PRELIMINARY ASSESSMENT OF THE GEOTHERMAL POTENTIAL AT THE PAPAGO FARMS, PAPAGO INDIAN RESERVATION, ARIZONA

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SUMMARY

The Papago Indian Reservation in south-central Arizona comprises 11,000 km^2 in the Basin and Range province. The region is typically one of fault-bounded ranges separated by deep, sediment-filled basins.

A reconnaissance geothermal assessment of the Papago Indian Reservation indicates that a geothermal anomaly exists at the Papago Farms and that one perhaps exists at Sells.

More detailed analysis of existing geologic, geophysical, and geochemical data definitely confirms the existence of a geothermal anomaly at the Papago Farms. Chemical geothermometers predict a minimum reservoir temperature of $80^{\circ}C$. Geochemical mixing models suggest that the maximum probable reservoir temperature may be as high as $140^{\circ}C$. Depth to the geothermal reservoir is uncertain, but may be as shallow as 1.5 to 2 km. The possible existence of two intersecting fault zones is suggested by gravity data and interpretations of water chemistry. The suspected fault zones trend N. 81° W. and N. 18° W. and intersect at the northeast corner of the Papago Farms, in the area of well PF-7. The fault intersection would comprise highly fractured basement rock, an ideal reservoir for geothermal fluids.

Additional resource assessment is necessary. Temperature logging of all wells at the Farms would facilitate identification of the area where warm water is rising to the surface. A shallow-depth (500 ft.) heat-flow survey should assist in defining the areal extent of the reservoir. Finally, a magnetotelluric survey should aid in predicting depth to the reservoir.

At the Papago Farms, 980 acres currently are under cultivation. All irrigation water is lifted several hundred feet to the surface from the ground water aquifer, using diesel-driven pumps. Diesel-run generators supply all other power at the Farms. The development of geothermal energy at the Farms would reduce diesel-fuel requirements, thereby making the Farms operation more self-sufficient and possibly more cost effective.

Geothermal energy can be used two ways at the Farms. 1) Off-the-shelf technology and equipment exist that use low-temperature geothermal fluids to heat and cool buildings. This technology can be applied to all offices, workshops, and bunkhouses at the Farms. 2) Sperry Research Center, corporate research facility of Sperry Corporation, has designed and is field testing a downhole geothermal pump that uses the energy of the geothermal fluid to lift (pump) the water to the surface. The geothermal fluid in this system arrives at the surface cold and usually is reinjected into the ground through a separate well. The "working fluid" in the system (usually Freon) arrives hot at the surface where it can be passed through another turbine to generate electricity.

Because the new Sperry system can generate one-third more electricity than a conventional geothermal plant from the same reservoir, lower-temperature reservoirs can be exploited more economically. It is anticipated that the Sperry system can be used efficiently in hot water wells with temperatures as low as 100 to 120°C. The system should be commercially available by 1983. Currently, representatives from the Sperry Corporation are seeking a suitable demonstration site in Arizona or Idaho.

At the Papago Farms, the cold "geothermal" fluids pumped to the sur-

face by the Sperry system could be used for irrigation rather than being reinjected into the ground. Electricity could be used for lighting and operating tools and appliances.

Numerous federal assistance programs are available for developing direct-use geothermal energy. These programs are detailed at the end of this report. Probably the program that would be most helpful at this time for developing the Papago Farms resource is the Department of Energy's Technical Assistance Program. This program provides up to 100 hours of free consulting services to potential users with limited experience. The consulting services currently include projects or studies to provide:

1) Evaluation of engineering feasibility
2) Resource evaluation
3) Economic evaluation
4) Conceptual design
5) Assistance for locating and applying for grant money or loans
6) Referrals or consultation to equipment vendors and consulting engineers
7) Informal seminars.

For additional information on this program, contact Gene Culver, Oregon Institute of Technology, Geo-Heat Utilization Center, Klamath Falls, Oregon 97601; phone (503) 882-6321.

A second valuable program is the Department of Energy, User Coupled Confirmation Drilling Program. This program provides federal cost sharing for exploration, drilling, and testing to confirm hydrothermal reservoirs for direct heat applications. It is necessary to submit a proposal, which must be approved by the Department of Energy, to participate in

this cost-sharing program.

For more information, contact Susan Prestwich, Idaho Operations Office, U. S. Department of Energy, Idaho Falls, Idaho 83401; phone (208) 526-1147.

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GEOTHERMAL RESOURCE ASSESSMENT

Introduction

The United States has ten percent of the world's population and consumes a third of the world's energy. In recent years increasing world demand for and dwindling supplies of fossil fuels have driven up fuel prices to such an extent that our nation is suddenly conscious of and concerned about the availability of energy. To this end the U. S. Department of Energy is encouraging and funding the development of alternate energy resources. Geothermal energy, which is above-normal heat occurring at very shallow depths in the earth, is one such resource.

Arizona is situated in the southern Basin and Range province, where the occurrence of low- to moderate-temperature geothermal resources ($< 150^{\circ}C$) are not uncommon. Most often the geothermal resources in this province occur as hydrothermal (hot water) convection systems, a result of deeply circulating ground water that is heated by the normal geothermal gradient and then rises toward the surface along fractures such as fault planes, fault intersections, or joint sets. Frequently, geothermal energy in such geologic settings is manifested at the surface by hot springs. Where surface expressions are absent, however, geologic, geochemical, and geophysical techniques can be employed to detect hydrothermal systems suspected in the subsurface. Occasionally domestic or irrigation wells encounter warm water at shallow depths in the subsurface.

In order to be economic, a low- to moderate-temperature geothermal resource must have an adequate temperature and fluid volume, and must oc-

cur at a reasonably shallow depth (less than about 1.5 km). In addition, the resource must be located near the user. On the Papago Indian Reservation most villages are small and often are located many miles from one another, so that development of a geothermal resource may not be economic. At the Papago Farms, however, or near the town of Sells, a geothermal system might be economic since a large enough user would be available. Warm wells at the Papago Farms and other subsurface indicators suggest that a low- to moderate-temperature geothermal resource does exist at the Farms and that another may exist at Sells. This paper reviews relevant data for the Papago Indian Reservation generally, and for the Papago Farms in particular, and recommends follow-up exploration that would define the resource more specifically. A short section is appended indicating possible uses of geothermal energy at the predicted temperatures and suggesting procedures for developing the resource in a timely manner. A report on the geothermal potential at Sells will be available at a later date.

Papago Indian Reservation

Location and Access. The Papago Indian Reservation comprises about 11,000 km^2 in south-central Arizona, largely in Pima County, with small areas in Maricopa and Pinal Counties. The reservation includes most of the region west of Tucson to Ajo and from Casa Grande south to the international boundary with Mexico (Fig. 1). About 7,000 Papago Indians reside on the reservation, of which 3,100 live in or near the principal town of Sells, 30 km southwest of Tucson on Arizona Highway 86. Villages on the reservation generally have populations of 40 to 100 people, but many are smaller. Several larger villages have populations ranging up

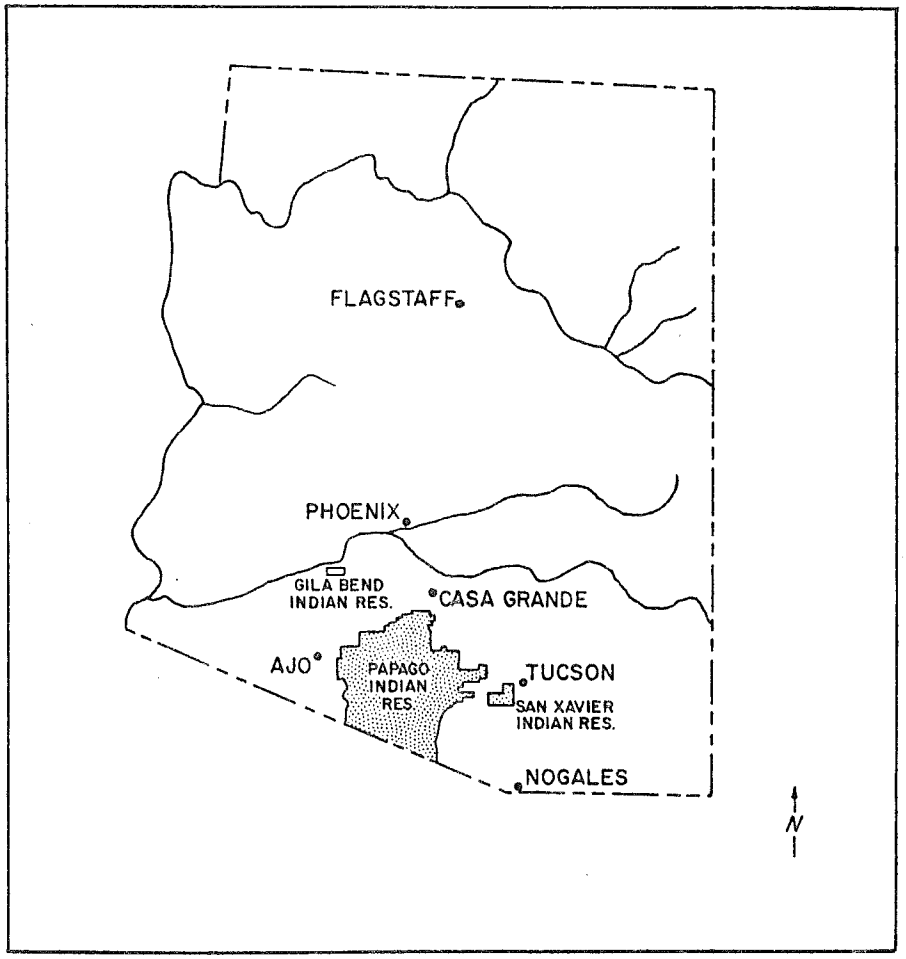


Fig. 1: Map of Arizona showing Papago Indian Reservation.

to about 1,000 people. The economy of the reservation is based largely on ranching and agriculture.

The climate is semiarid. Precipitation ranges from about 5 inches in the southwestern part of the reservation to about 20 inches in the Baboquivari Mountains (Heindl and others, 1962). Nearly half the rainfall occurs during the hard summer thunderstorms in July and August (U. S. Dept. of Commerce, 1973). At Sells the mean annual air temperature is 20°C. During summer months, however, temperatures on the reservation often exceed 38°C.

Previous Studies. Early investigations of the Papago region were reconnaissance surveys mainly concerned with ground water and mineral resource evaluations (Bryan, 1925; Clotts, 1915; Coates, 1954; Denton and Haury, 1946; Hadley, 1944; Heindl and Cosner, 1961; Matis, 1970; Romslo, 1950; Tenney, 1934; and Yost, 1953). Prior to the early 1970s, little geologic mapping was accomplished on the reservation (Bryan, 1920 and 1925; Bryner, 1959; Fair, 1965; Heindl, 1965a and b; Heindl and Fair, 1965; Heindl and McClymonds, 1964; McClymonds and Heindl, 1964).

Since the mid 1970s, nine 15-minute quadrangle reconnaissance geologic maps of the Papago Indian Reservation have been published by the U. S. Geological Survey, and ten of the 14 remaining maps are in preparation (Haxel and others, 1980).

General Geology. The Papago Indian Reservation is in the southern Basin and Range province, Sonoran Desert section or subprovince (Hayes, 1969). While this province is largely characterized in southern Arizona by northwest-trending, fault-bounded mountain ranges, separated by deep sediment-filled basins, most of the ranges and basins on the Papago reservation trend north-south. In the Sonoran Desert section of the Basin

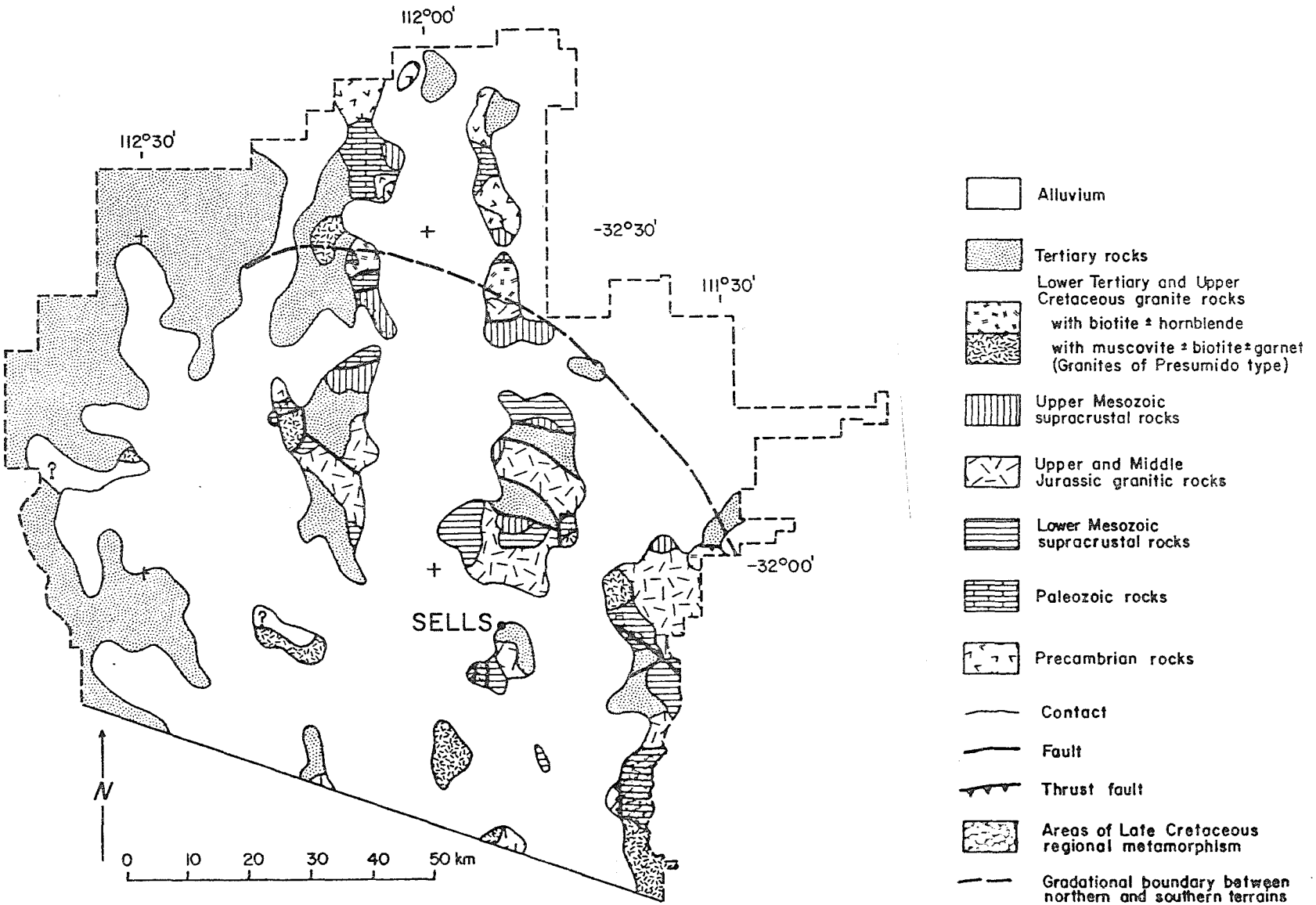


Fig. 2: Interpretative geologic sketch map of the Papago Indian Reservation. Dashed line denotes gradational boundary zone separating northern and southern terrains. (From Haxel and others, 1980, Figure 2.)

and Range province the ranges are lower and narrower than those in the Mexican Highland section to the east, and make up less than a fourth of the area of the section. Many of the ranges and peaks in the Sonoran Desert section are rugged and rise abruptly from the surrounding desert.

Haxel and others (1980, p. 20) divided the Papago reservation and immediate areas to the east into a southern terrane and a northern terrane (Fig. 2) on the basis of "significantly different rock assemblages and geologic histories."

Generally, the northern Papago terrane has a Precambrian through early Tertiary history similar to that of the Globe-Phoenix-Tucson region and southeastern Arizona. Haxel and others stated (p. 20),

> "...in the area of Slate, Vekol and Cimar Mountains... the Pinal Schist is intruded by the Oracle Granite... and these older Precambrian crystalline rocks are overlain by the younger Precambrian Apache Group, which is intruded by diabase sills and dikes. The Precambrian rocks are overlain by Paleozoic sandstone, limestone, dolomite, and siltstone...and by unmetamorphosed Mesozoic volcanic and sedimentary rocks...All of these rocks are intruded by Late Cretaceous and (or) early Tertiary biotite- and (or) hornblende-bearing granodiorites, granites, and related porphyries."

In the southern terrane Precambrian rocks appear to be nearly absent and Paleozoic rocks are sparse. Mesozoic sedimentary and volcanic rocks were affected by regional metamorphism during the Late Cretaceous. The "Laramide" (Late Cretaceous-early Tertiary) magmatic episode of southern Arizona is represented by muscovite- and garnet-bearing granitic plutons.

The reader is referred to Haxel and others (1980) for a more detailed

description of the southern Papago reservation geology and for selected references.

Hydrology. An investigation of the ground water supply of the Papago Indian Reservation was made by members of U. S. Geological Survey in the late 1950s (Heindl and Cosner, 1961; Heindl and others, 1962; Heindl, 1958). Matis (1970) studied the hydrogeology of the Sells area.

Heindl and others (1962) differentiated four types of ground water areas based on the water-bearing characteristics of the principal rock types. These areas are composed of "...(1) essentially non-water-bearing materials largely comprised of granitoid and metamorphic rocks but also including some indurated sedimentary and volcanic rocks; (2) locally water-bearing Paleozoic limestone; (3) locally water-bearing volcanic rocks; and (4) generally water-bearing alluvial deposits." They pointed out that the deep alluvial aquifers in the central parts of most basins on the reservation have the greatest probability of yielding sufficient amounts of water for irrigation. Depth to water in these deep sediment-filled basins varies from about 30 to 200 m (Heindl and others, 1962). Principal drainage on the reservation is north to the Gila River and south to the Rio Sonoyta, with the surface-water and ground-water divides generally coincident.

Presently an updated, detailed evaluation of the ground-water resources and basin hydrology of the reservation including water quality and hydrologic modeling is being made by members of the U. S. Geological Survey (Hollett, personal commun., 1980). Preliminary hydrologic maps should be available in mid to late 1980.

Gravity. Hargan (1978) made a regional gravity survey of the Papago Indian Reservation. He showed five areas on the reservation having nega-

tive gravity anomalies that are probably a result of deep basins filled with less-dense, unconsolidated or semi-consolidated sedimentary material. These areas are Santa Rosa, Quijotoa, Baboquivari and Tecolote valleys, and the Great Plain. The Sells area sits atop a gravity high, which Hargan interpreted as a possible high-density Precambrian basement that is much closer to the surface there than under some other ranges. Hargan attempted to correlate positive and negative second order residual Bouguer gravity anomalies with structures that are potentially favorable for the occurrence of hot dry rock and hydrothermal geothermal resources, respectively.

Greenes (1980) made a detailed gravity survey of the Papago Farms area, which will be discussed in more detail under that section.

Heat Flow. Average heat flow for the southern Basin and Range province is 84 mWm^{-2}, about 20 mWm^{-2} greater than the world average (Sass and others, 1980). This elevated heat flow in the Basin and Range province is generally attributed to the effects of thinner crust and to possible igneous intrusions into the crust in the southwestern United States.

On the Papago Indian Reservation two heat flow measurements were made, one at Roadside Mine (92 mWm^{-2}) and a second at Gunsite Hills (87.8 mWm^{-2}). A third measurement is being made in the Quijotoa Mountains by the U. S. Geological Survey, but the value is not yet available. Published heat flows ranging between 35.5 and 108.7 mWm^{-2} exist around the margins of the reservation (Fig. 3). Nearly all heat flow in the Papago region exceeds the average for the Basin and Range province, and is a result of "convective transfer associated with ground-water circulation" (Lachenbruch and Sass, 1978).

Swanberg and Morgan (1978/79) showed a linear relationship between

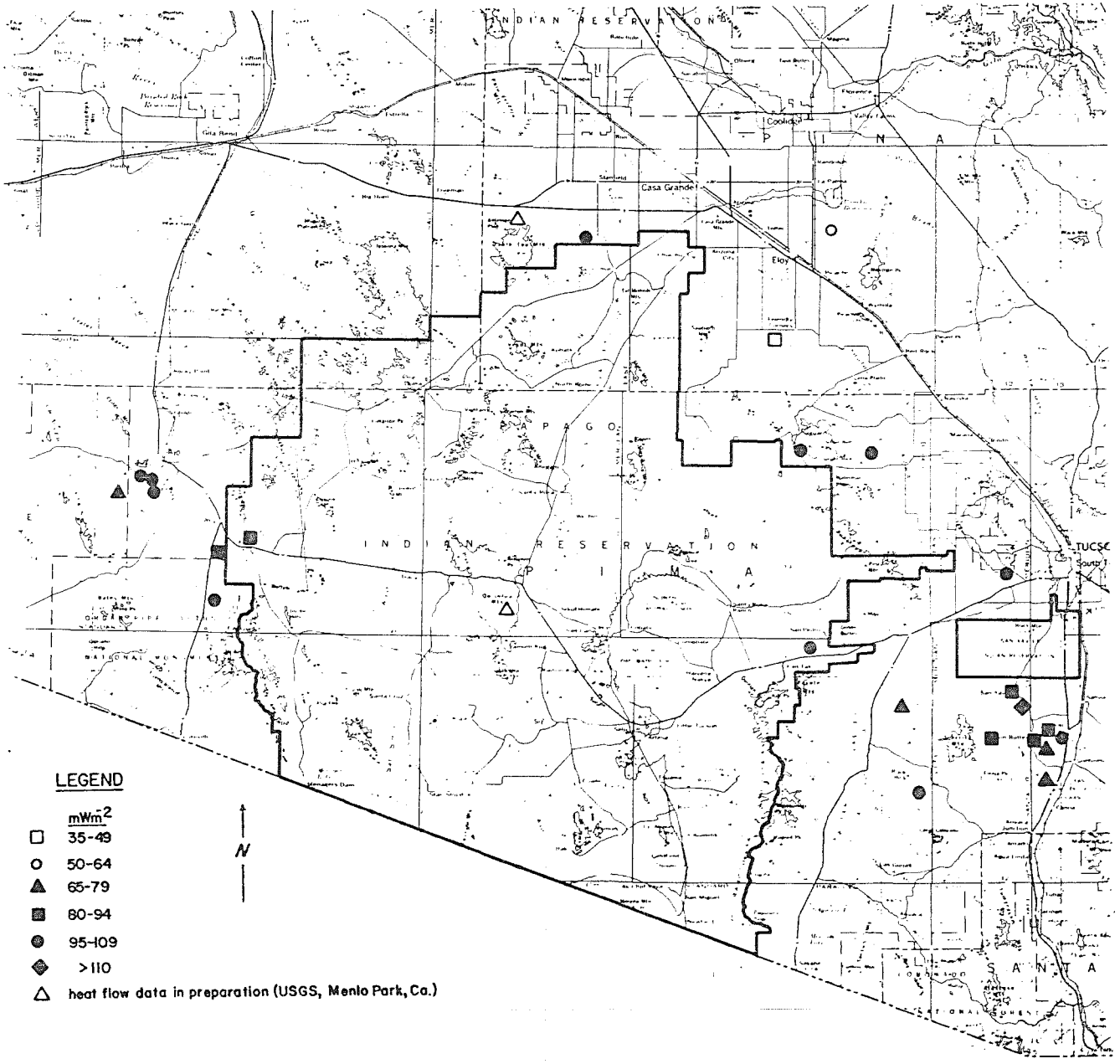


Fig. 3: Heat flow map of the Papago area. Published data from Roy and others, 1968; Sass and others, 1971. Unpublished data from Shearer, 1980; Bureau of Geology and Mineral Technology, Tucson, Arizona.

regional heat flow and temperatures based on the silica content of ground water. Their method was applied to 254 chemical analyses of ground water from the Papago reservation, with a resulting mean silica heat flow of 113 ± 24.9 mWm^{-2} (Fig. 4). On this basis I consider values exceeding 130 mWm^{-2} anomalous for this region. Figure 5 shows five areas with nearly linear bands of anomalous silica heat flow and numerous other single-value anomalies. The five anomalous areas are the Papago Farms, Sells, south of the Ko Vaya Hills, south of the Brownell Mountains, and west of an area from Bell Mountain to La Tortuga Butte.

Because of the size of the Papago Indian Reservation, I selected the Papago Farms and Sells for more detailed evaluation on the basis of high silica heat flow, the occurrence of warm wells and the proximity of both to users. The remainder of this report discusses the geothermal potential at the Papago Farms. A second report will cover the Sells area.

The Papago Farms

In 1977 the Papago Indian Tribe started a farming operation at the site of the old Papago Farm, about 40 miles southwest of Sells. Currently 980 acres of farmland are under cultivation (Hollett, personal commun., 1980). Intense irrigation is required for the farming operation.

Geology and Hydrology. The Papago Farms is located at the southeast end of the Mesquite Mountains in a broad, nearly flat region called the Molenitus area (Heindl, 1958) or the Great Plain (Fig. 6). The Great Plain is at the head of a north-south valley that extends about 40 km into Mexico. In Arizona the study area is bounded on the east by the north-trending La Lesna Mountains, a low range of Tertiary intermediate volcanic rocks that continue south into Mexico. The Kupk Hills, com-

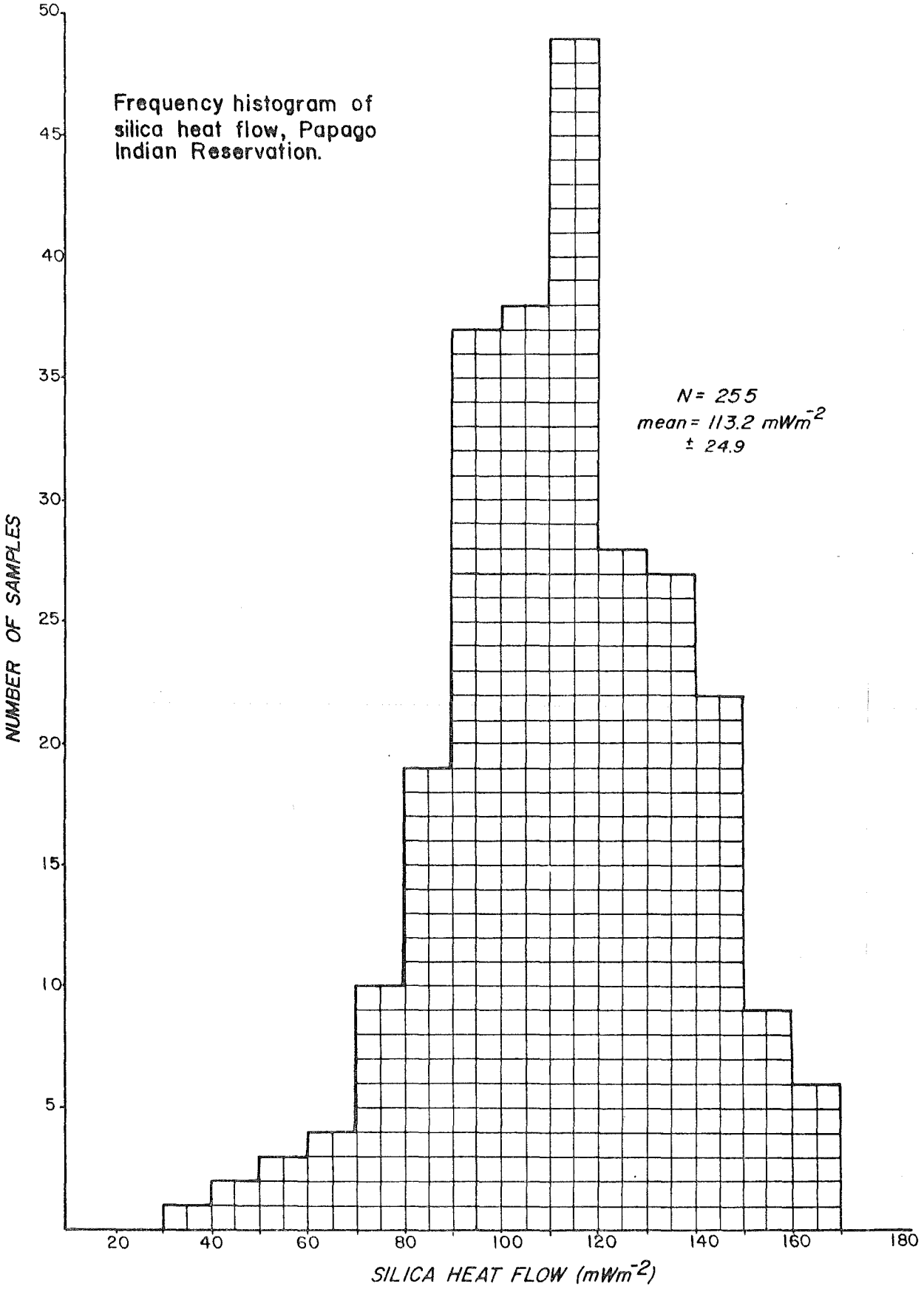


Fig. 4: Frequency histogram of silica heat flows.

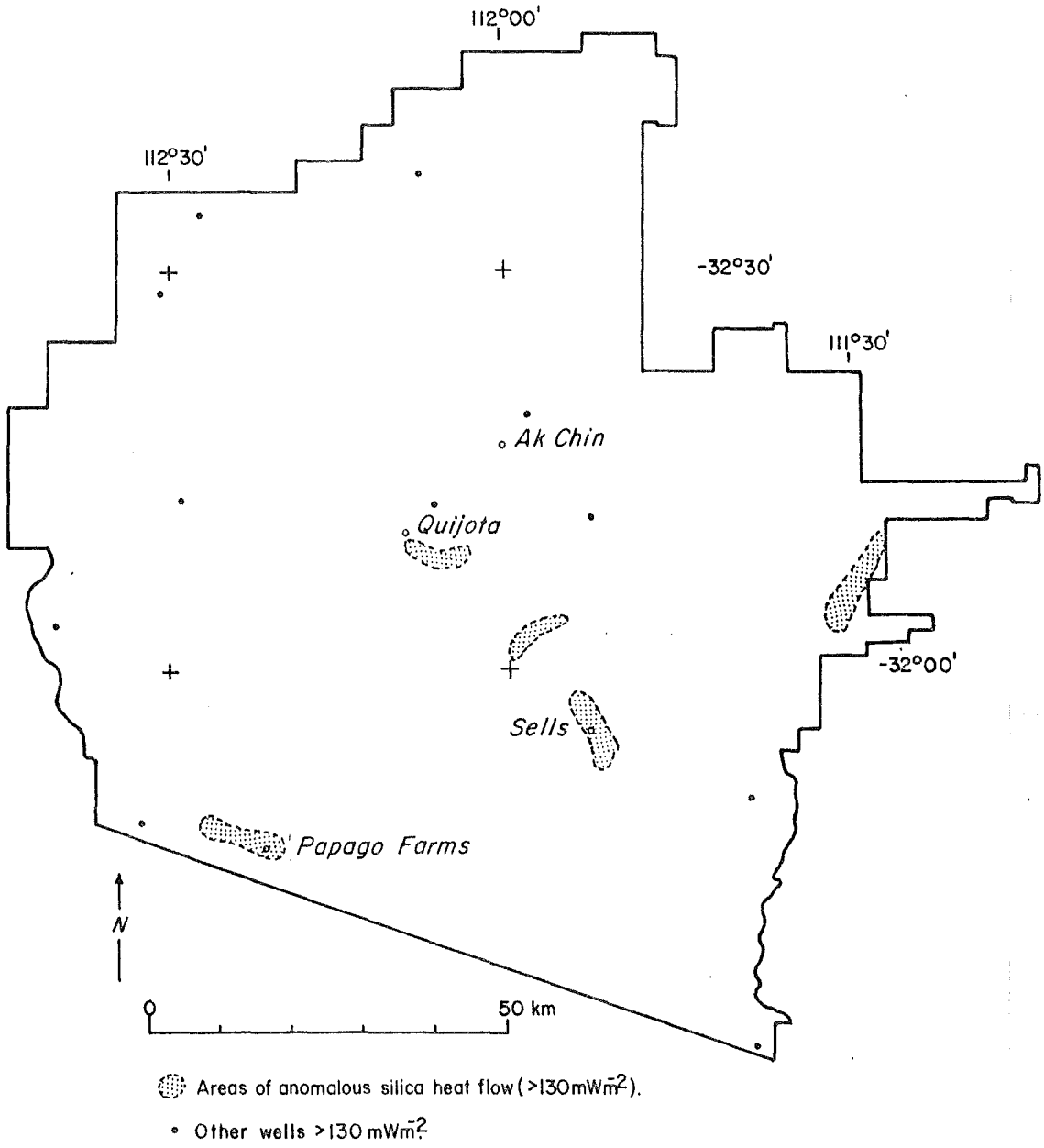


Fig. 5: Areas of anomalous silica heat flow, Papago Indian Reservation.

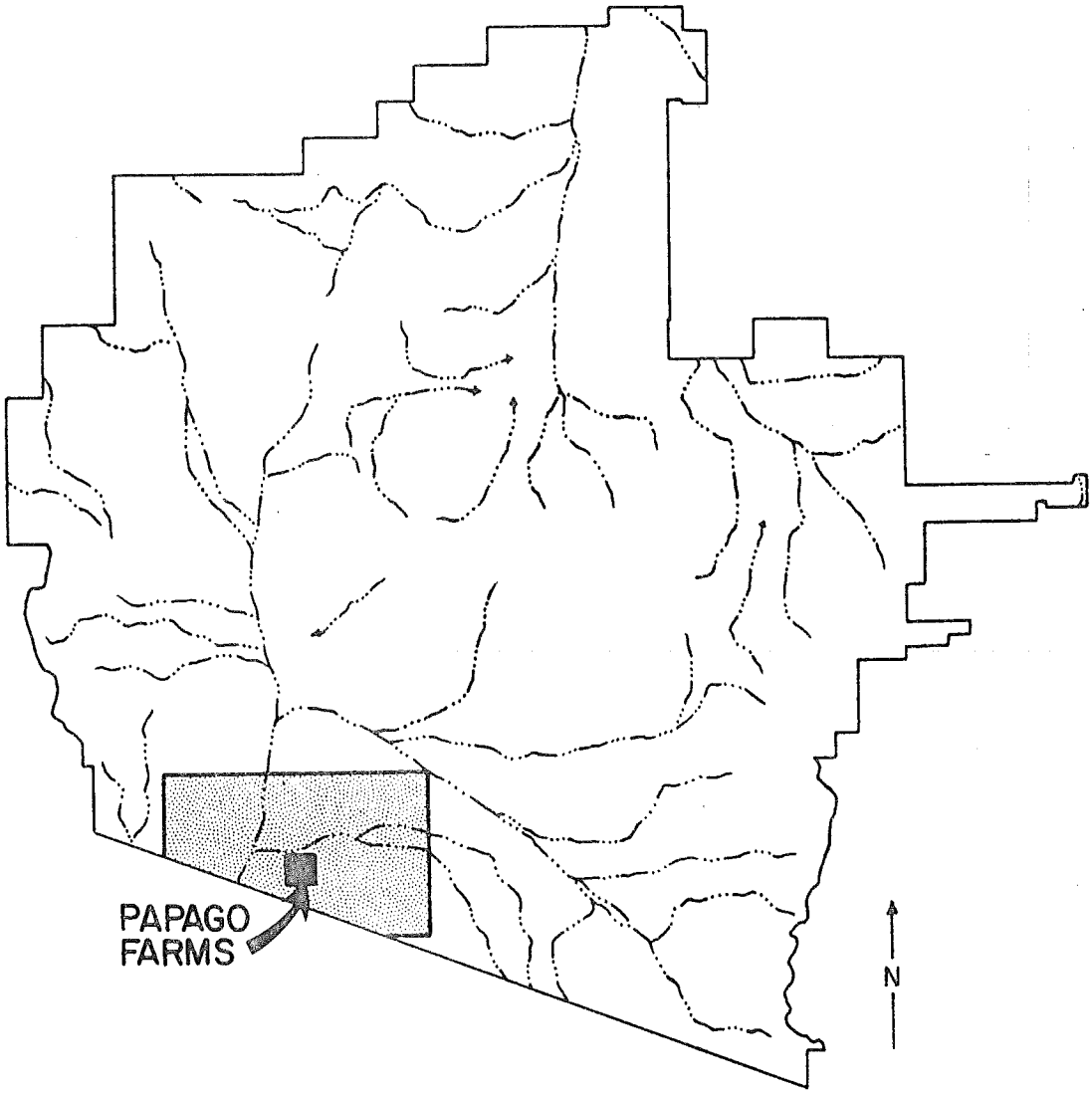


Fig. 6: Map of Papago Indian Reservation showing the Papago Farms and major surface drainage.

posed of late Cretaceous-early Tertiary gneiss, comprise the northern boundary of the Great Plain. The western edge of the area follows the south-flowing San Simon Wash, and the southern margin, for this study, coincides with the international boundary with Mexico.

Major surface drainage in the study area is the south-flowing San Simon Wash. Chukut Kuk Wash east of the La Lesna Mountains (Fig. 6) and Vamori Wash even farther to the east both trend northwestward out of Mexico and then west. Together with numerous smaller washes, they join San Simon Wash north and west of the Great Plain. All surface water then flows south into Mexico and joins Rio Sonoyta.

Ground water under the reservation moves largely along the axes of the valleys and generally moves in the same direction as the surface water (Heindl and others, 1962). Hollett (personal commun., 1980) pointed out from recent unpublished studies that ground water moves northwest principally beneath the Vamori and Chukut Kuk washes towards Kots Kug ranch and the Kupk Hills. North of the Great Plain, two arms of flow join the south-flowing ground water beneath San Simon Wash, while a third arm flows beneath the Chukut Kuk wash to join the flow beneath San Simon Wash near the international boundary. Ground water low in total dissolved solids (TDS) can be seen in Figure 7 to mimic the surface drainage of both Vamori and Chukut Kuk washes as they flow west to join San Simon Wash. To the south and north along San Simon Wash this pattern is disrupted by an area of exceedingly high TDS that Hollett (personal commun., 1980) suggests may be related to a shallow evaporite or lake-bed deposit.

Water Chemistry. Ground-water chemistry is a reliable, cost-effective and useful method of assessing the physical and chemical characteristics of a hydrologic system. Cation and anion ratios are good indicators

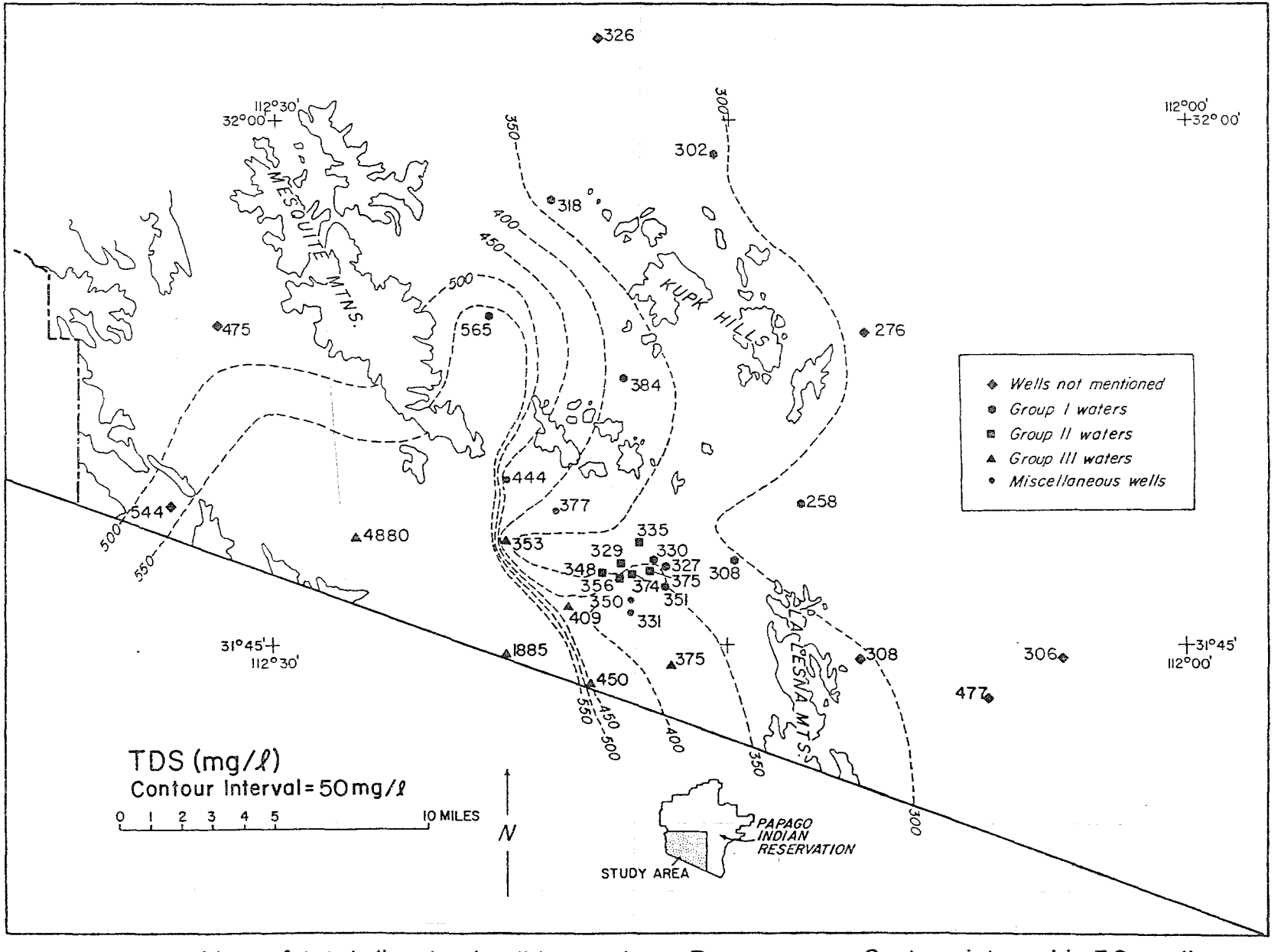


Fig. 7: Map of total dissolved solids, southern Papago area. Contour interval is 50mg/l.

of ground water similarities and differences, reflecting origin, age, direction of movement, and possible mixing with deep thermal waters. Chemical analyses of water from 26 wells in the study area and surrounding region are given in Table 1. Well locations are shown in Figure 8. Unless otherwise noted the data were taken from the most recent entry for each well listed in the U. S. Geological Survey's WATSTORE water quality file (USGS, WRD, Tucson, 1980).

Ground water with similar chemical affinities can be detected in a number of ways, two of which (a Piper diagram and Stiff diagrams) make use of HCO_3-SO_4-Cl and Na-Ca-Mg ratios. These methods are especially useful in characterizing dissimilar waters, but where chemical compositions are very similar it is more difficult by these methods to distinguish groups of water with like characteristics. Ground waters in the Papago Farms study area are largely similar in chemistry. For this reason a series of X-Y plots were generated (Figs. 9 through 12); waters plotting together in the same fields were placed in the same group. By this method three distinct groups of water were identified. The characteristics of these groups are outlined in Table 2.

Group I waters are mostly nonthermal ($T<31^{\circ}C$) and include ground water from wells at or near the east side of the Papago Farms (Group Ia: Toro-3 (T-3), GS-1, PF-3, PF-6, and PF-15) and north of the study area (Group Ib: DW-15, DW-32, DW-73, and DW-46). Group I waters have wellhead temperatures in the range $25-32^{\circ}C$, high Cl/F and Mg/Ca ratios, low Na/Ca and Na/K ratios, and generally low (323 ± 37 mg/l) total dissolved solids. These waters largely reflect ground water moving west beneath the Great Plain to join the south-flowing water beneath San Simon Wash. A full chemical analysis of PF-4 was available, too late to include in

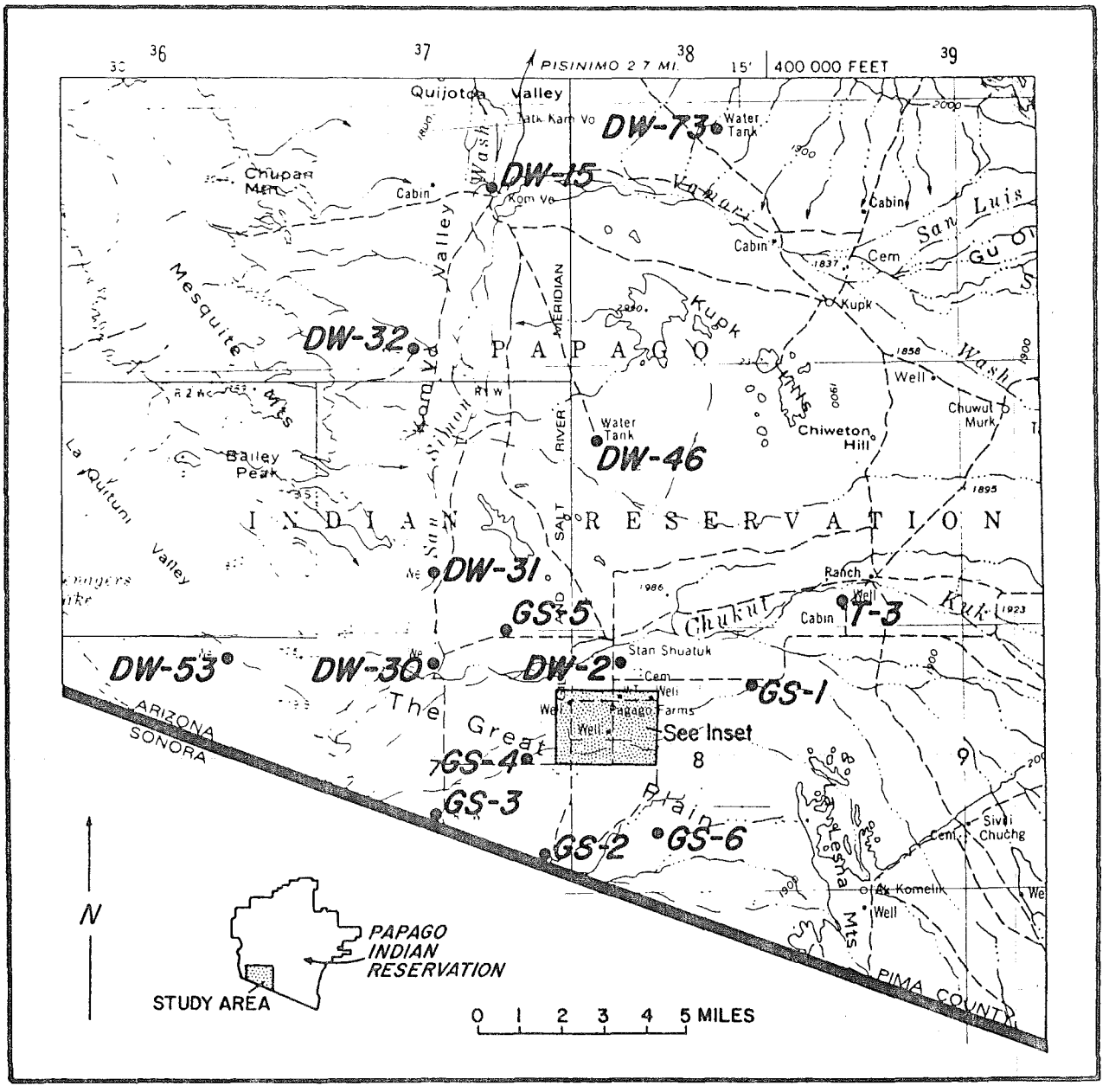
TABLE 1. Chemical Analyses of Ground Water, Papago Farms and Surrounding Areas

(Chemical constituents in milligrams per liter)

Sample No.	Location	pH	Na	K	Ca	Mg	SiO_2	Cl	SO_4	HCO_3	F	B	TDS
*USGS-1	D-19-01 11BBB	7.9	87	3.1	11.0	2.8	41	36	23	190	2.3	0.21	308
USGS-2	C-19-01 36ACC	-	170	0.9	3.2	0.4	27	59	45	270	12.0	0.68	450
USGS-3	C-19-01 28ADC	-	790	2.9	0.8	0.2	18	280	160	1140	54.0	16.0	1885
USGS-4	C-19-01 14DDD	-	150	0.8	1.8	0.3	43	31	24	300	7.9	0.5	409
USGS-5	C-18-01 35CDA	-	120	4.0	8.2	2.5	42	40	33	200	8.3	0.31	377
USGS-6	D-19-01 28CBC	-	110	0.6	13.0	5.9	45	59	37	200	4.0	0.22	375
DW-2	D-19-01 05CBC	7.7	110	3.2	8.1	1.5	37	31	26	220	9.2	0.52	335
PF-1	D-19-01 07DBB	8.0	110	3.2	8.1	1.2	53	31	30	220	11.0	0.32	356
PF-2	C-19-01 12DAA	7.7	110	2.5	6.8	1.1	50	30	30	220	9.3	0.27	348
PF-3	D-19-01 8DAA	-	94	3.3	13.0	2.3	52	26	22	210	4.3	0.24	327
PF-4	C-19-01 18ADA	-	-	-	14.0	3.3	55	40	31	224	12.0	-	390
PF-5	D-19-01 18DDD	7.9	110	2.6	8.8	1.9	38	33	24	210	8.4	0.22	331
PF-6	D-19-01 17AAA	7.9	99	3.4	11.0	3.8	57	23	20	240	7.6	0.24	351
PF-7	D-19-01 08DBB	8.3	120	4.5	7.5	1.8	61	30	30	220	9.4	0.31	374
PF-8	D-19-01 08CBB	-	120	3.1	12.0	1.6	60	30	29	210	8.8	0.75	375
PF-15	D-19-01 08ABD	-	96	3.7	13.0	1.5	53	23	22	220	4.3	0.23	330
PF-18	D-19-01 07BAD	-	-	-	-	-	-	-	-	-	-	-	-
PFD-A	D-19-01 07ABD	8.7	110	2.9	5.0	1.4	31	28	23	-	8.0	0.30	329
DW-30	C-19-01 04DAA	-	140	1.5	3.6	0.3	77	23	23	250	10.0	0.37	353
DW-31	C-18-01 28ABB	7.9	150	3.4	6.8	2.3	32	68	63	200	2.9	0.45	444
DW-53	C-19-02 03ADD	-	1400	11.0	160.0	100.0	35	2100	850	400	1.4	1.40	4880
+Toro-3	D-18-02 31BDA	8.1	72	2.5	13.0	2.9	31	22	18	180	1.6	0.20	258
DW-15	C-17-01 11BCA	7.4	113	3.0	3.4	0.9	28	15	20	222	2.6	0.34	318
DW-32	C-17-01 33BAC	-	-	-	13.0	2.8	30	128	91	170	1.8	-	565
DW-73	D-17-01 03BAA	-	100	2.1	22.0	4.4	32	21	17	220	1.5	0.17	302
DW-46	D-18-01 07ACA	7.4	-	-	17.0	6.4	38	43	45	237	2.0	-	384

*USGS wells in text, maps, and other tables are hereafter referred to by the shorter designation GS.

+Toro-3 in text, maps, and other tables is hereafter referred to as T-3.



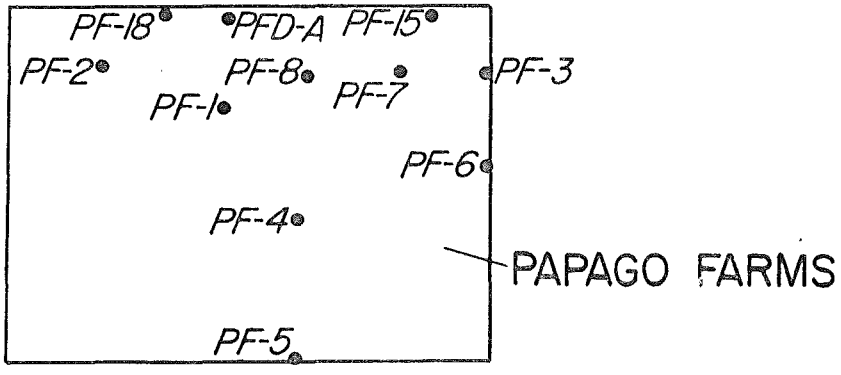


Fig. 8: Well locations, Papago Farms area.

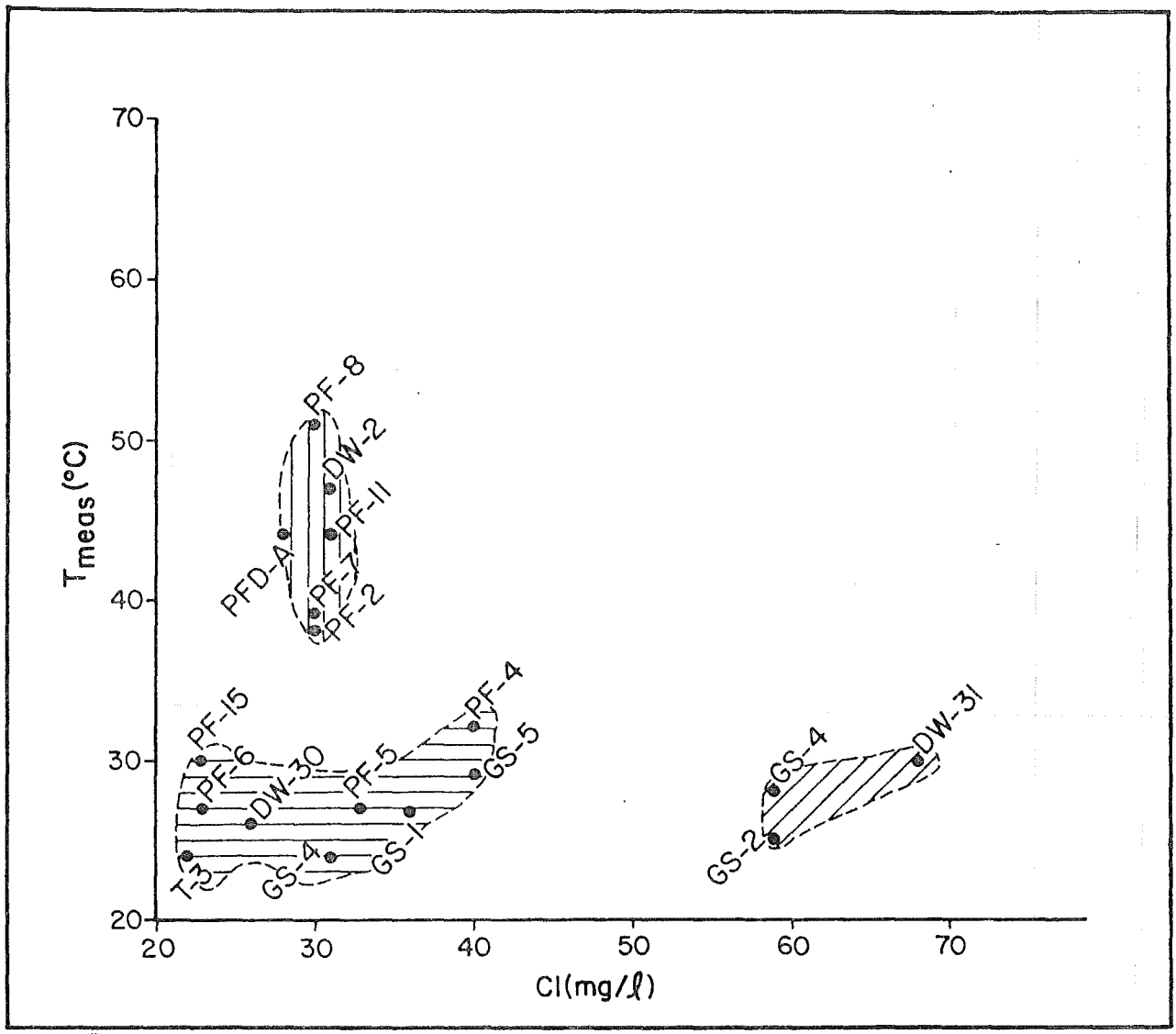


Fig. 9: T_{meas} versus Cl (mg/ℓ) diagram showing distinct groups of waters in the Papago Farms area.

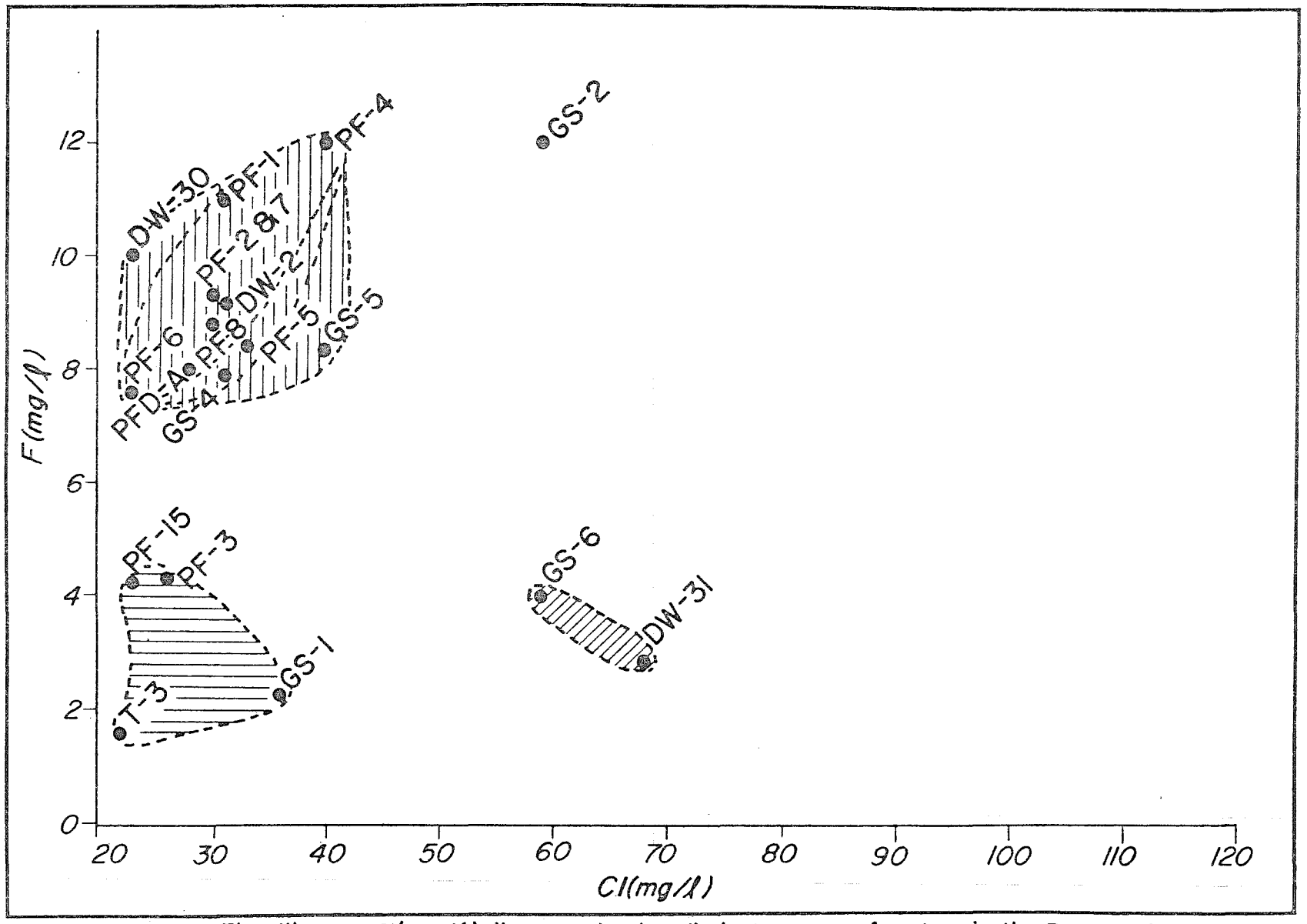


Fig. 10: F(mg/ℓ) versus Cl(mg/ℓ) diagram showing distinct groups of waters in the Papago Farms area.

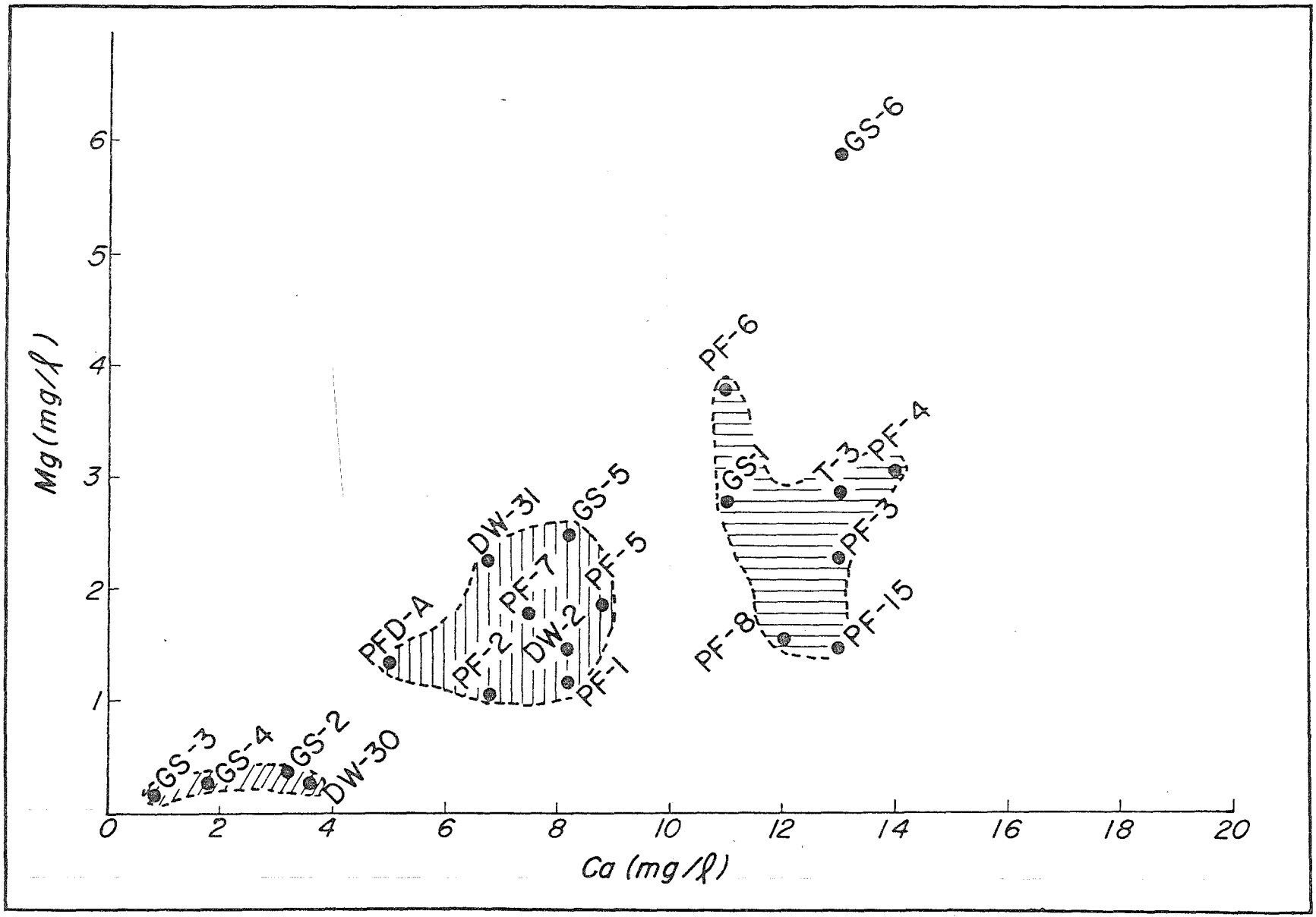


Fig. 11: Mg(mg/ℓ) versus Ca(mg/ℓ) diagram showing distinct groups of waters in the Papago Farms area.

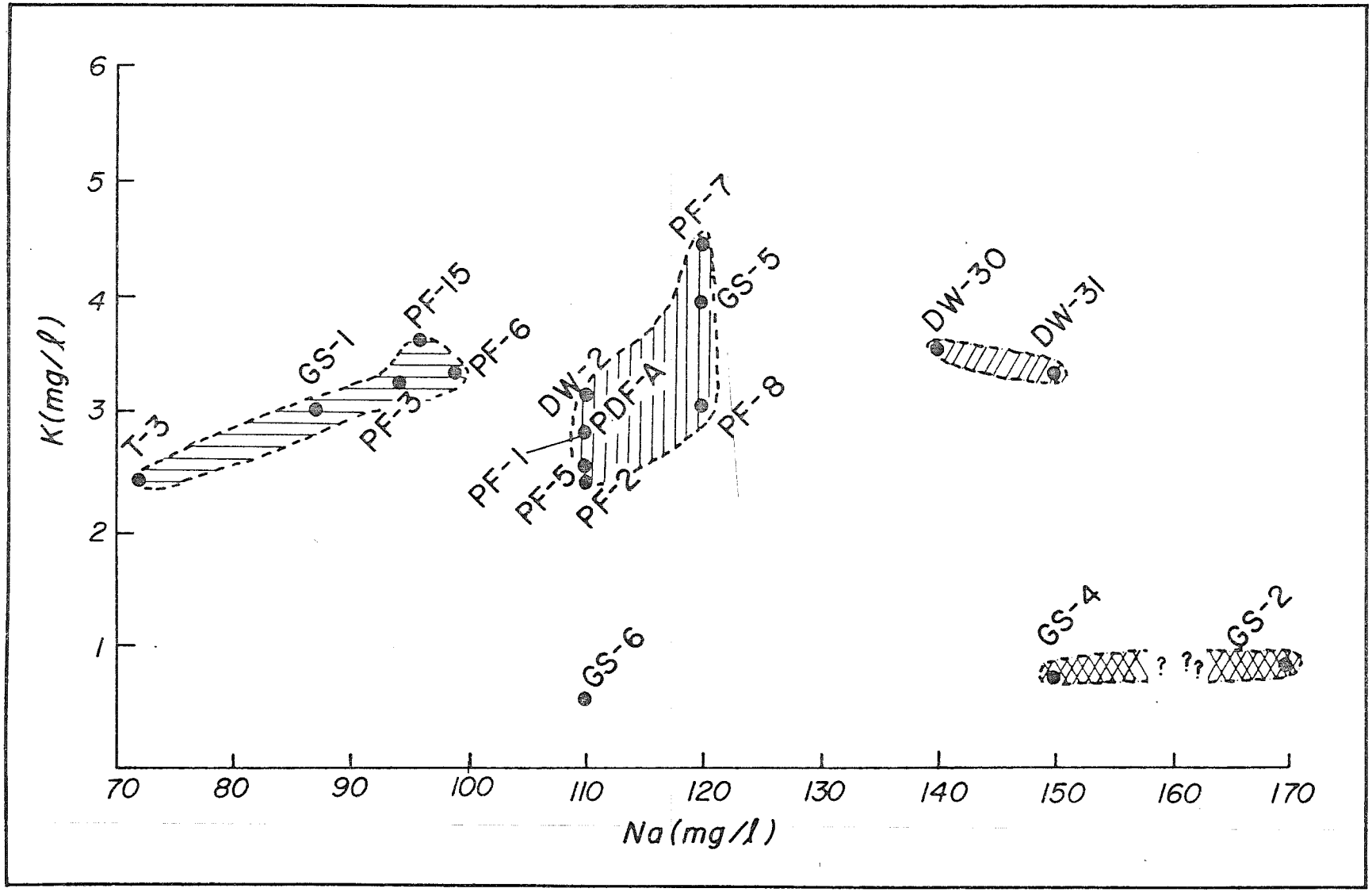


Fig. 12: K (mg/ℓ) versus Na(mg/ℓ) diagram showing distinct groups of waters in the Papago Farms area.

this report, but it is evident that this water will most likely resemble other Group I waters, with perhaps a small component of Group II water.

Group II waters occur slightly west of Group Ia and are thermal ($T>31^{o}C$). Well-head temperatures range between 38 and $51^{o}C$. Group II includes DW-2, PF-1, PF-2, PF-7, PF-8, and PFD-A, all of which are located in proximity, at or near the north end of the Farms. The waters have low Cl/F and Mg/Ca ratios and moderate Na/Ca and Na/K ratios relative to Groups I and III. Mean total dissolved solids is slightly higher than that of Group I: 353 ± 19 mg/l versus 320 ± 35 mg/l for Group I.

Group III waters (GS-2, GS-3, GS-4, GS-6, DW-30, and DW-53) exhibit fewer similarities as a group than do Groups I and II. Group III waters are nonthermal. They are distinguished by very high Na/K and Na/Ca ratios, both of which exceed Group I ratios by a factor of five or more (Table 2). These waters are the most westerly group and their chemistry is strongly influenced by the possible evaporite deposit mentioned above.

A chemical analysis and well-head temperature from PF-18 are not available, but the above-normal temperature, $35.4^{o}C$ at 120 m depth, and its proximity to the other thermal wells suggest that it belongs in Group II. GS-5 and PF-5 have temperatures less than $31^{o}C$, but are chemically similar to the Group II thermal waters. They may reflect Group II waters that have cooled. DW-31 does not show an affinity for any group. Chemical characteristics of PF-6, PF-8, PF-4, PF-5, GS-5, GS-4, and DW-30 waters suggest mixing in the subsurface as their atomic ratios show an affinity for two groups.

Chemical Geothermometers. Experimental evidence has established that the solubility of silica in water is largely a function of temperature and the silica species being dissolved. Fournier and Row (1966)

proposed a method of estimating subsurface temperatures in hot aquifers based on the concentration of silica in thermal water, assuming that there is equilibration of dissolved silica with quartz minerals in high-temperature aquifers and that the equilibrium is largely preserved as the thermal water flows to the surface. Their method appears to be the most accurate and useful for thermal waters in the temperature range 150 to 225°C (Fournier, 1977). Arnórsson (1970; 1975) found that chalcedony rather than quartz generally controls the silica concentration in Iceland's thermal waters when temperatures are below 100-110°C. Figure 13 is a plot of temperatures (°C) versus silica concentrations (mg/l), which shows that chalcedony controls silica concentrations in the study area. Between 110-150°C either species can be the controlling factor.

The sodium-potassium-calcium geochemical thermometer was devised by Fournier and Truesdell (1973) to estimate aquifer temperatures based on the molal concentrations of Na, K, and Ca in thermal waters. Fournier and Potter (1978) devised a method to correct the Na-K-Ca temperature for the effects of magnesium.

Many basic assumptions are made in using the geochemical thermometers to estimate subsurface temperatures. These were discussed in detail by Fournier, White, and Truesdell (1974) who emphasized that it is unlikely that all assumptions will be fulfilled everywhere. The basic assumptions are: (1) the chemical reactions are temperature dependent; (2) there is an adequate supply of all reactants; (3) water-rock equilibrium occurs at the reservoir temperature; (4) hot water ascends rapidly to the surface so no re-equilibration of the "indicator" constituents occurs; and (5) thermal and nonthermal waters do not mix during flow to the surface or evaluation of such mixing is possible. These assumptions

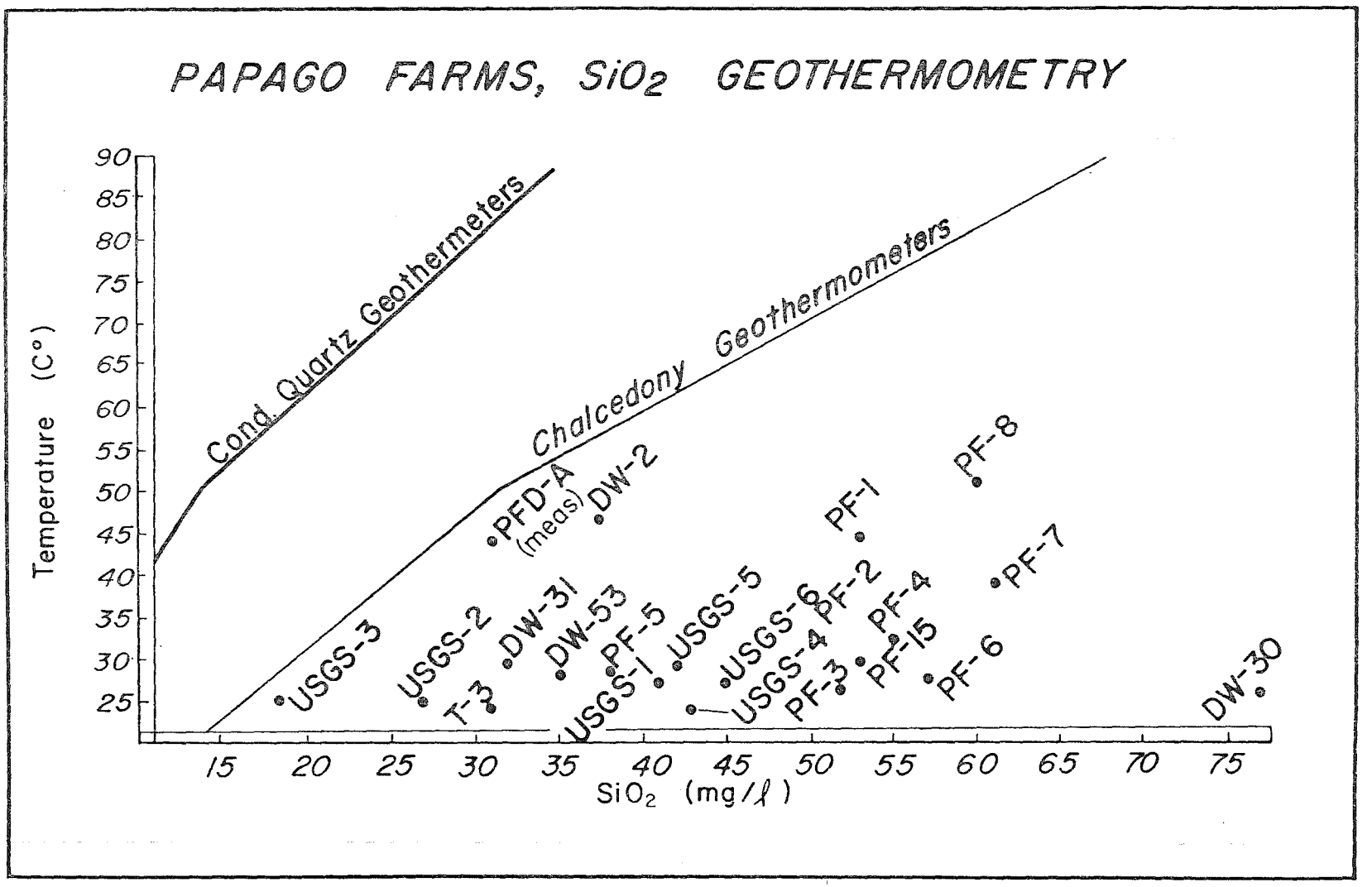


Fig. 13: Temperature (°C) versus SiO_2 (mg/ℓ) diagram showing that chalcedony controls silica concentrations in ground water from the Papago Farms area.

usually cannot be verified in the field so that geochemical thermometers must be applied with caution and with a full understanding of the uncertainties involved.

The chalcedony geochemical thermometer and the sodium-potassium-calcium geochemical thermometer with magnesium correction were used to estimate deep aquifer temperatures at the Papago Farms (Table 2). The most reliable temperatures are those where the silica temperature (T_{SiO_2}) and the sodium-potassium-calcium temperature ($T_{Na-K-Ca}$) for a given well agree within 20°C or less. It is evident from Figure 14 that this condition exists for 12 wells (Table 3), the four highest temperatures of which are from Group II thermal waters. The geochemical thermometers predict a minimum reservoir temperature of about 80°C.

Mixing Models. Dilution of thermal waters rich in silica with cool ground waters containing low silica concentrations would effectively lower the silica concentration of the thermal water and would indicate a lower reservoir temperature. Fournier and Truesdell (1974) suggested that mixing of thermal and nonthermal waters should be suspected where (1) the Na-K-Ca geochemical thermometer ($T_{Na-K-Ca}$) varies from the surface temperature by more than 20°C, indicative of nonequilibrium, and (2) regular variations in surface temperatures with non-reactive chemical constituents such as chloride and boron are observed from several wells in an area. Both conditions occur at the Papago Farms.

Fournier and Truesdell (1974) developed a method of predicting the maximum probable temperature of the hot-water component before mixing and the fraction of cold water in the mixed-water sample. They assumed that enthalpy (heat content) (H_c) of the cold water multiplied by the fraction of cold water (X), plus the enthalpy of the hot water (H_h) multiplied by

TABLE 2. RATIOS OF SELECTED CHEMICAL CONSTITUENTS, CHEMICAL GEOTHERMOMETERS, TOTAL DISSOLVED SOLIDS, TEMPERATURES, WELL DEPTHS, AND GEOTHERMAL GRADIENTS CALCULATED BY METHOD 1 (SEE TEXT) FOR 26 WELLS AT THE PAPAGO FARMS AND SURROUNDING AREAS.

SAMPLE NO.	MEAS. T(°C)	DEPTH (M)	GRADIENT (°C/KM)	CL/F[1]	NA/CA[1]	MG/CA[1]	NA/K[1]	T_{SiO_2} (°C)	$T_{Na-K-Ca}$ (°C)	TDS[2]
GROUP IA										
T-3	25	91.5	43.7	7.4	4.8	0.37	48.9	49.5	58.6	258
GS-1	27	153.7	39.0	8.4	6.9	0.42	47.8	62.6	71.8	308
PF-3	28	280.8	24.9	3.2	6.3	0.29	48.7	73.9	71.0	330
PF-6	27	170.7	35.1	1.6	7.8	0.56	49.4	78.6	56.3	327
PF-15	30	91.5	46.9	2.9	6.4	0.18	43.9	74.8	75.5	351
GROUP IB										
DW-15	25	110.0	36.3	3.1	28.9[3]	0.44	64.0[3]	45.1	63.4	318
DW-32	-	97.9	-	38.0[3]	-	0.35	-	48.1	-	565[3]
DW-73	32	-	-	7.5	4.0	0.33	80.6[3]	50.9	46.3	302
DW-46	30	96.6	93.2[3]	11.5	-	0.63	-	58.7	-	384
$\bar{X}$ =	28±2.5		37.6±7.8	5.7±3.5	6.0±1.4	.37±.10	47.7±2.2	60.2±12.9	63.3±10.4	323±37
GROUP II										
DW-2	46	128.0	195.3	1.8	12.0	0.30	58.3	57.4	81.4	335
PF-1	44	218.0	105.5	1.5	12.0	0.25	58.3	74.8	81.4	356
PF-2	38	290.2	58.6	1.7	14.1	0.26	74.7	77.9	76.9	348
PF-7	39	283.5	63.5	1.6	14.1	0.41	45.4	82.1	77.6	374
PF-8	51	193.6	155.0	1.7	8.7	0.22	66.1	81.3	73.3	375
PFD-A	30	120.0	141.7	1.9	19.1	0.48	64.6	49.5	84.5	329
$\bar{X}$ =	43±5.3		119.9±53.9	1.7±.14	13.3±3.4	.32±.10	61.2±9.8	70.5±13.7	79.2±4.0	353±19
GROUP III										
GS-2	25	152.4	26.2	2.6	46.2	0.19	321.3	43.5	65.8	450
GS-3	25	152.4	26.2	2.8	857.5[3]	0.50	463.5	27.3	63.7	1885[3]
GS-4	24	152.4	19.4	0.2	72.4	0.22	310.5	64.5	72.3	409
GS-6	28	153.7	45.5	7.9	7.4	0.75	318.7	66.7	25.9	375
DW-30	26	78.4	63.8	1.2	33.8	0.11	160.3	95.0	77.2	353
DW-53	28	86.9	80.6	800.3[3]	7.6	1.03	216.6	54.9	35.2	4880[3]
$\bar{X}$ =	26±1.7		43.6±24.4	2.9±2.9	33.5±27.5	.47±.36	298.5±104	58.7±23	56.7±21	397±42
MISC.										
GS-5	29	153.7	52.0	2.6	12.7	0.51	50.1	63.4	63.3	377
PF-4	27	290.2	20.6	1.4	22.7	0.35	106.3	64.5	79.4	350
PF-5	27	289.6	20.7	2.1	10.9	0.36	71.3	58.7	81.1	331
DW-31	30	95.1	94.6	12.7	19.2	0.56	74.9	50.9	60.6	444
PF-18	35[4]	105.0	-	-	-	-	-	-	-	-

1. ATOMIC RATIOS
2. MILLIGRAMS PER LITER
3. ANOMALOUS CONCENTRATION, EXCLUDED FROM MEAN-VALUE ESTIMATE
4. TEMPERATURE AT 120 M DEPTH

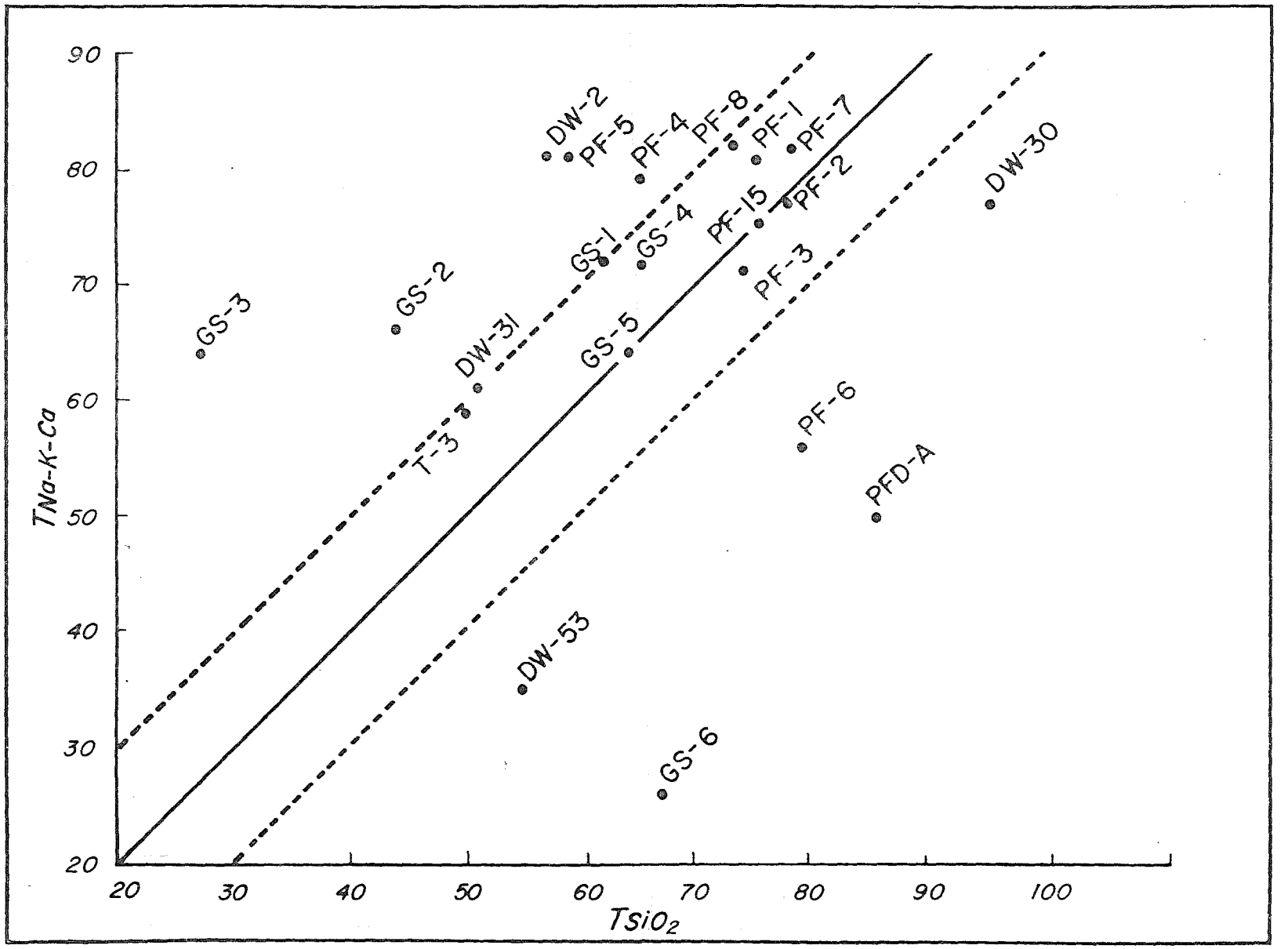


Fig. 14: $T_{Na-K-Ca}$ versus T_{SiO_2} diagram showing correlation between chemical geothermometers of ground waters from the Papago Farms and surrounding areas.

TABLE 3. Chemical geothermometers and predicted minimum reservoir temperatures for selected wells, Papago Farms and surrounding areas.

Well Name	T_{SiO_2} (°C)	$T_{Na-K-Ca}$ (°C)	Temperature (°C) Predicted*	Measured
PF-7	82.1	77.6	79.9 ± 3.1	39.0
PF-1	74.8	81.4	78.1 ± 4.7	45.0
PF-2	77.9	76.9	77.4 ± 0.7	38.0
PF-8	81.3	73.3	77.3 ± 5.7	51.0
PF-15	74.8	75.5	75.2 ± 0.5	30.0
PF-3	73.9	71.0	72.5 ± 2.1	28.0
GS-1	62.2	71.8	67.0 ± 6.8	27.0
GS-2	64.5	72.3	68.4 ± 5.5	24.0
GS-5	63.4	63.3	63.4 ± 0.1	29.0
DW-31	50.9	60.6	55.8 ± 6.9	30.0
T-3	49.5	58.6	54.1 ± 6.4	25.0
DW-73	50.9	46.3	48.6 ± 3.3	32.0

*Predicted temperatures are an average of T_{SiO_2} and $T_{Na-K-Ca}$.

the fraction of hot water (1-X) is equal to the enthalpy of the emerging warm water (H_w). This is represented by:

$$H_w = (H_c)\ (X) + (H_h)\ (1-X) \qquad (1)$$

The same conditions are assumed for silica content:

$$Si_w = (Si_c)\ (X) = (Si_h)\ (1-X) \qquad (2)$$

where Si_c is silica content of cold water, Si_h is silica content of hot water, and Si_w is silica content of the mixed-water sample.

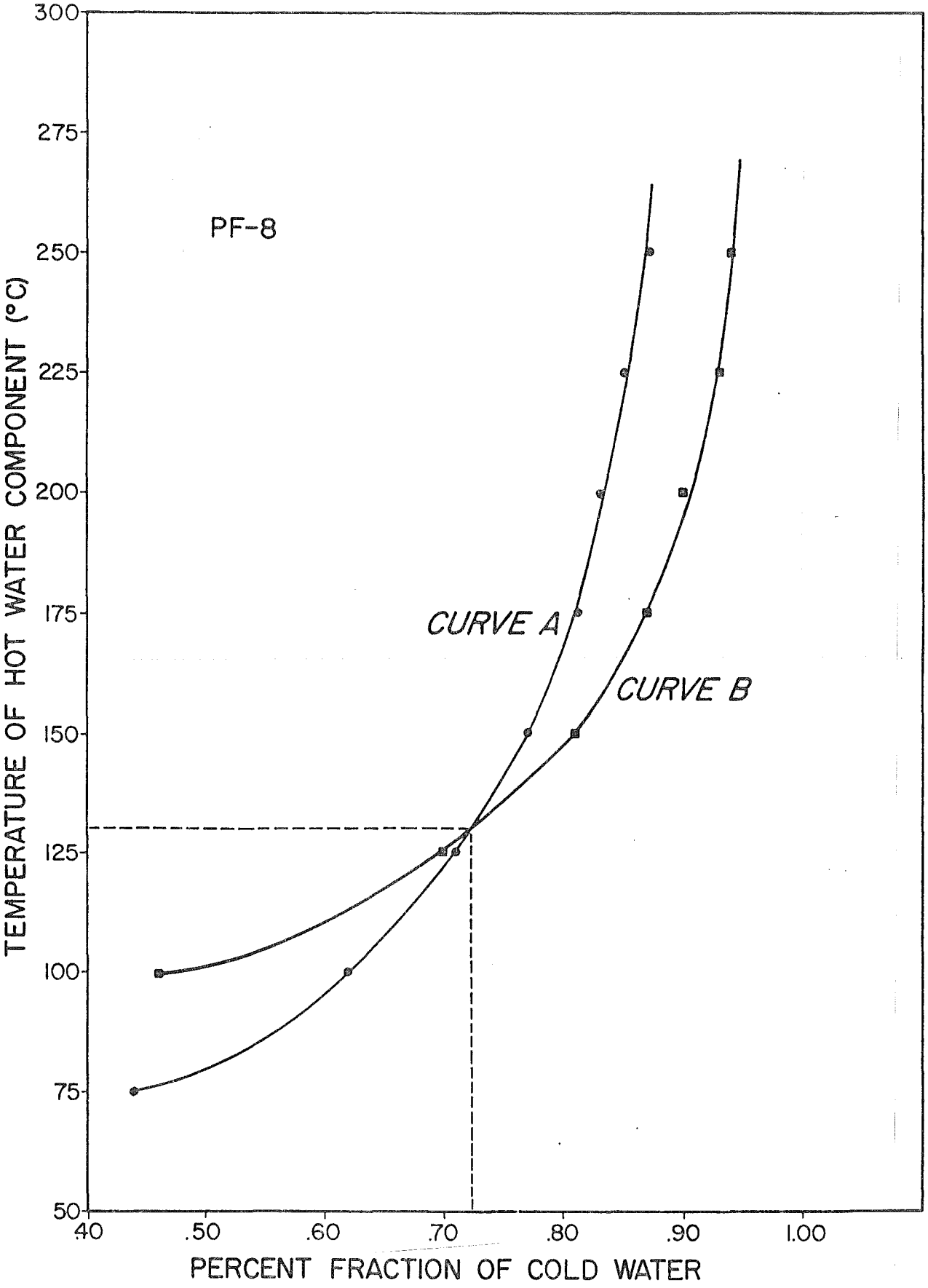


Fig. 15: Fraction of cold water relative to temperature for well PF-8, Papago Farms.

TABLE 4. Enthalpies of liquid water and chalcedony solubilities at selected temperatures. (Temperature and enthalpy data from Fournier and Truesdell, 1974. Chalcedony solubilities, this report.)

Temperature °C	Enthalpy cal/gm	Chalcedony mg/l
50	50.0	31.4
75	75.0	53.2
100	100.1	84.0
125	125.4	125.3
150	151.0	178.3
175	177.0	243.9
200	203.6	322.8
225	230.9	415.3

to be the same as the mean annual temperature in this region, 21°C.

Table 5 gives calculated X_t and X_{Si} values at selected temperatures and silica contents for the four wells showing mixed waters. Also shown in Table 5 are the maximum probable temperatures of the hot-water component before mixing and the estimated fractions of cold water.

Mixing was not indicated in other wells in the study area. However, Fournier and Truesdell (1974) cautioned that additional dissolved silica in the mixed water, owing to contact with amorphous silica or rock containing glass, could result in the two curves not intersecting or in their intersection at an unreasonably high temperature. They further pointed out (p. 266), "if either the temperature or silica content of the cold water were higher than the assumed value, the resulting estimated temperature of the hot-water component would be too high." It is likely that one or both of these conditions may be influencing mixing in PF-7, resulting in an unreasonably high temperature; and in PFD-A, DW-2, PF-3, PF-4, and PF-6, preventing the two curves from intersecting. Drill cut-

TABLE 5. X_t and X_{Si} values at specified temperatures and silica concentrations for mixing model calculations, Papago Farms, Papago Indian Reservation, Arizona. (Background silica = 32 mg/l. Mean annual temp. = 21°C.)

PF-1

Well temperature = 45°C
Silica = 53 mg/l

T (°C)	X_t	X_{Si}
75	.55	--
100	.70	.60
125	.77	.77
150	.81	.86
175	.84	.90
200	.87	.93
225	.88	.95

Temperature of unmixed water = 125°C
Percent of cold water = 77%

PF-2

Well temperature = 38°C
Silica = 50 mg/l

T (°C)	X_t	X_{Si}
75	.69	.15
100	.78	.65
125	.84	.81
150	.87	.88
175	.89	.92
200	.91	.94
225	.92	.95

Temperature of unmixed water = 142°C
Percent of cold water = 86%

PF-7

Well temperature = 39°C
Silica = 61 mg/l

T (°C)	X_t	X_{Si}
75	.67	--
100	.77	.44
125	.83	.69
150	.86	.80
175	.88	.86
200	.90	.90
225	.91	.92

Temperature of unmixed water = 200°C
Percent of cold water = 90%

PF-8

Well temperature = 51°C
Silica = 60 mg/l

T (°C)	X_t	X_{Si}
75	.44	--
100	.62	.46
125	.71	.70
150	.77	.81
175	.81	.87
200	.83	.90
225	.85	.93

Temperature of unmixed water = 131°C
Percent of cold water = 73%

tings reveal that PF-7 penetrates a section of volcanic rock greater than 200 feet in thickness (Hollett, personal commun., 1980), which probably contains a high percentage of glass, thus supporting the inference of excess silica in this sample.

PF-1, PF-2, and PF-8 have estimated maximum temperatures of 125°C, 142°C, and 131°C, respectively. The general agreement of these temperatures suggests that the maximum probable temperature of the aquifer supplying the hot-water component is about 140°C.

Geothermal Gradients. The geothermal gradient is a measure of the rate at which temperature increases with depth in the earth. The gradient is a result of conductive heat flow, thermal conductivity of rock through which the heat travels, hydrothermal convection, or some combination of these. The worldwide "normal" geothermal gradient is 30°C/km.

In geothermal exploration, gradients are typically extrapolated to some great depth in an attempt to predict depth to the hot aquifer. There are several ways to calculate such gradients, depending upon the available data. The results vary from reliable to erroneous.

Method 1 is used to estimate the geothermal gradient when only well-head temperature and well depth are known. The gradient is calculated by:

$$\Delta T/\Delta Z = \frac{T_{meas} - MAT}{Z\ 10^{-3}} \qquad (6)$$

where $\Delta T/\Delta Z$ = thermal gradient, °C/km
T_{meas} = measured well-head temperature, °C
MAT = mean annual temperature, (21°C at the Farms)
Z = well depth, meters

This method assumes that (1) the temperature increases linearly with depth and (2) the well-head temperature is the hottest and deepest tem-

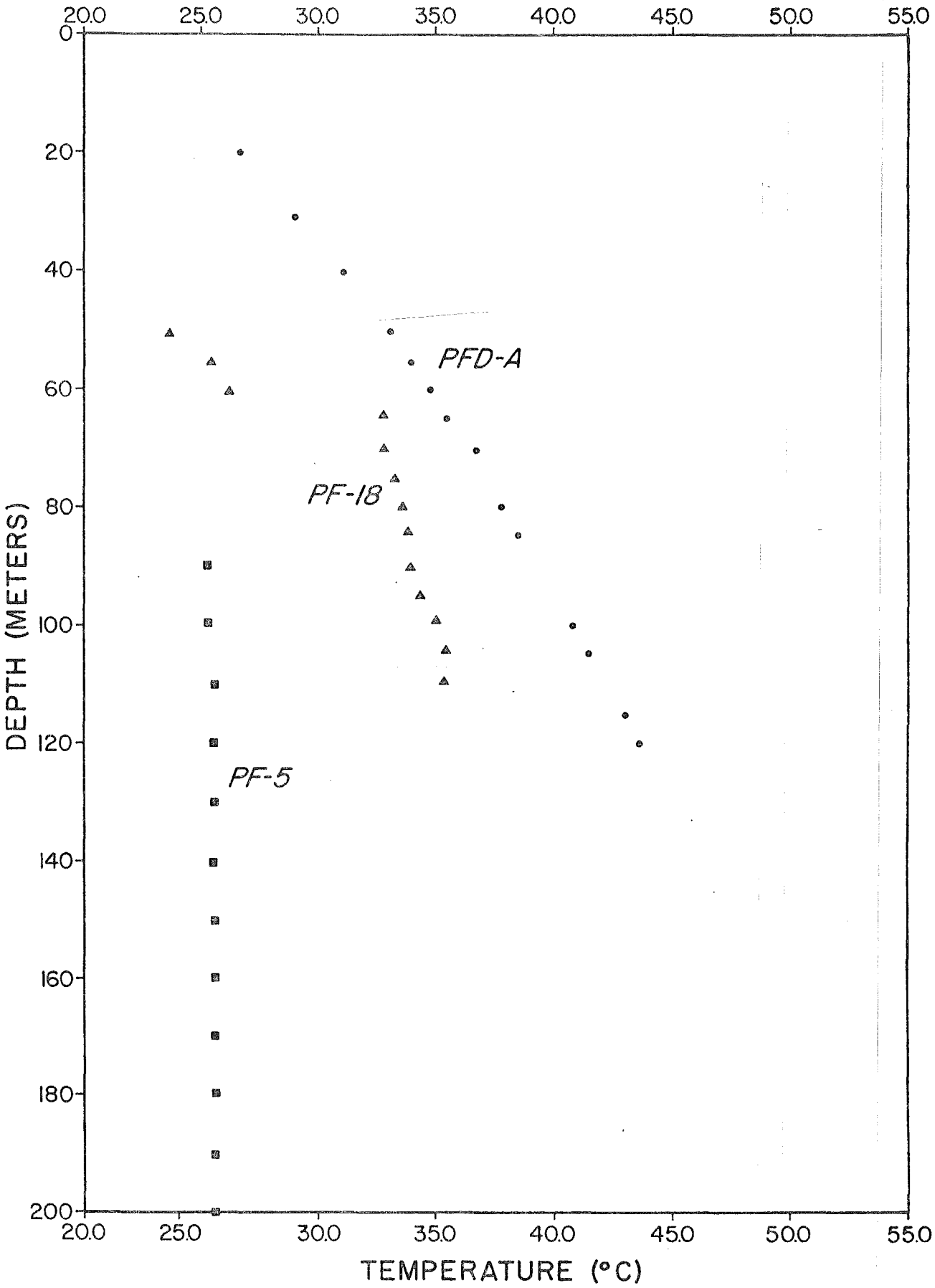


Fig. 16: Temperature versus depth profile for PF-18, PFD-A, and PF-5.

perature in the well. Generally one or both assumptions are not valid when shallow ground water is encountered in a system. PFD-A is an example of a well that disproves the second assumption. The well-head temperature for PFD-A is 38°C, but the measured bottom-hole temperature at 120 m is 43.7°C. The temperature-depth (T-D) profile of PF-18 (Fig. 16) shows that the first assumption at times is not valid either. In fact it can be seen that between 105 and 110 m the temperature of PF-18 actually decreases.

The second method of calculating the geothermal gradient also uses equation 6 but T_{meas} is the measured bottom-hole temperature. This method is somewhat more accurate than using the well-head temperature, but the same assumptions apply to this method as apply to the first method.

The most accurate way to obtain a geothermal gradient is to measure temperatures down a borehole at discrete intervals and then fit a straight line to the data using the statistical method of linear regression. This method allows calculation of the standard deviation and the correlation coefficient (a measure of how well the data fit the linear regression).

Three wells at the Papago Farms were temperature logged at 5-meter intervals and the geothermal gradients were calculated by the linear regression method. Table 6 shows the geothermal gradients for these wells, calculated by the three methods described. The discrepancy between methods 1 and 2 and method 3 is largest in PF-5, which has a nearly isothermal T-D profile, and smallest in PFD-A, which appears to have a nearly linear T-D profile (Fig. 16). Unfortunately, since there is no way of knowing which wells are isothermal and which approach linearity without having downhole temperature logs, it is nearly impossible to evaluate the reliability of calculated geothermal gradients for predicting depth to the

hot aquifer.

A problem arises in using even linear geothermal gradients to estimate depth to a reservoir, because linear gradients can be expected to change at depth when influenced by ground water or by changing rock thermal conductivity. A closer look at the T-D profile of PFD-A (Fig. 16) reveals that the true shape of this curve is really convex-upward, indicative of warm water rising toward the surface. The profile shows that the temperature is increasing at an ever slower rate. When the maximum temperature of the system is reached the gradient will become zero. Most likely the T-D profiles of the other thermal wells have similar shapes. The gradient measured in PFD-A suggests that the maximum reservoir temperature may be encountered at 1.5 to 2 km depth.

TABLE 6. Geothermal gradients calculated by three different methods. (See text for explanation.)

Well	Method 1 °C/km	Method 2 °C/km	Method 3 °C/km
PF-5	20.7	24.1	4.5 ± 0.17
PF-18	*	120.3	66.1 ± 1.02
PFD-A	141.7	188.8	165.0 ± 5.18

*Well-head temperature not available.

Geothermal gradients in a hydrothermal system are less reliable in predicting temperatures at depth than they are when used in a relative context, that is, in comparing the gradient in one well with those in surrounding wells. At the Papago Farms the highest geothermal gradients occur in the wells producing Group II thermal waters (Table 2). The gradient map (Fig. 17) shows a distinct northwest trend but it does not quite coincide with the trends seen in the gravity and silica heat flow

maps discussed in the next section.

T-D profiles of the three wells logged at the Farms show that warm water is rising in PFD-A and that water is descending in PF-5 and probably in PF-18. It can be inferred from these profiles that PFD-A is located within the geothermal anomaly and PF-5 is situated outside of it. The location of PF-18 with respect to the anomaly is less certain, but may be on the margin.

Gravity. Depth to bedrock in the Great Plain was modeled by Greenes (1980) (Fig. 18) who showed that it increases to the south towards Mexico, reaching a maximum depth in Arizona of about 2,700 m. The basin may be deeper in Mexico. Greenes also showed that the Papago Farms basin is asymmetrical with a subsurface bedrock scarp along the eastern pediment edge. He suggested that this scarp, indicated by the strong gravity gradient seen in his second order residual gravity anomaly map (Fig. 19), is probably due to faulting. Geochemical evidence, namely the distinct chemical and thermal differences between PF-15, PF-3, and PF-6 waters at the eastern edge of the Farms and DW-2 and PF-7 waters immediately to the west of them, suggests a northwest extension of this scarp through the Papago Farms, between these groups of wells. The presence of a fault or some other structural control between these wells helps explain the observed differences in water chemistry and temperatures.

Across the north end of the Papago basin the abruptly steepening gravity gradient (Fig. 19) suggests the presence of another scarp that may be due to faulting also. Intersection of the two proposed subsurface bedrock faults could explain (1) the anomalous bulge in the second order residual gravity at the north end of the Farms as being the result of highly fractured basement rocks and (2) the fact that PF-7, which sits

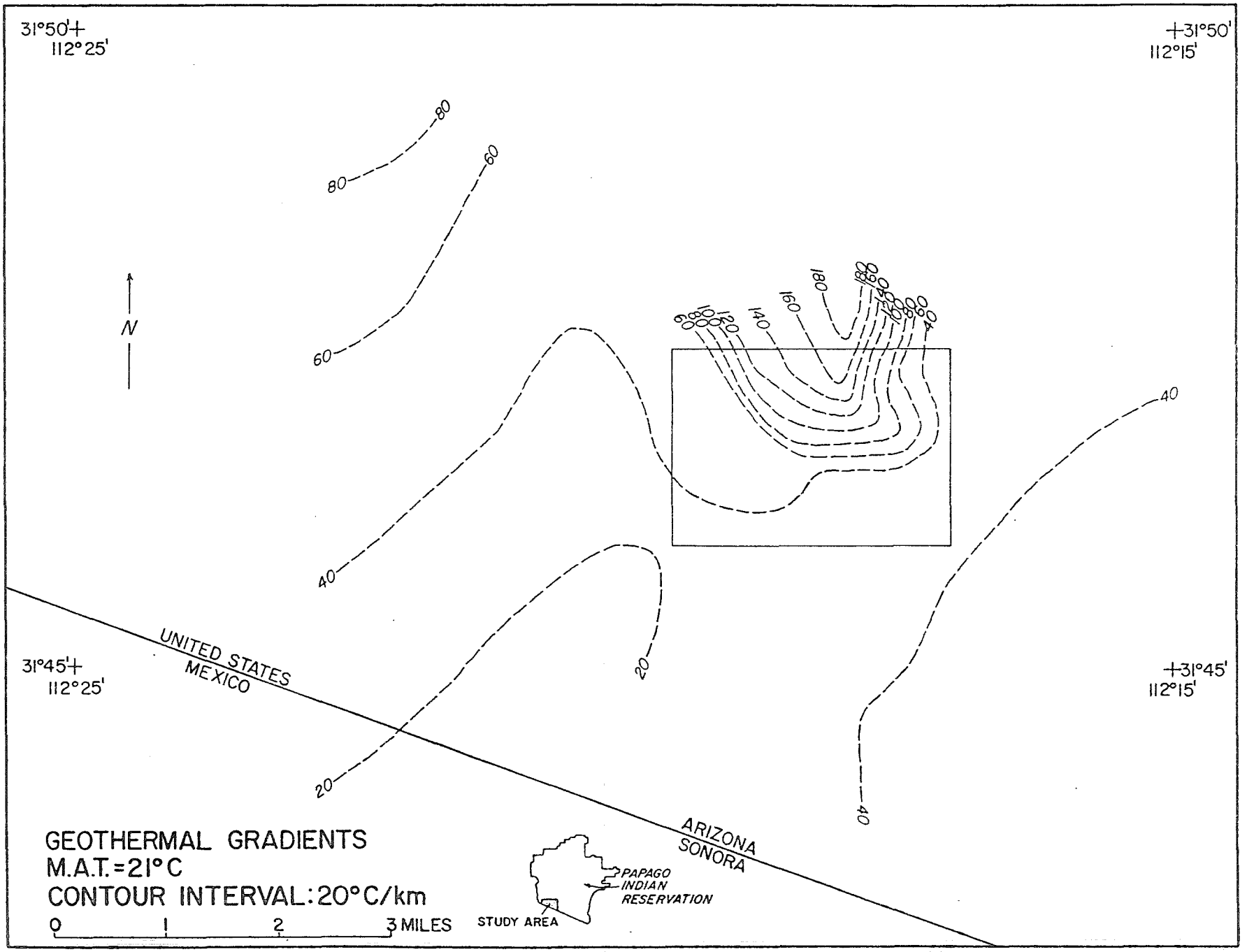


Fig. 17: Geothermal gradient map, Papago Farms and surrounding area. Contour interval is 20°C/km.

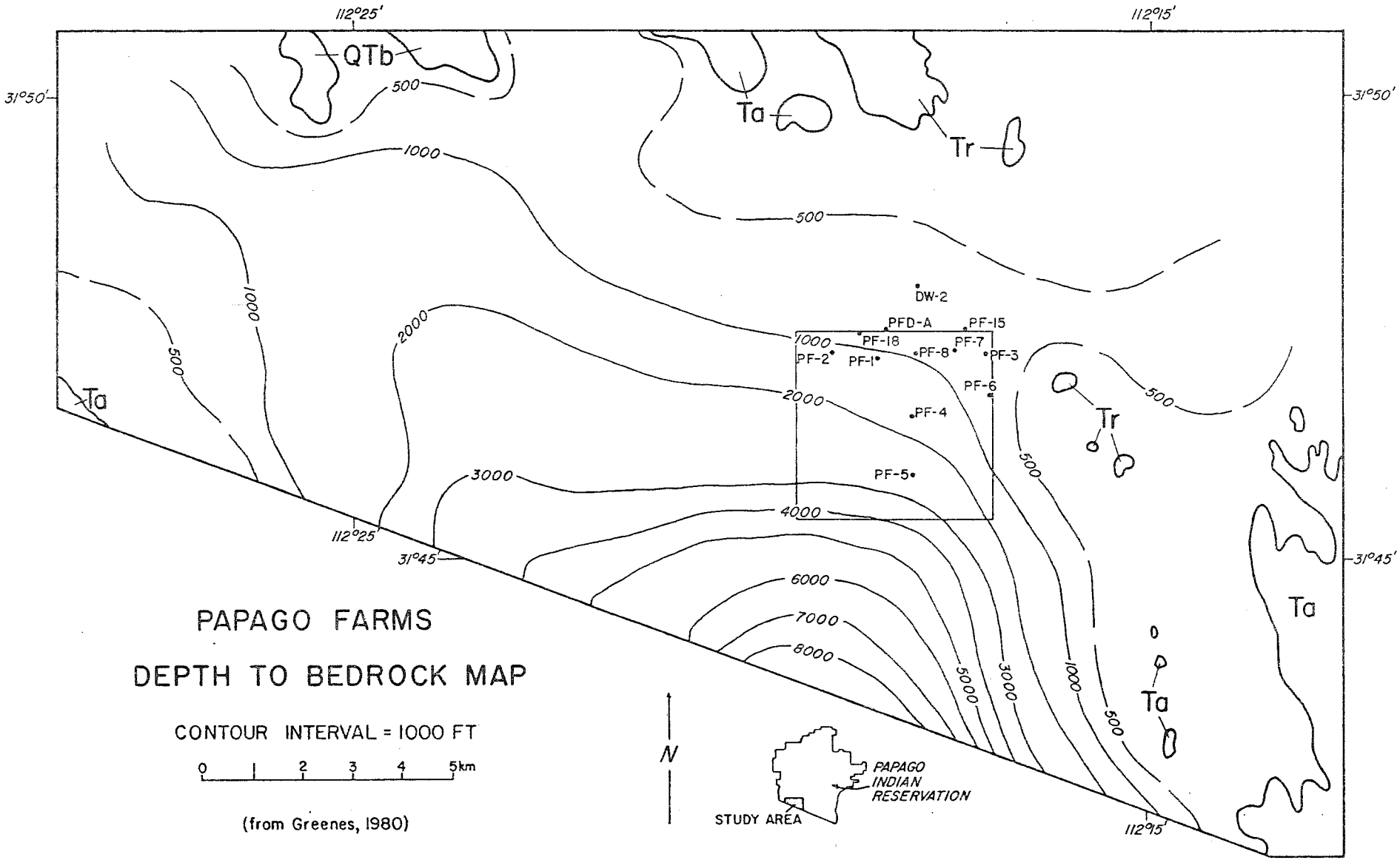


Fig. 18: Depth to bedrock map, with well names and locations referred to in text and tables. Square outline is Papago Farms. Contour interval is 1000 feet. (From Greenes, 1980)

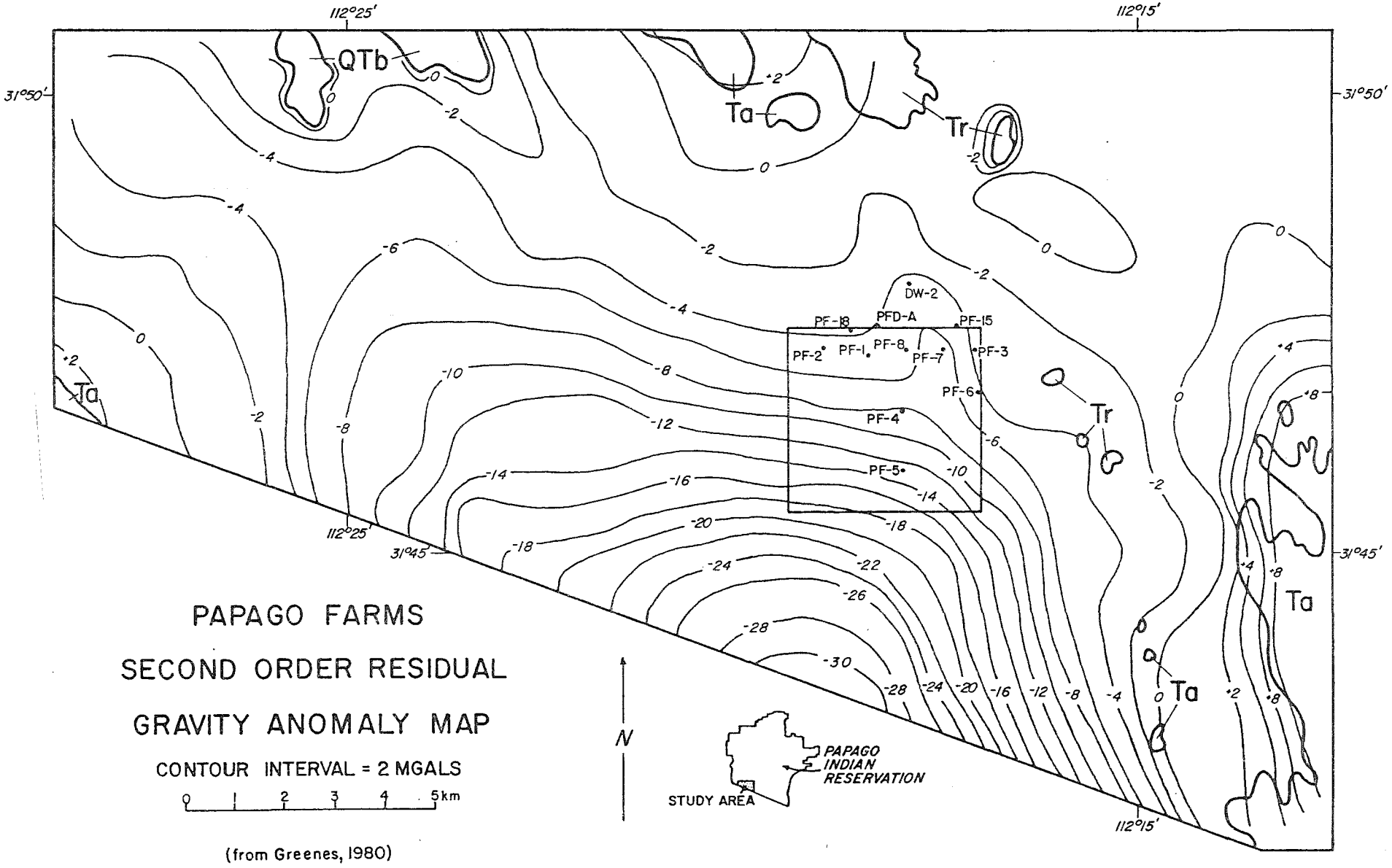


Fig. 19: Second order residual gravity anomaly map, with well names and locations referred to in text and tables. Square outline is Papago Farms. Contour interval is 2 mgals. (From Greenes, 1980)

in the bulge, is the hottest well at the Farms according to the geochemical indicators. This postulated fault intersection suggests that the geothermal fluids are held in a reservoir with fracture permeability.

While the silica heat flow method is generally considered to reflect areas of anomalous heat flow on a regional scale, use of such data locally is of questionable value. Nonetheless the contoured data at the Papago Farms and surrounding area (Fig. 20) show two distinct trends, N. 18° W. and N. 81° W., that coincide exactly with the faults and fault intersection suggested by the gravity data. I suggest that the fault zones are each about 1 km wide and intersect in the area of PF-7 (Fig. 21). The south and west margins of the fault zones are constrained by PF-2, PF-1, PF-4, and PF-5, which do not penetrate the volcanic sequence that the other wells penetrate (Hollett, personal commun., 1980). The east margin of the N. 18° W. fault zone is constrained by the thermal and chemical differences between DW-2, PF-7 waters and PF-3, PF-6, PF-15 waters. The northern boundary of the N. 81° W. fault zone is somewhat arbitrary.

Temperatures. Decreases in ground-water temperatures have been recorded at the Papago Farms over a 20-year period (USGS, WATSTORE, 1980). Between about 1958 and 1978 all wells for which data are available show an average temperature decrease of 2.2°C, with declines ranging between 0.5 and 5.0°C for individual wells. Two processes could account for the temperature decreases. The deep hot aquifer or reservoir is cooling off by hydrothermal convection. This is certainly occurring to some slow extent, but it is unlikely to be happening at as fast a rate as observed. The second and more likely explanation is that prolonged, large-volume irrigation pumping is introducing a larger fraction of cold water into the mixed waters that emerge at the surface.

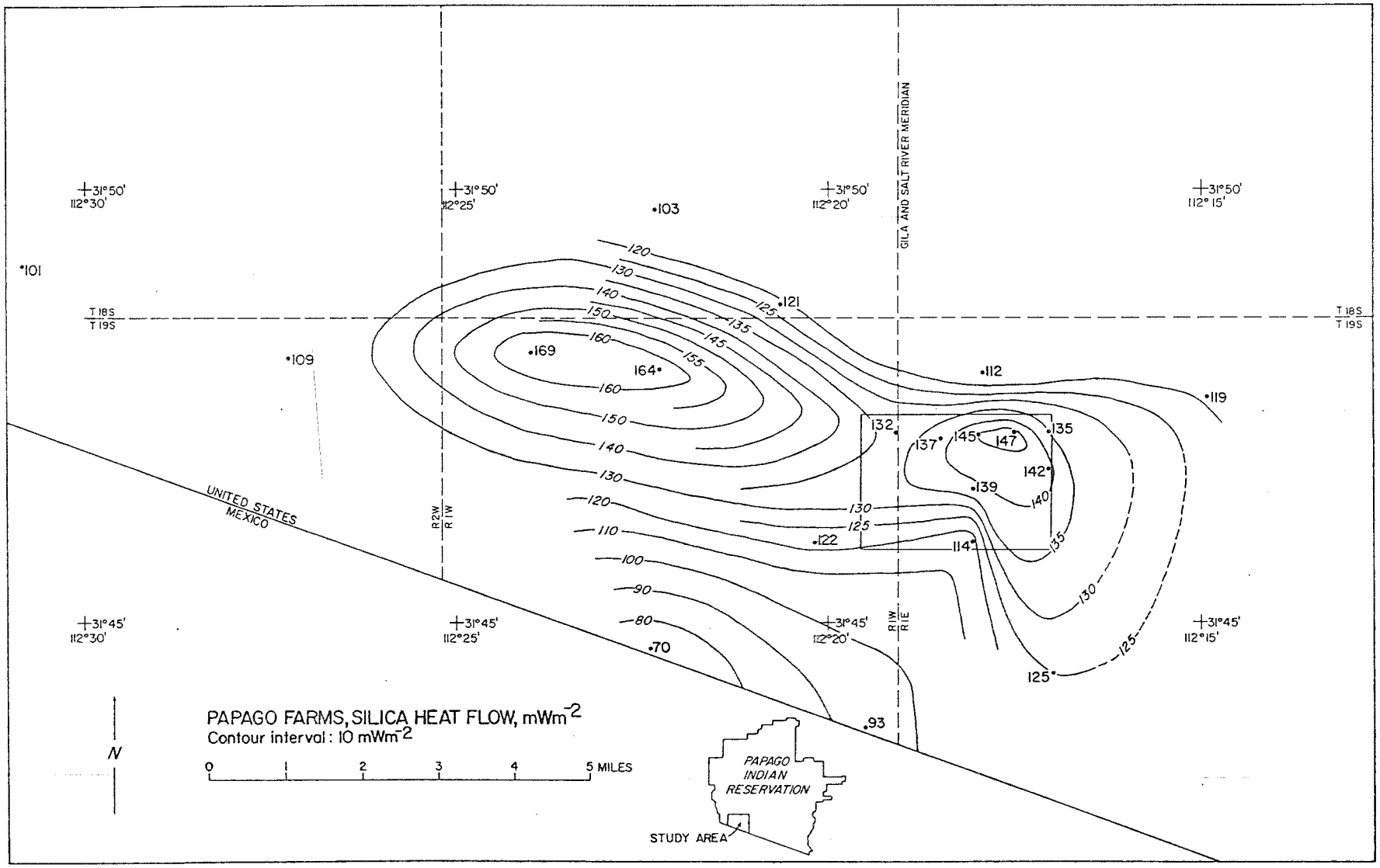


Fig. 20: Silica heat flow map, Papago Farms and surrounding area. Contour interval is 10 mWm^{-2}

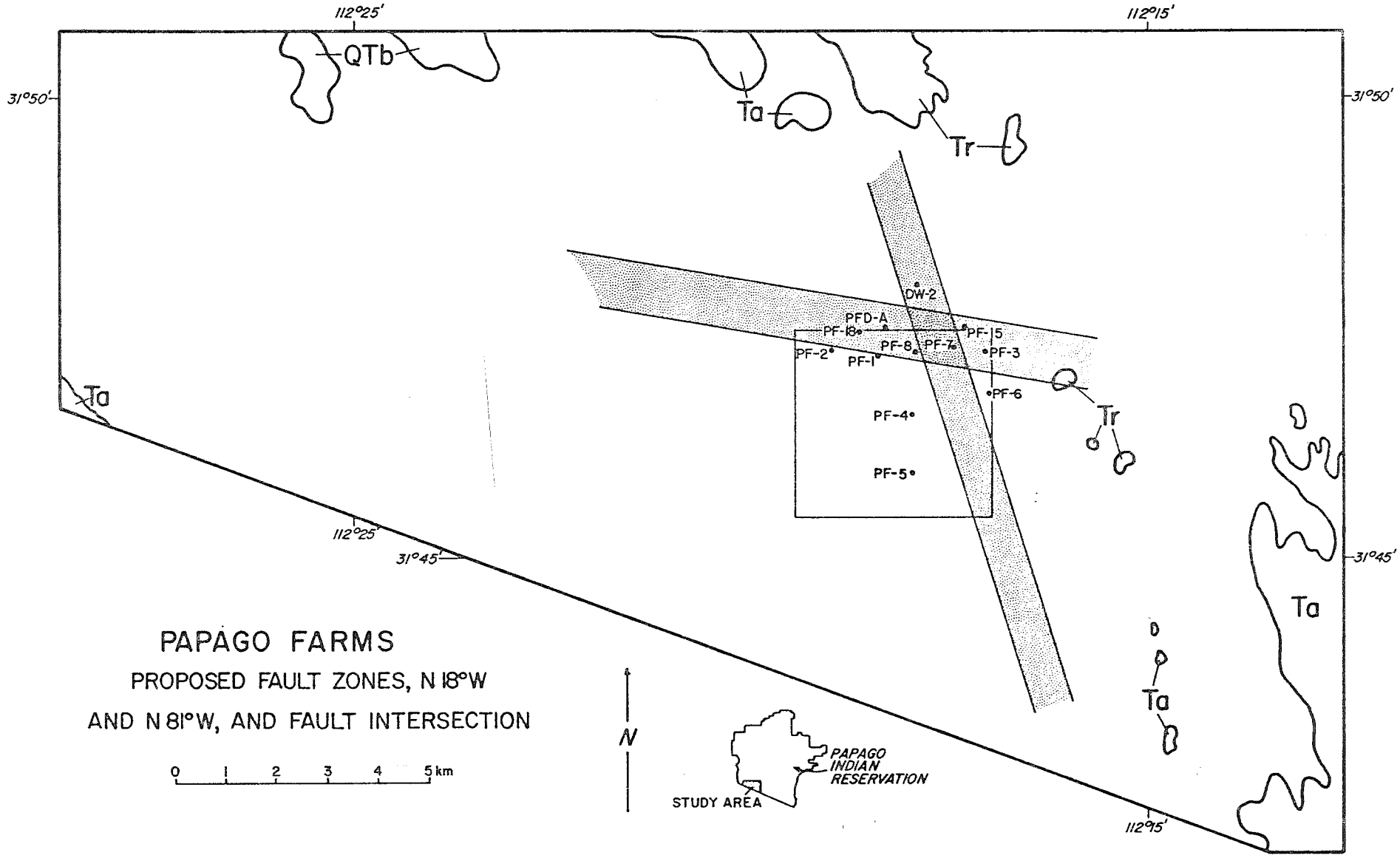


Fig. 21: Proposed fault zones, N. 18°W. and N. 81°W., and fault intersection, Papago Farms.

Conclusions

Geochemical data show that waters from a group of anomalously warm wells at the north end of the Papago Farms are similar to one another but are chemically distinct from waters in surrounding nonthermal wells. Chemical geothermometers and mixing models indicate that the reservoir fluid temperatures are in the range 80 to 140°C.

Geophysical evidence suggests that two fault zones, each about 1 km wide and trending N. 18° W. and N. 81° W., intersect in the area of PF-7. This fault intersection probably has generated an area of intensely fractured basement rocks that provides a fractured reservoir for the geothermal fluids.

Depth to the geothermal reservoir is unknown but may be as shallow as 1.5 to 2 km.

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RECOMMENDATIONS FOR SITE-SPECIFIC RESOURCE ASSESSMENT

Additional resource assessment is necessary to identify the areal extent of and depth to the reservoir. More definitive exploration is also necessary to constrain reservoir temperatures to a smaller more useful range.

The areal extent of the anomaly can be constrained by temperature logging all water wells at the Papago Farms and surrounding area. The temperature versus depth (T-D) profiles that result can be interpreted in terms of wells with rising (discharging) warm water and wells with descending (recharging) cold water. T-D profiles also reflect zones of inflowing and outflowing hot and cold water. Thus aquifer conditions can be identified at least to the depth of the well bottom. It is necessary, however, to pull pumps for access and to allow wells to sit idle for several weeks to allow non-pumping, equilibrium conditions to return to the well bores. Shallow (150 ft.) heat flow holes may also aid in defining the areal extent of the anomaly and occasionally are successful in identifying the reservoir itself. Sometimes, however, shallow ground-water conditions make a heat-flow survey of questionable value by attenuating the heat flux from depth. Heat flow holes are drilled to a specified depth, after which plastic tubing that is sealed at the bottom, is run into the hole and filled with clear water. This assembly is allowed to sit for several weeks to restore pre-drilling thermal equilibrium. The well is then temperature logged. Because heat flow is a result of heat fluxing from the earth and the thermal conductivity of the rocks through which

it moves, it is also necessary to measure the thermal conductivity of drill cuttings from each hole.

Depth to the reservoir is an important factor to know in assessing a geothermal reservoir. A magnetotelluric survey across the Farms would likely be successful in determining this parameter.

Finally, a deep test well (2,000-3,000 ft.) in the center of the geothermal anomaly would confirm the reservoir temperatures that can presently only be inferred from the geochemistry. Best use of the geothermal energy can be achieved only by knowing the maximum reservoir temperatures accurately. A deep test well could also support and confirm the results of the magnetotelluric survey in predicting the depth to the reservoir. Other tests on a deep well would provide valuable information about pressures, volumes, permeability, etc. that are necessary for reservoir engineering.

POTENTIAL USES OF GEOTHERMAL ENERGY AT THE PAPAGO FARMS

Direct use of geothermal energy was originally limited to hydrothermal systems with temperatures in the range of 90 to 180°C. Today technological advances allow thermal fluids as low as about 50°C to be used economically and efficiently in certain agri-business and space heating applications. The use of "heat pumps" permits the economic use of geothermal fluids with temperatures lower than 50°C. Moreover, heat pumps and heat exchangers can be purchased "off the shelf" thereby enabling low-temperature resources to be brought on line in a timely manner.

Space conditioning offices, work shops, and bunkhouses is possibly one of the most efficient ways to use the geothermal resource at the Papago Farms. Space heating can be achieved two basic ways: (1) with geothermal fluids higher in temperature than the required room temperature, a heat exchanger transfers the geothermal heat to the room air heat, much the same as running hot water through a radiator. Heat exchangers are uneconomic at temperatures below about 50°C and increase in efficiency as fluid temperatures increase above 50°C. (2) When geothermal fluid temperatures are lower than the required room air temperature, a heat pump transfers or "pumps" heat from a low temperature to a high temperature medium. The principal is identical to the operation of a refrigerator. The 28-story Mormon Church Office Building in Salt Lake City, Utah, is completely heated and cooled year round using 53°C fluids and heat pumps.

Geothermal fluids can also cool buildings, using an absorption refrigeration process. A geothermal absorption system substitutes the

geothermal fluid (hot water) for the gas or electrically produced heat. Fluid temperatures in the range of 80 to 150°C are sufficiently hot for the absorption refrigeration process. Offices, workshops, and bunkhouses would benefit from geothermally cooled air during the summer months.

Greenhouse heating is a common use of low-temperature geothermal energy. At the Papago Farms it may be possible to use the geothermal resource for greenhouse cooling, thus enabling the production of fruits and vegetables that otherwise cannot be grown there because of the severe summer heat. Irrigation pumping and the generation of electricity are much less likely to result from the geothermal energy at the Papago Farms, but the potential does exist because of a new down-hole pump developed by the Sperry Corporation. The patented Sperry gravity head system uses a pump and turbine, coupled together and placed about 2,000 ft. down a geothermal well beneath a string of concentric tube and heat exchanger sections that are installed from 800 to 2,000 ft. below the surface. The system takes advantage of the vertical shape of the wells to achieve more efficient energy conversion and pumping. This system enables exploitation of lower-temperature geothermal resources, possibly with temperatures as low as 100 to 120°C. The Sperry Corporation presently is seeking a demonstration site in Arizona or Idaho. It is expected that the system will be commercially available by 1983.