SPRINGERVILLE GEOTHERMAL PROJECT GEOLOGY, GEOCHEMISTRY, GEOPHYSICS FINAL REPORT

by

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CHAPTER 1

Geology, Hydrology, Geothermometry, and Geophysics

Introduction

The "Springerville area," Apache County, Arizona (Fig.1) initially was selected 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 that were defined by the alignment of young volcanics in the White Mountain volcanic field (Hahman, pers. commun., 1977). 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 exploration farther south between the towns of Springerville and Alpine, and to the west thereof.

Sufficient data were generated to indicate a potential geothermal resource and thus to encourage the Bureau of Reclamation to fund specific geophysical surveys (passive seismic, d.c. resistivity, telluric current, and heat-flow drilling) that supplemented investigations being funded by the Department of Energy, Division of Geothermal Energy.

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 being managed by the Bureau of Land Management (BLM). The southeastern area is Apache National Forest. To the southwest are the Sitgreaves and Apache National Forests and the White Mountain Apache Indian Reservation.

This report reviews the area geology, hydrology, geothermometry, and geophysics; the results of heat-flow drilling, and geoelectrical and passive geothermal project area. This resource appears to be of sufficient magnitude to warrant additional, detailed geological, geochemical, and geophysical studies to definitively locate and evaluate the geothermal reservoir.

SPRINGERVILLE GEOTHERMAL PROJECT

Summary Statement

A resource assessment has been made of the Springerville geothermal project area (1) using available geologic and geophysical data and (2) by generating some new data with studies funded by the Bureau of Reclamation for this purpose.

Geologically, the Springerville area is comprised of relatively flat-lying sedimentary rocks of Tertiary to Paleozoic age overlying granitic basement rocks. The sedimentary rocks are only locally exposed, being covered by extrusive igneous rocks of the White Mountain volcanic field. Volcanism has been nearly continuous in the field from 32 m.y. to at least 10,000 years ago. However, rock chemical analyses show that volcanic activity has occurred in three distinct pulses, suggesting renewed episodes of partial melting in the mantle. The cause of periodic melting events is unknown, but probably is related to global plate tectonics.

Geochemical evidence, locally anomalous silica concentrations in the groundwater that are indicative of high heat flow, supports the probability of a geothermal resource in the Springerville area.

Geophysical evidence likewise supports this conclusion. Measured heat flow, 115 mWm^{-2}, is above the Colorado Plateau average of 49 mWm^{-2}. A zone of low resistivity has been identified in the project area. Anomalous gravity and magnetic lows occur in the project area. Other geophysical surveys indicate that a mantle upwarp or shallow low velocity zone exists beneath the area.

The conclusion drawn from the present resource assessment is that a geothermal resource of uncertain magnitude exists in the Springerville

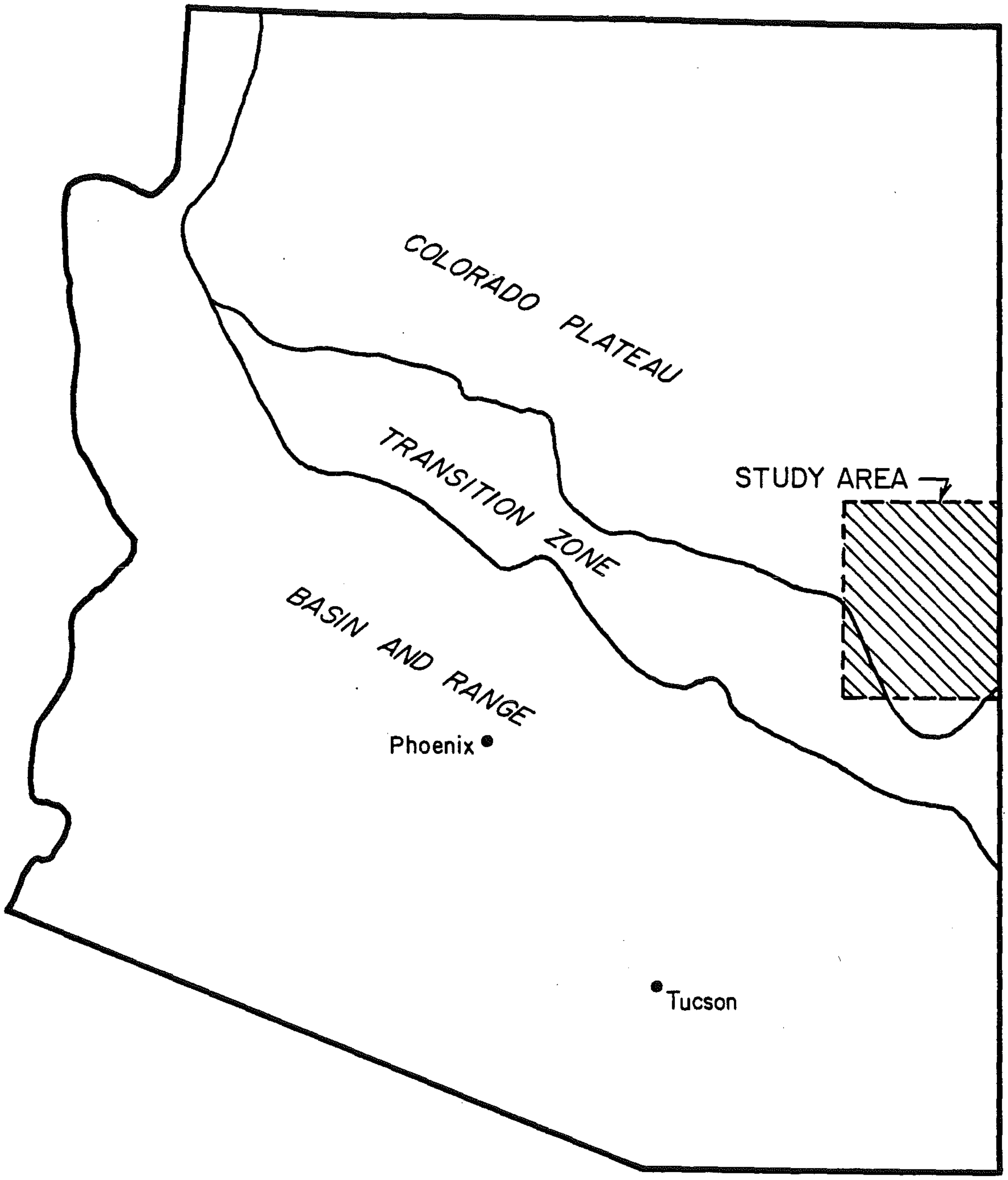

FIGURE 1: Location map with physiographic provinces.

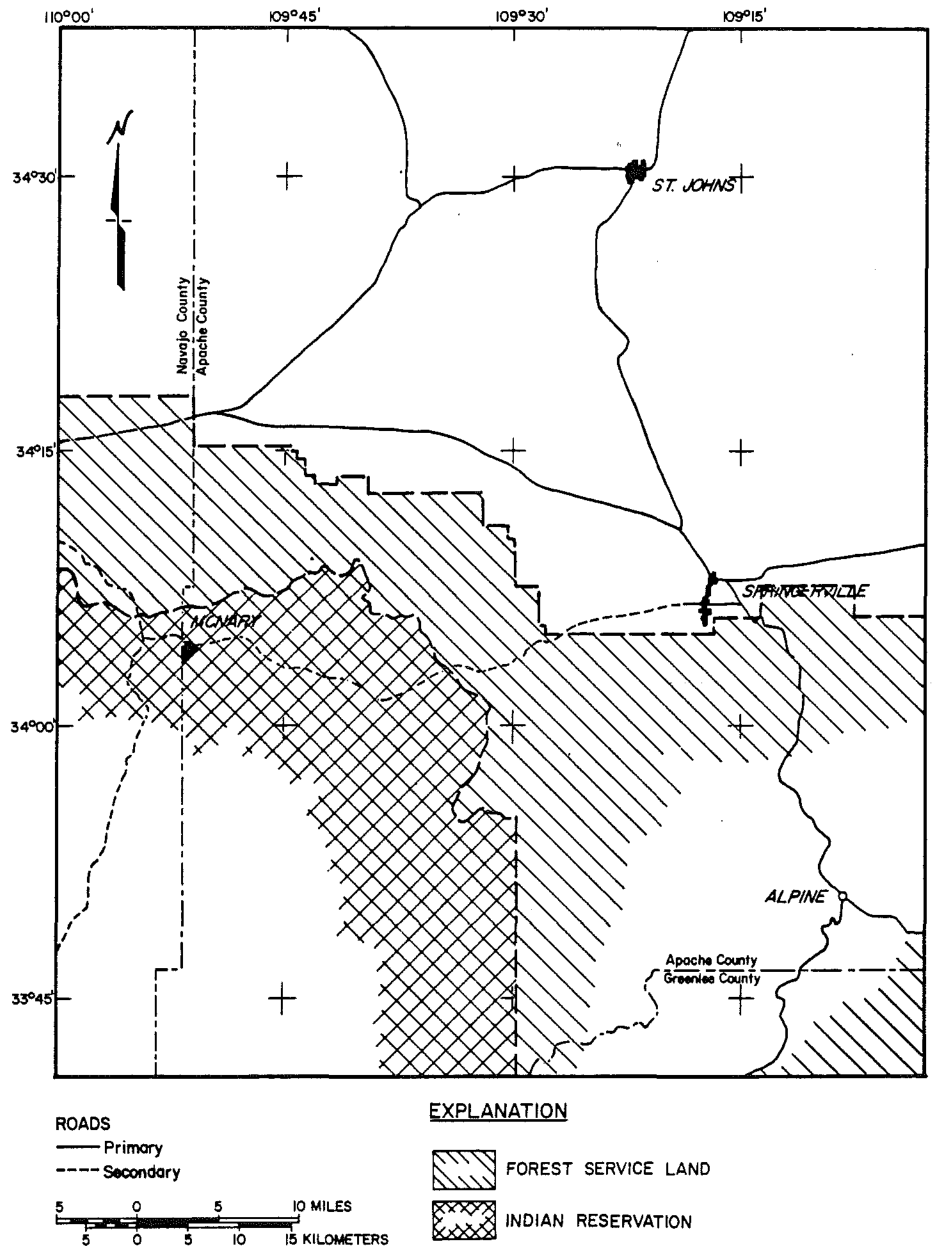

FIGURE 2: Land status map.

seismic studies; inferred reservoir characteristics; and environmental considerations. Recommendations are made throughout the report for additional studies that are needed to supplement the present report, to confirm or negate the presence of a viable, economic geothermal resource. Conclusions and recommendations are summarized in the final chapter.

Geology

A review of the regional geology of the Springerville Geothermal Project area is presented below. For details, the reader is referred to the reports of Akers (1964), Merrill (1974), Merrill and Péwé (1977), Sirrine (1958), Wrucke (1961), and Aubele and Crumpler (unpub. report, 1979).

The southern part of the study area comprises principally the Miocene-age Datil Formation that 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 Quaternary age. Two outcrops of the Pennsylvanian or Permian 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 separtes 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^{o} southward. Wrucke states that the area has few faults and that he can find no structural evidence of separation between the Transition Zone and the Colorado Plateau.

The northern portion of the study area, the Mogollon Slope, is lithologically more varied in both outcrop and subsurface. The sedimentary rocks range in age from late Pennsylvanian to Quaternary. 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 2300 to 4600 ft. A single deep borehole east of Springerville (Peirce and Scurlock, 1972) confirms the continuation of the principal Paleozoic units beneath the White Mountain volcanic field. These stratigraphic units are the Kaibab Limestone, the Coconino Sandstone and the Supai Formation, all of Permian age. However, exactly how far south these units occur and where they thin and pinch out is unknown. Stratigraphic test holes are recommended in the study area to resolve this question.

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. Minor rhyolite flows occurred to the south and east of the Mount Baldy area. This initial phase of volcanism 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 1600 ft. Merrill and Péwé identified an upper and lower member and presented 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 m.y.B.P. An age of 8.6 ± 0.4 m.y. 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 basaltic rock 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 Mountains occurred about early Pliocene time.

Aubele and Crumpler (1979) 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 basaltic rocks from this region range from about 6.03 to 0.19 m.y. (Damon and Shafiquallah, personal commun., 1979) from which it can be inferred that basaltic volcanism has been nearly continuous since its inception nearly 9 m.y. ago. Aubele and Crumpler (1979), through field examination, placed a lower age limit of greater than 10,000 years on all volcanism in their study area. Additional age dates are recommended to identify the youngest possible rocks and to determine whether a possible spatial-temporal relationship exists in the volcanic field.

Crumpler (1978) confirmed the suspected WNW and NE orientation of fissures and the alignment of cinder cones along the fissures. He inferred from the topography in general that the area is "chopped up with minor faults" but stated that the faults predate the lavas of the intermediate unit.

Aubele (1978) 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 are expressed as regional lineaments, based on the alignment of young volcanic fields (Fig. 3) (Chapin and others, 1978; Lepley, 1977; Swanberg and others, 1977). These lineaments intersect in the White Mountain volcanic field and undoubtedly have a dynamic influence on continuing magma generation and volcanism in the region.

Deep drill holes are unknown in the study area between Springerville and Alpine. Consequently, the subsurface stratigraphy and the depth to crystalline basement are not known. It is inferred that south of Springerville, beneath the Tertiary (and Cretaceous?) sediments, the Kaibab Limestone and Coconino Sandstone, the principal groundwater aquifer of the region, are present in the subsurface. However, west of this region these units have been beveled by erosion and locally have been removed. Therefore it is highly speculative to place a great deal of confidence in such inferences without stratigraphic test holes to verify their existence and to measure their thicknesses beneath the volcanic pile. It is recommended that five stratigraphic test holes, two of which are sited to the east in New Mexico, be drilled in the study area to answer this question.

To date only reconnaissance mapping has been done in the Springerville-Alpine region and part of the area has never been mapped. It is recommended that detailed mapping be conducted in the study area and in New Mexico, supplemented by air-photo interpretation and radiometric age dating to understand the regional and local geological, structural and tectonic environment of the potential geothermal reservoir.

Hydrology

Parts of the following section have been abstracted from a report by Hargis (1979). The upper Little Colorado River basin drains most of the

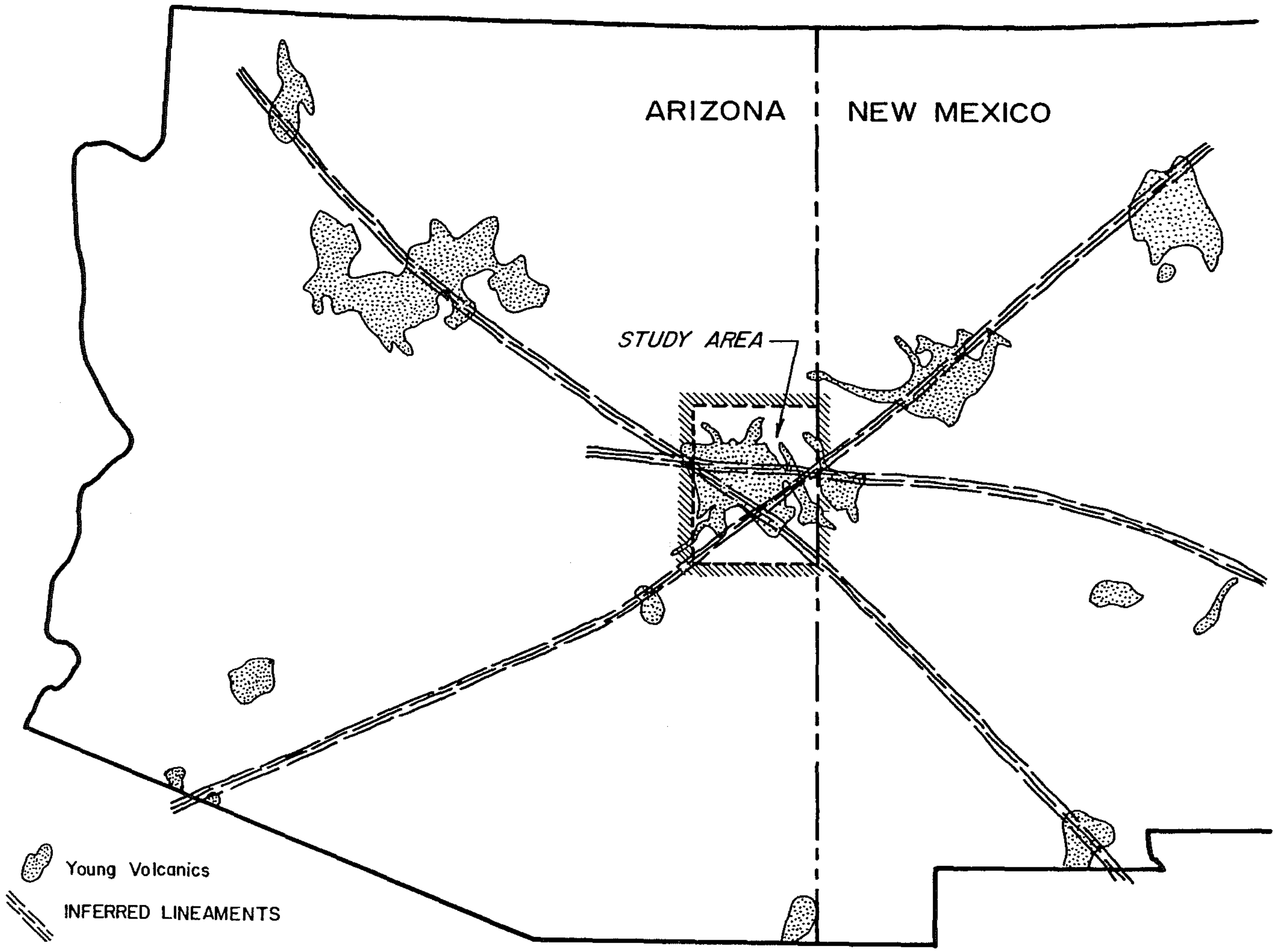

FIGURE 3: Lineament map based on alignmet of young volcanics.

northeastern part of Arizona and comprises the principal stream system in the study area. The study area lies mainly within the structural subdivision known as the Mogollon Slope, a broad homocline that extends from the Mogollon Rim northward to the Black Mesa Basin and Definance Uplift. The Mogollon Slope extends from Springerville on the east to Flagstaff on the west. The Mogollon Rim, a southward-facing belt of mountainous terrain, bounds the southern edge of the Mogollon Slope, and drains southward via the Black River and its tributaries. The Black River is a tributary to the Salt River.

Groundwater supplies are obtained from alluvial deposits along the floodplain of the Little Colorado River and its major tributaries; from Tertiary and Cretaceous sandstone; from the Permian formations (Kaibab Limestone-Coconino Sandstone); and from volcanic rocks in the headwaters areas of the Little Colorado River and the Black River. The principal groundwater reservoir is the Permian Kaibab-Coconino multiple aquifer system which extends throughout much of the northeastern quarter of Arizona. Some groundwater discharge from the Kaibab-Coconino aquifer is believed to occur at the present time via springs and seeps in the St. Johns area, and to feed the tributaries of the Little Colorado River and Black River. The springs are usually small and many do not provide a sustained discharge during drought periods.

Potential aquifers in the Springerville geothermal project area can be delineated from inferred hydrogeological conditions and well performance data. As stated above, there are no deep wells in the area between Springerville and Alping that have penetrated the Triassic or Paleozoic rocks. Their presence in the subsurface is inferred from geologic evidence in the area between Springerville and St. Johns (Akers, 1964). Well yeilds of several tens to several hundreds of gpm (gallons per minute) would be expected from the Quaternary alluvium and volcanic rocks. Similarly, well yields of as much as

200 gpm might be obtained from the Tertiary unconsolidated gravels, Datil Formation, and other undifferentiated sedimentary rocks. The Triassic Chinle and Moenkopi Formations probably function primarily as confining beds of low permeability overlying the Paleozoic rocks, but well yields as high as 50 gpm might be obtained from sandy zones. The major potential aquifer in the Springerville-Alpine area if present in the subsurface, is the Kaibab-Coconino aquifer system, where yields of several thousand gallons per minute might be expected where the Kaibab Limestone is fractured and fully saturated.

The potentiometric surface in the Kaibab-Coconino aquifer shallows to the north. Harper and Anderson (1976) 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.
> ...The chemical quality of the groundwater in the Kaibab-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." (Fig. 4)

In the study area, total dissolved solids are generally less than 500 mg/l.

Very little pumping from the Kaibab-Coconino aquifer is estimated to have been done to date (Harper and Anderson, 1976). Only one or two detailed studies that included sustained pump testing and drawdown projections based on digital model simulations have been made of the aquifer, and these tests were confined to very discrete areas. The studies were made in conjunction with designing and developing water well fields to supply coal-fired power plants under construction east of St. Johns (Salt River Project) and north-northeast of Springerville (Tucson Electric Company), about midway between St. Johns and Springerville.

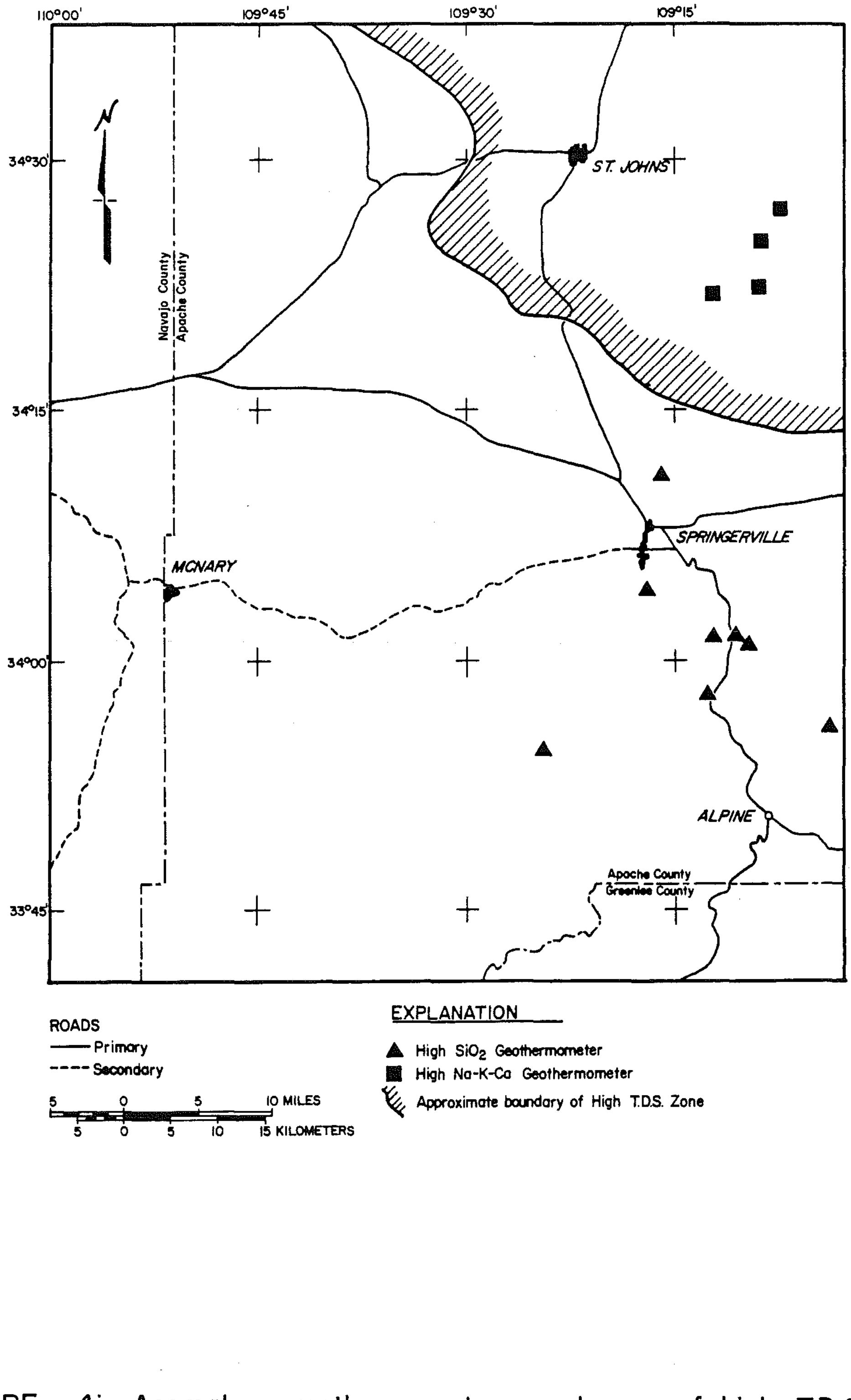

FIGURE 4: Anomalous geothermometers and zone of high T.D.S. water.

Drawdown projections for the Springerville well field, for 35 years of continuous pumping at a rate of 9800 gpm or about 15,800 AF/yr (acre-feet per year), indicated that the ten-foot drawdown contour would occur at a radius of about 15 miles from the pumping center and would be slightly enlongated to the northwest. The model simulation also indicated that a maximum of about eight feet of drawdown might occur at St. Johns after 35 years of pumping but that it would not significantly reduce seepage or spring discharge. It can be concluded from this study that development of a well field in the Kaibab-Coconino aquifer 25 miles farther south would have no effect upon seepage or spring discharge at St. Johns.

While it is known that groundwater in the project area generally moves from south to north, very little else is known. Aquifer characteristics between Springerville and Alpine, and eastward into New Mexico are unknown, as are the rate of groundwater movement, age of groundwater, source and rate of recharge. It is recommended that extensive hydrologic field studies and computer model simulations, including isotopic dating of groundwater, be conducted on a regional scale to determine the short- and long-term effects of using groundwater from the Kaibab-Coconino aquifer.

Geothermometry

Chemical analyses of well and spring waters sampled in the study area (Witcher, pers. commun., 1979) and analyses taken from published reports (Swanberg and others, 1977; Akers, 1964) show waters with anomalous Na-K-Ca temperatures in the range of 170-190^{o}C around and northeast of the Lyman Lake travertine deposits (Fig. 4) mapped by Aubele and Crumpler (1979). The deposition of travertine in that area implies that the high Na-K-Ca geothermometers are more likely a result of calcium depletion in the water rather than of a true geothermal anomaly (Eckstein, 1975). However, care must be taken in accepting such a simplistic explanation for the anomalous geothermometers. First, an overlarge percentage of wells and springs with temperatures of 20°C or more (Fig. 5) fall within the general area of the high Na-K-Ca geothermometers. Second, anomalously-high geothermal gradients (Fig. 6), and groundwater with high total dissolved solids (Fig. 4), also occur in that region. These indicators suggest the presence of thermal water in the area, possibly as a result of leakage.

A second group of springs and wells, located between Springerville and Alpine, have SiO_2 geothermometers in the range of 80-90°C (Fig. 4). Since the average SiO_2 geothermometer for the Colorado Plateau is 53.4°C (Swanberg and Morgan, 1978/79), and all other SiO_2 geothermometers in the study area cluster around this average, the higher values are distinctly anomalous. More importantly, Swanberg and Morgan (1978/79) found a linear relation between temperatures based on the silica content of groundwater and regional heat flow in the United States. The relationship suggests that this region, where silica geothermometers are nearly twice the background value, is an area of high heat flow, as will be shown later.

Numerous springs and shallow wells exist in the study area. It is recommended that all available waters be chemically analyzed and that mixing models be run to determine whether hydrothermal fluids are leaking from the geothermal reservoir and mixing with shallow groundwater. If it can be shown that leakage is occurring, then reservoir temperatures can be predicted by the mixing models.

Geophysics

Geothermal Gradients - Geothermal gradients were measured by calibrated thermistor probe at 18 sites within the study area. Five measured gradients are anomalously high, and two are anomalously low. The two

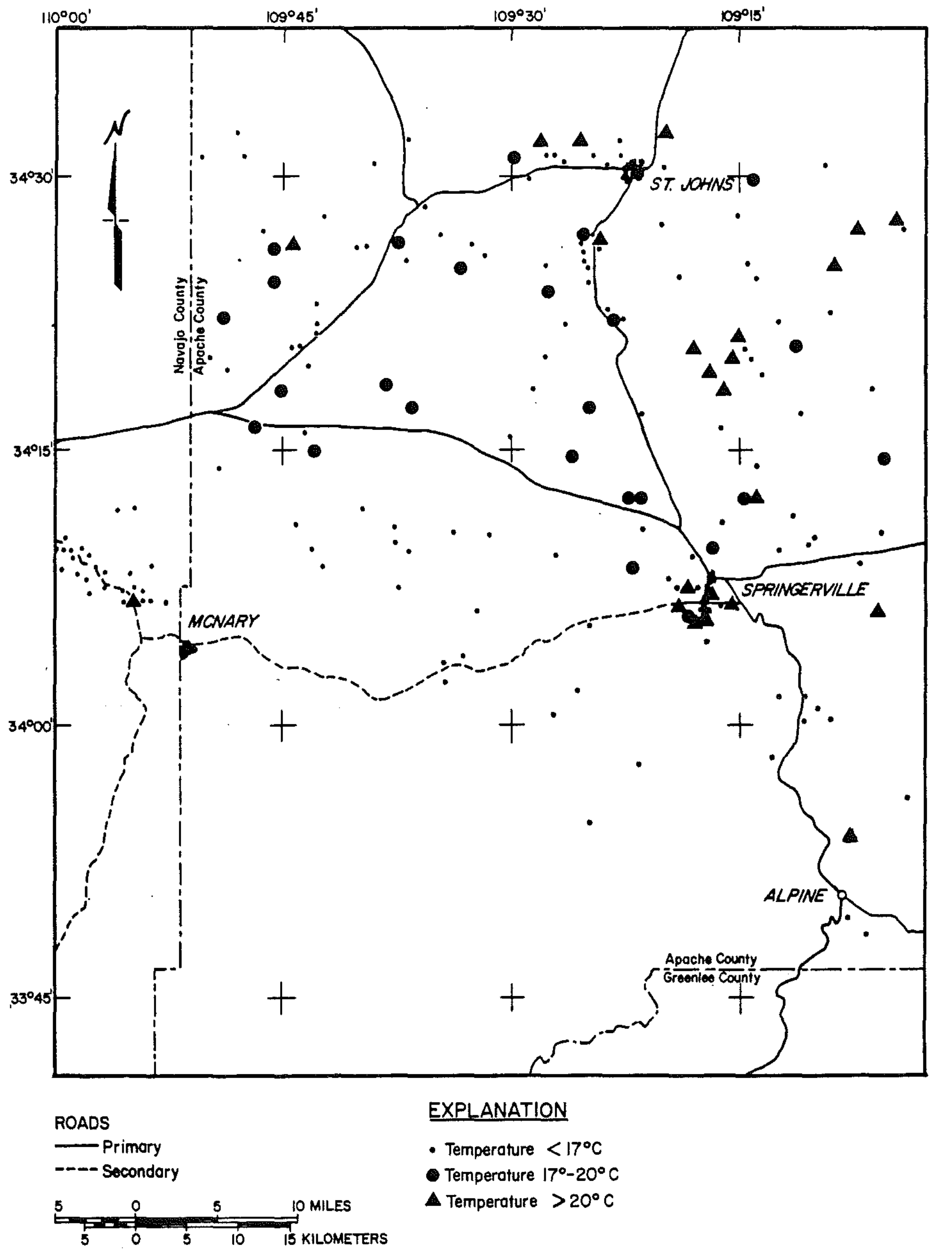

FIGURE 5: Well locations with measured temperatures.

measured wells with low gradients each exhibited two zones of convection that were not observed in other measured wells. Additional gradients were computed for this report from published 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 were greater than normal for a given depth were identified as anomalous. It can be seen in Figure 6 that the wells with low gradients occur in the western part of the study area while those with anomalously-high geothermal gradients coincide with the occurrence of geochemical anomalies to the east.

<u>Gravity</u> - A large negative Bouguer gravity anomaly, -250 milligals, occurs between Springerville and Alpine (West and Sumner, 1973) (Fig. 7) and is confirmed by the residual Bouguer gravity anomaly of Aiken (1975) (Fig. 8). A gravity low can represent (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 United States, such as Long Valley, California (Kane, Mabey, and Brace, 1976). However, gravity data cannot be properly interpreted without adequate knowledge of the surface geology and the subsurface structure and stratigraphy.

<u>Magnetics</u> - A magnetic low can be seen to exist in the same area as the gravity low. It exhibits a strong northeast trend that is only suggested by the gravity. A magnetic low also can be caused by many effects, one of which is the hydrothermal alteration of magnetite to pyrite. Studt (1964) suggested this as a cause of the magnetic minimum in New Zealand, and Kane and others (1976) suggested a similar cause for the magnetic low at Casa Diablo in Long Valley, California. Like gravity, magnetic anomalies cannot be interpreted without adequate geological and geophysical support.

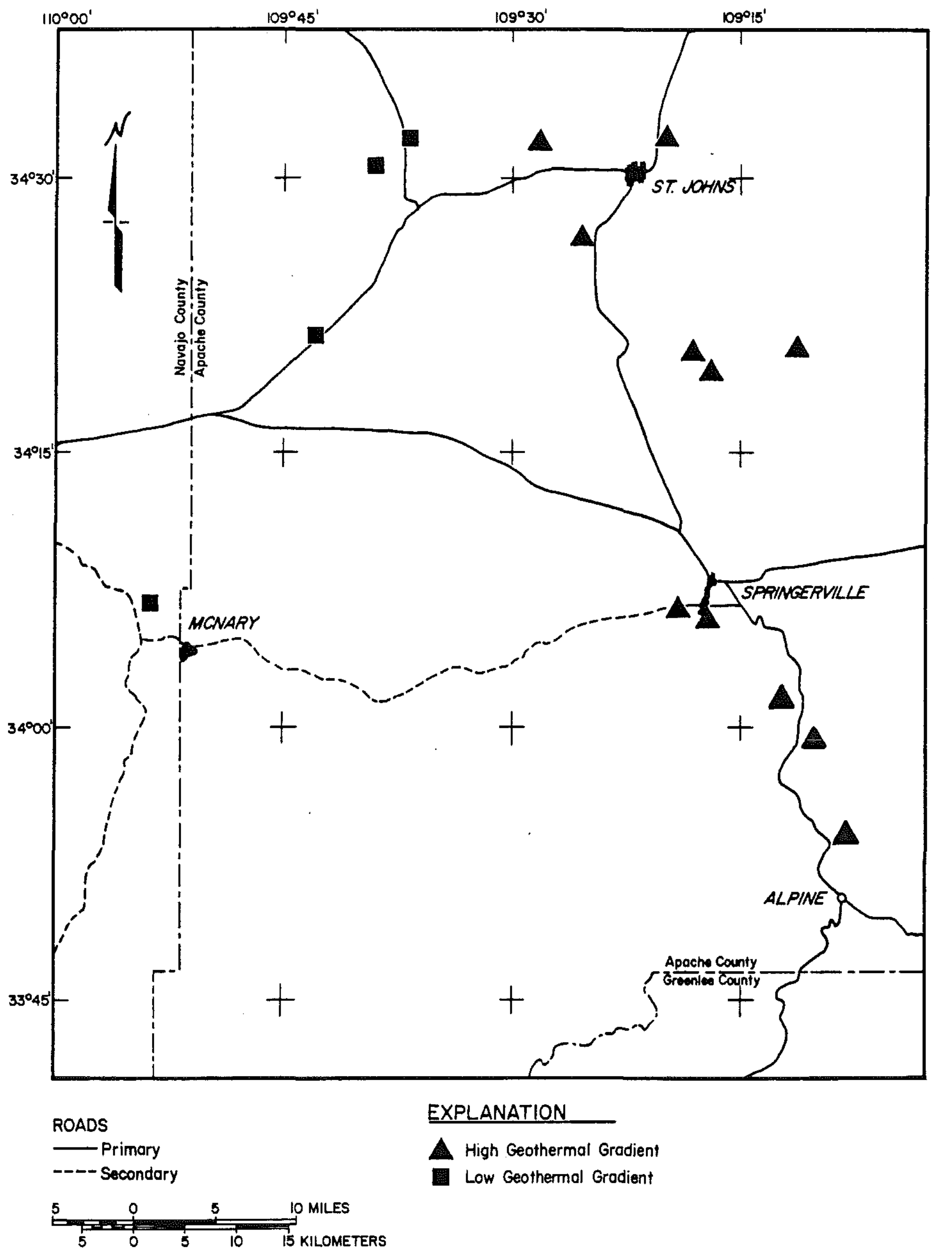

FIGURE 6: Anomalous gradients.

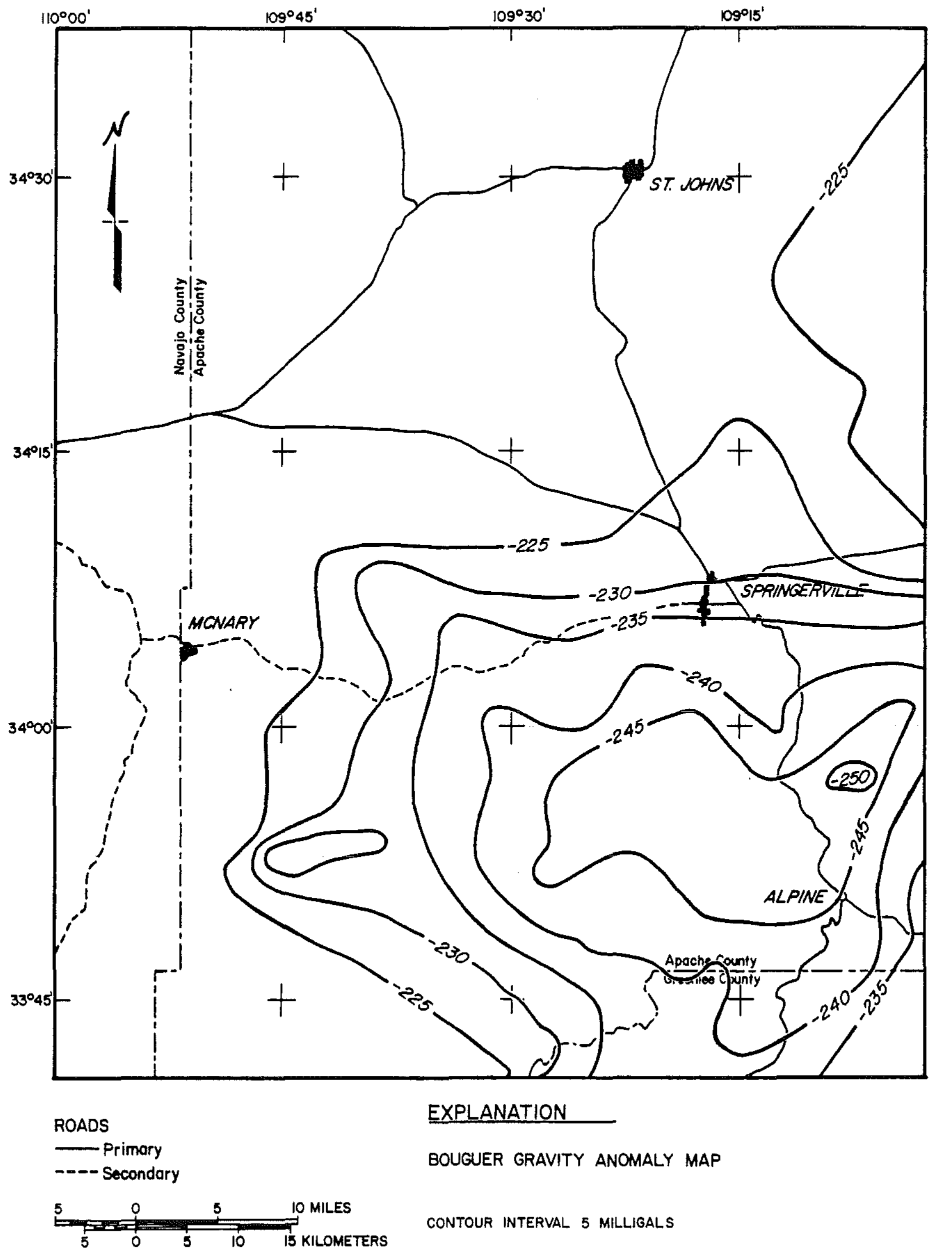

FIGURE 7: Bouguer gravity anomaly map. (After West and Sumner, 1973.)

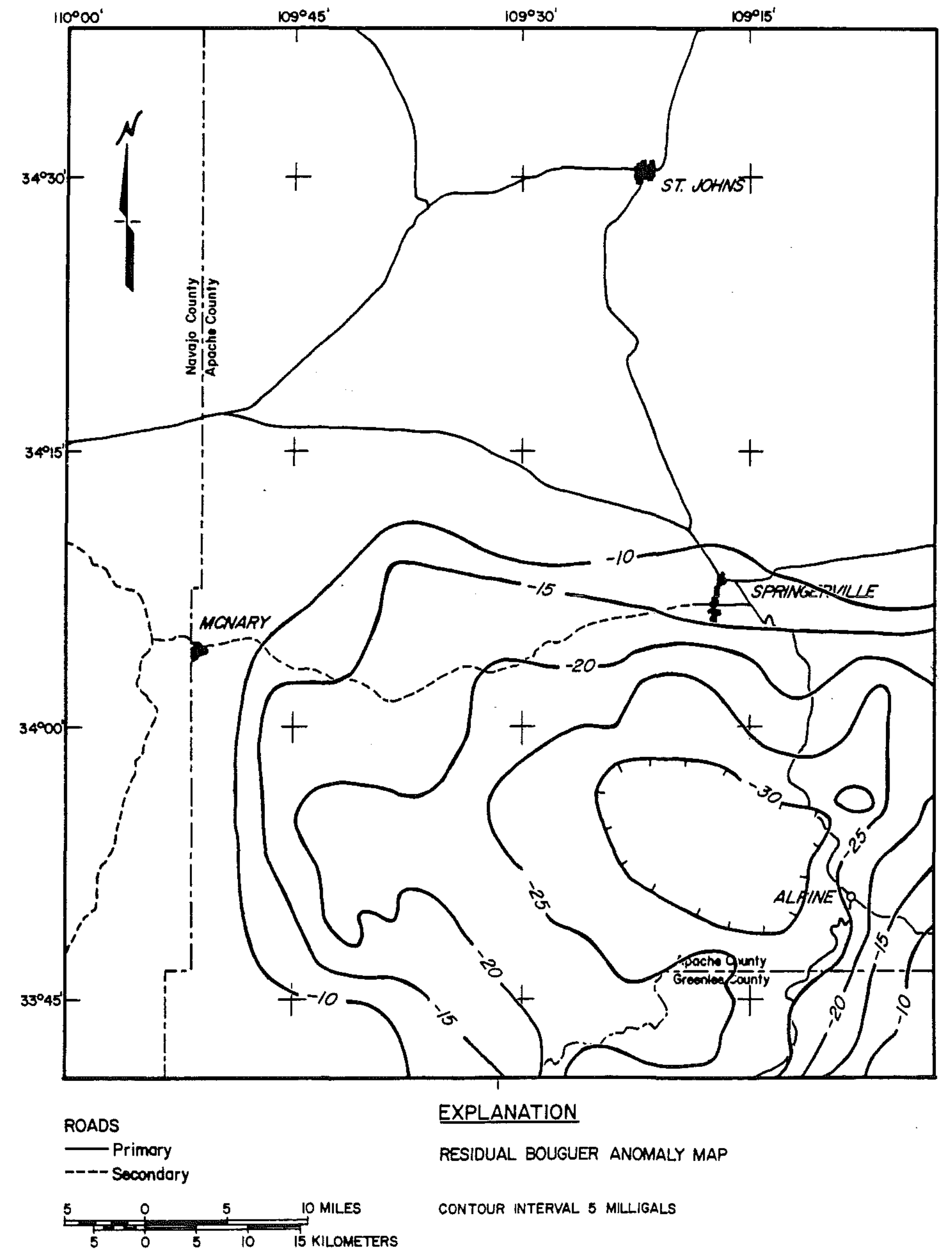

FIGURE 8: Residual bouguer gravity and gravity map. (After Aiken, 1975.)

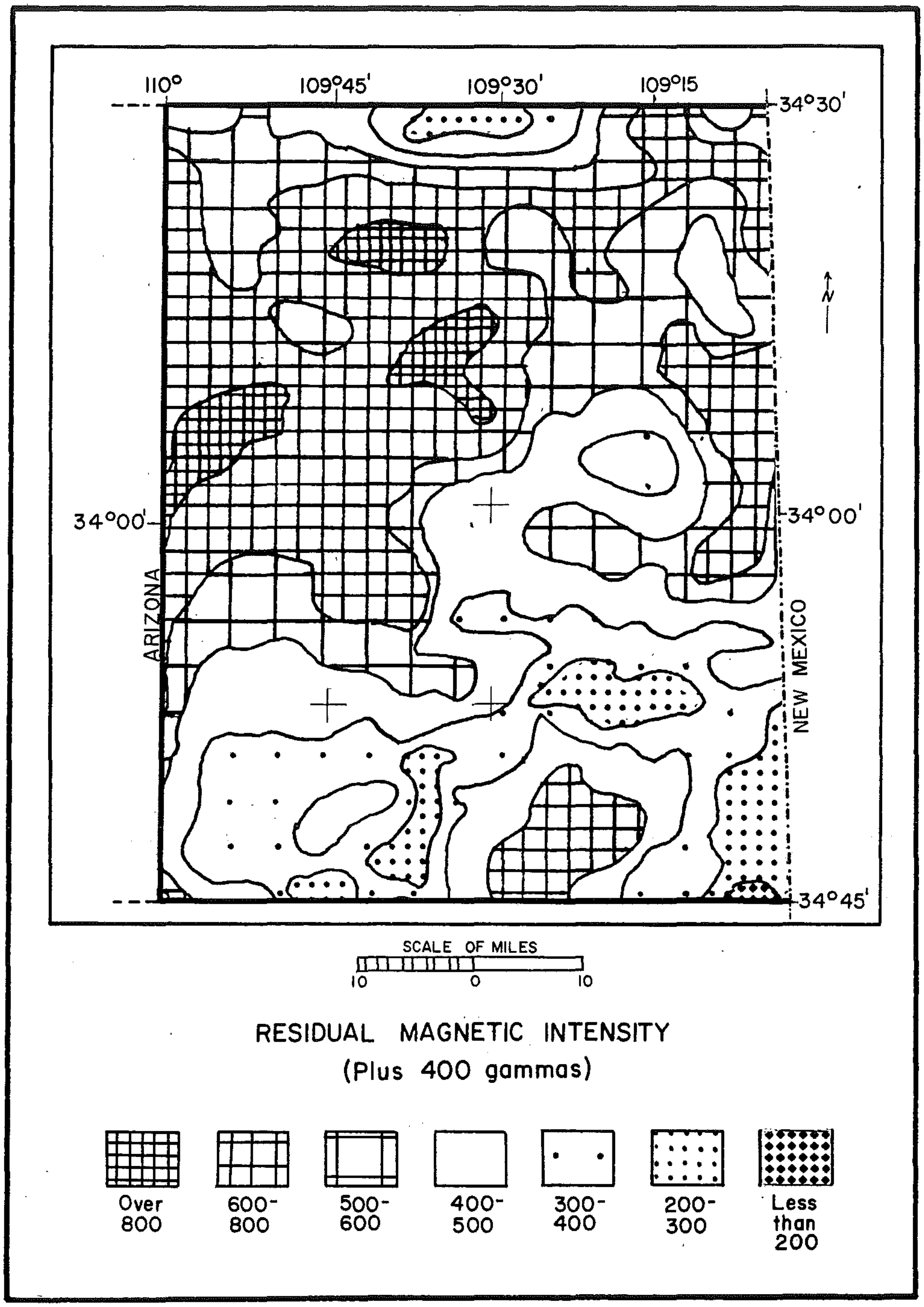

FIGURE 9: Residual aeromagnetic map. (After Sauck and Sumner, 1970.)

Miscellaneous Geophysical Studies - Thompson and Burke (1974) showed a pronounced upper-mantle LVZ (low velocity zone) trending northeast through the study area and interpreted it as thicker LVZ or lower upper-mantle velocity, indicative of a greater degree of partial melting. In another geophysical study, cited by Thompson and Burke, Porath and Gough (1971) estimated variations in depths to the surface of the electrical conductor, inferred to correspond approximately with the 1500^{o}C isotherm. The depths are 190 km under the Basin and Range province and 350 km under the Colorado Plateau. A high ridge occurs beneath the boundary (Transition Zone?) at a depth of only 120 km. A study by Byerly and Stolt (1977) supports the results of Porath and Gough. Byerly and Stolt identified a narrow zone crossing central Arizona where depth to the base of the magnetic crust shallows to about 10 km 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^{o}C in their study.

Geoelectrical and Passive Seismic Surveys - Telluric current, d.c. resitivity, and passive seismic studies funded by the Bureau of Reclamation were conducted in the Springerville Geothermal Project area during the summer of 1978. The passive seismic survey was two weeks duration and results were negative. Results of the geoelectrical studies, presented in Chapter 2, support the possibility of a geothermal anomaly in the project area.

It is recommended that a long-term program be established to continuously monitor passive seismic events in the project area, as two weeks is too short a time to detect possible events. It is further recommended that detailed telluric or magnetotelluric surveys be conducted in the area of the anomaly to map the zone more accurately and to determine the depth to the heat source.

Heat Flow - A single heat flow measurement of 79.7 mWm^{-2} was made from an observation water well north of Springerville. The heat flow was calculated by multiplying the geothermal gradient over each linear section of the temperature profile, which corresponds to changes in lithology, by the appropriate measured rock thermal conductivity. 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) and it falls within the upper limits of heat flow predicted for the area by the silica-content method of Swanberg and Morgan (1978/79).

Additional heat flow measurements were obtained in the Springerville area as a result of heat flow drilling carried out by the Bureau of Reclamation during the summer of 1979. Results of the heat flow drilling, presented in Chapter 3, confirm the existence of anomalous heat flow in the area.

The number of heat flow values is too few, however, to identify the size and exact location of the anomaly. It is recommended that at least ten additional heat flow holes be drilled in the study area and to the east in New Mexico to precisely define the target area.

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

DEPTH RANGE meters	CONDUCTIVITY W/mk	THERMAL GRADIENT $^{o}C/km$	HEAT FLOW mWm^{-2}
160-226	2.48	31.3	77.6
226-338	3.96		
	3.04		
	3.08		
	2.89		
	3.00		
	4.44		
	Mean 3.40 ± .64	24.0	81.6
338-420	5.28		
	5.02		
	5.28		
	Mean 5.19 ± .15	15.4	79.9

Mean Heat Flow - 79.7 mWm^{-2}

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