GEOTHERMAL RESERVOIR SITE EVALUATION IN ARIZONA

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COMPLIANCE WITH CONTRACTUAL REQUIREMENTS

The principal investigator, W. Richard Hahman, Sr., in accordance with Article I and Article A-I of Appendix A of DOE Contract EG-77-S-02-4362 has devoted his full time, from July 15, 1978, through January 15, 1979, to the contract work. This completes the contract work for EG-77-S-02-4362. The principal investigator plans to devote his full time to a new annual contract for the continuation of the program from January 16, 1979, through July 15, 1979. The principal investigator and the program are in compliance with the requirements of the contract.

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RESEARCH OBJECTIVES

The principal research objective of this program is the development of successful economic exploration techniques for the location, evaluation and development of low-to moderate-temperature geothermal resources for use by the general public and private industry. The development of such a program will require the close coordination of research in the three geoscience disciplines: geology, geophysics and geochemistry.

Current plans call for the complete development of three demonstration projects utilizing low-to moderate-temperature geothermal energy. The first two projects are somewhat experimental in that they must develop a successful, economic exploration and development program. The third demonstration project then must be brought on stream utilizing these cost-effective techniques.

While the detailed or site-specific exploration, evaluation and development programs are in progress, the reconnaissance exploration will continue to attempt to locate additional areas of interest over the entire state of Arizona. At present most data is confined to the Basin and Range physiographic province so that extensive exploration is necessary to identify potential geothermal resources which may exist in the Colorado Plateau region.

Another objective of this program is to compile and publish a more comprehensive geothermal energy resource map of the state of Arizona, 1:500,000 scale. This map will be produced through a joint effort by the U.S.G.S. Geothermal project, the National Oceanic and Atmospheric Administration and the Arizona Bureau of Geology and Mineral Technology, Geological Survey Branch. It is anticipated that the map will be available to the public in 1980.

Finally, the program is continuing to compile a reference library on all aspects of geothermal energy: exploration, development, evaluation, utilization, etc., for use by the public. The library is located at the Geological Survey Branch, Bureau of Geology and Mineral Technology, Tucson, Arizona.

INTRODUCTION AND REVIEW

The present Arizona geothermal energy program was initiated in May 1977, in response to prior geothermal research and reconnaissance programs conducted primarily under the aegis of the federal government. The initial program was extremely limited in scope but expanded rapidly to include the entire state of Arizona.

In response to the rapid expansion of the program, the staff in the past twenty months has increased from one full-time geologist and a half-time research assistant to four full-time geologic technicians, a full-time secretary, a half-time research assistant and temporary part-time graduate assistants as needed.

Most of the work on the program is of an ongoing nature, but several projects have been completed to date. The following projects are complete.

1. Landsat lineament map and report; constructed by Dr. Larry K. Lepley from Landsat imagery; scale 1:1,000,000.
2. Geothermal Areas Map, State of Arizona; constructed by the Arizona Oil and Gas Conservation Commission.
3. Preliminary Map: Geothermal Energy Resources of Arizona; scale 1:1,000,000; compiled by the Bureau of Geology and Mineral Technology,

Geological Survey Branch, Geothermal Group.

4. Thermal Gradient Anomalies in Southern Arizona: Report of Investigations 6; compiled by the Arizona Oil and Gas Conservation Commission.
5. Ranking of Geothermal Resources in Arizona by Chandler A. Swanberg, New Mexico State University.

One additional project was completed this past six month period: the 1:500,000 scale Skylab Lineament Map of Arizona with Tectonic Model and Exploration Guide for Geothermal Resources by Larry K. Lepley. This study was conducted to supply data for the 1:500,000 geothermal energy map of Arizona to be published by the National Geophysical and Solar-Terrestial Data Center, Environmental Data Services, National Oceanic and Atmospheric Administration. Lepley's report, which is currently in preliminary, unedited form on file with the Geothermal Group in Tucson, is being used as an aid in the planning of current and future geothermal exploration. It includes the optical Fournier analysis of the 1977, 1:1,000,000 Landsat lineament map of Arizona. All projects are continuing on schedule.

On October 1, 1978, the U.S. Department of the

Interior, Bureau of Reclamation, funded a high temperature geothermal energy exploration program. The purpose of this program is to couple geothermal electric power generation and a desalination plant with a saline aquifer and produce fresh water suitable for agriculture and/or human consumption. This project could be of considerable significance to the state of Arizona which has an annual fresh water deficit in excess of 2,000,000 acre-feet. Electrical power generation via geothermal energy is also of considerable importance to Arizona as the state is a net energy importer.

AN OVERVIEW OF THE GEOTHERMAL POTENTIAL OF THE SPRINGERVILLE AREA, ARIZONA

by C. Stone

I. INTRODUCTION

The "Springerville area," Apache County, Arizona (Fig. 1) initially was selected (Hahman, personal commun., 1977) as a site-specific target for geothermal exploration on the basis of: 1) moderate to high chemical geothermometers, 2) the proximity of young volcanics, and (3) the intersection of regional lineaments based on the alignment of young volcanics, in the White Mountain volcanic field. Based on prior work by Swanberg and others (1977), the initial program focused on the area between the towns of Springerville and St. Johns. Later work directed serious attention as far south as the town of Alpine.

The land status of the study area can be seen in Figure 2. North of Springerville land ownership is a checkerboard of private, state, and federal land, the latter managed by the Bureau of Land Management (BLM). The southeastern area is Apache National Forest. To the southwest are lands of the Sitgreaves and Apache National Forests and the White Mountain Apache Indian Reservation.

II. GEOLOGY

A brief description of the regional geology is presented below. For details, the reader is referred to the reports

LOCATION MAP – PHYSIOGRAPHIC PROVINCES

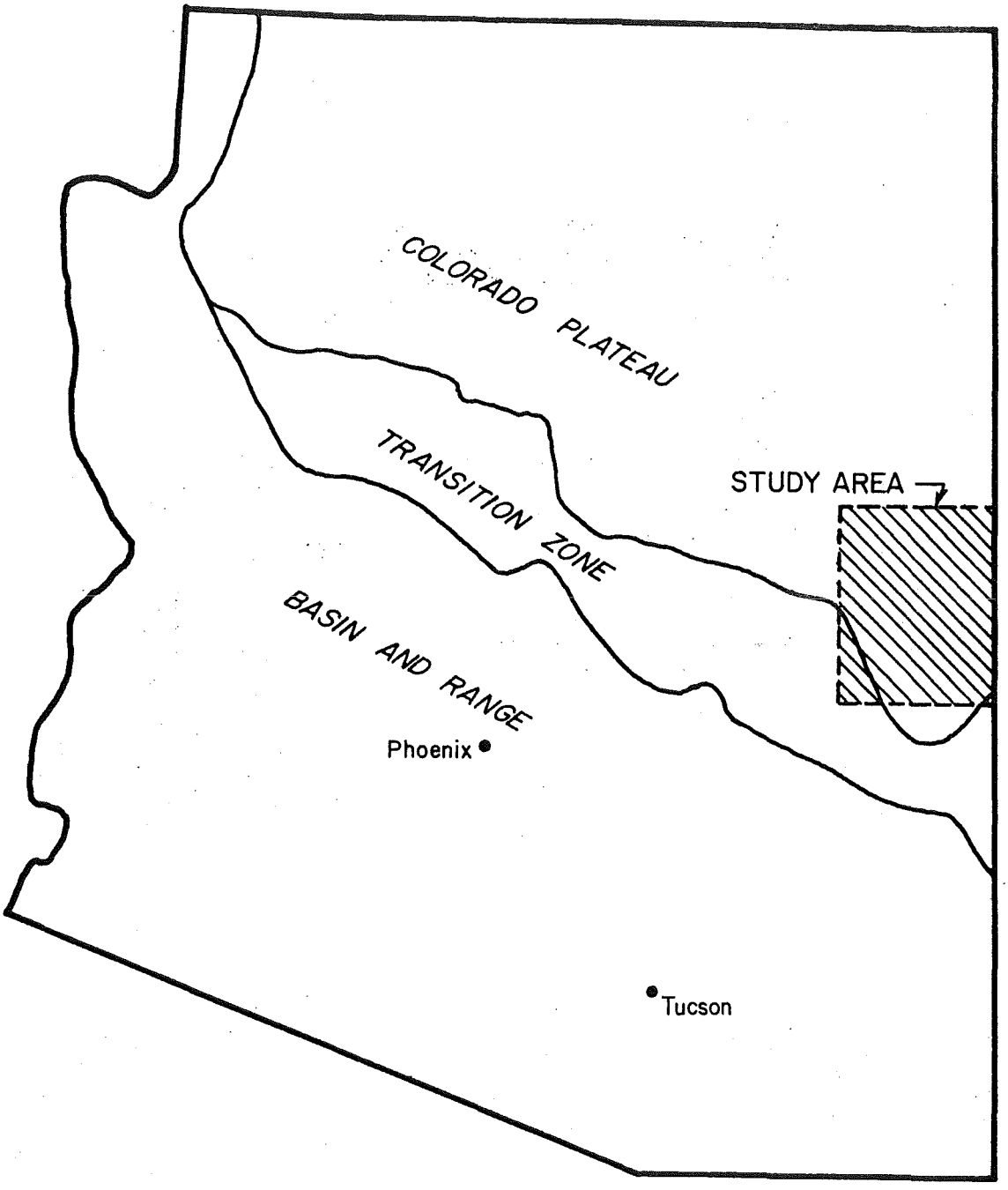


FIGURE 1

LAND STATUS MAP

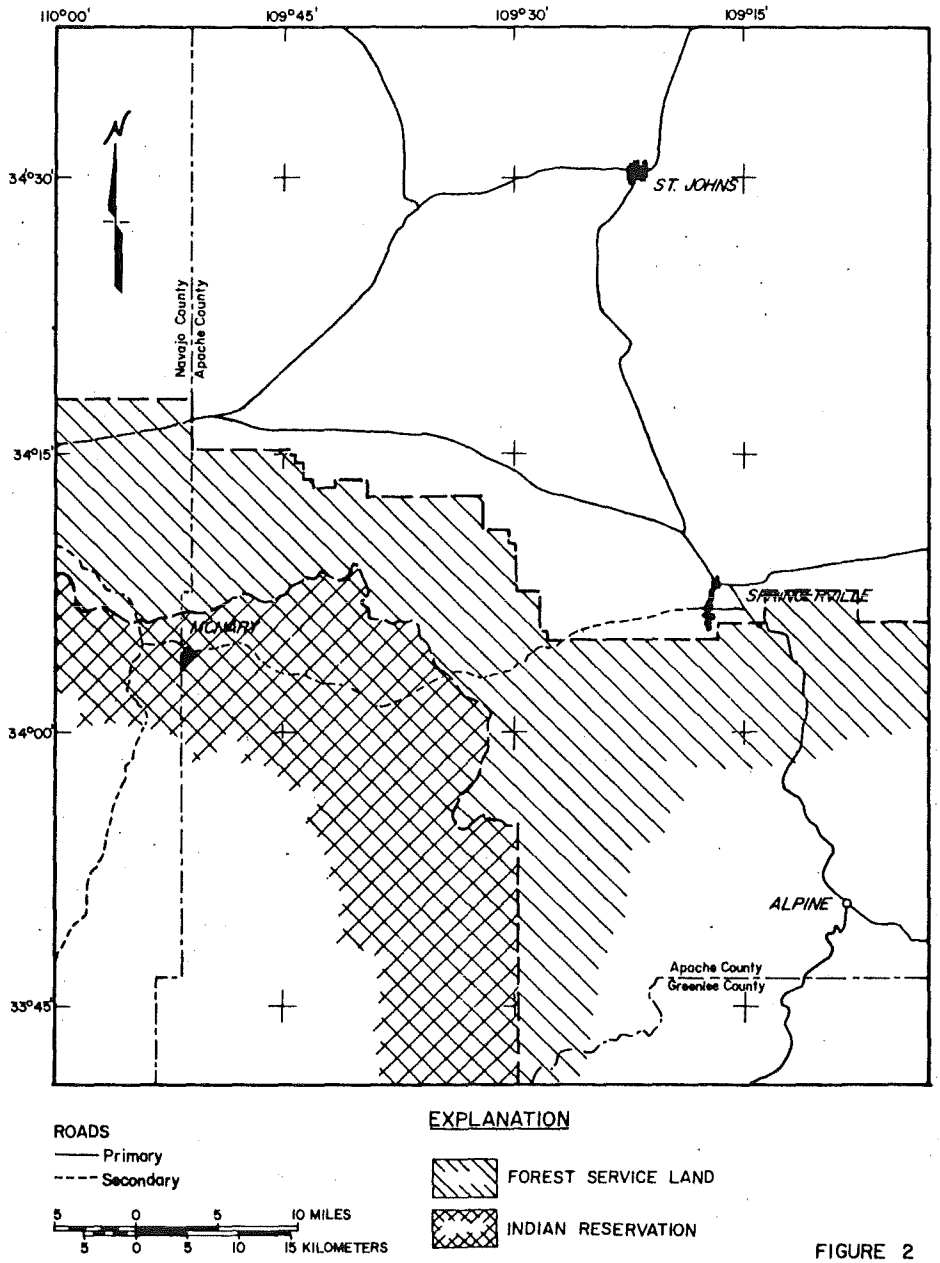


FIGURE 2

of Akers (1964), Merrill and Péwé (1977), Sirrine (1958), and Wrucke (1961). Reconnaissance mapping by Aubele and Crumpler (unpub. reports, 1978) completes the preliminary geologic survey of nearly all of the study area outside the boundaries of previously published reports.

The southern part of the study area comprises principally the Miocene-age Datil Formation which consists of a lower sedimentary member of mainly volcanic detritus and an upper member composed of porphyritic andesite. Overlying the Datil are sandstone, the "upper sedimentary formation" of Wrucke (1961), and basalts of Tertiary and Quarternary age. Two outcrops of the Pennsylvanian or Permain age Naco (?) Formation also were mapped in this area by Wrucke, but their outcrops occur hundreds of feet higher than their usual position in the region. Wrucke states they "may not represent bedrock on which younger formations were deposited," but may be xenoliths rafted in the Datil andesites. Structurally, this southern part of the study area is at the northern edge of the Transition Zone which separates the Colorado Plateau and Basin and Range physiographic provinces (Fig. 1). The Cenozoic formations, while nearly flat-lying, lap northward onto the Colorado Plateau and dip about 1° southward. Wrucke states that the area has few faults and that he can find no structural evidence of separation of the Transition Zone from the Colorado Plateau.

The northern portion of the study area, the Mogollon slope, is lithologically more varied both in outcrop and sub-surface rocks. The sedimentary rocks range in age from late Pennsylvanian to Quarternary. The pre-Cretaceous rocks of the Mogollon slope are characterized by a broad gentle dip to the northeast. During pre-Late Cretaceous time, erosion removed the entire Jurassic system and beveled the surface so that progressively older rocks crop out to the south. Drilling logs indicate the depth to Precambrian granitic basement ranges from about 700 to 1400m. A single deep borehole east of Springerville (Peirce and Scurlock, 1972) confirms the continuation beneath the White Mountains of the stratigraphic units exposed to the west of the volcanic field, specifically the Kaibab Limestone, the Coconino Sandstone and the Supai Formation, all of Permian age.

Volcanism began in the White Mountain volcanic field in middle Tertiary time with the eruption of volcanic and volcaniclastic rocks of basaltic to trachyandesitic composition, with minor rhyolite to the south and east of the Mount Baldy area. This initial phase was nearly continuous between about 38 and 12 m.y.B.P. (Merrill and Péwé, 1977). The second episode of volcanism, the Mount Baldy volcanics, began in late Miocene time. These rocks are composed principally of latite, quartz latite and alkali trachyte and have an aggregate thickness of less than

500m. Merrill and Péwé identified an upper and lower member and present chemical analyses showing that the upper member is more differentiated than the lower and that both units are more differentiated than the pre-Mount Baldy volcanics. The faulted character of the initial, middle Tertiary volcanics versus the relatively unfaulted Mount Baldy Formation led Merrill and Péwé to conclude that the Mount Baldy episode began about 12 million years B.P. An age of 8.6 ± 0.4 million years was obtained from a late-stage rhyolite flow from the top of Mount Baldy (Merrill, 1974) and provides a probable minimum age to the Mount Baldy episode. A second age determination by Merrill on a basalt from the base of the Mount Baldy area yielded an age of 8.9 ± 0.9 m.y. and suggests that the transition from intermediate to basaltic volcanism in the White Mountain volcanic field occurred about early Pliocene time.

Aubele and Crumpler (unpub. reports, 1978) identified three units of basaltic lavas, with some late-stage differentiation including silicic domes, that were erupted during the third and latest pulse of activity in the White Mountain volcanic field. New age dates on basalts from this region range from about 6.03 to 0.19 m.y. (Damon and Shafiqullah, personal commun., 1979) from which it can be inferred that basaltic volcanism has been nearly continuous to almost 10,000 years B.P. since its inception

nearly 9 million years ago. Aubele and Crumpler through field examination place a lower age limit of greater than 10,000 years on all structures in their study area. Crumpler confirms the suspected WNW and NE orientation of fissures and the alignment of cinder cones along the fissures. He infers from the topography in general that the area is "chopped up with minor faults" but states that the faults predate the lavas of the intermediate unit. Aubele mapped very young travertine mounds and deposits covering an extensive area around Lyman Lake, immediately north of the volcanic field.

An AFM diagram depicting chemical trends of the three major episodes of volcanism (Merrill and Péwé, 1977) clearly shows that the lavas were not generated by continuous differentiation from a single source. It is likely that major tectonic events of the western United States periodically reactivate partial melting at depth along zones of inherent lithospheric weakness. Three such major zones of weakness expressed as regional lineaments, based on alignment of young volcanics, (Fig. 3) (Chapin and others, 1978; Lepley, 1977; Swanberg and others, 1977) intersect in the White Mountain volcanic field and undoubtedly have a dynamic influence on continuing magma generation and volcanism in the area.

III. HYDROLOGY

A summary of ground water conditions in the study area, condensed from Harper and Anderson (1976), follows:

> "...Ground water is present in several aquifers that are made up of one or more formations. The aquifers are stacked one on the other and are generally in poor hydrologic connection. ...in 1974 ground water withdrawal was estimated to be 7,400 acre-ft., which probably is typical of the quantity pumped in recent years."

The Coconino is the principal aquifer in the region; it comprises the Kaibab Limestone, the Coconino Sandstone, and the uppermost part of the underlying Supai Formation. The potentiometric surface in this aquifer shallows to the north. Harper and Anderson state:

> "...Groundwater generally moves from south to north. The depth to water ranges from several feet above the land surface to more than 650 feet below the land surface and depends, to some extent, on the topography. Well yields range from about 100 to 2,500 gal/min...The chemical quality of the groundwater in the Coconino aquifer varies greatly with location. In general, west of Concho the water is of excellent quality and contains less than 300 mg/l (milligrams per liter) of dissolved solids; east of Concho, the quality of water is poor, and the dissolved-solids concentrations are as much as 2,500 mg/l." (See Fig. 5).

Spring and well temperatures are shown in Figure 4. Temperatures greater than 20°C are considered anomalous as the mean temperature for the Colorado Plateau is 16.1°C (Swanberg and others, 1977). It can be seen that a large number of anomalous temperatures occur in the northeast portion of the study area.

LINEAMENT MAP BASED ON ALIGNMENT OF YOUNG VOLCANICS

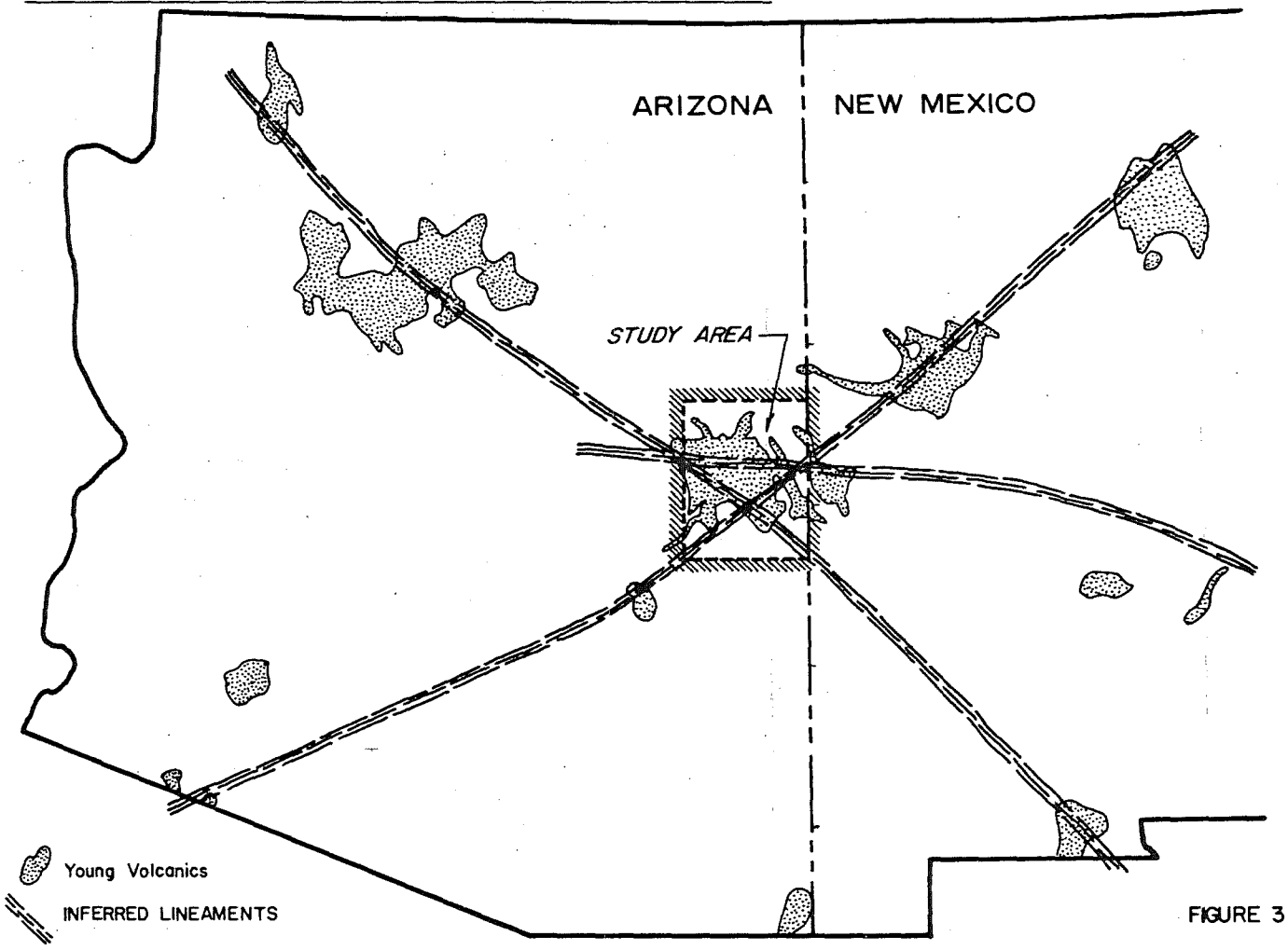


FIGURE 3

WELL LOCATIONS, MEASURED TEMPERATURES

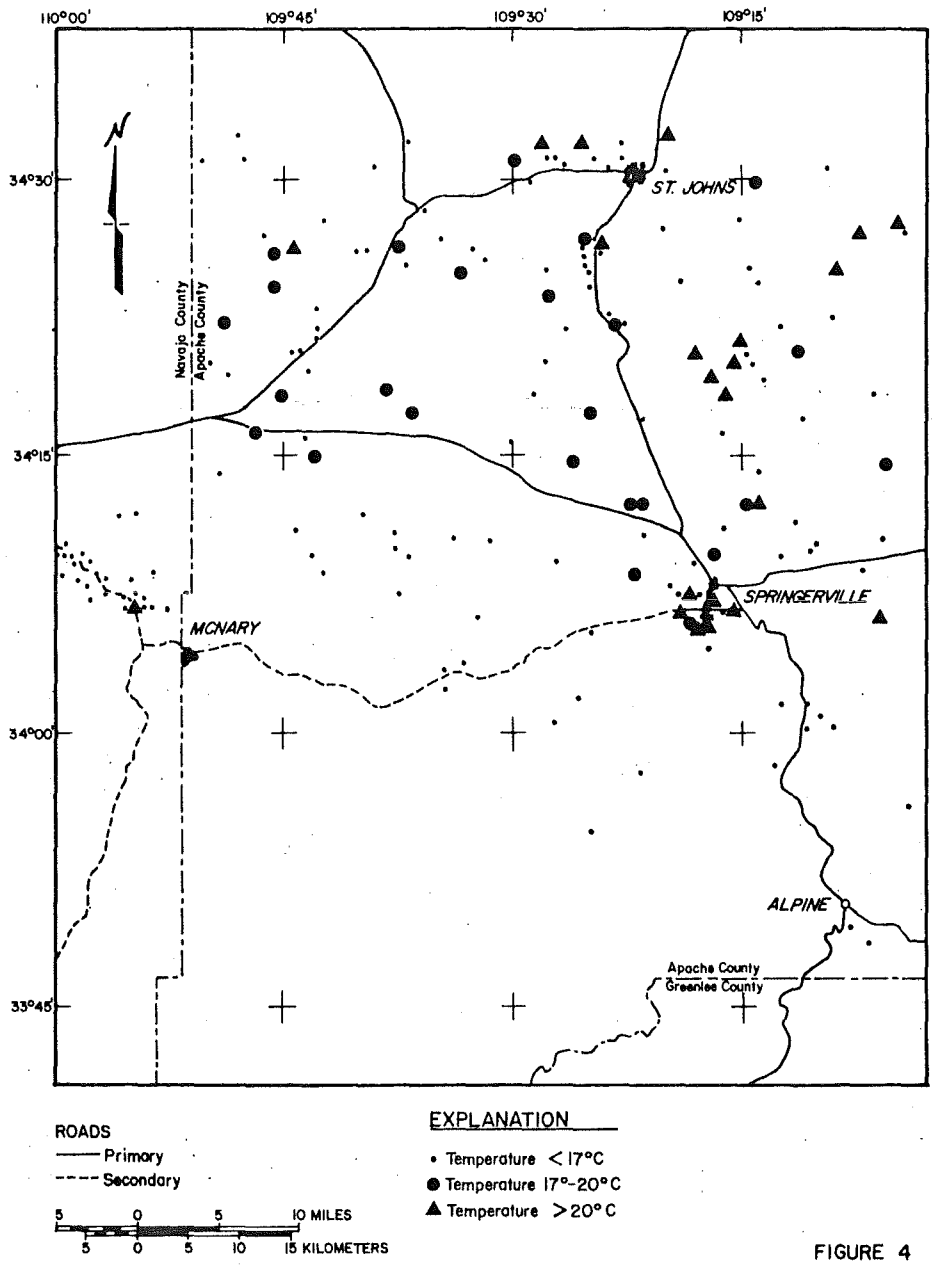


FIGURE 4

IV. GEOCHEMISTRY

Chemical analyses of well and spring waters sampled in the study area (James C. Witcher, personal commun., 1979) and analyses taken from published reports (Swanberg and others, 1977; Akers, 1964) show anomalous Na-K-Ca temperatures, in the range of 170-190°C, around and northeast of the Lyman Lake travertine deposits mapped by Aubele. The deposition of travertine in that area implies that the high Na-K-Ca geothermometers are more likely a result of calcium deposition than of an actual geothermal anomaly (Eckstein, 1975). A problem arises, however, in categorically accepting such a simplistic explanation for the anomalous geothermometers. First, an overlarge percentage of wells and springs with anomalous in situ temperatures of 20°C or greater fall within the general area of the high Na-K-Ca geothermometers (Fig. 4). Most anomalously high geothermal gradients discussed below (Fig. 6), and ground water with high total dissolved solids (Fig. 5) also occur in the same area. These indicators clearly suggest at least qualitatively the existence of a geothermal anomaly.

A second group of springs and wells between Springerville and Nutrioso locally have anomalous SiO_2 geochemical temperatures in the range of 80-90°C (Fig. 5). The average SiO_2 geothermometer for the Colorado Plateau is 49.8°C (Swanberg and others, 1977) so this range is not

especially high. Nonetheless, the silica contents (mg/l) of these waters are more than twice the background value for the study area. Qualitatively, this local concentration may also signify a geothermal anomaly.

Geothermal gradients were measured by calibrated thermistor probe at 12 sites within the study area. Additional gradients were computed from tables of water temperatures and well depths (Harper and Anderson, 1976). The data were plotted on a Thermal Gradient versus Depth Plot and gradients that appear anomalous for a given depth were identified. Of the measured gradients two were anomalously high, 27.7°C/km over a 400m depth and 29.1°C/km over a 420m depth and two were anomalously low, 12.3°C/km over a 160m depth and 11.8°C/km over a 200m depth. The two wells with low gradients each exhibited two zones of convection that were not observed in other measured wells. It can be seen in Figure 6 that the wells with low gradients occur mainly in the western part of the study area while those with high geothermal gradients coincide with the occurrence of other geochemical anomalies to the east.

IV. GEOPHYSICS

A large negative Bouguer gravity anomaly, -250 milligals, occurs between Springerville and Alpine (Fig. 7) (West and Sumner, 1973) and is confirmed by Aiken (1975)

ANOMALOUS GEOTHERMOMETERS AND ZONE OF HIGH T.D.S.

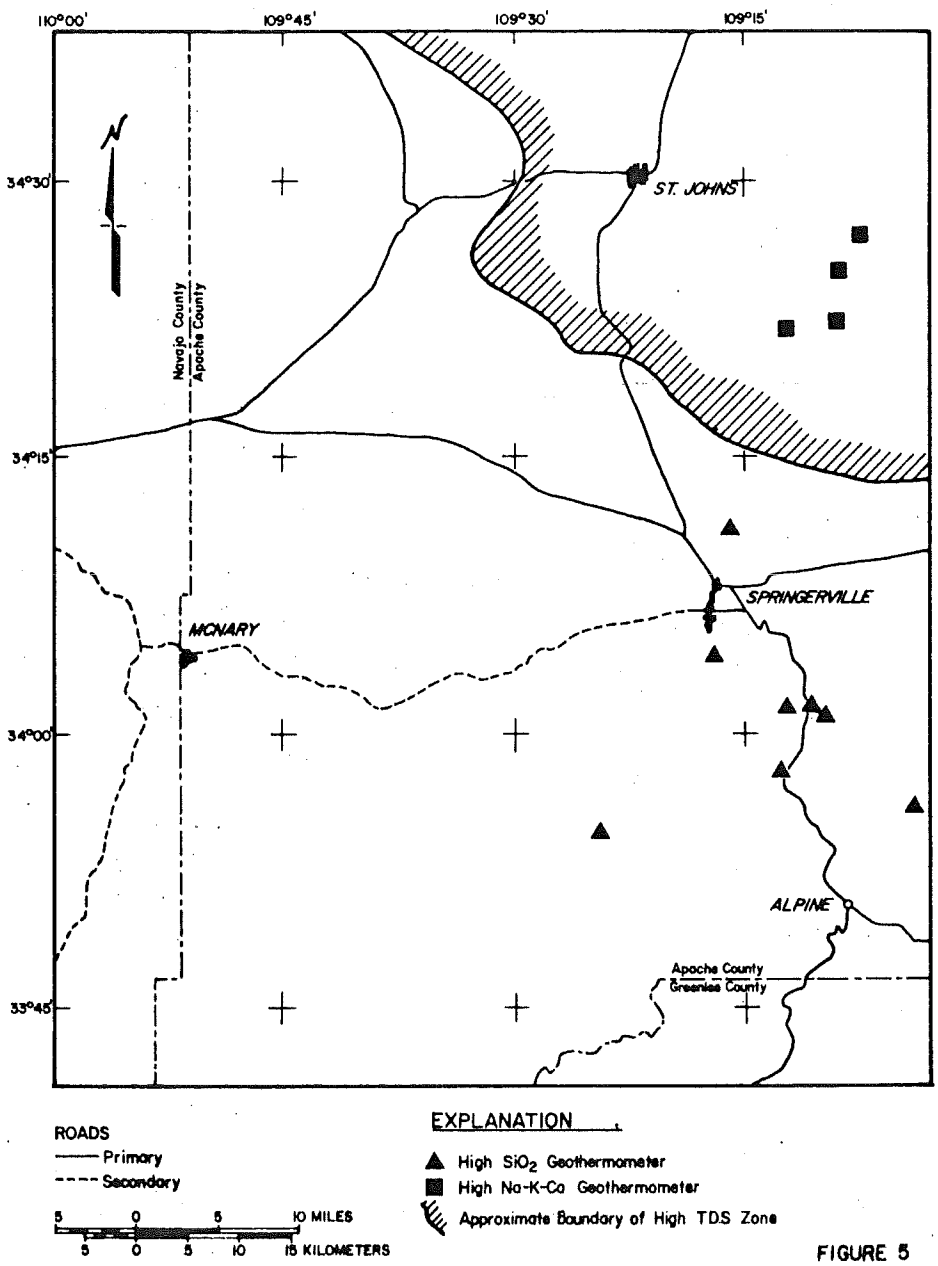


FIGURE 5

ANOMALOUS GEOTHERMAL GRADIENTS

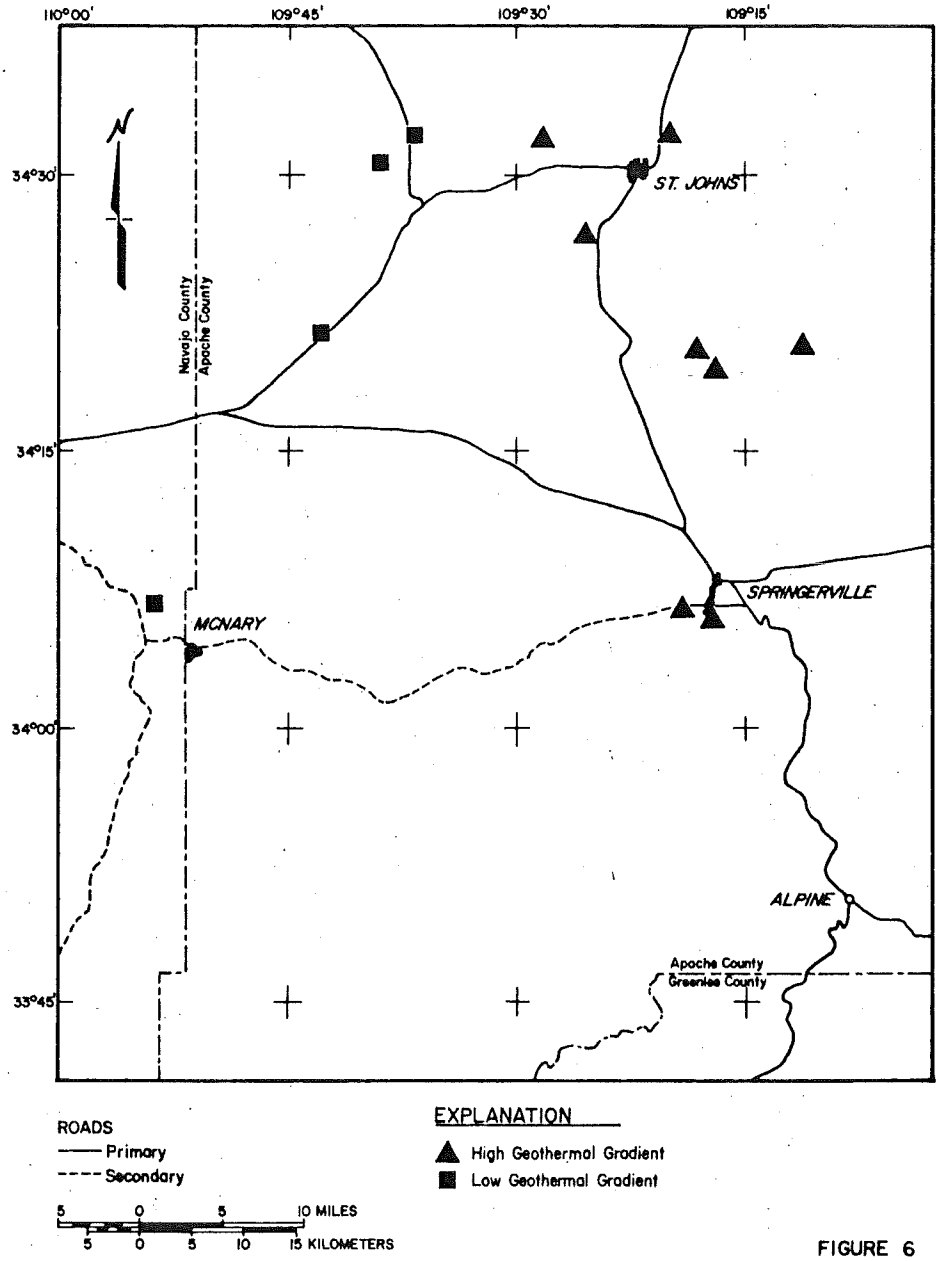


FIGURE 6

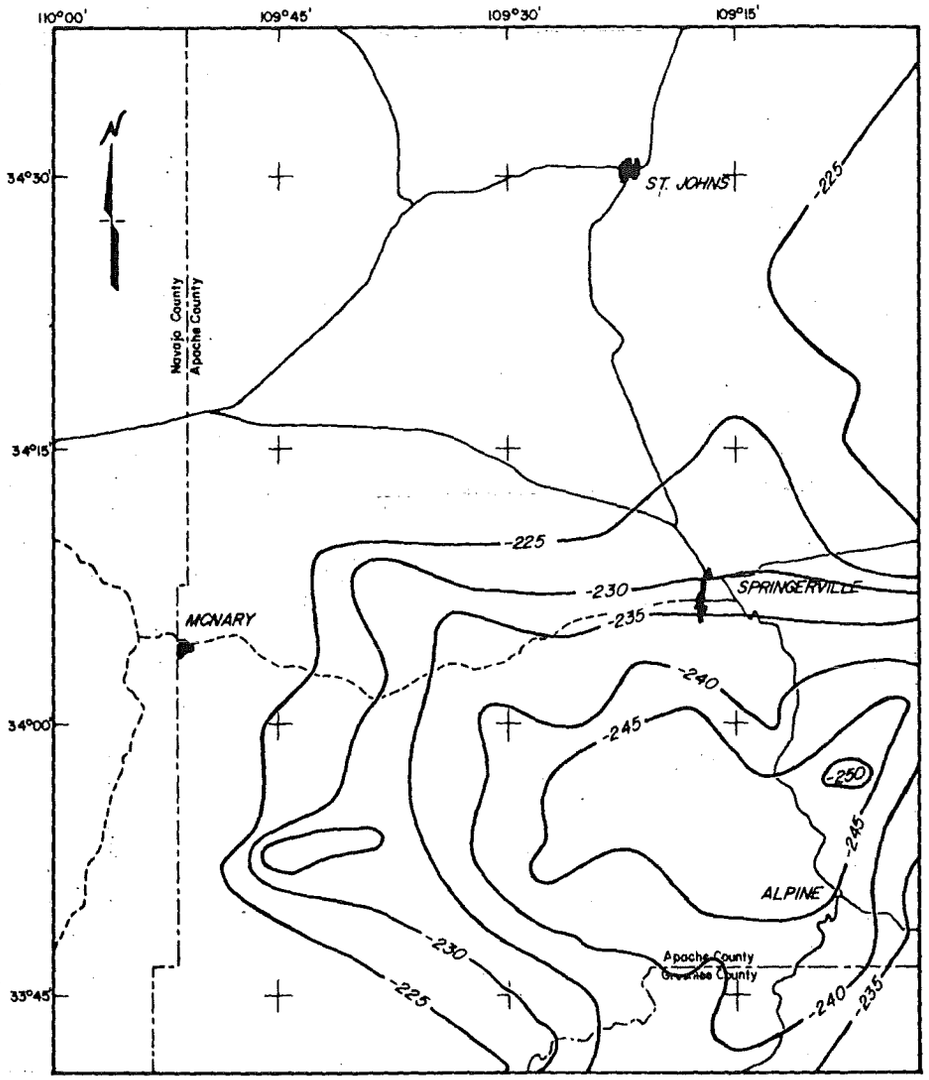
(Fig. 8). Such a local gravity low possibly represents: 1) less dense strata, 2) hydrothermal alteration 3) a magma reservoir, or 4) a buried pluton. Negative Bouguer gravity anomalies of similar magnitude occur in many geothermal areas of the Western U.S.

A single heat flow measurement of 80mWm^{-2} was made from an observation water well north of Springerville. The heat flow was calculated by multiplying the temperature gradient over each linear section of the temperature profile by the appropriate thermal conductivity (Sass and others, 1978). The data are presented in Table 1. This heat flow value falls within the range of regional heat flow inferred for the area by Lachenbruch and Sass (1977) as well as within the upper limits of heat flow predicted for the area by the silica-content method of Swanberg and Morgan (1978).

TABLE 1. MEASURED VALUES USED TO CALCULATE HEAT FLOW FOR SPRINGERVILLE AREA

DEPTH RANGE meters	CONDUCTIVITY W/mK	THERMAL GRADIENT °C/k	HEAT FLOW mWm^{-2}
160-226	2.48	32.3	80.1
226-338	3.80		
	3.04		
	3.08		
	2.98		
	3.00		
	3.16 AVE.	25.0	79.1
338-420	4.44		
	5.28		
	5.02		
	5.28		
	5.01 AVE.	16.1	80.6

BOUGUER GRAVITY ANOMALY MAP



ROADS
Primary
Secondary

5 0 5 10 MILES
5 0 5 10 15 KILOMETERS

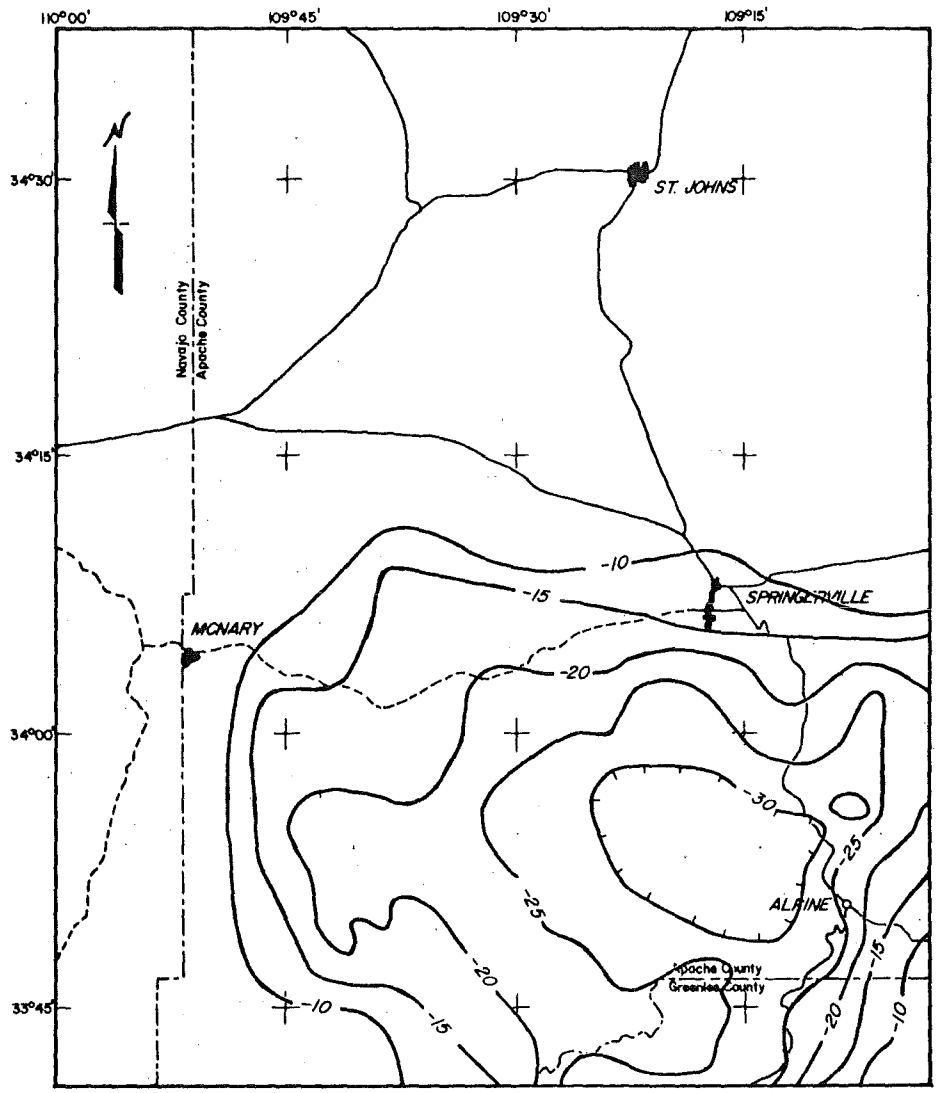
EXPLANATION

BOUGUER GRAVITY ANOMALY MAP
(After R. West and J. Sumner, 1973)

CONTOUR INTERVAL 5 MILLIGALS

FIGURE 7

RESIDUAL BOUGUER GRAVITY ANOMALY MAP



ROADS
—— Primary
---- Secondary

5 0 5 10 MILES
5 0 5 10 15 KILOMETERS

EXPLANATION

RESIDUAL BOUGUER ANOMALY MAP
(After C. Aiken, 1975)

CONTOUR INTERVAL 5 MILLIGALS

FIGURE 8

Preliminary interpretation of a telluric current survey over much of the study area (Young, unpub. report, 1979) shows a broad area of low resistivity, generally south of the highway between Springerville and McNary (Fig. 9). Specifically the survey indicates higher resistivity over the more-northerly sedimentary rocks and lower resistivity over the volcanic rocks to the south. Young interprets the low resistivity as anomalous and possibly indicative of a geothermal anomaly since the survey results are the opposite of those predicted from the geology.

Thompson and Burke (1974) show a pronounced upper mantle LVZ (low velocity zone) trending northeastward through the study area and interpret it as thicker LVZ or lower upper mantle velocity, indicative of a greater degree of partial melting. In another important study, cited by Thompson and Burke (1974), Porath and Gough (1971) estimate variations in depths to the surface of the electrical conductor, inferred to correspond approximately with the 1500°C isotherm. The depths are 190km under the Basin and Range and 350km under the Colorado Plateau, with a ridge beneath the boundary at a depth of 120km. A study by Byerly and Stolt (1977) supports the results of Porath and Gough (1971). Byerly and Stolt identified a narrow zone crossing central Arizona where

RESISTIVITY MAP

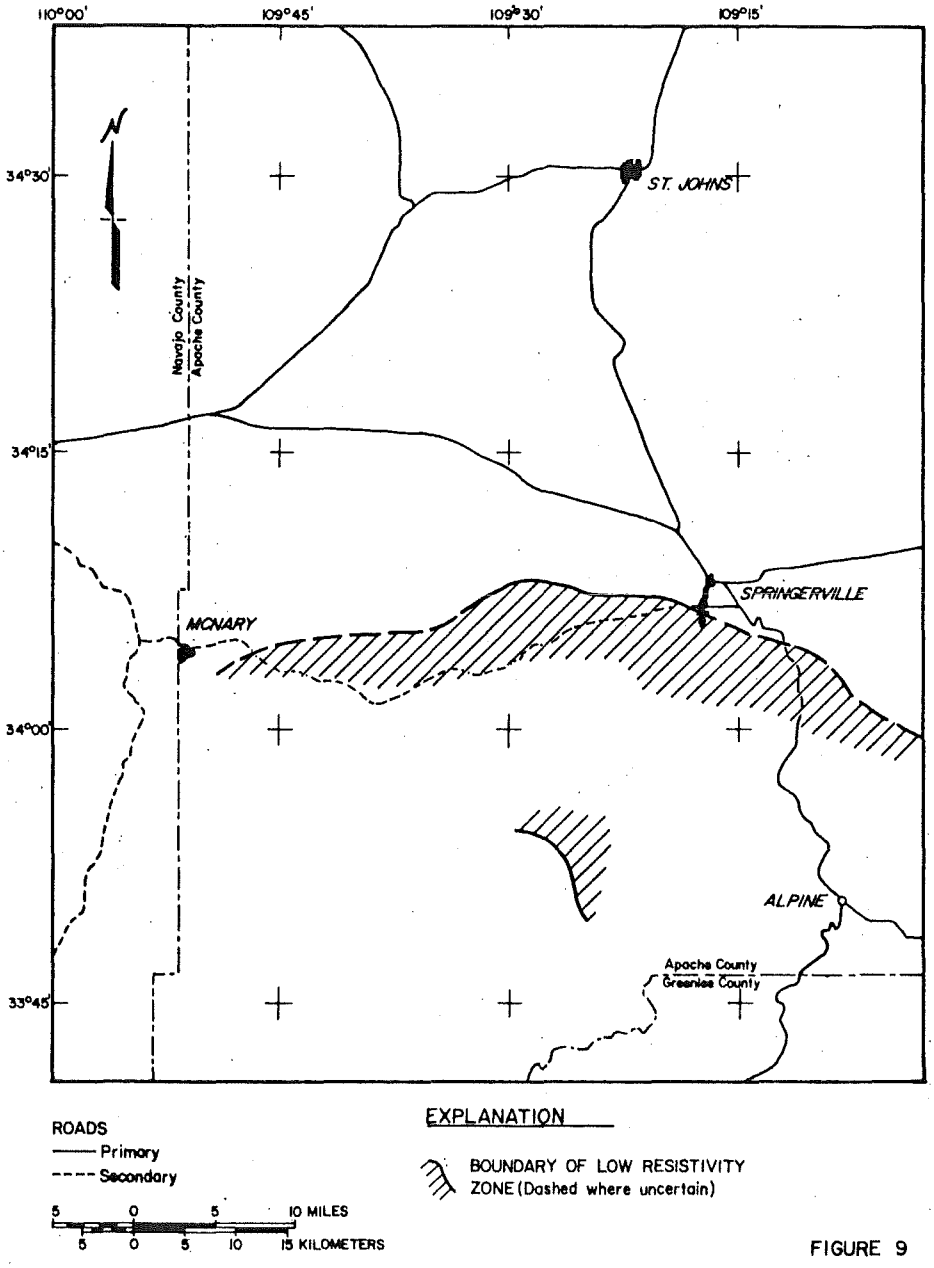


FIGURE 9

depth to the base of the magnetic crust shallows to about 10km or less. The base of the magnetic crust is interpreted by the authors as an isothermal surface at approximately the Curie temperature, taken as 500°C in their study.

V. SUMMARY

Various geological, geochemical and geophysical evidence has been presented describing the geothermal characteristics of the Springerville area. Reactivation of partial melting in the upper mantle (?) along regional zones of fundamental lithospheric weakness has resulted in recurrent volcanism since about 38 million years B.P. Anomalous Na-K-Ca geochemical thermometers occur near Lyman Lake, coincident with: 1) young travertine deposits, 2) anomalous in situ temperatures, and 3) anomalously high geothermal gradients. High silica concentrations are found further south, with slight overlap of both geochemical geothermometers at the town of Springerville. Geophysical data reveal a large negative residual Bouguer gravity anomaly and an electrical resistivity low stacked over the area between Springerville and Alpine. Additional studies from the literature present evidence for a pronounced LVZ, a mantle upwarp, and a rise in the Curie isotherm beneath the region.

VI. CONCLUSIONS

The paucity of geochemical data for the southern part of the study area and a lack of site-intensive geophysical investigations preclude a more definitive assessment at this time of the "Springerville" geothermal anomaly. Still, two inferences can be drawn from the apparent correlation among the known geological, geochemical, and geophysical parameters presented. First, a relatively shallow heat source of unknown character and dimensions exists, probably beneath the area between Alpine and Springerville. Because the single heat flow value north of Springerville is in the normal range the anomaly is most likely small in areal extent. The precise location of the heat source may coincide with the surface expression of the negative residual Bouguer gravity anomaly (Fig. 8). Second, ground water supplying the eastern half of the study area is positively affected by this heat source.

It appears that meteoric water from higher elevations in the White Mountains percolates to some depth where it is heated. This less dense "hot" water then rises along permeable fracture zones. Some of the hot water eventually mixes with cold water from the shallow aquifers and leaks out at the surface in the two areas suggested by the geochemical anomalies. The number of geothermal indicators is greater north of Springerville possibly because hot

water more easily intersects the land surface there, where the surface is no longer veneered by insulating volcanic rocks. An alternative explanation is that the fracture permeability is greater in that area than elsewhere.

Several additional studies would enable a more precise evaluation to be made of the geothermal anomaly. First, additional water chemistry and temperature data are needed, along with an understanding of the hydrologic regime south of Springerville. These problems should be resolved in the near future by planned heat flow drilling. Second, geochemical mixing models should be calculated to estimate percent mixing and maximum reservoir temperatures. A detailed gravity survey south of Springerville is necessary to determine reservoir characteristics, and a detailed resistivity survey is essential to define the depth to and size of the geothermal anomaly outlined by the preliminary survey.

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A PROGRESS REPORT OF GEOTHERMAL INVESTIGATIONS IN THE CLIFTON AREA

by J. C. Witcher

Clifton Hot Springs are adjacent to one of two KGRA's (known geothermal resource area) in Arizona, the Clifton Hot Springs KGRA. Hot water up to 61°C discharges from numerous seeps and small springs 2 miles north of Clifton along the San Francisco River into Clifton.

J. D. Hem (1950) calculated the total discharge of the hot springs using measured river discharges above and below the hot springs. Hem's calculations gave a hot springs discharge of 2.5 cubic feet per second. This flow is rather large, especially when considering the small discharges observed in the springs along the river. However, Hem's calculations are probably accurate because large unobserved discharges no doubt occur in the San Francisco River. Data from Swanberg (1977) confirm large discharges in the river. Swanberg's data show a significant increase in the temperature and chloride content in the San Francisco River between an upstream measurement and a downstream measurement from the hot springs. The hot springs degrade the chemical quality of the San Francisco River.

Lindgren (1905) comments on the high salinity of these springs in his paper on the Clifton-Morenci mining district. The hot springs are very salty and salt crystals

are sometimes seen growing on rocks adjacent to spring discharges. The source of the sodium chloride is not readily apparent because there are no evaporite deposits observed in the area. However, the salt may be from brines discharged from a high temperature reservoir (>150°C). The high magnesium content of the springs presents problems concerning geothermometry interpretation. Magnesium content of the hot springs is somewhat high compared to their in situ temperatures because the solubility of magnesium carbonates is very low at higher temperatures. The relatively high magnesium content may be evidence of the reservoir lithology or simply water-rock interactions that have taken place after the hot water left the reservoir.

Mariner, et al., 1977, present deuterium and chloride data that suggest that the spring discharges are mixes of hot and cold water. A plot of boron concentration versus chloride concentration of hot springs and river agrees very well with Mariner's conclusion. Chloride and boron concentrations have a linear relationship which is expected if very low concentration cold water mixes with high concentration hot water (See Figure 1). Chloride and boron are not assumed to be involved in water-rock reactions after the hot water has left the reservoir. The different concentrations are mostly the result of different mixes of hot and cold water.

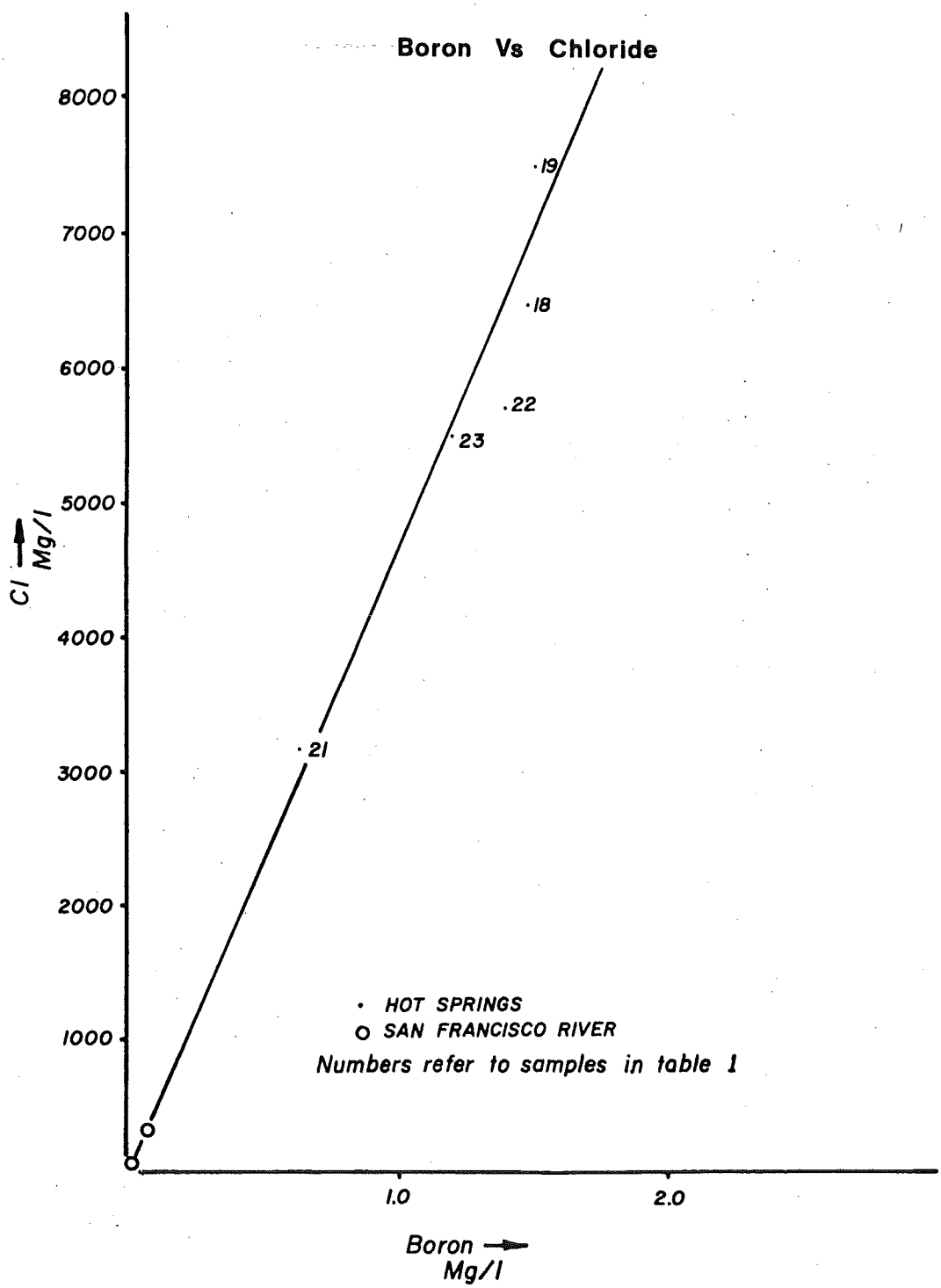
Boron Vs Chloride
8000
7000
6000
5000
4000
3000
2000
1000
Cl → Mg/l
·19
·18
·22
·23
·21
• HOT SPRINGS
O SAN FRANCISCO RIVER
Numbers refer to samples in table 1
1.0
2.0
Boron → Mg/l

FIGURE 1

Even though these hot springs are mixed waters, silica geothermometry will provide minimum reservoir temperatures. The spring with the highest chloride content, 7485 mg/l, also has the highest silica content, 131 mg/l. This spring, reported by Swanberg (1977), gives a quartz geothermometer of 150°C and a chalcedony geothermometer of 136°C. The spring with the highest discharge temperature, 61°C, was sampled by the geothermal group. The chloride content is 4400 mg/l and the silica content is 95 mg/l. The quartz and chalcedony geothermometers are 134°C and 109°C respectively. The quartz geothermometer calculations assume conductive cooling of the waters after they leave the reservoir. The last silica equilibrium is assumed to have occurred at reservoir temperature.

Figure 2 is a plot of silica and temperature of hot springs and the river versus chloride. The numbers refer to analyses in Table 1. If silica content and temperature are the result of mixing, then they will plot on a straight dilution line. However, this is certainly not the case for samples 16, 18, 22 and 23. They are most likely cooled (conductively) and silica deficient due to precipitation. Figure 3 is a plot of calcium versus chloride. Samples 16, 18, 22 and 23 also appear to be involved in a water-rock reaction involving calcium in addition to being cooled and

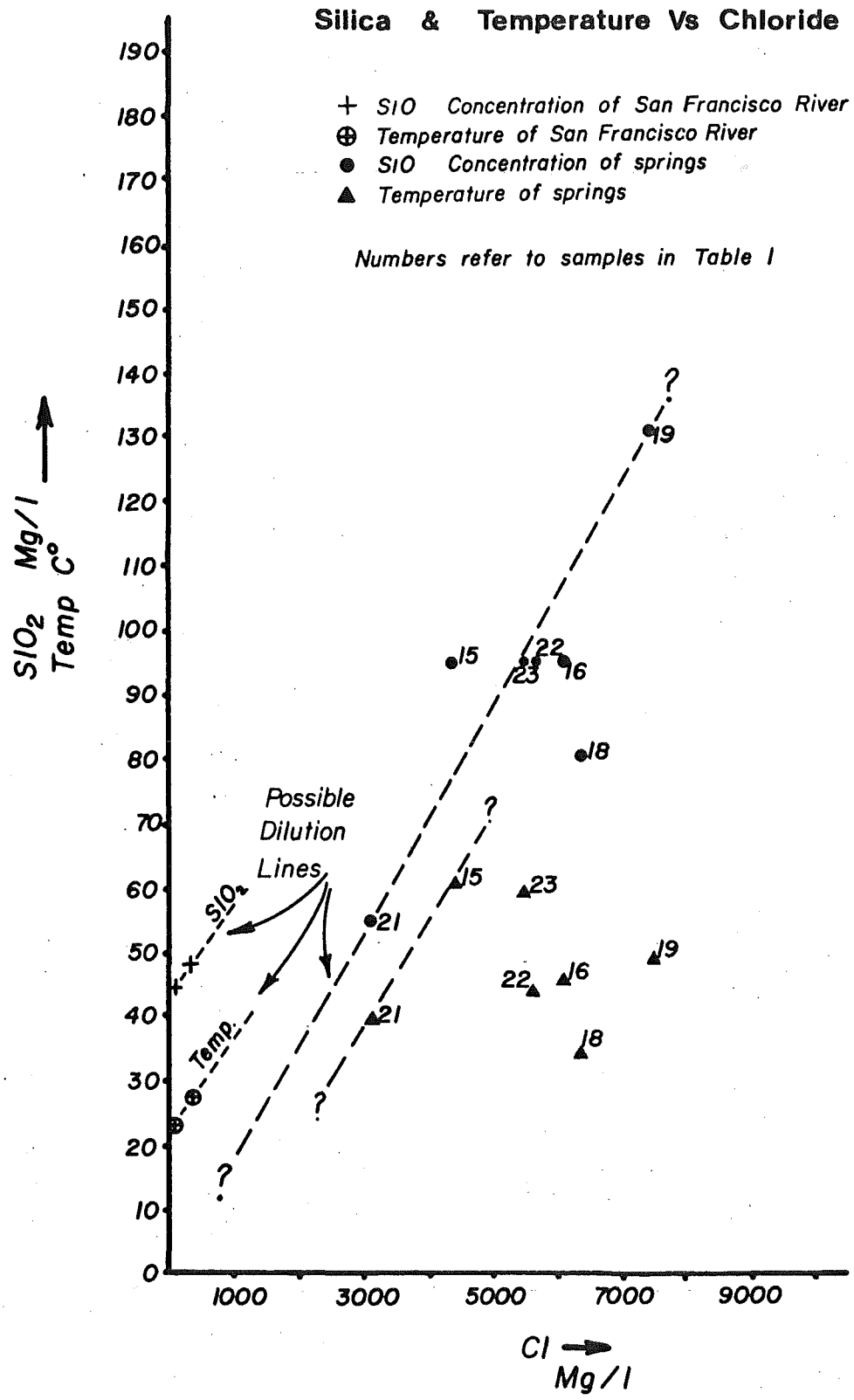
Silica & Temperature Vs Chloride
+ SIO Concentration of San Francisco River
⊕ Temperature of San Francisco River
● SIO Concentration of springs
▲ Temperature of springs
Numbers refer to samples in Table I
SiO2 Mg/l
Temp C°
Possible Dilution Lines
SiO2
Temp.
Cl Mg/l
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
1000
3000
5000
7000
9000

FIGURE 2

TABLE 1 (CONTINUED)

CHEMISTRY OF CLIFTON AREA GROUND WATER

Number	F	B	TDS	SiO_2	Reference
1	4.3	-	8740	-	1
2	4.1	-	8880	-	1
3	5.0	-	8940	-	1
4	3.6	-	7490	-	1
5	3.0	4.0	9790	58	1
6	4.0	-	8330	-	1
7	-	-	8830	-	1
8	4.1	2.5	5320	57	1
9	1.8	-	1920	-	1
10	1.0	1.5	2380	42	1
11	1.0	1.2	2160	39	1
12	.4	-	256	-	1
13	1.1	-	434	-	1
14	-	-	643	37	2
15	-	-	7205	95	2
16	-	-	10141	95	2
17	.65	.02	380	44.6	3
18	1.8	1.48	12576	81.7	3
19	3.5	1.51	14548	131.4	3
20	.83	.08	808	47.9	3
21	2.3	.64	5526	55	4
22	2.7	1.4	9696	94	4
23	2.8	1.2	9352	95	4

References

1 - Hem, J.D., 1950
2 - This Report
3 - Swanberg, et. al., 1977
4 - Mariner, et. al., 1977

TABLE 1

CHEMISTRY OF CLIFTON AREA GROUND WATER

Number	Location	Temperature	Na	K	Ca	Mg	Cl	SO_4	HCO_3	pH	Ref.
1	T4S,R30E,30BD	48.8	2540*	-	767	37	5230	110	111	-	1
2	T4S,R30E,30BD	40.0	2570*	-	782	43	5280	138	136	-	1
3	T4S,R30E,30BD	37.8	2620*	-	754	41	5280	178	129	-	1
4	T4S,R30E,30BD	40.6	2212*	-	619	38	4470	68	152	-	1
5	T4S,R30E,30BD	43.3	2608	142	860	41	5800	153	109	-	1
6	T4S,R30E,30AD	48.8	2426*	-	711	48	5000	75	126	-	1
7	T4S,R30E,30AD	-	2000*	-	750	33	5260	120	128	-	1
8	T4S,R30E,30AD	-	1596	74	355	17	3030	99	168	-	1
9	T4S,R30E,30AD	-	583*	-	145	13	1050	46	181	-	1
10	T4S,R30E,30AD	-	652	37	184	17	1300	44	208	-	1
11	T4S,R30E,30AD	-	591	35	168	16	1160	43	209	-	1
12	San Francisco R	-	37*	-	44	13	45	21	190	-	1
13	San Francisco R	-	90*	-	58	14	147	25	196	-	1
14	T4S,R30E,18C	20.3	160	5.9	74	15	104	40	198	7.25	2
15	T4S,R30E,18C	61.0	2015	175	601	13	4400	58	114	7.45	2
16	T4S,R30E,18C	45.0	2502	239	959	23	6060	59	130	7.45	2
17	San Francisco R	22.5	49.7	3.9	42	10.1	57.8	48.4	183.2	8.12	3
18	T4S,R30E,19AC	34.8	3207	210	1064	52.2	6460	-	91.5	7.74	3
19	T4S,R30E,18DC	48.0	3586	243	926	22.9	7485	-	150	7.86	3
20	San Francisco R	27.0	187	12	74	11.4	307	46.1	190.3	8.22	3
21	T4S,R30E,30AC	39.0	1500	82	430	16	3150	72	163	7.00	4
22	T4S,R30E,18C	44.0	2700	170	790	21	5700	62	146	6.58	4
23	T4S,R30E,18C	59.0	2600	170	740	20	5500	68	145	7.07	4

Analyses from Reference 2 reported in parts per million (ppm), all others in milligrams per liter (Mg/l), temperature in ^{o}C.

*No analyses reported as Na and K.

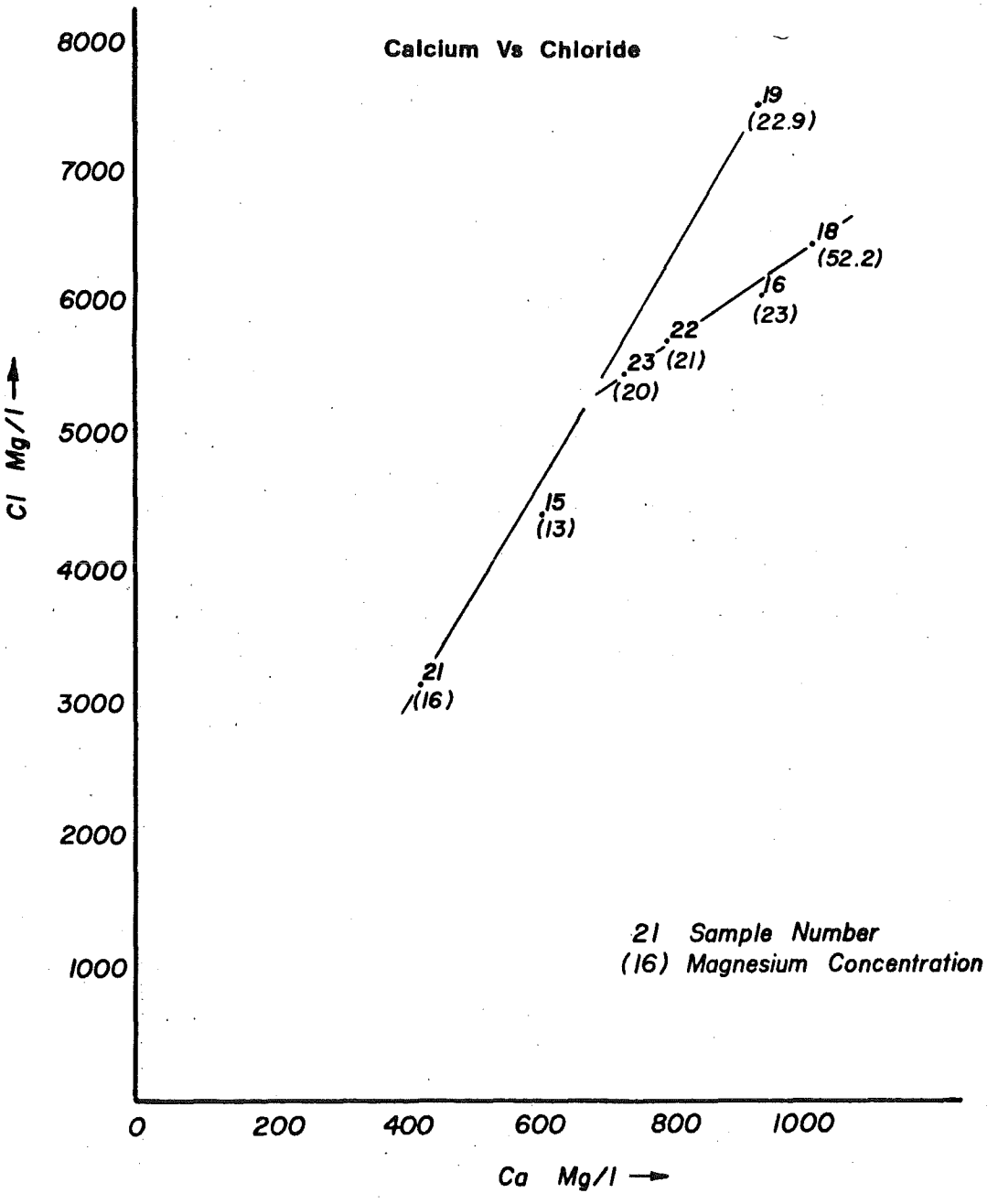
Calcium Vs Chloride
8000
7000
6000
5000
4000
3000
2000
1000
Cl Mg/l
0
200
400
600
800
1000
Ca Mg/l
19
(22.9)
18
(52.2)
6
(23)
22
(21)
23
(20)
15
(13)
21
(16)
21 Sample Number
(16) Magnesium Concentration

FIGURE 3

silica deficient. The numbers in parantheses are magnesium and they suggest that a major portion of the magnesium is dervied from post reservoir water-rock reactions. As a result, samples 16, 18, 22 and 23 are probably useless for geothermometer calculations.

Figure 4 is a plot of silica versus temperature. Lines A and B are assumed dilution lines from the cold well sample through Samples 21 and 15 respectively. Minor temperature and silica losses are likely from causes other than mixing, but these springs are probably nearest to a true dilution. Quartz mixing models of Lines A and B give 150°C and 188°C respectively. Table 2 and Figure 5 show the mixing model results of dilution line B. Na-K-Ca geothermometers, 160-170°C, agree with the mixing model calculations.

The preliminary chemical geothermometer studies of the Clifton Hot Springs point toward a high temperature reservoir that is greater than 150°C. Total dissolved solids of 25,000 to 50,000 or greater are likely in the reservoir. Further study of this area is warranted. Development of the indicated resource may provide hot water for electricity, space heating and cooling, and industrial applications. In addition, the inflow of salty water to the San Francisco River and Duncan Basin could be curtailed by the use of this resource thereby improving water quality downstream and providing additional good quality water supplies.

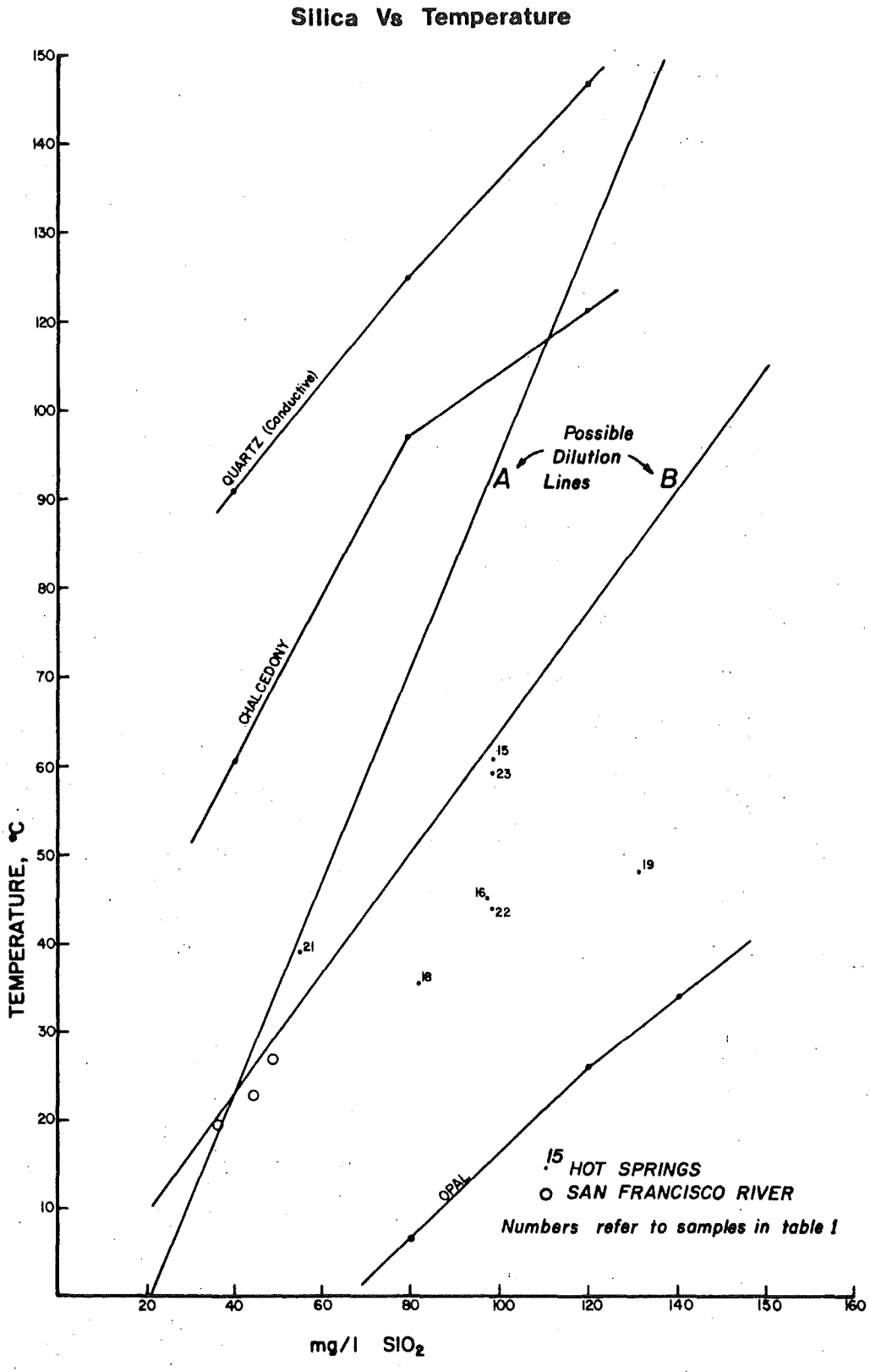
Silica Vs Temperature
TEMPERATURE, °C
mg/l SiO2
QUARTZ (Conductive)
CHALCEDONY
OPAL
Possible
Dilution
Lines
A
B
15
23
19
16
22
21
18
15 HOT SPRINGS
SAN FRANCISCO RIVER
Numbers refer to samples in table 1

FIGURE 4

TABLE 2

MIXING MODEL CALCULATIONS

DILUTION LINE B

Cold Water	20°C	37 mg/l SiO_2
Hot Spring	61°C	95 mg/l SiO_2

$$Hc\ (x) + Hh\ (1 - x) = H\ spr$$

x	Hh
.1	65.5
.2	71.3
.3	78.5
.4	88.3
.5	102.0
.6	122.5
.7	156.7
.8	225
.9	430

$$Sic\ (x) + SiH\ (1 - x) = Si\ spr$$

x	Si spr	SiO_2 Temp.
.2	109.5	137
.3	119.9	141.2
.4	133.7	146.9
.5	153.0	153.9
.6	182.0	163.1
.7	230.0	176.2
.8	327.0	197.4
.9	617.0	

Temperature in Degrees Celsius - Assumed to be Equivalent to Enthalpy in Calories per Gram.

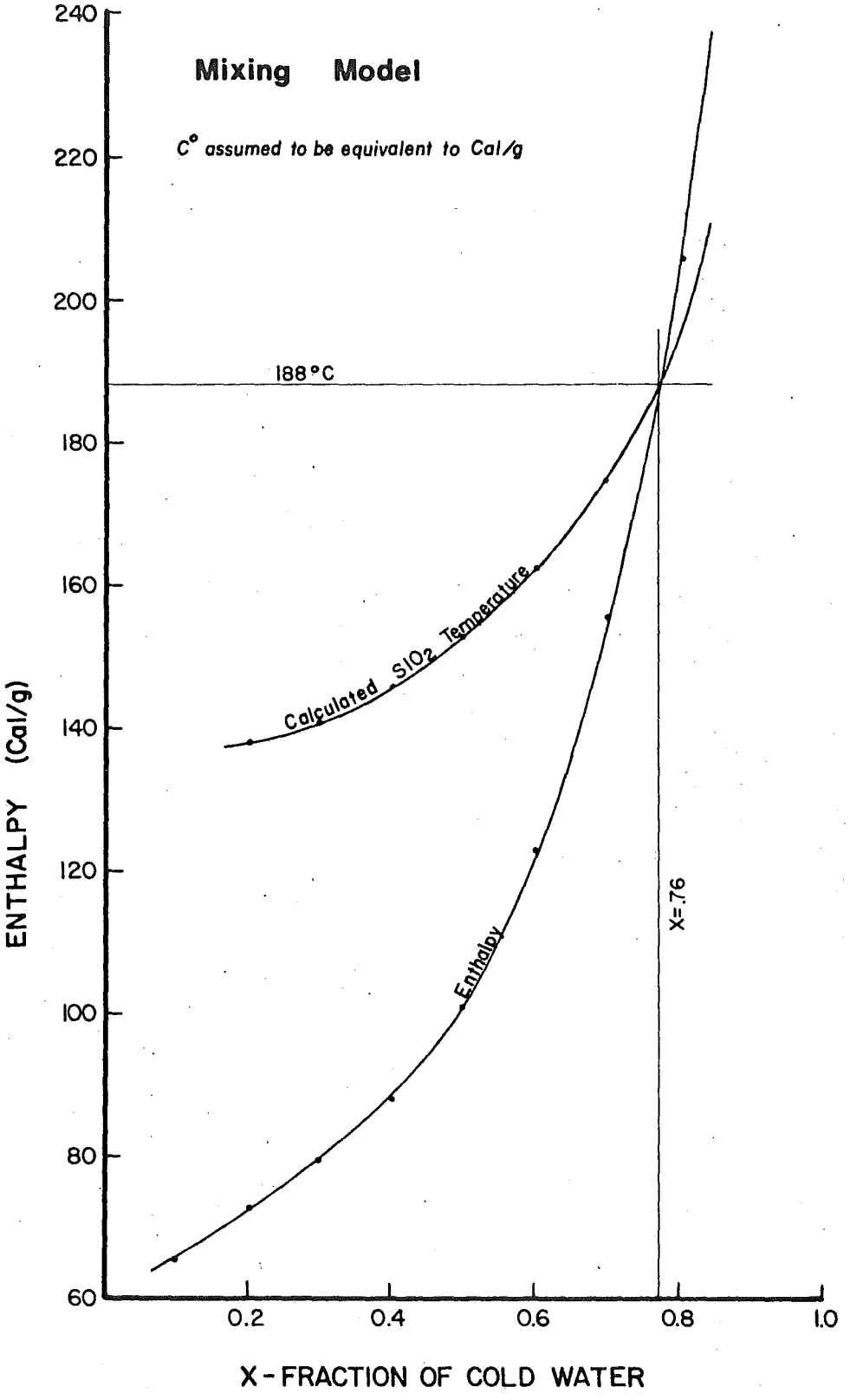

FIGURE 5 **(See Table 2 for Calculations)**

Geologic mapping is in progress in the area and additional geochemical surveys are planned when high river waters recede late this spring. One or two shallow gradient holes may be drilled during 1979.

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A PRELIMINARY REPORT ON THE GEOTHERMAL ENERGY POTENTIAL OF THE SAFFORD BASIN SOUTHEASTERN ARIZONA

by J. C. Witcher

INTRODUCTION

Hot (>30°C) water has been reported from the Safford area for at least seventy years. The most notable hot water occurrence, Indian Hot Springs, is located northwest of Safford near Fort Thomas. Indian Hot Springs, a health resort at the present time, includes several hot springs and an artesian well about 182 meters deep (Knechtel, 1938). Collective discharge of the springs and well is 320 gallons per minute (gpm) and the highest published discharge temperature is recorded at 48.3°C (Knechtel, 1938).

Nearly all wells deeper than 244 meters in the Safford area discharge artesian water. The deepest of these wells, the Mary Mack, was drilled in the NW¼, NE¼, Sec. 13, T6S, R.24E during 1929 and was completed to a depth of 1148 meters (Knechtel, 1938). The well encountered water flows at 495, 524, 676, 707, 978, and 1079 meters (Knechtel, 1938). In 1933, the well discharged 2500 gpm of 58.9°C sodium chloride water containing 3251 parts per million (ppm) total dissolved solids (TDS) and 4.9 ppm fluorine (Knechtel, 1938). Present status of the well is not known because a field check of the described well location failed to find the well; but the well has probably been plugged and covered.

Several hot wells (> 30°C) have been drilled near Buena Vista northeast of Safford, and one of these is known to have artesian flow. That well, located in NW¼, NW¼, NW¼, NW¼, Sec. 11, T.7S, R.27E, flows at about 800 gpm. The 49.5°C water discharges from around the base of a pump installed over a 24 inch surface casing.

An artesian well in the NW¼, SW¼, Sec. 36, T.6S, R25E northwest of Safford and north of Thatcher flows an estimated 500 gpm at 43.5°C from an 18 inch open surface casing. In the past this well supplied water to the Mount Graham Mineral Bath. During the flood in December 1978 the Gila River changed course and washed away the bath house. At the present time, the well discharges water containing 8292 milligrams per liter (mg/l) TDS into the Gila River (Swanberg, et al., 1977).

The Cactus Flat Artesia area just south of Safford has the largest concentration of hot artesian wells (>30°C). These wells are used for irrigation, health spas and for water supplies to Dankworth Lake, Roper Lake, and several ponds.

Rising costs and supply problems for hydrocarbon fuels have intensified the search for alternative energy sources. The hot wells and springs in the Safford area show that a geothermal resource is present. Developing the geothermal resource around Safford could bring such benefits as reduced energy costs, a constant, assured energy supply, and

generating new agricultural-related businesses. This area warrants a detailed geological evaluation of the geothermal resource potential.

GEOLOGY

Geothermal fluids may evolve through three geological processes or mechanisms: (1) intrusion and cooling of magmas in the water bearing shallow crust, (2) deep circulation of meteoric water in areas with high or normal heat flow, (3) and high heat flow in areas with confined aquifers capped by a heat-insulating blanket of low heat-conductive rock. The youngest volcanism in the region consists of basalt eruptions. Basalt may not indicate a large quantity of heat because basalt (mafic) intrusions are usually tabular or pipe-like; basalt is very fluid and flows into fractures, bedding planes, and faults very quickly exposing a large cooling surface compared to their volume causing them to cool in a very short time. On the other hand, granitic (silicic) intrusions provide the best heat source because they are viscous and generally intrude as large bulbous masses that take a hundred thousand to a million years or more to cool. However, the last silicic intrusions of magma in the Safford area probably occurred around 26 million years ago in association with the eruption of silicic lavas that are exposed in the Gila Mountains where basaltic andesite dated at 26.9 $\pm$ .5 mybp overlie silicic ash flow tuffs at Bryce Mountain (Strangway, et al.,

1976). The interval of 26 million years is more than enough time for these magmas to have cooled to the ambient temperature of the intruded country rock. Therefore, magma intrusion and cooling may not be an important heating mechanism in the Safford area.

The heating mechanism for the hot wells in the Safford area is probably deep circulation of water and/or high heat flow into confined aquifers capped by an insulating blanket of overlying sediment. The Gila River valley - San Simon valley at Safford form a sediment filled basin probably bounded by unexposed normal faults along the valley margins. Rocks forming the basement of the sediment filled Safford basin are probably similar to exposed rocks in the surrounding mountains. An interpretation of Safford area gravity data suggests that up to 6,000 feet (1.8 km) of sediment may overlie the basement rocks in the deepest parts of the Safford basin (Muller, et al., 1973) (Aiken, C.L.V. and Sumner, J.S., 1974). Probable graben structure and thick basin fill point towards deep circulation as the most likely heat source. Deep circulation usually results in temperatures less than 150°C; but it doesn't preclude high temperature reservoirs (>150°C). Heat is not the only requirement for a geothermal resource. Hot water must be stored in rock and must be easily extracted from that rock. In other words, the rock has to be porous and permeable. Some of the sediment fill of the Safford basin probably will meet these requirements.

Lithology, hydrologic character, and geometry of the basin fill sediments may be the most pertinent geological parameters controlling the geothermal reservoir(s) in the Safford basin. The basin fill sediment are deeply eroded along the trend of the Gila River and somewhat less eroded along the trend of the San Simon River. Post mid-Pleistocene erosion has carved three major terrace surfaces into the fill along the Gila River Valley (Harbour, 1966). A cobble to boulder conglomerate caps the terraces and basin fill sediments.

The inner valley or flood plain of the Gila River, San Simon River, Marijilda Wash and Stockton Wash contain up to 100 feet of predominately fluvial flood plain deposits overlying the incised basin fill sediments. The flood plain deposits are the most important agricultural aquifer, but have little or no geothermal potential. Basin fill will probably be the host to additional geothermal reservoirs. Harbour (1966) divides the basin fill into upper and lower units. Contact between them is believed to be the Pliocene-Pleistocene time-stratigraphic boundary as based on fossil and climatological evidence recorded in the sediment (Harbour, 1966). Upper basin fill consists of fluvial and minor lacustrine deposits. Local fanglomerates occur at the mouths of large canyons that drain the mountains. The fanglomerates are relatively small and do not extend very far into the basin. Wells drilled into the upper basin fill do not

encounter hot water (30°C).

Lower basin fill consists of three major facies (Harbour, 1966). The upper facies, green clay facies, is exposed in the lower terraces along the axis of the valley where downcutting has removed upper basin fill. The green clay facies, 400 to 800 feet thick, is mostly clay and siltstone with minor interbedded sands and gravel. Upstream drainage originating from the Duncan basin deposited a local deltaic sequence in the Sanchez area which is contemporaneous with green clay facies. The deltaic deposit consist of thick-bedded silt with channel conglomerates consisting of volcanic bounders (Harbour, 1966).

A clayey evaporite facies lies beneath the green clay facies and has been observed only in well cuttings (Harbour, 1966). The log of a Southern Pacific railroad well drilled in 1906 at Safford shows the evaporites facies to be 1100 feet thick (Knechtel, 1938). The evaporite facies appears to be confined to the basin axis and indicates former internal (closed) drainage.

The Mary Mack well bottomed in coarse fluvial sediments that are called the basal conglomerate facies by Harbour (1966). Little is known about this facies, in particular, whether or not it may be hydrologically connected to the fluvial sediment and local fanglomerates adjacent to the mountain block. Water in these topographically higher sediments may give the basal conglomerate the artesian

pressure observed in the Mary Mack well.

Hot artesian wells (>30°C) are also reported from the green clay facies near the basin margins at the Cactus Flat-Artesia area south of Safford. Artesian flows originate from channels of fluvial sand and gravel interbedded with the fine grained green clay facies and may be hydrologically connected to the topographically higher sand and gravels adjacent to the Pinaleno Mountains.

TEMPERATURE AND DEPTH DATA OF WELLS

A literature search revealed 36 wells in the Safford 15 minute and the Artesia 7.5 minute quadrangles which yield hot water (>30°C). Except for two wells in the Buena Vista area, all are flowing at the surface. An additional hot well (49.5°C) at Buena Vista was visited which was previously unreported. The well has considerable flow from around the base of an installed pump. All hot wells from these areas are tabulated in Table 1.

Using 18°C as the mean annual air temperature, temperature gradients were calculated by subtracting the observed surface temperature from the mean annual air temperature. The difference was divided by the depth; then the quotient was multiplied by 1000 to give the gradient. The gradient will be in units of °C/km if degrees celsius and meters are used for the temperature and depth.

Calculated gradients range from 216°C/km to 43°C/km. The highest calculated gradient is from a 90 meter well at

TABLE 1

WELLS IN THE SAFFORD AREA WITH TEMPERATURES GREATER 30°C

Number	Location	Temperature °C	Depth Meters	Map Quadrangle	Reference
1	T8S, R26E, 7AC	35.0	329.2	Safford	1 (See 33)
2	T8S, R26E, 7CA	33.0	243.8	Safford	1
3	T8S, R26E, 7BA	36.0	344.4	Safford	1 (See 27)
4	T8S, R26E, 7CD	34.0	289.6	Artesia	1
5	T8S, R26E, 7BD	35.0	365.8	Safford	1
6	T8S, R26E, 7BB	33.0	262.1	Safford	1 (See 35)
7	T8S, R26E, 7BD	34.0	396.2	Safford	1
8	T8S, R26E, 7BB	35.8	320	Safford	1
9	T8S, R25E, 12AA	30.6	304.8	Safford	1
10	T8S, R26E, 7AD	30.6	244.3	Safford	1
11	T8S, R26E, 18AC	34.0	244.3	Artesia	1
12	T8S, R26E, 32DA	33.0	121.9	Artesia	1
13	T8S, R26E, 32CB	33.0	109.7	Artesia	1
14	T8S, R26E, 33AC	33.0	225.6	Artesia	1
15	T8S, R26E, 33CA	33.0	121.9	Artesia	1
16	T8S, R26E, 33CA	33.0	121.9	Artesia	1
17	T8S, R26E, 33CA	33.3	152.4	Artesia	1
18	T8S, R26E, 32DC	33.0	121.9	Artesia	1
19	T8S, R25E, 12AA	36.7	320	Safford	2,4,6 (See 32)
20	T8S, R25E, 12AD	34.5	244.3	Safford	1,2
21	T8S, R25E, 1DD	35.6	213.4	Safford	1,2
22	T7S, R27E, 2CC	35.6	91.5	Safford	4
23	T8S, R25E, 12AC	34.4	320	Safford	4
24	T6S, R25E, 36CBB	46.5	659	Safford	4,5,6

TABLE 1 (CONTINUED)

WELLS IN THE SAFFORD AREA WITH TEMPERATURES GREATER 30°C

Number	Location	Temperature °C	Depth Meters	Map Quadrangle	Reference
25	T7S, R27E, 2ADD	41.0		Safford	5
26	T8S, R26E, 7DD	42.0		Artesia	6
27	T8S, R26E, 7BA	41.5	344.4?	Safford	6 (See 3)
28	T7S, R27E, 11BBB	43.5		Safford	6
29	T7S, R27E, 2ACA	37.5		Safford	6
*30	T8S, R26E, 20DBC	44.0	395	Artesia	6 (Fig. 2)
31	T8S, R26E, &DAB	41.5		Safford	6
32	T8S, R25E, 12AAA	39.0	320	Safford	6 (See 19)
33	T8S, R26E, 7ACC	37.0	329.2?	Safford	6 (See 1)
34	T8S, R26E, 7AB	34.5		Safford	6
35	T8S, R26E, 7BB	33.5	262.1?	Safford	6 (See 6)
*36	T8S, R26E, 8BDC	39.4	195	Safford	6 (Fig. 3)
37	T7S, R27E, 11BBB	49.5		Safford	7

*Temperature Log

References

1 - Knechtel, 1938
2 - Hem, 1950
3 - Haigler, 1969
4 - Giardina, 1978
5 - U.S.G.S., WATSTORE File
6 - Swanberg, 1977
7 - This report

Buena Vista that has a 35.6°C surface temperature. The lowest calculated gradient is from the Mount Graham Mineral Bath well which is 659 meters deep and 46.5°C. The intermediate calculated gradients are from wells in the Cactus Flat-Artesia area.

Temperature and depth data for 44 artesian wells in the Cactus Flat-Artesia area are in Table 2 (Knechtel, 1938). The temperature gradients were then calculated for these wells. Well depths ranged from 79m to 400m with temperatures ranging from 20°C to 35.8°C. The range of calculated gradients was 29.7°C/km to 138°C/km. Figure 1 shows histograms of gradient variations from four 100 meter intervals. Shallow wells, 0 to 200 meters, exhibit three apparent gradient distributions. The two higher gradients in the shallow wells are thought to be the result of deeper hot-artesian aquifers leaking or flowing upward into the shallower aquifers. The majority of wells in the Cactus Flat-Artesia area have gradients around 50-60°C/km.

In order to delineate aquifers or zones of aquifers within the wells, drillers' comments reported by Knechtel (1938) were reviewed, and the reported water flows and depths noted. These data are tabulated in Table 3. All wells with reported aquifers below 140 meters have similar gradients, although the wells are of different depth and temperatures. These data suggest that the temperatures of the lower aquifers increase with depth systematically.

TABLE 2

TEMPERATURE
GRADIENT DATA(1)
FOR
CACTUS FLAT - ARTESIA AREA

Temperature and Depth Data From (Knechtel, 1938)

18°C Is The Mean Annual Air Temperature Used In Gradient Calculations.

T8S R25E

Number	Section/Quarter Section		Depth Meters	Observed Surface Temperature	Calculated Gradient °C/KM
1	1	DD	213.4	30.0	60.9
2	12	AA	182.9	21.1	22.4
3	12	AA	304.8	30.6	44.6
4	12	AA	304.8	29.4	40.7
5	12	AD	244.3	32.2	62.2
6	12	AD	243.8	32.2	62.3
7	12	AD	243.8	30.0	53.3
8	12	AC	400.2	28.9	29.7

T8S R26E

Number	Section/Quarter Section		Depth Meters	Observed Surface Temperature	Calculated Gradient °C/KM
*9	6	B	518.2?	28.3?	22.9?
10	7	AB	252.9	30.0	51.4
11	7	AB	76.2	25.0	104.9
12	7	AB	76.2	26.7	127.3
13	7	AB	91.4	26.7	106.1
14	7	AB	213.4	28.9	55.8
15	7	AC	152.4	25.6	56.4
16	7	AC	213.4	30.0	60.9
17	7	AC	213.4	28.9	55.8
18	7	AC	121.9	24.4	63.2
19	7	AC	329.2	35.0	54.7
20	7	AC	82.3	24.4	89.9

(1) Only flowing wells are tabulated.

* Lower sections of the well may have caved before measurements were made.

TABLE 2 (CONTINUED)

TEMPERATURE
GRADIENT DATA(1)
FOR
CACTUS FLAT - ARTESIA AREA

Temperature and Depth Data
From Knechtel, 1938

18°C Is The Mean Annual Air Temperature Used In Gradient Calculations.

T8S R26E (Continued)

Number	Section/Quarter Section		Depth Meters	Observed Surface Temperature	Calculated Gradient °C/KM
21	7	AC	91.4	25.0	87.1
22	7	AC	106.7	23.9	62.8
23	7	AC	231.7	28.3	48.7
24	7	AD	251.5	29.9	51.3
25	7	AD	244.3	30.6	55.7
26	7	AD	152.4	25.0	52.5
27	7	DA	79.2	24.4	90.9
28	7	CA	243.8	32.8	64.8
29	7	CD	289.6	33.9	58.4
30	7	BA	244.3	29.4	50.8
31	7	BA	344.4	35.6	54.0
32	7	BD	365.8	35.0	49.2
33	7	BD	396.2	33.9	42.6
34	7	BB	262.1	32.8	60.3
35	7	BB	320.0	35.8	58.8
36	8	DA	121.9	25.0	65.6
37	8	BC	243.8	29.4	50.9
38	8	BC	243.8	28.9	48.8
39	8	BC	137.2	25.0	58.3
40	9	D	188.9	27.8	57.2
41	16	BC	115.8	26.1	78.6
42	16	BC	146.3	25.6	58.8
43	16	BC	182.9	27.2	55.8
44	18	AC	244.3	33.9	69.1
45	20	DA	126.5	24.4	58.5

(1) Only flowing wells are tabulated.

* Lower sections of the well may have caved before measurements were made.

TABLE 2 (CONTINUED)

TEMPERATURE
GRADIENT DATA(1)
FOR
CACTUS FLAT - ARTESIA AREA

Temperature and Depth Data
From Knechtel, 1938

18°C Is The Mean Annual Air Temperature Used In Gradient Calculations.

T8S R26E (Continued)

Number	Section/Quarter Section		Depth Meters	Observed Surface Temperature	Calculated Gradient °C/KM
46	20	DA	30.5	21.7	154.1
47	20	AC	91.4	25.6	94.1
48	20	AB	213.4	30.6	63.7
*49	21	BB	243.8?	20.0?	12.3?
50	28	CC	152.4	28.3	74.2
51	32	AD	228.6	25.0	34.9
52	32	DB	121.9	32.2	124.7
53	32	DC	103.6	29.4	119.7
54	32	DC	121.9	32.8	129.6
55	32	CA	152.4	27.8	70.9
56	32	CB	109.7	32.2	138.6
57	33	AC	225.6	32.8	70.0
58	33	CA	121.9	32.8	129.6
59	33	CA	121.9	32.8	129.6
60	33	CA	152.4	33.3	106.9

(1) Only flowing wells are tabulated.

* Lower sections of the well may have caved before measurements were made.

TABLE 3

AQUIFERS OR ZONES OF WATER FLOW FROM FLOWING WELLS IN THE CACTUS FLAT - ARTESIA AREA[1] IN 1938

Depth Meters	Well Numbers[2] From Table 2	Range of Observed Surface Temperature	Range of Gradient Values °C/KM	Zone Number
24-30	26, 47, 46	21.7	154.1	1
76-91	11, 19, 27, 47	24.4-25.6	89.9-94.1	2
137-152	6, 7, 39	25.0	58.3	3
182-213	6, 7, 10, 14, 16, 17, 19, 32	28.9-30.0	55.8-60.9	4
244-267	6, 7, 10, 19, 25, 28, 32, 37	29.4-32.8	50.9-64.8	5
315-338	19, 31, 32, 35	35.6-35.8	54.0-58.8	6

(1) Data are from drillers' comments in the remarks column of tables in Knechtel, 1938.

(2) Well numbers which are underlined, 26, have only one flow from the zone or depth interval in which they are reported.

Conductive heat flow probably creates these temperature gradients. The upper flows, however, calculate to much higher gradients which probably result from convection or upward leakage of hot water from the lower aquifers. The 50-60°C/km gradients of the lower aquifers are high and may continue with depth. The deepest well in the basin, the Mary Mack well, which lies 15 air miles northwest of the Cactus Flat-Artesia, has a calculated gradient of 36°C/km. The 36°C/km gradient is slightly above normal.

TEMPERATURE LOGS

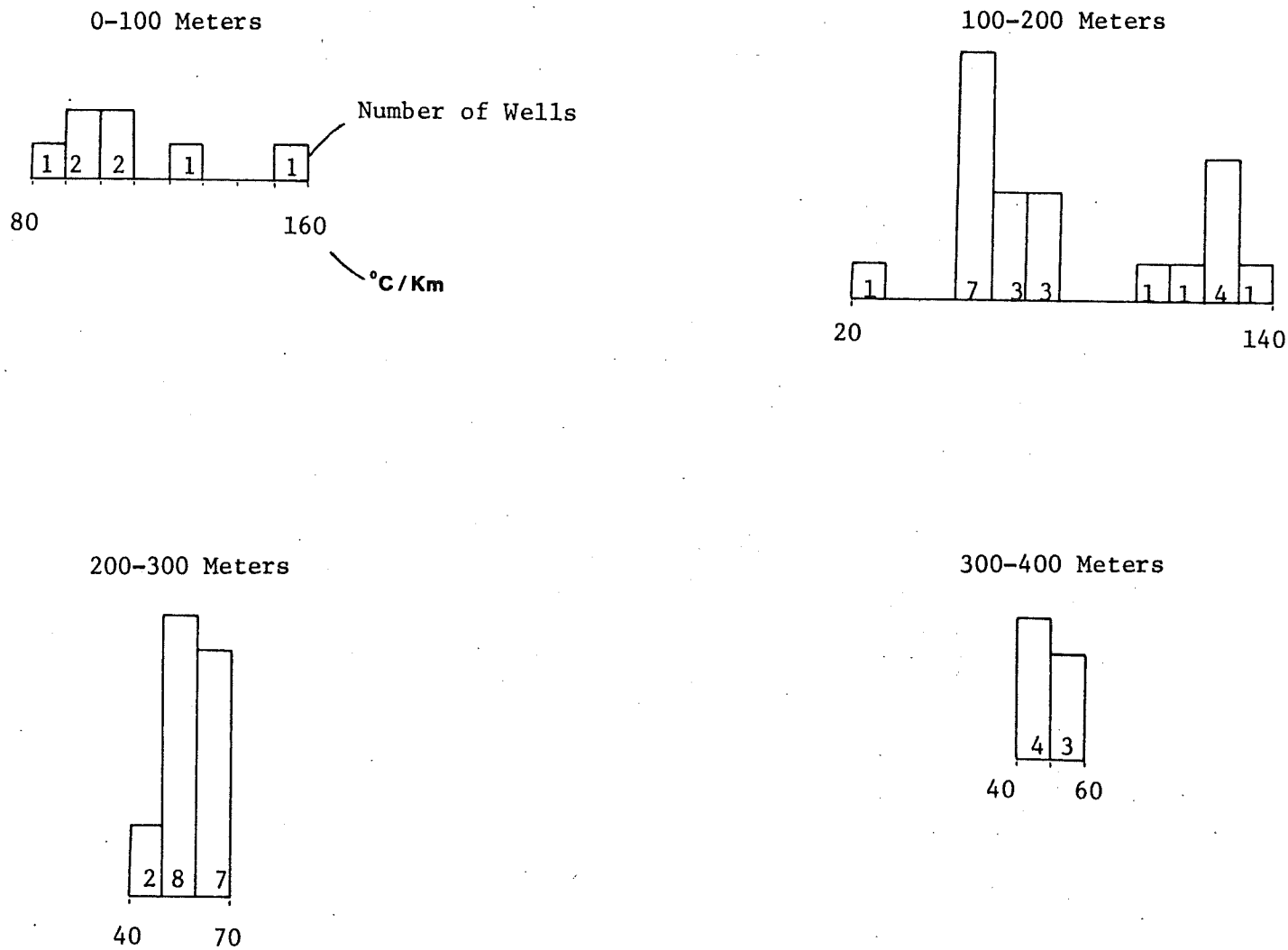
Two flowing wells, 6 inches in diameter, about 2.5 miles apart and approximately the same surface elevation were temperature logged. Temperature readings were taken at 5 meter intervals and recorded to the nearest hundredth of a degree celsius. Temperature logs of the wells are shown in Figures 2 and 3.

The well near Roper Lake is 195 meters deep and increased only 0.5°C from the surface to the bottom. Three zones of cold water mixing with upward flowing hot water were observed. The largest volume of cold water mixing with hot water is at 140 to 145 meters interval.

The well near Dankworth Lake is 390 meters deep; the surface temperature measured 44.61°C while the bottom temperature is 45.39°C. At 175 meters to 185 meters, upward flowing hot water appears to be flowing laterally out of the

FIGURE 1

HISTOGRAMS OF TEMPERATURE GRADIENTS
AT DIFFERENT DEPTHS FROM
WELLS IN THE CACTUS FLAT - ARTESIA AREA
IN 1938



Temperature and depth of flowing wells from Knechtel, 1938.

FIGURE 2

Temperature Log of Well Near Roper Lake

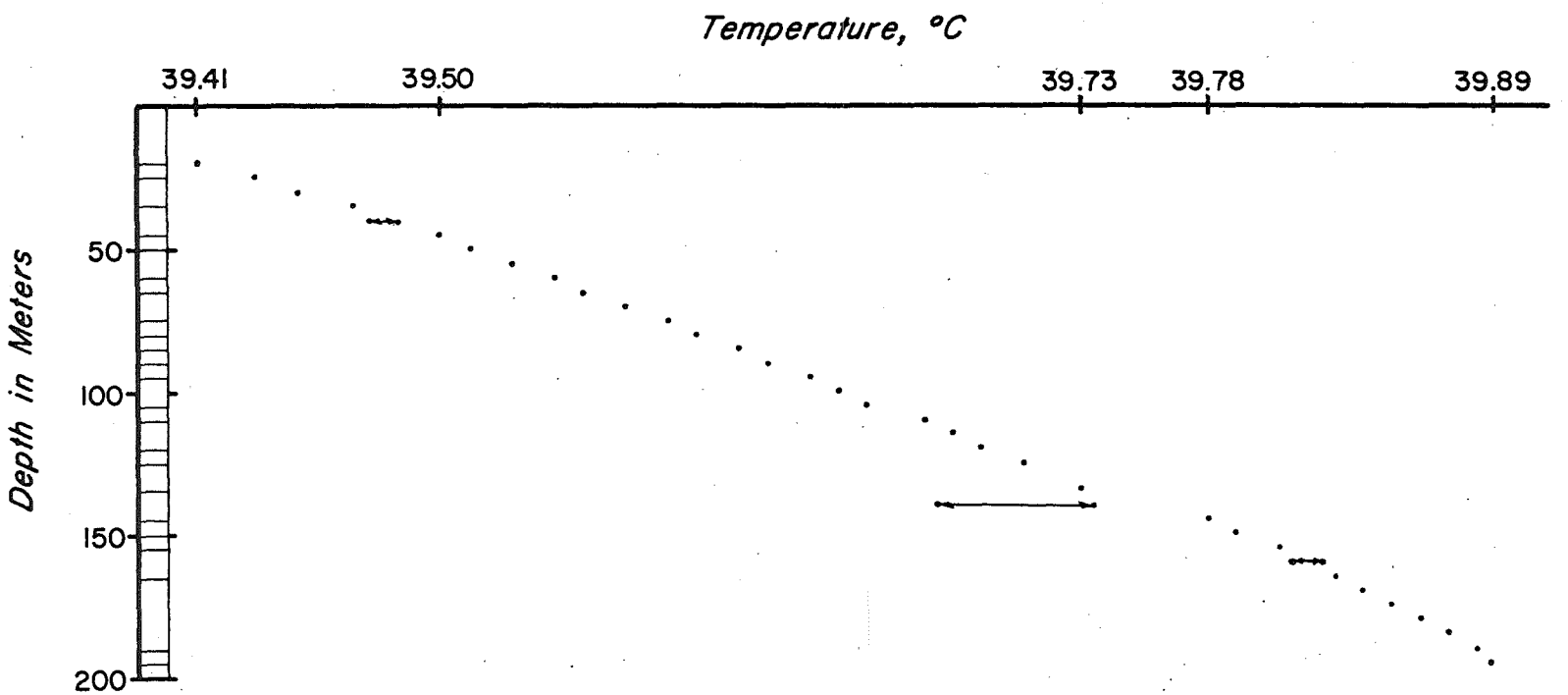
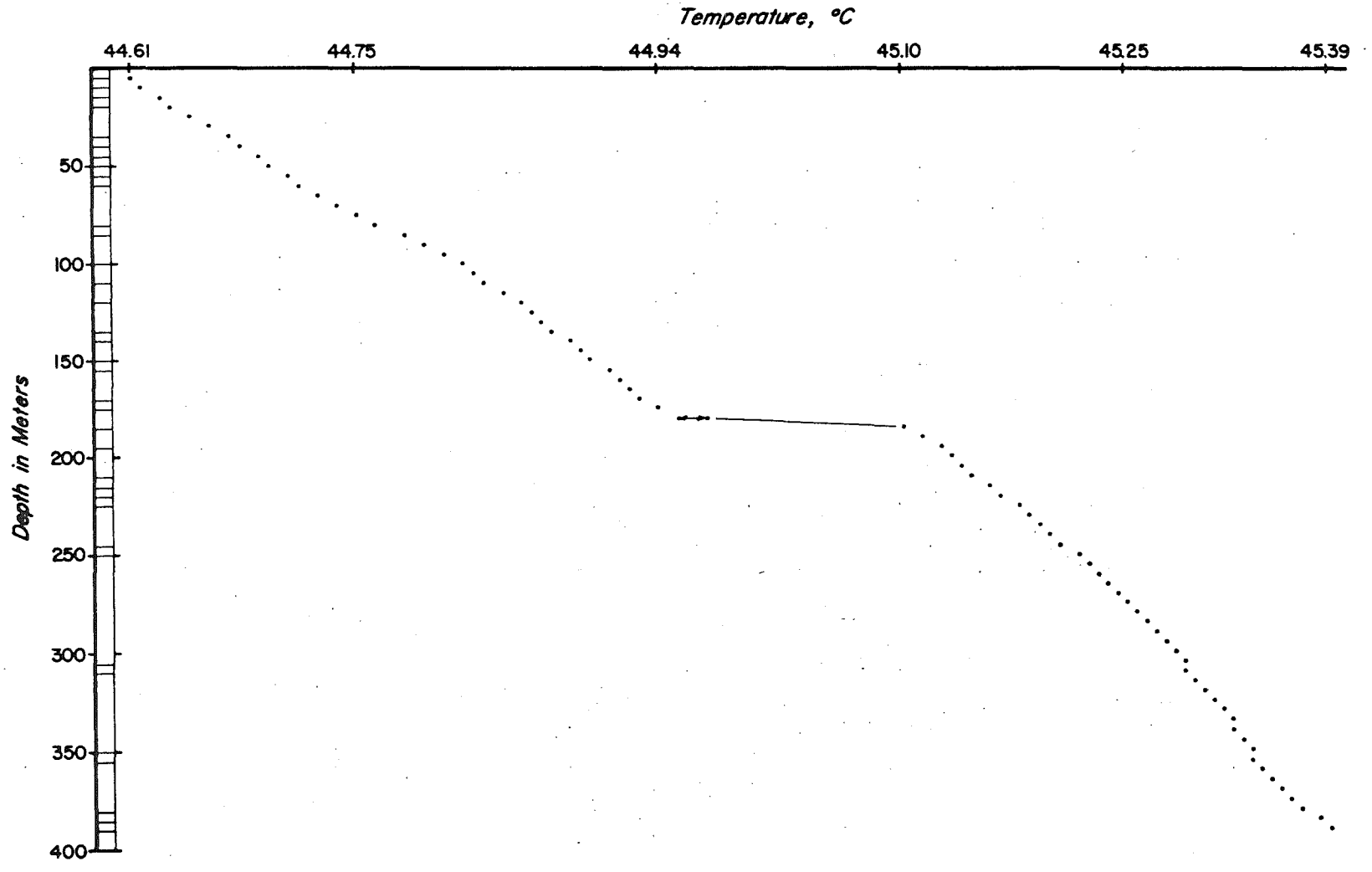


FIGURE 3

Temperature Log of Well Near Dankworth Lake



well and into a shallow aquifer.

The two logged wells are essentially isothermal, and the cooling that does occur is possibly due to adiabatic cooling. Conductive transfer of heat out the well into the country rock as the water flows upward to the surface is also a probable cooling mechanism. Interestingly, the two zones or aquifers that mix with the artesian flow are correlative to Zones 3 and 4 of Table 3. The Roper Lake well may derive its flow from Zone 4. If the aquifers are correlative with the 1938 data, then the aquifers have increased in temperature by several degrees celsius. Hot water losses to Zone 4 by the Dankworth well provides a possible mechanism for such a temperature increase.

GEOTHERMOMETRY

The silica concentration in hot water has been used to predict the base reservoir temperatures of geothermal systems (Fournier, 1977). Dissolution of silica from quartz, chalcedony, and opal is temperature dependent (Fournier and Rowe, 1966). The highest temperature waters will dissolve the most quartz, chalcedony, or opal. Silica geothermometry is therefore very useful in predicting minimum subsurface temperature when quartz and chalcedony equilibria controls the silica concentration in the reservoir, and when very little precipitation of silica occurs after the hot water leaves the reservoir (Fournier, White, and Truesdell, 1974). Silica geothermometry is most

applicable where the hot water has not mixed with cold water. If mixing of hot and cold water is known to occur, additional techniques to include mixing model calculations may be used (Fournier and Truesdell, 1974).

Weathering and alteration of alumino-silicates (feldspars, kaolinite, zeolites) also contribute silica to natural waters (Garrels and MacKenzie, 1967). However, silica concentrations will tend to be controlled by quartz or chalcedony equilibrium since these reactions are reversible. Silica concentration with respect to quartz and chalcedony may be metastable at lower temperatures. Therefore, waters whose silica contents are mostly derived from the weathering or alteration of alumino-silicate rocks may have silica concentrations out of equilibrium with quartz or chalcedony. Silica introduced into water by dissolution of alumino-silicates at low temperatures will thus tend to cause anomalously high concentrations of silica with respect to theoretical quartz and chalcedony equilibrium concentrations. Silica geothermometry is used with the assumption that temperature dependent dissolution of quartz and chalcedony in the geothermal reservoir controls the silica concentration in these waters rather than any nonreversible reactions involving alumino-silicates after the water leaves the geothermal reservoir.

Silica concentrations of wells in the Safford area are plotted against temperature in Figure 4. The concentration

of silica from the dissolution of quartz and chalcedony at increasing temperature are shown by the quartz geothermometer and the chalcedony geothermometer lines. Silica concentrations of wells in the Cactus Flat-Artesia area cluster around the chalcedony predicted temperature and indicates that these waters are probably in equilibrium with chalcedony. Observed surface temperatures are very close to the predicted silica temperatures. Therefore, the wells' observed temperatures are close to their bottom hole temperatures predicted by silica geothermometry. The two temperature logs agree with the geothermometry results.

The well at Mount Graham Mineral Bath and the wells at Buena Vista have much higher silica concentrations which may predict higher temperature reservoirs. Temperatures indicated by the chalcedony geothermometer for these wells is 85°C to 90°C. Bottom hole temperatures of these wells are not known. Since the wells have good artesian flow, large amounts of cold water are probably not mixing with these hot waters and cooling them as they flow to the surface, but rather the observed surface temperature is close to the bottom temperature of the well. The geothermometer temperatures are the temperatures of reservoirs at greater depth or nearby.

Ratios of sodium, potassium and calcium concentrations in geothermal waters have also been used to predict base temperatures of reservoirs (Fournier and Truesdell, 1973).

The Na-K-Ca geothermometer is less reliable in predicting reservoir temperatures than the silica geothermometer because the constituents used in the calculation may be involved in many non-temperature dependent reactions after leaving the reservoir.

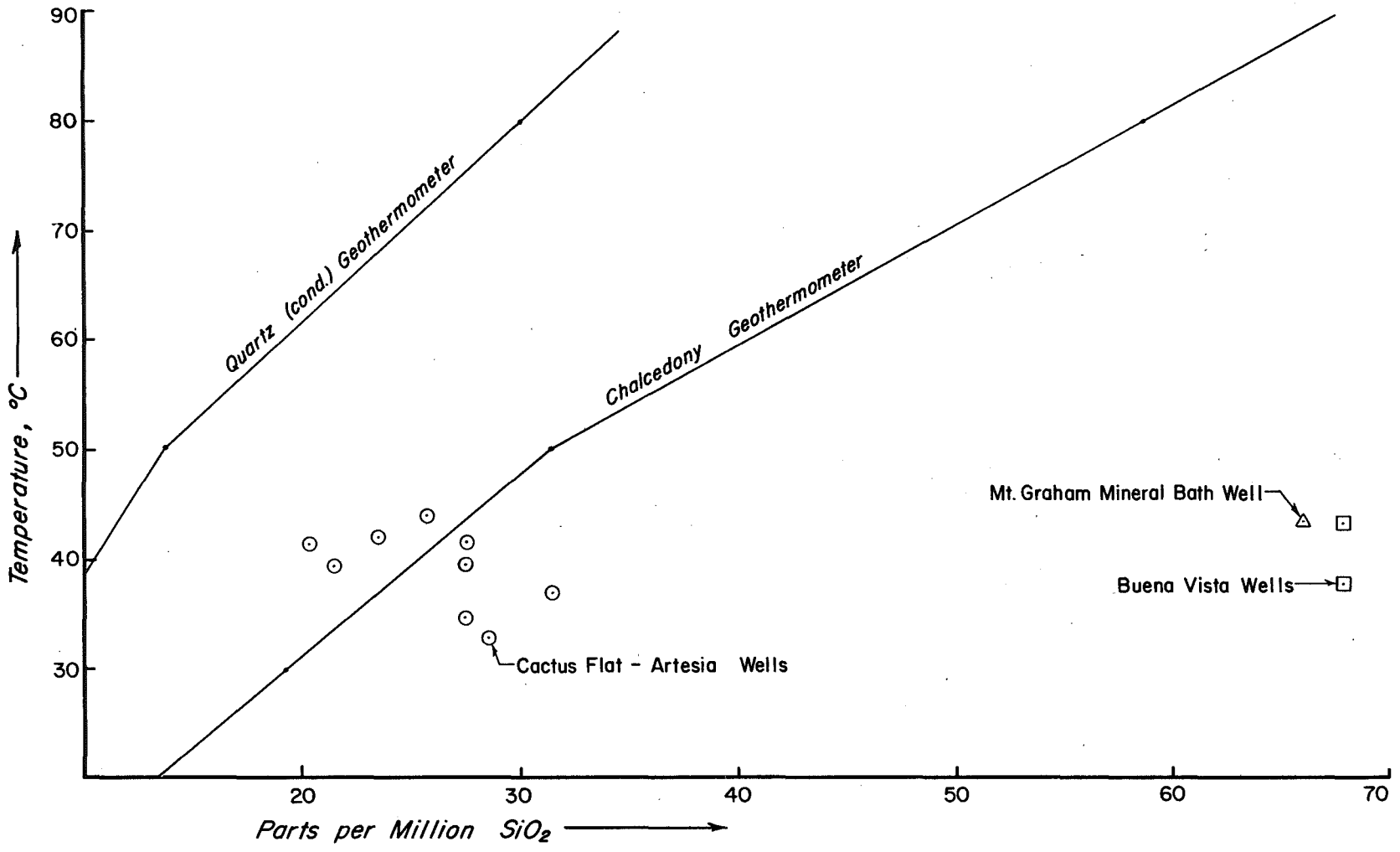
The Na-K-Ca temperature of the Mount Graham Mineral bath is around 70°C. The Na-K-Ca temperature is close to the chalcedony prediction, 85°C-90°C.

Buena Vista wells give Na-K-Ca temperature predictions of 115°C. 115°C is not in close agreement with the chalcedony prediction 85°C-90°C; however, the quartz geothermometer predicts 115°C for these wells. Therefore, these waters may be from a 115°C geothermal reservoir at depth or near Buena Vista.

Na-K-Ca temperatures of the Cactus Flat-Artesia area vary between 60°C and 90°C. These temperatures are suspect, but they may be indicative of higher temperature reservoirs since the quartz geothermometers of 75°C are in close agreement. It should be pointed out that these wells appear to be in equilibrium with chalcedony (see Figure 4), so that the quartz geothermometer is probably lower than the real temperature of the postulated reservoir because some chalcedony precipitated from solution thereby decreasing the original silica concentration. If so, then the Na-K-Ca geothermometer prediction would be more realistic.

FIGURE 4

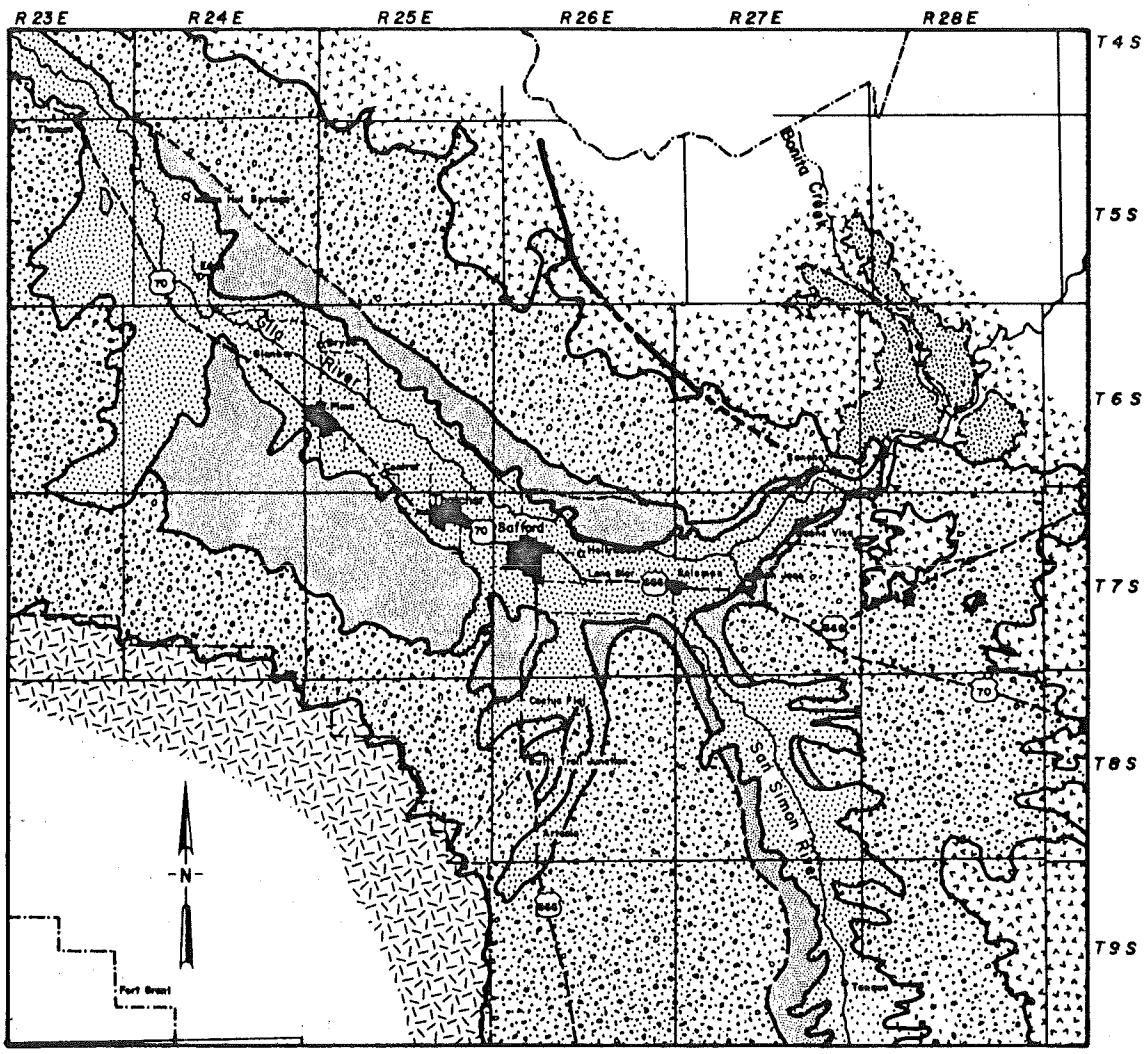
Temperature Vs Silica



Data for the geothermometry calculations are from Swanberg, et al., 1977, and from sampling by the Arizona Bureau of Geology and Mineral Technology Geothermal Group.

FIGURE 5

Generalized Geologic Map of Safford Area



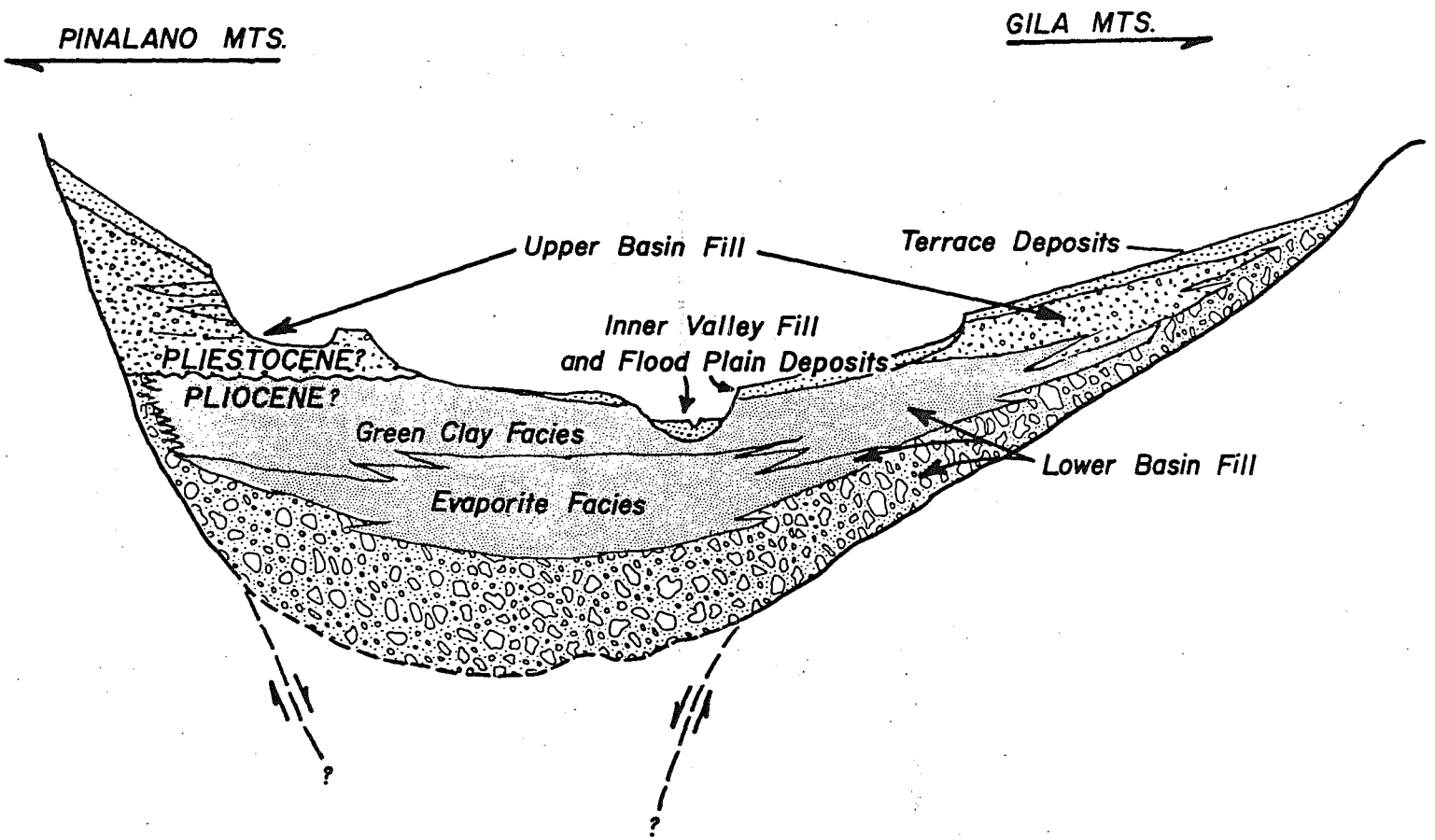
Geology From Harbour (1966)

- Terrace Deposits, Inner Valley Fill
- Upper Basin Fill
- Green-Clay Facies
- Evaporite Facies
- Basal Conglomerate
- Volcanic Rocks
- Plutonic and Metamorphic Rocks
- Fault

FIGURE 6

Generalized Sketch Showing Basin-Fill Relationships

Modified After Harbour, 1966



CONCLUSIONS

Preliminary study of the Safford area shows an excellent geothermal potential for low and intermediate temperature reservoirs. Available geothermometry and gradient data predict 50°C to 120°C geothermal water at reasonable depths (760m to 1200m). The basal conglomerate facies of the lower basin fill is the most likely reservoir and probably stores a large volume of hot water. Very good artesian flows are probable as was reported in 1938 at the Mary Mack well near Pima. Sodium chloride water with high fluoride content is likely. Total dissolved solids ranging from 1,000 mg/l to 10,000 mg/l or greater would be expected. Good geothermal reservoirs are also likely in alluvial channel deposits in the green clay facies along the basin margins. Further studies are needed to confirm these preliminary conclusions concerning the geothermal potential in the Safford basin. A high temperature resource (<150°C) is also possible, so additional studies are definitely warranted.

The most likely heating mechanism for the postulated geothermal resources is deep circulation of water in a normal or above normal heat flow regime. High heat flow through confined aquifers that are capped by low heat conductive rocks may be as important in this area. Land status of the Safford area appears to be favorable for

geothermal exploration and development. The development of geothermal energy is favorably looked upon by the people living in the Safford area.

Geothermal uses in the Safford area include heat for new agricultural businesses and processes, space cooling and heating of large buildings and neighborhoods, desalination of brines (making more water available for domestic and agricultural use), hot fluids for economic in-place-leaching of low grade copper deposits and/or mine dumps, and possibly electrical power generation as new technology is invented that produces electricity with intermediate temperature geothermal resources (90°C to 150°C).

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A PRELIMINARY STUDY OF THE GEOTHERMAL POTENTIAL OF THE TUCSON METROPOLITAN AREA

by J. C. Witcher

INTRODUCTION

Assessment of low temperature geothermal resources (<90°C) of the Tucson metropolitan area is under preliminary investigation. Low temperature geothermal reservoirs, a viable alternative source of energy, may provide heat energy for spacial heating and cooling, and many industrial processes to include drying and curing. By definition, a low temperature geothermal reservoir would be characterized by 30°C to 90°C water (White, D.E., and Williams, D.L., 1975). In order to be of use, a low temperature reservoir must:

1. Contain the heat for the desired application.
2. Store a large volume of hot water.
3. Be permeable to insure adequate withdrawal of hot water.
4. Be of good chemical quality to avoid abnormal corrosion and scaling of the hot water plumbing system.

The Tucson metropolitan area is situated in a broad valley surrounded by mountains. Geologically, the valley is a sediment filled basin which will be called the Tucson basin in the remainder of this report.

The Tucson basin lies in an area of high regional heat flow (Sass, J.H., et al., 1976). Several heat flow values

greater than 2.0 HFU[1] are measured in the surrounding Sierrita mountains, Tucson mountains, and Silver Bell mountains. Numerous shallow wells less than 300 meters deep encounter water ranging from 28°C to 40°C. Also, a hot spring, Agua Caliente, discharges 30.4°C water from Tertiary sediment near the Tucson basin's border with the Catalina Mountains. Geothermal occurrences such as these target the basin for further geothermal resource investigation. Since geothermal systems are a geologic phenomenon, the geologic environment of the Tucson area is reviewed with respect to possible heating mechanisms and hot-water storage sites.

GEOLOGY

Volcanoes and magma intrusions are sources of heat for many geothermal systems. In the Tucson area, volcanic activity and magma intrusion have left a sequence of igneous rocks in the Tucson Mountains. The youngest of these rocks were extruded between 28.0 MY and 23.7 MY ago (Damon, 1968) (Shafiqullah, et al., 1978). The heat associated with this activity dissipated long ago; therefore, another heating mechanism is more likely for the observed anomalies.

In general, temperatures increase with depth into the earth's crust. In areas where the natural heat flux from

[1]HFU (Heat Flow Units) is equivalent to units x 10^{-6} Cal/ Cm^2 Sec.

the earth's interior is higher than other areas, the temperatures increase faster with depth. These temperature increases with depth or temperature gradients are most likely responsible for the observed temperatures in some of Tucson's wells.

Water is stored in the voids and fractures in rock. The porosity (per cent of voids in rock storing water), the permeability (a measure of the amount of stored water that may be withdrawn in a given length of time), the depth and volume (heat content) of the rocks will determine in part where a usable resource exists.

In the Tucson area, the gross geologic structure and the rocks in that structure will control the geothermal reservoir(s) location.

Eberly and Stanley (1978) presented an interpreted seismic reflection profile of the Tucson basin. The profile extended from northwest to southeast across the axis of the basin. If the profile were extended, the southern end of the Tucson Mountains, Martinez Hill, would be at the northwest end, and the Santa Rita Mountains would be on the southeast end. The seismic interpretation is tied into a deep stratigraphic test drilled by Humble (Exxon). Humble No. 2, State (32) was drilled to a total depth of 3832 meters below the surface. Seismic interpretation indicates a deep sediment filled basin whose bottom slopes from the mountains towards the

basin axis. A relatively narrow graben occurs along the basin axis. The fault bound and down-dropped crustal block in the center of the graben is buried beneath 2218 meters of basin fill sediments. The sloped basement on both sides of the narrow, deep central graben may be broad pediments that were buried under basin fill as the mountain fronts eroded back.

Basin fill of the Tucson basin probably would provide the best site for a geothermal reservoir that could be tapped at reasonable drilling depths. Many water wells have been drilled in the upper sediments for municipal uses. The only well known to penetrate the complete section in the basin is the Humble (Exxon) well in Section 5, T16S, R15E. Figure 1 is a log of that well interpreted from data reported by Eberly and Stanley, (1978). The upper sands and gravels are the source of most groundwater supplies in the Tucson basin and are called the Fort Lowell Formation (Davidson, E.S., 1973). Fine grained sediment and clays beneath the Fort Lowell Formation contain abundant gypsum crystals between 564 and 686 meters. Sand and conglomerate occur from 914 meters to 1170 meters. Interbedded sand, silt and clay occur down to 2218 meters along with a 3 meter anhydrite bed at 2164 meters. The sediment overlain by the Fort Lowell Formation is probably the equivalent of the Tinaja Formation of Davidson (1973). The volcanics and sediments beneath the Tinaja Formation may be highly

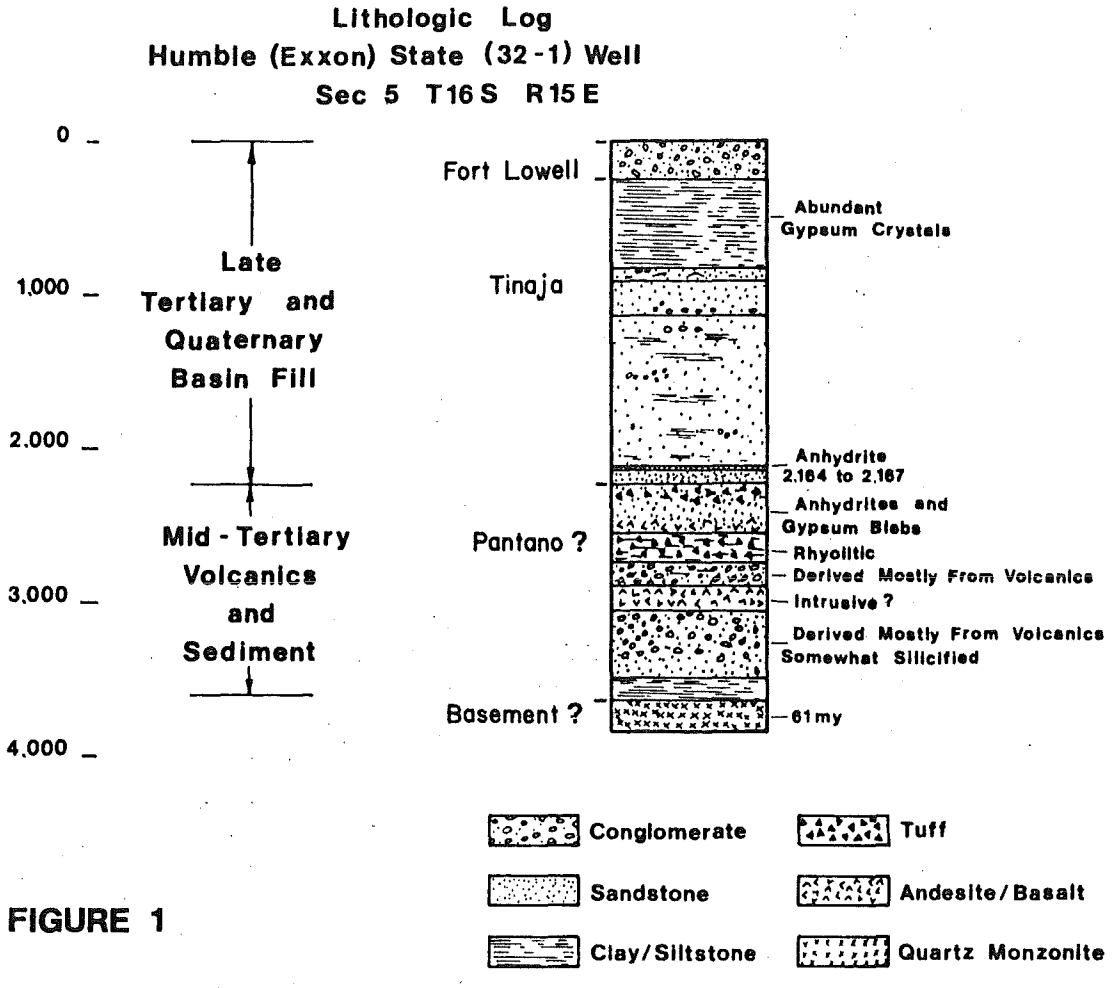
Lithologic Log
Humble (Exxon) State (32-1) Well
Sec 5 T16S R15E
0
1,000
2,000
3,000
4,000
Late Tertiary and Quaternary Basin Fill
Mid-Tertiary Volcanics and Sediment
Fort Lowell
Tinaja
Pantano ?
Basement ?
Abundant Gypsum Crystals
Anhydrite 2,164 to 2,167
Anhydrites and Gypsum Blebs
Rhyolitic
Derived Mostly From Volcanics
Intrusive ?
Derived Mostly From Volcanics Somewhat Silicified
61 my
Conglomerate
Sandstone
Clay/Siltstone
Tuff
Andesite/Basalt
Quartz Monzonite

FIGURE 1

disturbed by faulting and may be laterally discontinuous. The volcanics and sediments are not considered to be basin fill and may be equivalent to the Pantano Formation which is pre-Basin and Range "disturbance" (Eberly and Stanley, 1978) (Scarborough and Peirce, 1978). Rocks such as these overlain by basin fill may provide an excellent reservoir, but they may be constrained in lateral extent and permeability due to possible faulting and cementation; thereby possibly limiting their geothermal potential.

TEMPERATURE GRADIENTS

Geothermal systems beneath the Tucson area could make their presence known by upward or lateral leakage of hot water or conduction of heat to the overlying rock to create the observed anomalous temperature gradients. Thus, temperature gradients in shallow wells may help to identify specific areas having deeper geothermal potential.

Temperature gradients for 131 wells in Pima County and mostly in the Tucson area have been calculated using surface discharge temperature, well depth and mean annual air temperature data. Using 19°C as the mean annual air temperature, the temperature gradients were calculated by subtracting the observed surface temperature from the mean annual air temperature. The difference was divided by the depth; then the quotient was multiplied by 1000 to give the gradient. The gradient is in units of °C/km if degrees celsius and meters are used for the temperature and depth.

Temperature gradients have been averaged over the depth intervals of surface to 61m, 61m to 122m, and 122m to 183m. Average temperature gradients for each respective depth interval are plotted in Figure 2. The abscissa is the gradient and the ordinate is the depth. Ranges in the gradient values for each depth interval are plotted at the base of that interval. Average gradients decrease exponentially to a depth of 250 meters; thereafter, the gradient stabilizes at 37°C/km. 37°C/km is interpreted to be the average basin wide gradient below 250 meters. The average temperature gradient in the 3832 meter Humble (Exxon) well is 34°C/km using a reported bottom hole temperature of 147°C. The Humble (Exxon) well gradient is in reasonable agreement with the 37°C/km average gradient.

The increasingly higher gradients at shallower depths are interpreted to be the result of very slow upward or lateral flow of hot water. Also, gradients which fall to the right of Curve A in Figure 2 are interpreted to be anomalously high.

GEOTHERMOMETRY

The aqueous solubility of quartz, chalcedony and opal are directly temperature dependent (Fournier, R.O., and Rowe, J.J., 1966); therefore, the SiO_2 content of ground water is a valuable tool in delineating geothermal potential (Fournier, R.O., White, D.E., and Truesdall, A.H., 1974; Fournier, R.O. and Truesdall, A.H., 1974; and Arnorsson, S.,

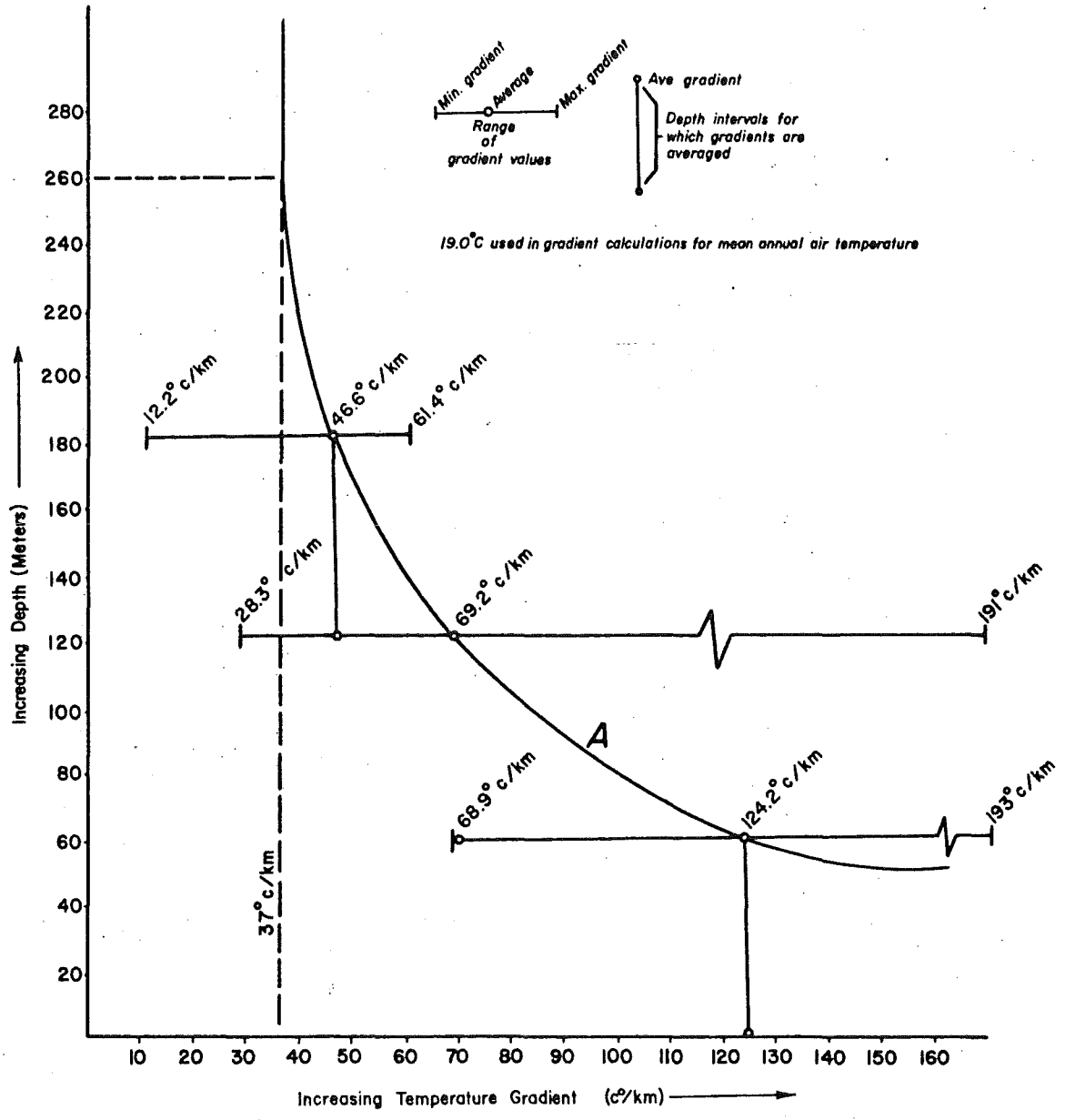
Min. gradient
Average
Max. gradient
Range of gradient values
Ave gradient
Depth intervals for which gradients are averaged
19.0°C used in gradient calculations for mean annual air temperature
12.2° c/km
46.6° c/km
61.4° c/km
28.3° c/km
69.2° c/km
191° c/km
A
68.9° c/km
124.2° c/km
193° c/km
37° c/km
Increasing Depth (Meters)
Increasing Temperature Gradient (c°/km)

FIGURE 2

1975). The technique is advantageous because SiO_2 is slow to reach equilibrium at lower temperatures. Thus, a cooled geothermal water will retain most of its originally high silica concentration. The dissolution of alumino-silicate minerals (feldspars, clays and zeolites) may contribute anomalous silica concentrations which are not the result of temperature dependent solubilities. However, silica concentrations in waters with temperatures greater than 30°C are probably less likely to be controlled by alumino-silicate dissolution and more likely to be the result of temperature dependent solubility of quartz and chalcedony. One well with a temperature greater than 30°C and whose temperature gradient was above average for its depth had a quartz geothermometer temperature of 85°C and chalcedony temperature of 55°C. The other wells above 30°C had quartz or chalcedony geothermometer temperatures that were close to the in situ temperature. These data are tabulated in Table 2. The silica geothermometers appear to give only shallow reservoir temperatures or they may reflect very slow, upward flows which allow time for silica precipitation as the water cools. Since the silica concentrations are relatively low, the use of silica geothermometry in the Tucson basin to interpret subsurface reservoir temperatures is mostly predictive of temperatures in shallow reservoirs.

The molal ratios of Na-K-Ca cations may be used to estimate a reservoir temperature (Fournier, R.O. and Truesdall,

A.H., 1973). The average Na-K-Ca calculated temperatures of the Tucson basin, 21.4°C, agrees closely with the average in situ temperature (26.2°C) of wells in the basin. The maximum Na-K-Ca temperature in the Tucson basin is 123°C. The Na-K-Ca predicted reservoir temperature, however, is unreliable due to possible calcite precipitation, the presence of evaporites.

Figure 3 is a map of the Tucson area showing sections containing one or more wells with anomalous temperature gradient and/or chemical geothermometer temperatures. Hot wells that are tabulated in Table 1 are also plotted on the map.

As suggested by this preliminary study, several interesting possibilities exist for exploring for low temperature geothermal reservoirs in the basin and range region of Arizona.

1. Basins situated in regions of normal to higher than normal heat flow with basin fill greater than 2km thick are likely to contain water at 50°C to 120°C.
2. Temperature gradient data are very useful in delineating zones of slow upward or lateral flow of hot water. Areas with anomalously high gradients are the best areas to apply chemical geothermometry techniques.

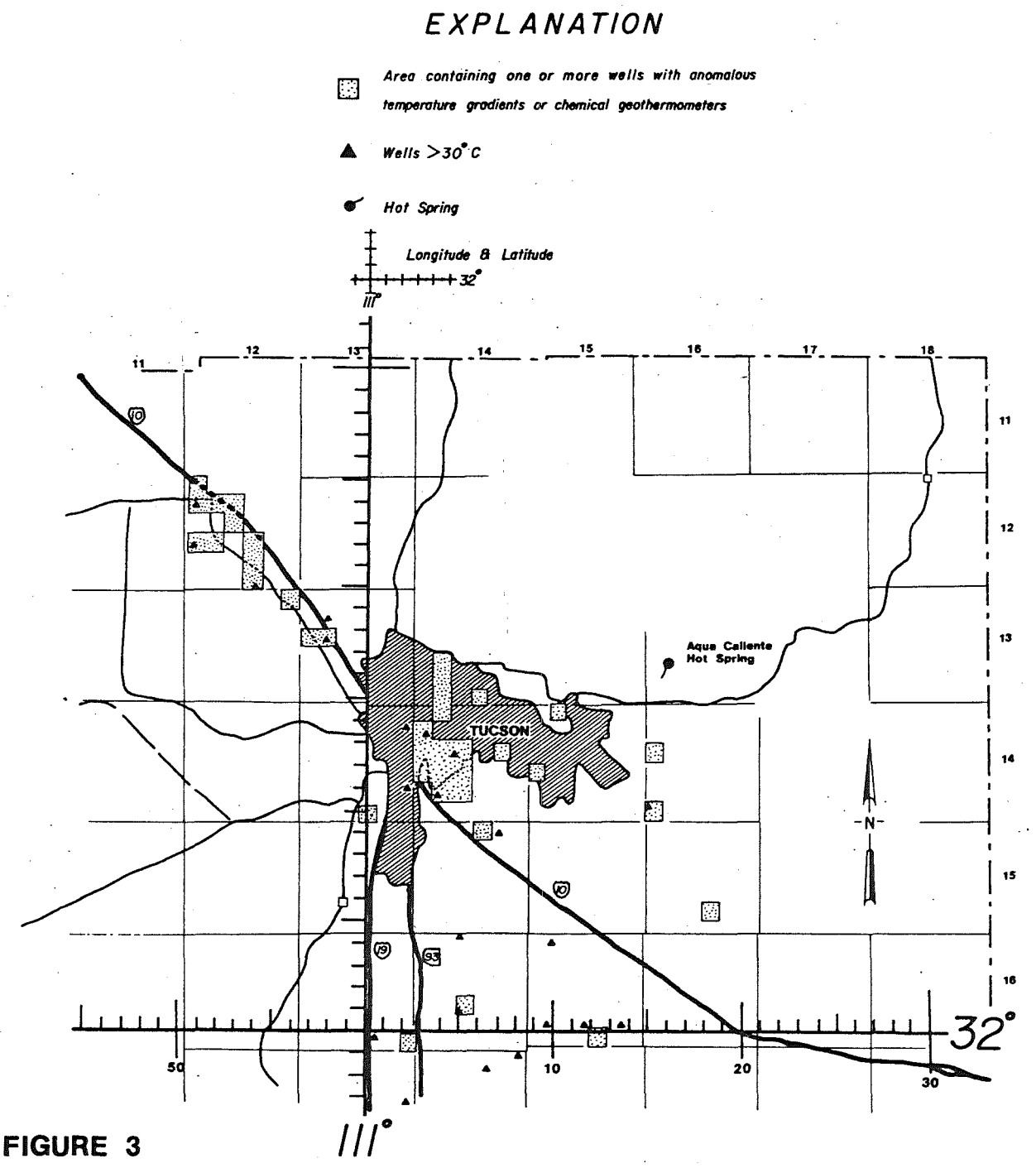
EXPLANATION
Area containing one or more wells with anomalous temperature gradients or chemical geothermometers
Wells >30°C
Hot Spring
Longitude & Latitude
32°
111°
11
12
13
14
15
16
17
18
Aqua Caliente Hot Spring
TUCSON
N
10
93
50
10
20
30
32°
111°

FIGURE 3

3. The silica geothermometers should be used with caution when applied to waters less than 30°C. Many anomalously high silica concentrations occur in probable recharge zones having very low temperature gradients. Silica concentrations in these areas may result from alumino-silicate dissolution and not from temperature dependent solution of quartz and chalcedony.

CONCLUSIONS

The Tucson metropolitan area has excellent potential for low temperature geothermal resources. Hot water, 50°C to 100°C, is probably within drilling depths of 2,500 feet to 5,000 feet deep in areas with anomalous subsurface temperature gradients. The Tucson basin probably stores a large volume of 50°C to 100°C hot water. The chemical quality and recovery rates from possible reservoirs is unknown; but available data suggest high fluoride contents and possibly low total dissolved solids.

Preliminary evaluation of data is favorable to the use of these waters for heating and cooling of large buildings and new subdivisions. Demand and consumption of electricity is highest during the summer in the Tucson area. Therefore, the use of geothermal energy to cool buildings would be very significant in reducing peak load demand,

stabilizing costs and saving fossil fuels. In addition, the use of geothermal energy in the area could provide more water for municipal use by two ways. First, new agricultural businesses using geothermal energy for aquaculture and to run greenhouses would be less water intensive and more water efficient, making more water available for other uses. Secondly, assuming good chemical quality, the cooled geothermal effluents from heating or cooling could be used to augment existing municipal water supplies.

Additional studies are ongoing in the Tucson area which will delineate the geothermal potential further and better determine its character.

Many of the data used for the preliminary Tucson basin geothermal evaluation are from Dutt, G.R., and McCreary, T.W., February 1970, The Quality of Arizona's Domestic Agricultural and Industrial Waters, Report 256, Agricultural Experiment Station, The University of Arizona.

TABLE 1

Wells with Temperatures Greater Than 30°C

in the Tucson Area[1]

Number	Location	Temperature °C	Depth Meters	Gradient C°/km	Reference
1	T12S R12E SEC7 CAA	30.8	107	110.3	1
2	T12S R12E SEC34 DCC	31.9	93	138.7	1
3	T12S R12E SEC34 DBD	37.8	96	195.8	1
4	T12S R12E SEC34 DBB	31.9	91	141.7	1
5	T12S R12E SEC19 CB	35.0	110	145.4	6
6	T13S R13E SEC8 BDD	31.8	79	162.0	5
7	T13S R13E SEC17 CAA	31.9	64	201.5	1
8	T14S R13E SEC25 DA	33.3	167	85.6	2
9	T14S R13E SEC25 DA	30.6	152	76.3	2
10	T14S R13E SEC12 ABC	30.0	91.5	120.2	3
11	T14S R14E SEC29 CBC	30.7	270	43.3	1
12	T14S R14E SEC16 CBB	35.0	370	43.2	2
13	T14S R14E SEC16 CCCB	30.0	426	25.8	2
14	T14S R14E SEC29 CB	44.8	152	169.7	5
15	T14S R14E SEC7 DDA	31.1	137	88.3	3
16	T14S R16E SEC31 BDC	30.6	91	127.5	2
17	T15S R14E SEC2 CAC	52.2	762	43.5	6,2
18	T16S R13E SEC34 AAB	31.1	152	79.6	2
19	T16S R13E SEC34 AAB	32.2	219	60.2	6,2
20	T16S R14E SEC21 CCB	40.6	183	118.0	1
21	T16S R14E SEC4 BA	40.0	523	40.2	6
22	T16S R15E SEC5 CA	147.0	3840	33.3	6
23	T16S R15E SEC28 DDD	31.8	305	41.9	4
24	T16S R15E SEC26 DDD	30.8	340	34.7	4

TABLE 1 (Continued)

Number	Location	Temperature °C	Depth Meters	Gradient C°/km	Reference
25	T16S R15E SEC30 DDD	31.5	305	40.9	4
26	T17S R13E SEC13 CDD	36.5	545	32.1	2
27	T17S R14E SEC1 BAA	33.5	456	31.8	4
28	T17S R14E SEC3 DCC	31.5	305	40.9	4

(1) 19°C is used as the mean annual air temperature in the calculation of gradients.

References:

1 - Dutt, G.R. and McCreary, T.W., 1970

2 - U.S.G.S. Watstore File

3 - Mburu, S.G., 1975

4 - City of Tucson, Ground-water Files - City Hydrologist's Office

5 - Supkow, D.J., 1971

6 - Giardina, Jr., S. and Conley, S.N., 1978

TABLE 2

WELLS GREATER THAN 30°C WITH
CALCULATED GEOTHERMOMETERS

Well	ΔG[1]	SiO_2	Temperature	Quartz	Chalcedony	Na/K/Ca
3	110	12	37.8	45.3	12.8	45.7
20	71	25	40.6	72.0	40.5	11.8
7	80	12	31.9	45.3	12.8	22.5
4	52	11	31.9	42.4	9.8	37.0
2	49	35	31.9	85.9	55.0	20.8
5	32	34	30.8	84.6	53.7	-
11	7	-	30.7	-	-	31.7

[1] ΔG equals the calculated gradient minus the gradient on Curve A in Figure 2 at the depth of the well.

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