTRODUCTION

Geothermal leases were acquired in San Bernardino Valley, Arizona, in about 1979 by Southland Royalty Company. Based on a proposal to the Southwest Border Regional Commission in 1980, the area was considered a favorable geothermal prospect for the following reasons: (1) extrusive basaltic rocks, which cover large areas of the valley surface are 3 m.y. old and younger; (2) numerous very young cinder cones in the valley; (3) recent igneous intrusions beneath the surface lava flows, indicated from geophysical studies; (4) numerous warm wells with measured surface discharge temperatures between 30°C and 40°C; and (5) reservoir temperatures between 100°C and 200°C, indicated from preliminary chemical geothermometers. The leases were later acquired from Southland Royalty by Trans-Pacific Geothermal, Inc.

PURPOSE. The purpose of this study has been (1) to make a preliminary evaluation of the three geothermal prospect areas in San Bernardino Valley; (2) to rank them in terms of relative value; (3) to recommend which leases to retain, transfer, or abandon; and (4) to recommend additional exploration work in areas that appear favorable.

SCOPE. The geology of the San Bernardino volcanic field has been adequately described by Lynch (1972) and reviewed by McMurdie in 1979. Therefore, we have treated the general geology of the area only briefly. Instead we have emphasized local and regional structure and tectonic setting as they affected southeastern Arizona in general and San Bernardino Valley (SBV) in particular. Additionally, we have interpreted the geochemical and temperature data sets in detail because they can target a heat anomaly and because qualitatively they provide information on its depth, extent, and possible maximum temperature.

To make this evaluation, we have reviewed all published and unpublished data and reports; held detailed discussions with collegues who have worked in SBV; collected additional chemical and temperature data; compiled and evaluated new and existing chemical, temperature, and geophysical data; located nearby electrical transmission lines; examined potential direct-heat uses; and compiled an up-to-date bibliography. Finally, because the Paleozoic and Mesozoic rocks of the Pedregosa basin, which underlies southeastern Arizona, are of interest in petroleum exploration, we have included a statement on the oil and gas potential of the geothermal prospect areas.

LOCATION. The Baker Springs, Cottonwood Draw, and Johnson Windmill prospects lie within T 23-24 S, R 29-32 E, in San Bernardino Valley (figure 1), a southern continuation of San Simon Valley (figure 2). This region is located in Cochise County, in the extreme southeastern corner of Arizona,

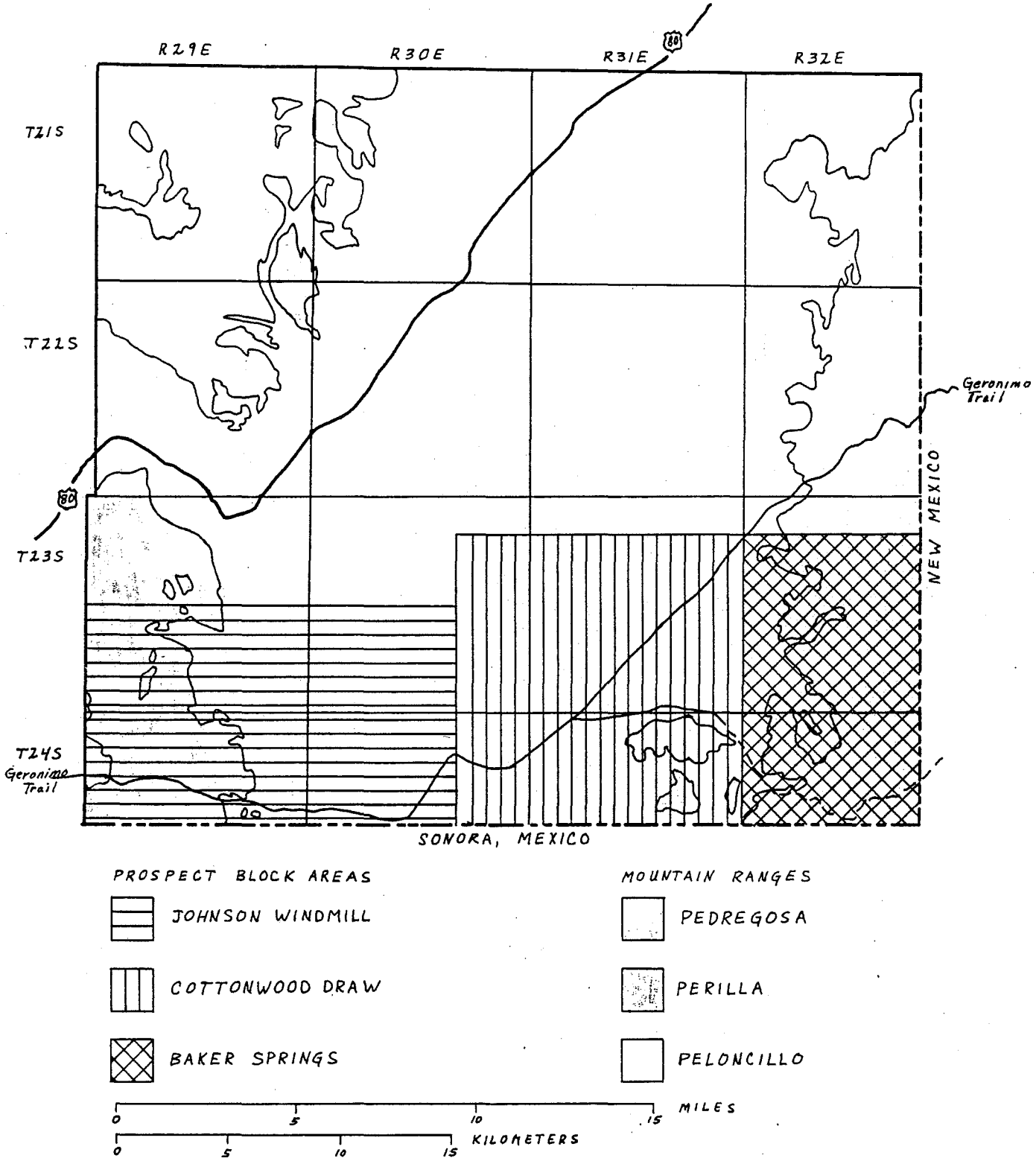


Figure 1. San Bernardino Valley and area of this report. Also shown are prospect blocks, mountain ranges, and major roads.

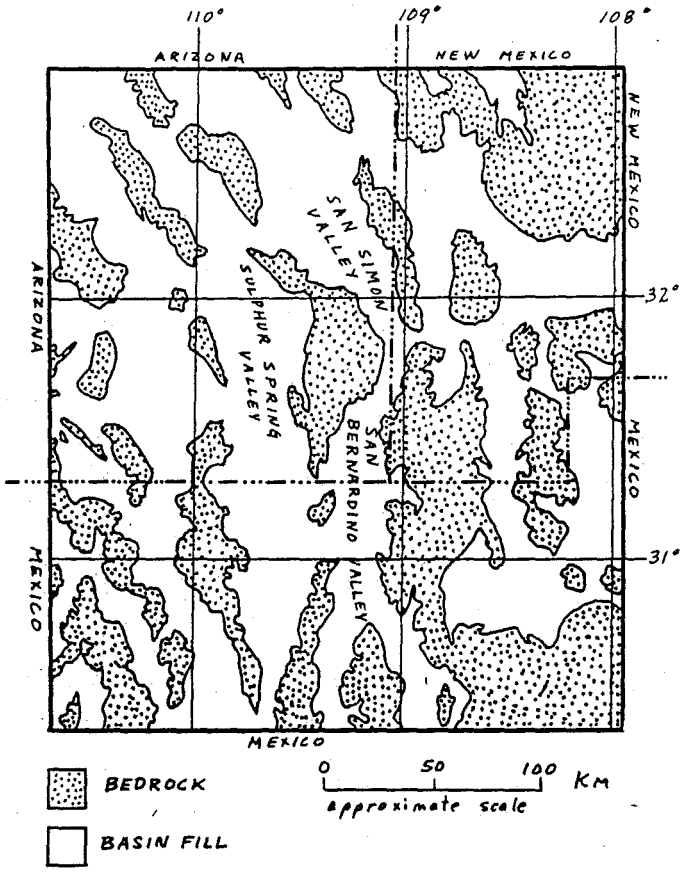


Figure 2. Generalized map of southeastern Arizona and adjacent areas in New Mexico and Mexico. This map illustrates the continuation of San Bernardino Valley into Sonora, Mexico.

along the border of New Mexico to the east and Mexico to the south. The closest town of size is Douglas, Arizona, about 13 km west of the Johnson Windmill prospect.

PHYSIOGRAPHY. San Bernardino Valley lies within the southern Basin and Range physiographic province, Mexican Highland subprovince. Compared with other subprovinces, the Mexican Highland section has generally higher elevations and a valley-to-range ratio of 1:1. By contrast, the Sonoran Desert subprovince to the west has elevations that are generally 600 to 900 m lower than those in the Mexican Highland section and a valley-to-range ratio of greater than 4:1.

SBV trends north-northeast to nearly north-south. It is 20 to 25 km wide and has a total length of about 100 km. Approximately two-fifths of the valley is in Arizona and the remaining three-fifths is in Sonora, Mexico (figure 2). The valley is bounded at its northern end by the southern terminus of the Chiricahua Mountains on the northwest and the southern end of San Simon Valley on the northeast. It ends against the northern margin of Sierra El Tigre in Sonora. El Tigre Valley and Bavispe Valley bifurcate at Sierra El Tigre, continuing southwest and southeast, respectively, from SBV. In Arizona, the Peloncillo Mountains lie to the east of the valley; the Pedregosa and Perilla Mountains comprise the western boundary (figure 1). These mountain ranges are uniformly about 1,000 m higher in elevation than the adjacent valley floor, which has an elevation of about 1,500 m at the northern end and 900 m at the extreme southern end in Sonora.

General elevation of the prospect area is 1,200 m; the topography is gently rolling to flat. Exceptions are low hills in the Cottonwood Draw and Johnson Windmill blocks (elevations to about 1,470 m), and the higher mountainous terrane in the Baker Springs prospect (elevations to 1,825 m). We have included appropriate USGS topographic maps, scale 1:62,500, to show the detailed lease holdings relative to the local relief and topography (See Plates I and II in pocket.)

ACCESSIBILITY. The southern part of SBV lies south and east of paved U.S. Highway 80, which connects Douglas, Arizona with Lordsburg, New Mexico. Dirt roads extend south from the highway into the block area, but are generally inaccessible because they cross patented ranch lands and they are in poor condition owing to numerous bad washouts where the roads cut across the drainage. A graded dirt road, the Geronimo Trail, connects Douglas with the southern Animas Valley, New Mexico, via a pass through the Peloncillo Mountains. Numerous ungraded dirt roads extend from the Geronimo Trail into nearly all parts of the Johnson Windmill and Cottonwood Draw prospects. In a few areas, four-wheel drive is needed. The Baker Springs prospect comprises the most eastern block, has the most rugged

terrane, and is the least accessible. Roads into Baker Spring (the spring itself) are inaccessible even by 4WD, according to a nearby rancher. Hiking and horseback are the only ways into all but the southern part of this prospect.

CLIMATE. The prospect areas lie in a typically semi-arid portion of the southwestern United States. Mean annual air temperature is 17°C and mean precipitation is 11.8 inches annually at Douglas. Rainfall occurs as desert thunderstorms mostly during July and August. Washed-out roads are especially common during this season. Gentle rains occur during winter. Winds in SBV have been recorded up to 70 miles per hour.

LAND OWNERSHIP. Nearly all land in SBV is patented ranch land, state trust land, or national forest. Very little land is administered by the Bureau of Land Management. However, a block of land in the Baker Springs prospect area was declared a Wilderness Study Area, No. 4-70, by the BLM on July 18, 1980. This WSA block comprises sections 14-15, 22-23, and 26-27 in T 23 S, R 32 E. Sections 22-23 and 26-27 are part of Trans-Pacific Geothermal's Baker Springs geothermal prospect (See Plate I). Geological studies of this area by the USGS have been completed, but publication date is uncertain. This land will remain a WSA until the BLM recommends it to be removed or until it is declared a Wilderness Area by the U. S. Congress. WSA status does not preclude geothermal exploration, but development of a resource could be delayed for many years or simply prohibited. In any case, action by the BLM and (or) Congress is likely to take years.

PREVIOUS WORK (Published). Prior to a master's thesis on the San Bernardino volcanic field that was based primarily on aerial photogeologic mapping and a gravity survey (Lynch, 1972), work in this region was limited to stratigraphic and structural studies of surrounding mountain ranges, theses on the Paleozoic limestone outcrops at the southeastern end of the valley, chemical analysis of the San Bernardino basalts, and a reconnaissance geologic map of southeastern Cochise County. These papers have been reviewed by Lynch (1972).

In the past ten years, a great deal has been published on the structure, stratigraphy, and tectonic history of southeastern Arizona, much of which is relevant to SBV on a regional scale. Work specifically in SBV since Lynch consists of maps showing ground-water conditions, a passive seismic survey, a geomorphic analysis of neotectonic features, and a chemical analysis of spinels from the basaltic lavas. Erb (1979) completed a Ph.D. dissertation on the southern Peloncillo Mountains and associated large cauldrons of southeastern Arizona and southwestern New Mexico.

(Unpublished). Unpublished work on San Bernardino Valley, contained in the confidential files of Trans-Pacific Geothermal, Inc., consists of a

review of the local geology, interpretation of an aeromagnetic survey over the valley, Na-K-Ca and silica temperatures, and temperature-depth measurements. We incorporated the temperature and chemical data into the data we collected during the present study. Following are discussions of the geologic and aeromagnetic reports.

The geology of SBV, as presented in the geologic report, was taken almost exclusively from the Lynch thesis. Additional information appears to have come from the aeromagnetic report, well logs, and a 1976 paper on Arizona seismicity. Geochemical temperatures and temperature-depth data were appended to the report, but were not mentioned or evaluated. The author suggested locations of potential reservoirs. However, these suggestions were weakly based on the coincidence of gravity and aeromagnetic "lows", without respect to the possible causes for such geophysical anomalies, and with no attempt to correlate these anomalies with other information, such as thermal gradients, stratigraphy, or geochemical temperatures. We disagree with the conclusion that available information supports the existence of a "potential reservoir" if a heat anomaly can be found. Very little is known about the structure and stratigraphy, porosity and permeability of subsurface formations beneath SBV, except as might be extrapolated from studies of similar strata in other basins, such as the Permian basin. This is not to say reservoir conditions do not exist, only that such have not been proven.

We agree with the suggestion that SBV may be a potential oil or gas target. Petroleum leases have been acquired in SBV in the past and geologic evaluations of the valley have been made on this basis. The Pedregosa basin has been favorably compared to the Permian basin.

The aeromagnetic report identified two major "intrusives" 1,000 to 2,000 feet below the surface and three "igneous plugs" exposed at the surface in the southern part of the valley in Arizona. It is apparent that the aeromagnetic interpretation was made without benefit of geologic or topographic information. Published and unpublished geologic maps and reports clearly present no evidence of coarse-grained plutonic rocks exposed at the surface in SBV. The only exposed intrusive rocks are minor outcrops of fine-grained hypabyssal latitic to dacitic porphyries (61 to 65 m.y. old?) that occur in the southern Perilla Mountains, and mid-Tertiary(?) rhyolite dikes in the southern Peloncillo Mountains. A pluton probably underlies the Geronimo Trail cauldron (discussed later) in the southern Peloncillo Mountains, but its age is surely mid-Tertiary as are the ages of the latite and rhyolite flows and tuffs erupted from it (24.2 $\pm$ 0.52 m.y.). This pluton is likely to be much deeper than 1,000 to 2,000 feet beneath the surface, but it may be the cause of the southeastern aeromagnetic anomaly.

Several types of outcrops viewed on aerial photographs could have been interpreted as plutonic rocks. (1) Examination of white, bleached rock outcrops in, and float from several canyons revealed intense but localized zones of

hydrothermal alteration of the Tertiary volcanic rocks in the areas of the two southernmost "exposed igneous plugs". (2) Low small hills of Paleozoic limestone crop out just south of Paramore Crater in the immediate area of the third "exposed igneous plug". At the site visited, fragmental blocks imbedded in the ejecta from Paramore Crater included only rhyolitic and basaltic lavas and limestones. Lynch (1972) made no mention of seeing intrusive rocks in the Paramore Crater ejecta.

We believe the hydrothermally altered volcanic rocks and the limestone blocks were interpreted from aerial photographs as "exposed intrusive rocks". The causes of the aeromagnetic anomalies in SBV are uncertain. The unlikely temporal and spatial association of massive igneous plugs of Quaternary age with Quaternary basalts renders the given interpretation suspect. It would be instructive to reinterpret the data in conjunction with the known geology and structure of the valley.

Additional unpublished petroleum and geothermal exploration work has been carried out in SBV by major companies (Table I) and individuals over at least the past 25 years. The recent work by Union Geothermal is the most relevant to our study. Union leased 11,329.25 acres (five tracts) in SBV in March, 1980. They drilled a single 218-m gradient hole in T 23 S, R 30 E, sec. 8, in November. This hole had a reported "linear gradient of about 1.0°C/km" and a bottom-hole temperature of "less than 80°F" (26.7°C). Union also temperature logged a newly drilled ranch well about 4 km west of their gradient hole, and they had an 8-station MT survey run by Phoenix Geophysical, Inc. The MT survey was conducted principally to "field test the equipment" and reportedly "found nothing". Union dropped the leases on their two western tracts in March, 1981 and on the remaining three tracts about a year later.

SOURCES OF DATA. The data used in this report were collected during three trips to San Bernardino Valley, which totaled 20 field days. We also drew heavily upon conversations with Christopher M. Menges, who is completing a geomorphic analysis of neotectonic features in Arizona for the USGS, and upon published and unpublished maps and articles. While many reports are listed in the bibliography for completion, we relied largely upon the following: Cooper, 1959; Deal and others, 1978; Dirks, 1966; Drewes, 1980; DuBois and others, 1982; Epis, 1956; Erb, 1979; Greenwood and others, 1977; Kelly, 1966; Lynch, 1972; Natali and Sbar, 1982; Seager and Morgan, 1979; Swanberg and others, 1977; and Titley, 1976.

HYDROLOGY

GROUND WATER. Meteoric water falling in the mountains percolates downward and laterally toward the basin axis, at which point it flows down gradient into Mexico. Because the water table generally mimics topography, depth to water is about 180 to 200 m below the land surface along most of the length of the basin axis. This situation changes dramatically at the southern end of the valley, however. Whereas wells to the north are generally 250 to 300 m deep and require pumps, the more southern wells are often less than 50 m deep and the water can be lifted by windmill. Warm artesian wells have been flowing continuously for tens of years at San Bernardino Ranch along the international border.

The limited data suggest three simultaneous processes at work here. (1) The artesian wells demonstrate that at least at the southern end of the valley, southward-flowing ground water becomes confined beneath impermeable clays, such as were recorded in Union's lithologic log of the ranch well. Water in wells near the artesian wells is ten to less than one meter deep and is obviously confined. Whether such clays are ubiquitous in the subsurface or occur only locally is unknown. (2) As ground water flows south, the static water table is dropping at a slower rate than the surface elevation is decreasing. This condition results overall in shallower depths to water at the southern end of the valley. (3) Gravity (figure 3) shows that bedrock shallows to a saddle and causes the basin to constrict slightly north, and in the area of San Bernardino Ranch.

We believe the hydrologic conditions at the southern end of the valley are characterized by a shallow confined aquifer. The warmer temperatures measured for artesian waters at the ranch are a result of forced convective flow of deep ground water over the bedrock saddle at the constricted basin hydrologic outlet. Morgan and others (1981), concluded that this same mechanism is responsible for the low-temperature geothermal anomalies in the Rio Grande rift.

SURFACE WATER. Surface drainage in the valley is not well developed, to the extent that a through-flowing axial stream does not exist. In fact, the volcanic field occurs on a divide between two regional drainages. At the northern end of the valley, intermittent streams draining the Chiricahua Mountains flow northward into San Simon Valley and the Gila River system. South of that, intermittent streams flow into Silver Creek and Cottonwood Draw, and then into Mexico. These two streams join to become Rio San Bernardino about 2 km south of the border.

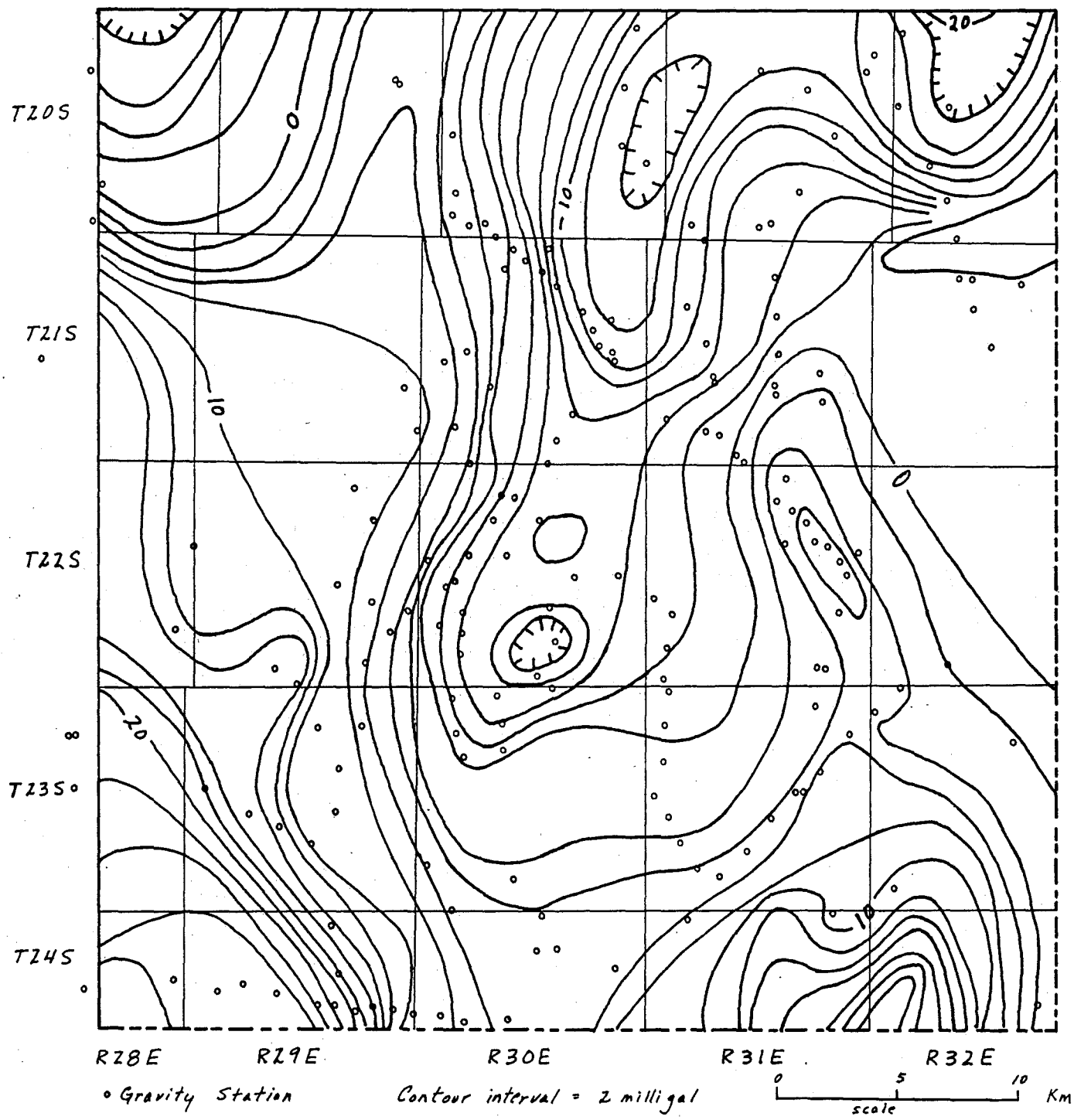


Figure 3. Complete residual Bouguer gravity map, San Bernardino Valley (from Aiken and others, 1980).

GEOLOGY

GENERAL GEOLOGY. The general geology of San Bernardino Valley and the adjacent ranges can be seen in figures 4 and 5. The valley margins are covered by older basalt lava flows (about 3 m.y. old) perched on the mountain areas. These older basalts are inferred to exist in the subsurface beneath younger lavas, which together with cinder cones cover most of the valley floor today. Recent gravel, sand, and silt cover the distal margins of the younger lavas.

The mountains on both sides of the valley are composed chiefly of Miocene to Late Cretaceous rhyolite flows, ash flow tuffs, and volcaniclastic sediments. Paleozoic and Mesozoic sedimentary rocks are exposed in isolated outcrops along the southeastern side of the valley. More extensive exposures of Mesozoic rocks are found in the western mountains. Late Cretaceous-early Tertiary (Laramide) latite to dacite porphyritic and aplitic rocks crop out at the southern end of the Perilla Mountains. Younger (24 to 29 m.y. old) intrusive rhyolitic to rhyodacitic plugs, laccoliths, and dikes crop out farther north in the Pedregosa Mountains. Rhyolite, quartz latite, and dacite domes and flows of Oligocene age have been mapped in the Peloncillo Mountains where they erupted along the ring fracture zones of the Geronimo Trail cauldron.

STRATIGRAPHY. San Bernardino Valley lies within the northwestern-most extension of the Pedregosa basin (figure 6), a region of late Paleozoic deposition that underlies southwestern New Mexico, southeastern Arizona, and northern Mexico. The basin was the site of thick sedimentation and pronounced subsidence particularly during Pennsylvanian and early Permian times. The Paleozoic rocks, which comprise a thick and extensive sequence of mostly dolomites and limestones, were deposited unconformaly on Precambrian basement. If Triassic and Jurassic rocks were laid down in the Pedregosa area, they were removed by subsequent erosion. Lower Cretaceous rocks lie unconformably on Permian, and are in turn unconformably overlain by Upper Cretaceous or Tertiary sedimentary or Tertiary-Quaternary volcanic rocks. Quaternary basalt and Recent gravels veneer the valley floor today.

Formations and thicknesses present in the SBV graben are not known with certainty. One estimate is that roughly 2,440 m of Paleozoic section underlie Tertiary-Quaternary clastic rocks beneath the prospect area and that Cretaceous rocks probably are missing. In contrast, another worker suggested that the section beneath approximately the same area consists of, in ascending order, 1,800 m of Paleozoic strata, 1,500 m of Lower Cretaceous Bisbee Group sediments, Tertiary volcanic rocks as much as 900 m thick, and 300 to 900 m of Tertiary-Quaternary basaltic lavas.

Well control, upon which stratigraphic interpretations can be based, is poor. Most wells in SBV are drilled for stock or domestic water uses, and

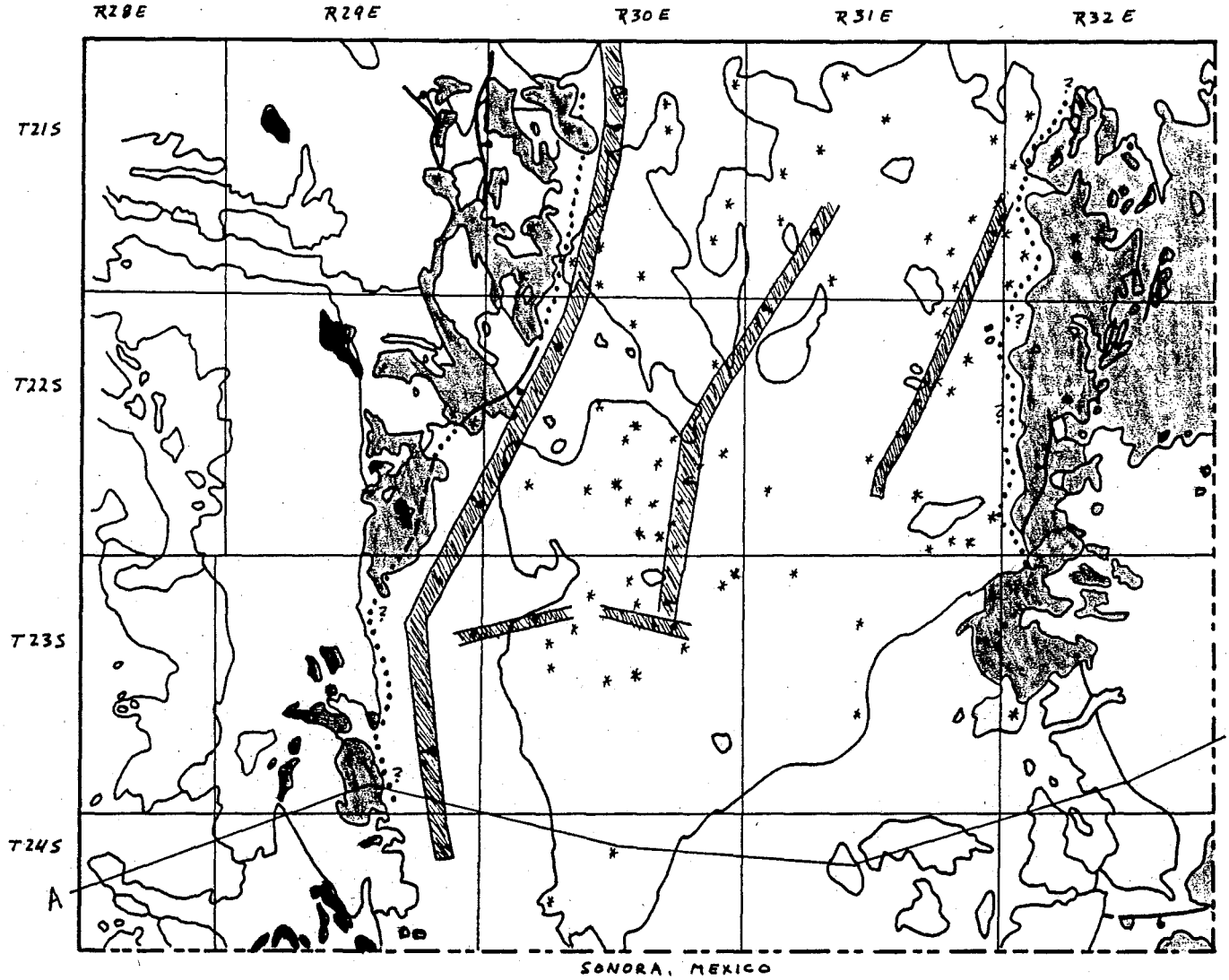
generally terminate in basaltic rocks. Up to 245 m of basalt flows have been encountered in a well drilled in the center of the valley. Only two deep oil and gas wildcats have been drilled in SBV (Table 1). Thus it is possibly only to speculate on the presence and(or) thickness of potential geothermal reservoir rocks in the subsurface, at this point in time.

STRUCTURAL HISTORY. Several regional structural grains, periodically reactivated during different geologic times, have been identified in southeastern Arizona. The earliest recognized is an older Precambrian (1.71 to 1.625 b.y.) NNE structure. Superimposed on this grain were younger Precambrian (1.41 b.y.) WNW-trending shears associated with batholithic intrusions throughout the state. The Paleozoic era was characterized by low-amplitude epeirogenic warping. During Triassic (?) to Early Cretaceous time, a series of NW-trending major linear discontinuities were activated in southeastern Arizona (figure 6), and reactivation occurred along the WNW trends. Most movement was vertical during this period. The NW linear discontinuities separate crustal blocks 30 to 40 km wide. One of these structures, the Dragoon discontinuity, crosses SBV. Because of periodic reactivation along these trends, discrete sections of this discontinuity could contain zones of important structural permeability.

A possible rift system(?), reactivated along WNW to NE trends, crossed Arizona during Early Cretaceous. Into the graben created by this rifting was deposited the Glance Conglomerate, basal unit of the Bisbee Group. Some reactivation occurred during this time along the NW-trending structures.

Between 90 and 85 m.y. ago, E-W to WNW steep reverse faults and wedge uplifts (basement-cored uplifts) resulted from NNE-SSW compression. NE overturned folding and NE-directed thrusting marginal to the uplifts were the dominant structural features. Latest Cretaceous to Paleocene calc-alkalic plutons and dike swarms with NE to E-W trends were emplaced between the WNW and E-W-trending faults. Details of Eocene tectonism are unclear in extreme southeastern Arizona except for the existence of a wide-spread erosional surface of this age.

Between 30 and 14 m.y. ago (mid-Tertiary) extensive intermediate to silicic volcanism was accompanied by crustal extension, mostly characterized by listric normal faults. Large plutons of intermediate and silicic compositions were emplaced at shallow crustal levels during this time. This mid-Tertiary magmatism resulted in large (greater than 15 km diameter) resurgent ash-flow tuff cauldrons in southwest New Mexico, extreme southeastern Arizona, and probably northern Mexico (figure 6). In Arizona, these cauldrons are restricted to the area roughly outlined by the thick Paleozoic sediments in the Pedregosa basin. One of these structures, the Geronimo Trail cauldron, forms the eastern boundary of SBV. The cauldron is an elliptical volcanic collapse feature 22 km long and 16 km wide, filled with the Guadalupe Canyon ash-flow tuff. The northern margin of the cauldron is obscured by a band of rhyolite flows and domes



Quaternary to Pliocene alluvium and basin-fill sediments

Younger basalt, Quaternary (less than 1.5 m.y.)

Older basalt, early Quaternary to late Pliocene (1.5 to 3.0 m.y.)

Ring fracture zone volcanic flows and domes associated with Geronimo Cauldron

Miocene to Late Cretaceous volcanic flows, volcaniclastic sediments, ash-flow tuffs

Laramide or Mid-Tertiary intrusive rocks

Late Cretaceous to Cambrian sediments, including Bisbee Group

0 5 10 MILES

0 5 10 15 KILOMETERS

* Cinder cone

Fault zone, dotted where concealed, queried where uncertain

Subsurface structure or structural basin boundary (inferred from residual gravity anomalies) bar and ball in down dip direction

A-A' Line of cross section

Figure 4. Generalized geologic map of San Bernardino Valley and adjacent mountain ranges.

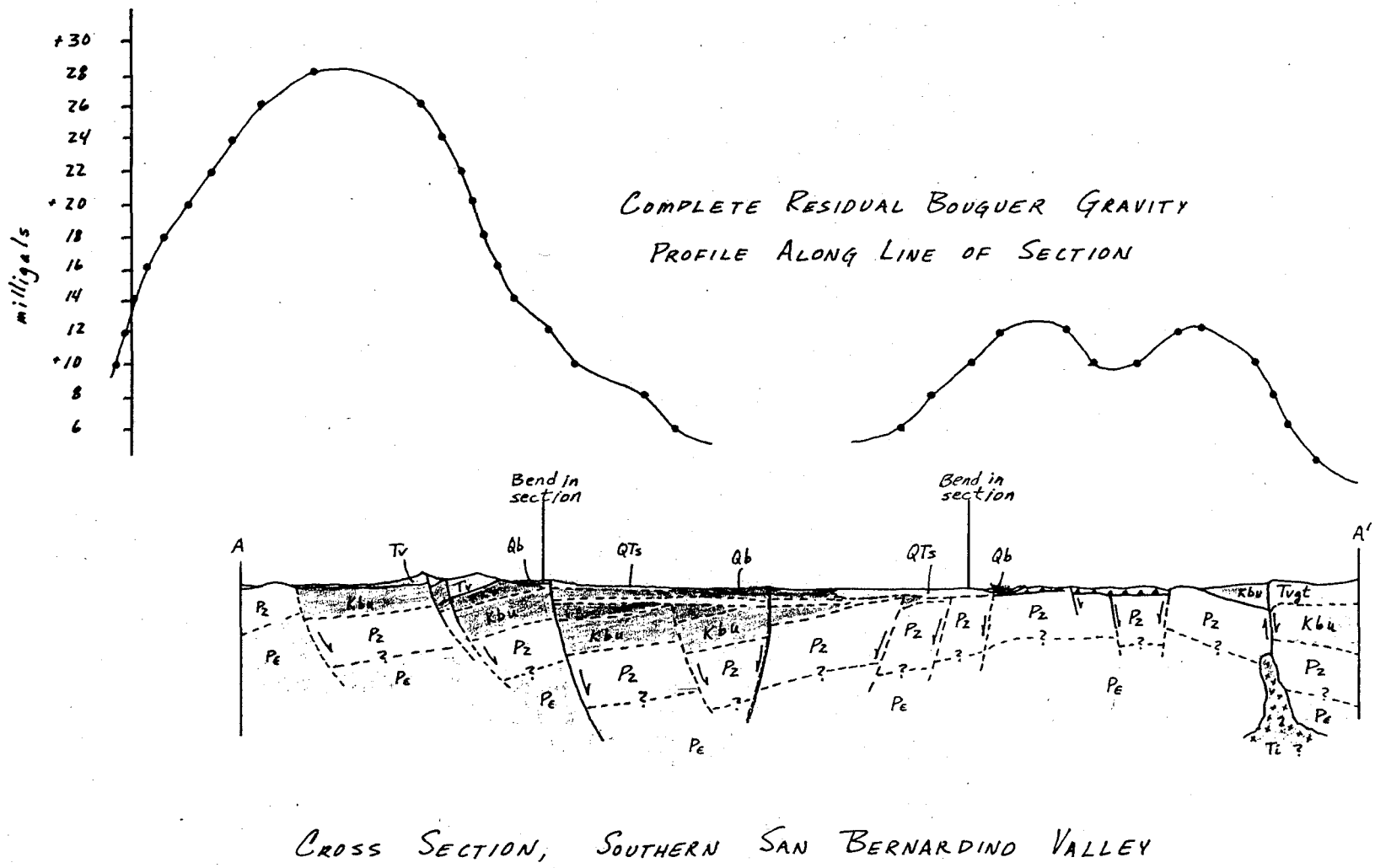


Figure 5. Generalized geologic cross section and complete residual Bouguer gravity profile across southern San Bernardino Valley. See Figure 4 for line of section.

TABLE 1. Exploration in San Bernardino Valley

Date	Operator	Location	Target	Survey	TD (m)	Remarks
1982	Phillips Petroleum	(D-23-29) 14bba	oil & gas	wildcat	2,152	Spudded in alluvium; term. in Lower Cret.seds. No oil, gas, water. Grad. 27°C/km. Well P & A. Leases dropped.
1980	Union Geothermal	(D-23-30) 8bab	geothermal	gradient hole	218	Gradient, "1°C/km", "linear"
	Union Geothermal	(D-23-30) 10dac	geothermal	temp. log	218	Gradient, 85°C/km
	Union Geothermal	same gen. area	geothermal	MT survey	-	Phoenix Geophysical ran to "field test eqpt.". "Found nothing". Leases dropped.
1977-79	Southland Royalty	T.23-24S., R.29-32E.	geothermal	temp. log	-	Several high gradients.
	Southland Royalty	same gen. area	geothermal	water samples	-	Several high geothermometers. Leases sold (?).
1971	Guadalupe Exploration Corp.	(D-24-31) 2caa	oil & gas	wildcat	1,731	Spudded & term. in Paleozoic. Initially "dry hole". Fresh water zone is 457m. Water level is 150m. Leases dropped.
1961	L. H. Thomson	(D-24-31) 2acd	oil & gas	wildcat	245	Small show of gas when plugging. Leases dropped.

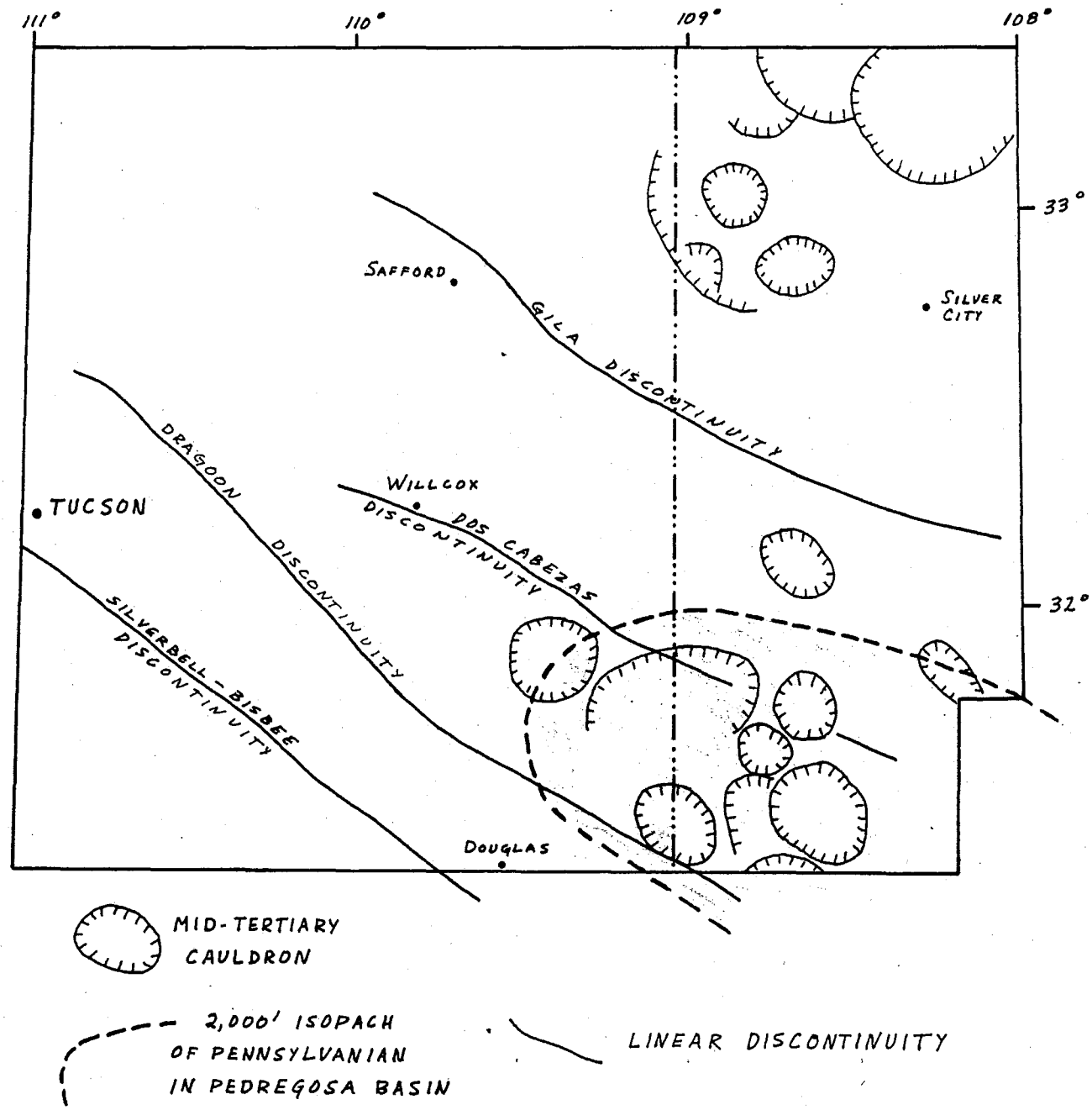


Figure 6. Extent of Pedregosa basin in southeastern Arizona. Also shown are major linear discontinuities and ash-flow tuff cauldrons of mid-Tertiary age.

erupted along the northern ring fracture during or after resurgent doming of the cauldron interior. The western and southern margins are formed by ring-fracture faults and latite-rhyolite domes (see figure 4). Strong mid-Tertiary hydrothermal alteration is locally intense along the faults and adjacent to the domes. The Baker Canyon fault, which is in the Baker Springs prospect area, is the largest segment of the ring-fracture fault observed along the western boundary. It displaced the cauldron facies of the Guadalupe Canyon tuff and the breccia of Hog Ranch into fault contact with the Lower Cretaceous Bisbee Group. Bisbee Group sediments and upper Paleozoic limestones are highly silicified along bedding planes and along faults in this region. Such silicification produces very brittle zones easily fractured by Quaternary tectonism. If such fractures remain open, they could provide important controls on deep flows of water.

The most recent structure to be superimposed on southeastern Arizona (between 13 and 5 m.y. ago) has been high-angle, normal block faulting on older NW, WNW, and E-W fabric and on new N-S breaks between the WNW and E-W systems. This faulting is associated with regional extension during the Basin and Range disturbance. Intersection of such deep-seated normal faults with ring-fracture zones of the Geronimo Trail cauldron also could provide important fracture permeability for circulating thermal fluids. A geothermal system in the Lightening Dock KGRA, New Mexico occurs in a ring-fracture zone on the margins of the mid-Tertiary Muir ash-flow cauldron. An intermediate-temperature geothermal system (between 102 and 170°C) is structurally controlled by the outer ring-fracture zone of this cauldron where it is transected by the Pliocent-Quaternary Animas Valley fault.

The past 5 m.y. in southeastern Arizona have been a time of less intense Basin and Range tectonism and significant pedimentation of mountain fronts.

PRESENT DAY STRUCTURE. Gravity (figure 3) shows that the San Bernardino graben strikes north-northeast to nearly north-south and is faulted or tilted down on the west. The two basins that can be seen in SBV, Arizona are separated from the basin(?) in Sonora by an erosional bedrock saddle or horst block in the area of the international border. This saddle plays an important role in the thermal manifestations (32°C water) in this area, as discussed in a subsequent section.

Geomorphic studies show that tectonism is very recent and(or) is continuing in the valley today. The anomalous tectonic nature of the SBV area is most evident from studies of Quaternary faulting in Arizona. An elongated region coincident with the valleys on either side of the Arizona-New Mexico border has a much greater occurrence of Quaternary fault scarps than other nearby valleys (figure 7). A similar band of young fault scarps occurs in the Rio Grande rift, an area that is geologically and structurally distinct from the rest of the southern Basin and Range province. Characteristics of the Rio Grande rift include (1) generally deeper structural basins, (2) more Quaternary fault scarps, and (3) Quaternary volcanism. Because SBV and its extensions to the north and south

collectively show characteristics similar to the Rio Grande rift, Seager and Morgan (1979) suggested that SBV may also be a discrete, incipient rift system with its own strip of anomalous crust and mantle.

GEOMORPHIC INTERPRETATION OF SAN BERNARDINO VALLEY. Menges (1982, personal communication) offered the following evaluation of recent tectonic events in SBV, based on geomorphic studies. Prior to volcanism (about 3 m.y. ago) the San Bernardino area may have been a mixed alluvium-bedrock pass between the Chiricahua and Peloncillo Mountains. The valley subsided, coincident with the main period of volcanism (3 to 1 m.y. ago), to accommodate the accumulation of interbedded basalts and sediments found in the subsurface. Subsidence probably occurred by a combination of the following: (1) faulting on structures--asymmetric graben, down on the west side; (2) sag--subsidence without discrete faulting; (3) tilting of the valley towards the west, against the west-side master fault zone. Faulting and subsidence essentially ceased about 1 m.y. ago, evidence by the fact that most structures are buried by the youngest basalt flows, which mantle most of the valley floor. During the past 1 m.y., minor volcanism (mostly pre-0.3 m.y.) and minor local faulting have taken place. An integrated drainage system has not yet established itself on the young valley surface. Multiple fans have been deposited along the mountain fronts, with the development of some pedimentation and mountain-front escarpment erosion. Fault scarps along the west side of the valley are mostly Pleistocene, and some young, unentrenched fans occur along parts of the west escarpment. Older dissected fans are on the east side of the valley.

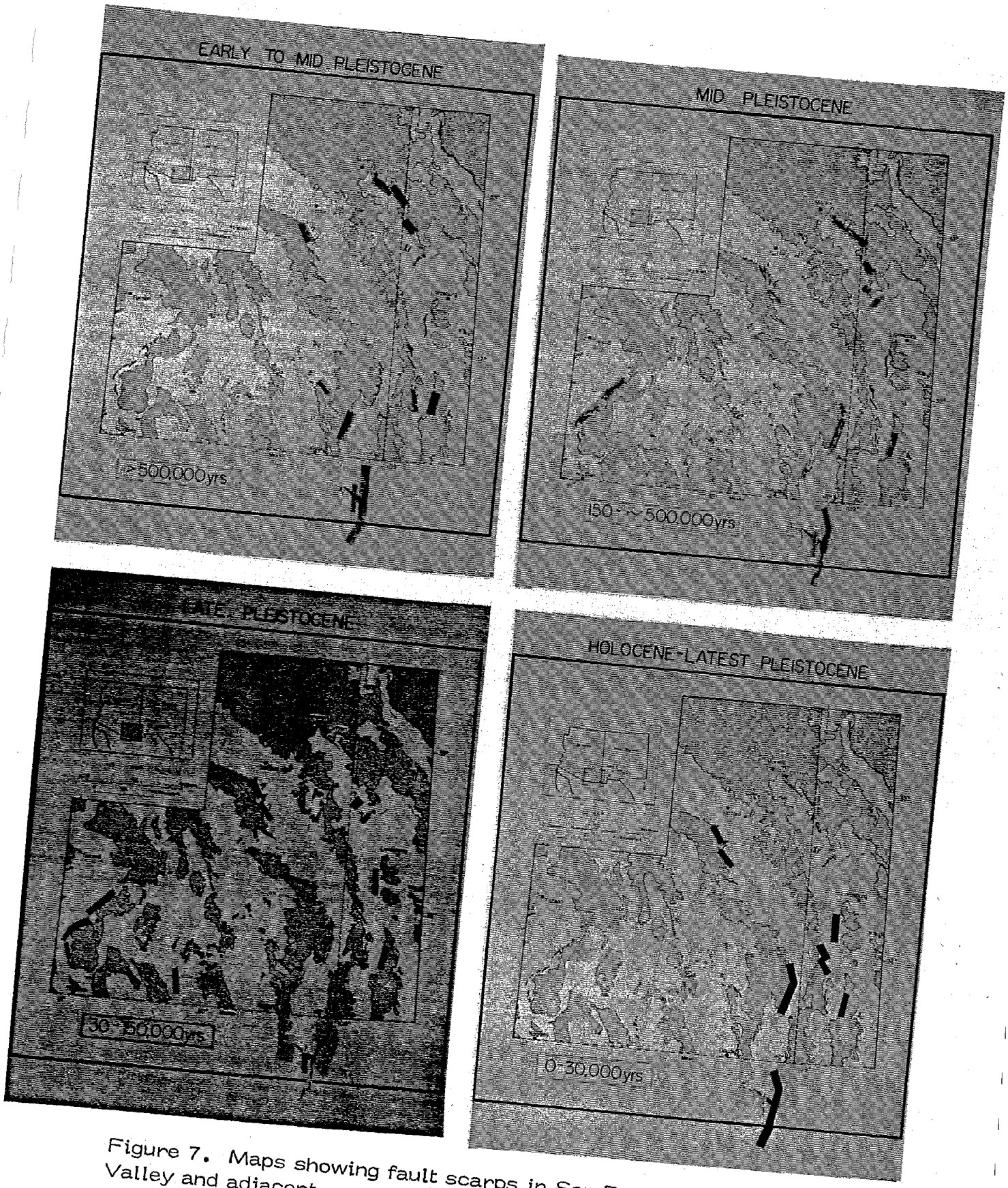


Figure 7. Maps showing fault scarps in San Bernardino Valley and adjacent areas during the past 1 m.y.

THERMAL GRADIENTS

Temperatures were measured in six holes by Southland Royalty and in three holes during this study. Additional measured temperature-depth information was available from an oil-and-gas wildcat drilled and logged in 1971 (and re-logged in 1979 by Southland Royalty) and from work done in this area in 1980-81 by Union Geothermal. Temperature-depth profiles for measured wells are shown in figures 8 through 10. Thermal gradients were derived for the measured wells by least-squares fit, represented by the solid line through each profile. In addition, we have estimated thermal gradients from measured water temperatures and from reported temperatures and well depths for another 23 wells in the valley (Table 2). Heat flow measurements have not been made in SBV.

Thermal gradients for all wells are shown in plan view in figure 11. Two trends are noticeable on this map. (1) A distinct north-northeast boundary, which follows the structural axis of the basin, separates low to normal gradients on the west from above-normal gradients on the east. Note that the gradients are consistently lower on the west and higher on the east, regardless of whether they were estimated or measured. The reason for this difference is unknown. (Union Geothermal dropped their western tracts a year before dropping their eastern ones.) (2) The second trend is that gradients increase to the south. The maximum gradient in a well more than 50 m deep, 112°C/km, is at the southern end of the valley.

Only two wells are deep enough (below the water table) to provide some insight into the hydrology and thermal regime of this part of the valley (see figures 8 and 9). In both wells the gradient in the upper 170 to 180 m is significantly higher than that measured below the water table. A number of thermal and(or) hydrologic conditions could produce such temperature-depth curves. However, it is difficult to determine which effects predominate, especially when the history of the drill hole is not known. Effects due to thermal refraction or thermal conductivity contrasts may be present, for example, but we do not believe these effects are significant in this area. We also do not believe the high gradients in the upper part of the drill holes are a result of conductive heat transfer in impermeable rocks above a geothermal reservoir. There is no evidence to support this hypothesis.

We believe the evidence shows that temperature effects in San Bernardino Valley are due to ground-water flow, both in the drill hole and in the aquifer. For example, if drill holes have not been grouted, water flow may exist within the hole between two or more aquifers that have been connected by drilling or between one aquifer and the surface. Generally these conditions result in a stair-step type of temperature-depth curve, exactly what is seen in hole G and is less apparent but present in hole F (see figure 9). Another temperature effect due to water flow can be seen in the overall convex-up shape of the temperature-depth curves. This shape is typical of the upflow portion of an aquifer, and is a

condition to be expected in this part of SBV. As previously explained in the Hydrology section, forced convection of "deep" ground water at the basin hydrologic outlet brings warm water close to the surface as the water flows south into Mexico through the bedrock constriction. If the basin is deep enough, even in a normal-gradient regime, a low or moderate-temperature geothermal anomaly may result. A third temperature effect due to water flow can be predicted from hydrologic conditions in the area of San Bernardino Ranch, where the land surface converges with and nearly intersects the water table. Under these conditions, lateral flow of water down the valley brings warm water closer to the surface in this area. Water that is 27°C at 300 m depth at the north end of the valley will be only a few meters below the land surface at the south end of the valley. Morgan and others (1981) described similar conditions (forced convection and lateral flow) in the Rio Grande rift in New Mexico. In the case of SBV then, the high geothermal gradients above the aquifer are a result of the difference between the water temperature and the mean annual surface temperature, and are not directly related to the actual heat flow below the aquifer. SBV is most probably an area of normal heat flow. Properly drilled, cased, and grouted heat-flow holes in this area would confirm our interpretation.

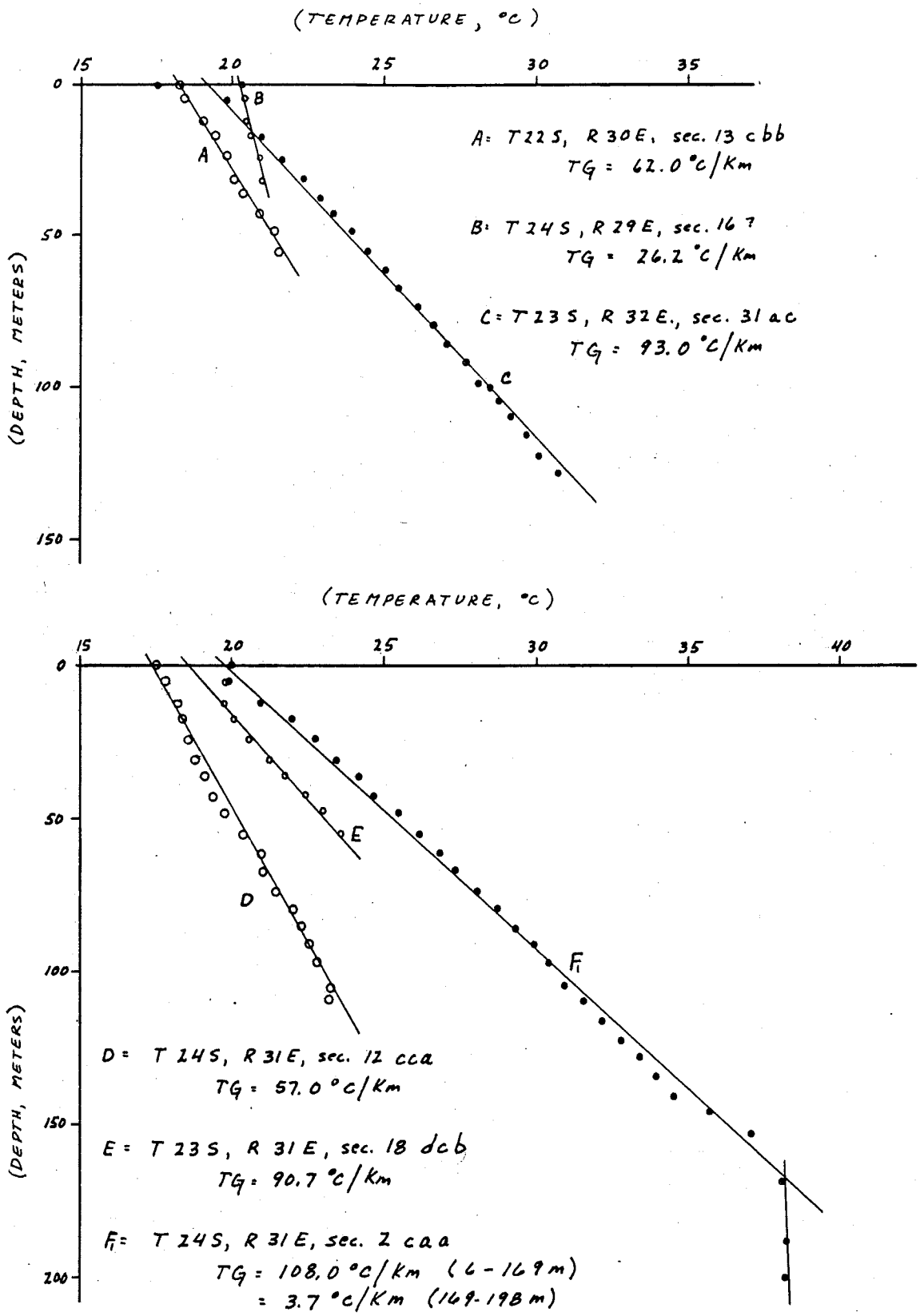


Figure 8. Temperature-depth profiles for wells measured by Southland Royalty.

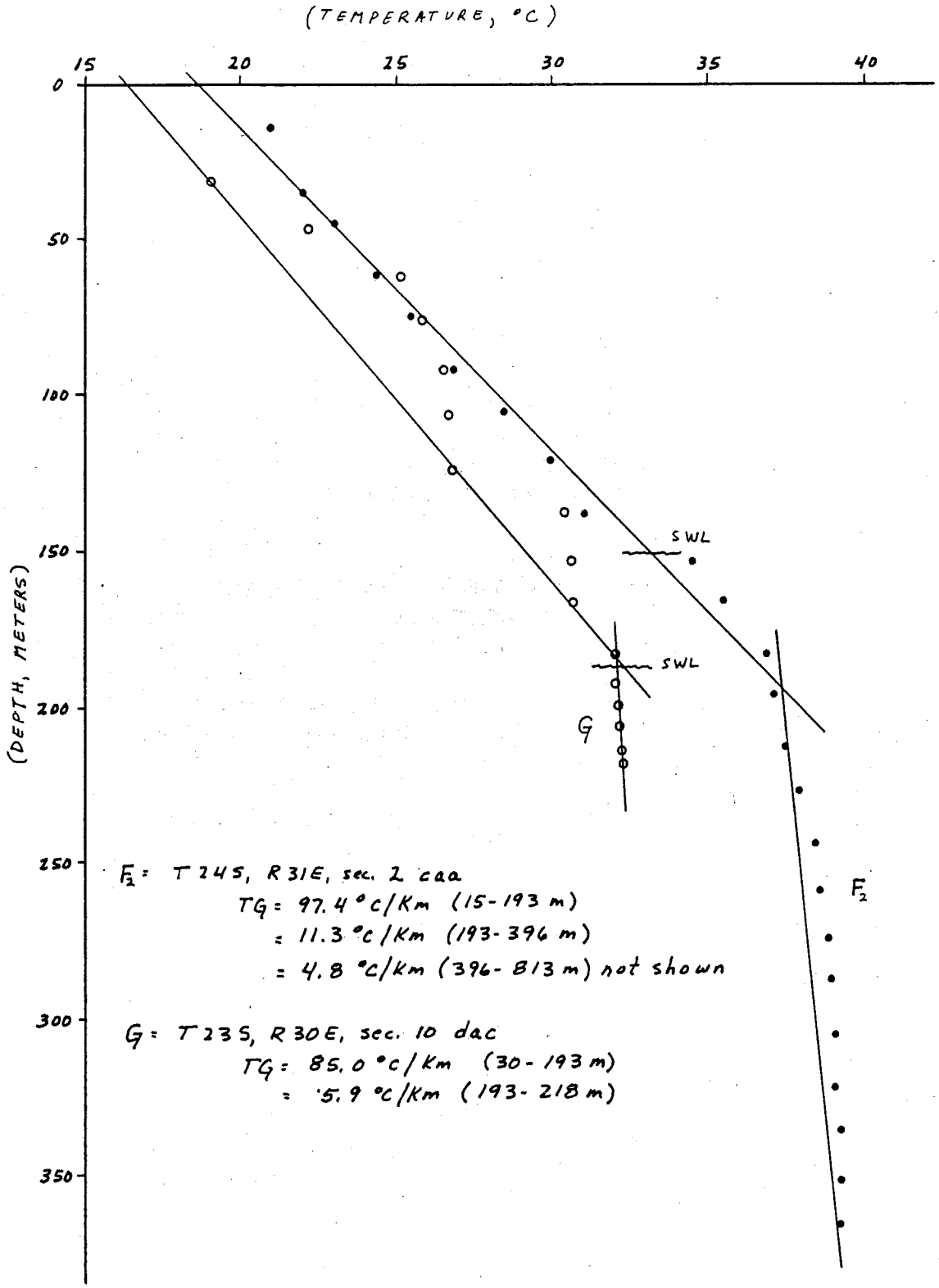


Figure 9. Temperature-depth profiles for wells measured by Guadalupe Exploration (F_2) and Union Geothermal (G).

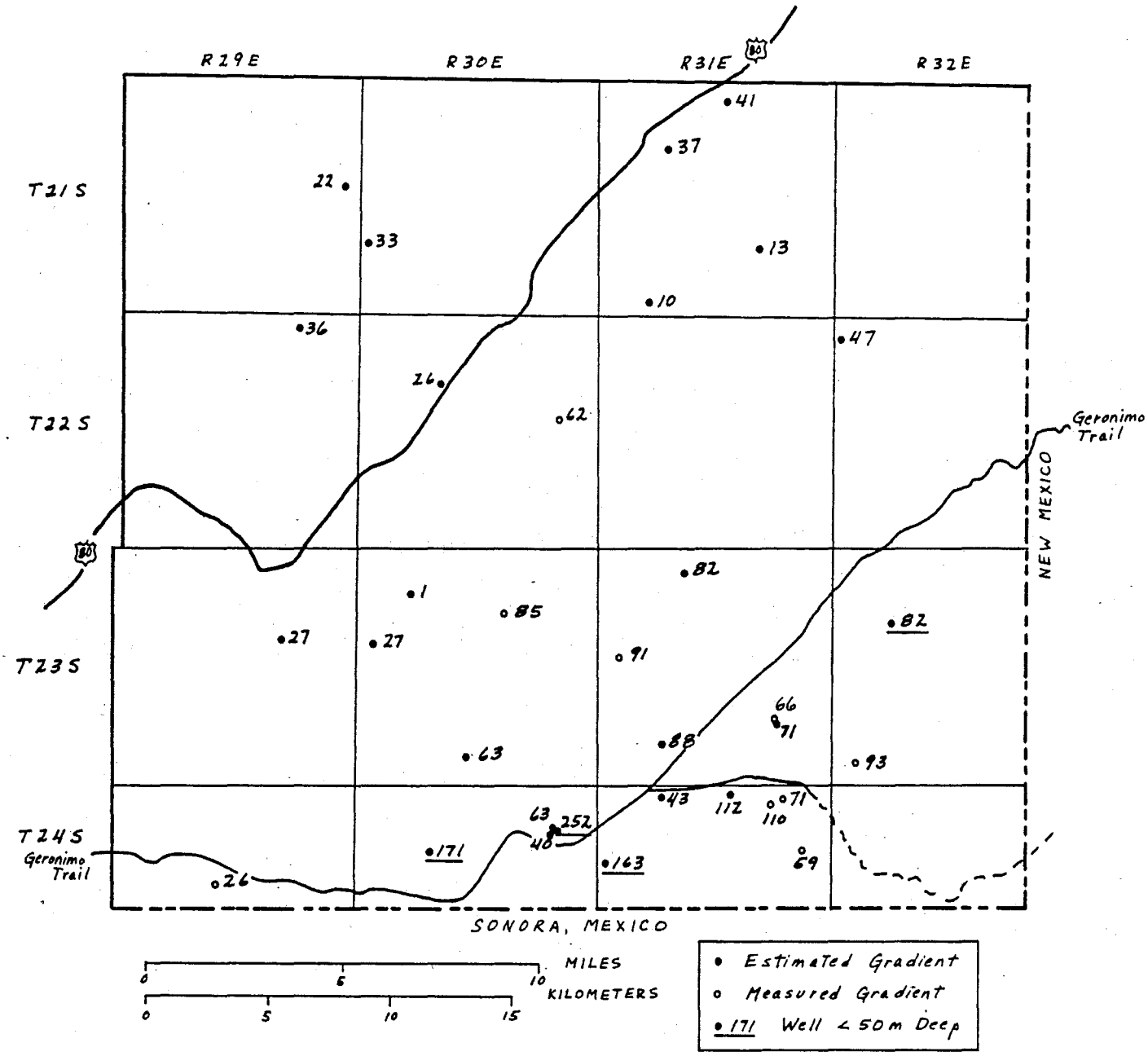


Figure 11. Map of thermal gradients, San Bernardino Valley. Underlined gradients are for wells less than 50m deep.

TABLE 2. Temperatures and thermal gradients, San Bernardino Valley

Name or No.	Location	Temp°C	Depth (m)	TG (°C/km)	Depth Interval (m)	Correl. Coeff.	MAT (°C)	T°C at 1 km	Source
1971 Guadalupe (1)	(D-24-31) 2caa	41	812.8	70.3 M[1]	0-305	0.9690	20.78	91.1	-
1978 Guadalupe (2)	(D-24-31) 2caa	38 +	198.2	109.6 M[2]	0-140	0.9922	19.70	129.3	2
TGI-3	2adb	25 +	50	71.2 M	15-45	0.9635	21.58	92.8	1
--	3bab	29 *	107	112.2 E	-	-	-	-	4
--	5acc	24 *	152	42.8 E	-	-	-	-	4
--	7ccd	24 *	43	162.8 E	-	-	-	-	4
AZ-141	10dd	26 *	-	-	-	-	-	-	3
--	10ccc	26 *	-	-	-	-	-	-	4
--	12cca	24 +	110	57.0 M	6-107	0.9951	17.27	74.3	2
5S82	(D-24-30) 8daa	23 *	35.1	171.1 E	-	-	-	-	1
AZ-138	11bb	24 *	Astin Spr.	-	-	-	-	-	3
6W82	11aad$_1$	29 *	182.9	62.9 E	-	-	-	-	1
5W82	11aad$_2$	28 *	274.1	40.1 E	-	-	-	-	1
7W82	11aad$_3$	27 *	39.6	252.3 E	-	-	-	-	1
--	11caa	30 *	flowing	-	-	-	-	-	2
--	11cad	30 *	flowing	-	-	-	-	-	2
--	14bac	28 *	flowing	-	-	-	-	-	2
--	14bda$_1$	23 *	flowing	-	-	-	-	-	2
--	14bda$_2$	28 *	flowing	-	-	-	-	-	2
--	14cbd	29 *	flowing	-	-	-	-	-	4
--	15dad	32 *	flowing	-	-	-	-	-	2
--	(D-24-30) 15ddc	32 *	flowing	-	-	-	-	-	2
6S82	23bab	30 *	flowing	-	-	-	-	-	1
--	(D-24-29) 16 ?	21 +	30.5	26.2 M	6-31	0.9923	20.2	46.4	2
TGI-1	17ddd	20 ±	18	neg. M	3-18	-	-	-	1
--	(D-23-32) 6aad	22 *	-	-	-	-	-	-	4
--	31ac	31 +	131.7	93.0 M	0-128	0.9923	19.13	112.2	2
8W82	8dcc	20 *	36.6	82.0 E	-	-	-	-	1
--	(D-23-31) 4cab	28 *	134	82.1 E	-	-	-	-	4
--	18dcb	24 +	55	90.7 M	12-55	0.9985	18.47	109.2	2
TGI-2	26ab	25 +	90	66.2 M	10-90	1.0	19.34	85.6	1
10W82	26abc$_2$	24 *	99.1	70.7 E	-	-	-	-	1
4W82	29dca	25 *	91.5	87.5 E	-	-	-	-	1
AZ-143	18cd	28 *	-	-	-	-	-	-	3

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