73 Humboldt Wells
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OPEN-FILE REPORT
GEOLOGY AND GEOTHERMAL POTENTIAL NORTH OF WELLS, NEVADA

by

Paul W. Jewell

November 1982

Work performed under contract DE-AC07-80ID12079

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Salt Lake City, Utah

Prepared for
U.S. Department of Energy
Division of Geothermal Energy

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ABSTRACT

The geology north of Wells, Nevada is dominated by approximately 2150 m of Tertiary lacustrine siltstones and conglomerates. The sediments are cut by a high-angle, range-bounding fault and several associated step faults. Hydrothermal alteration and silicification are associated with the high-angle faults. Two ages of Quaternary sediments locally overlie the Tertiary sediments.

Lithologic and well log analyses define numerous potential aquifers in the Tertiary sediments. The shallowest of these aquifers is overlain by a tuffaceous siltstone which appears to act as an aquitard for hot water moving through the aquifers. Three possible subsurface hydrologic models can be constructed to explain the spatial relationships of the thermal water near Wells.

Cost-effective steps taken to expedite geothermal development in the area might include deepening an existing domestic well in the city of Wells to at least 180 m in order to penetrate the tuffaceous siltstone aquitard, running borehole logs for all existing wells, and conducting a shallow temperature-probe survey in the Tertiary sediments north of Wells.

INTRODUCTION

Recent interest in alternative energy applications has prompted a study of the geology and geothermal resources near Wells, Nevada, a small town of about 1200 people in the northeastern part of the state. Hot springs have been known to exist along the western flank of the Snake Mountains north of Wells for nearly a century (Adams and Bishop, 1884, p. 192). Recent publications discussing these hot springs include Garside and Schilling (1979) and Trexler et al. (1979).

The existence of two warm wells within 1.5 km of the city has come to light only recently. Relatively high temperatures in the Dalton #1 oil test well (113°C at 1220 m) (236°F at 4000 ft) and a shallower domestic well (49°C at 168 m) (120°F at 550 ft) are not mentioned in any previous publication on the geothermal resources of Nevada. They were brought to the attention of the Earth Science Laboratory/University of Utah Research Institute by Mr. Joseph Reynolds, a rancher near Wells and owner of the 168 m domestic well. A study to determine the controls of the entire geothermal system near Wells was undertaken as a part of the Department of Energy's User Assistance Program.

Work on the area proceeded sporadically over a 16-month period. An initial site visit by two ESL staff members was made in mid-March, 1980 to make a reconnaissance examination of the area and meet Mr. Reynolds and the mayor of Wells. During June, 1980, cuttings from the upper 869 m (2850 ft) of the oil test were logged at the Nevada Bureau of Mines and Geology in Reno to help determine the stratigraphy of the area. Later that month, three days were spent mapping the surface geology north of Wells.

GEOLOGY

Northeastern Nevada is a part of the Basin and Range Province, a tectonic regime characterized by relatively thin crust, high heat flow, and high-angle faulting. This portion of Nevada also constitutes a major portion of a conspicuously high heat flow area known as the Battle Mountain high (Sass et al., 1971). Geothermal systems within the Battle Mountain heat flow high are related to deep circulation along faults and are often found to be moderate-temperature (90-150°C) resources (Brook et al., 1979).

The city of Wells lies near the headwaters of the Humboldt River between three Basin and Range fault blocks (Figure 1). Rocks ranging in age from early Paleozoic to Tertiary are found in the Snake Mountains to the north (Garside, 1968; Peterson, 1968), the East Humboldt Range to the southwest, and the Wood Hills-Windermere Hills to the east (Thorman, 1970). A thick sequence of Eocene to Pliocene lacustrine sediments forms aprons around all three ranges. Quaternary alluvium has accumulated along the Humboldt River drainage and in the basins between the ranges.

Tertiary Sediments

Only rocks of Tertiary age and younger are exposed in the area of this study (Figures 2 and 3). The Tertiary section consists largely of siltstones, tuffaceous siltstones, and conglomerates. Tertiary sediments exposed throughout the Great Basin are believed to range in age from Eocene to Pliocene (Van Houten, 1956). The Eocene-Oligocene sedimentary and volcanic rocks near Elko (Solomon et al., 1979) and the Eocene-Pliocene rocks of the Carlin-Pinon Range (Smith and Ketner, 1976) have been dated and mapped in detail. Only reconnaissance stratigraphic work and no age determination have been made of the Tertiary sediments north of Wells (Van Houten, 1956; Garside, 1968; Peterson,

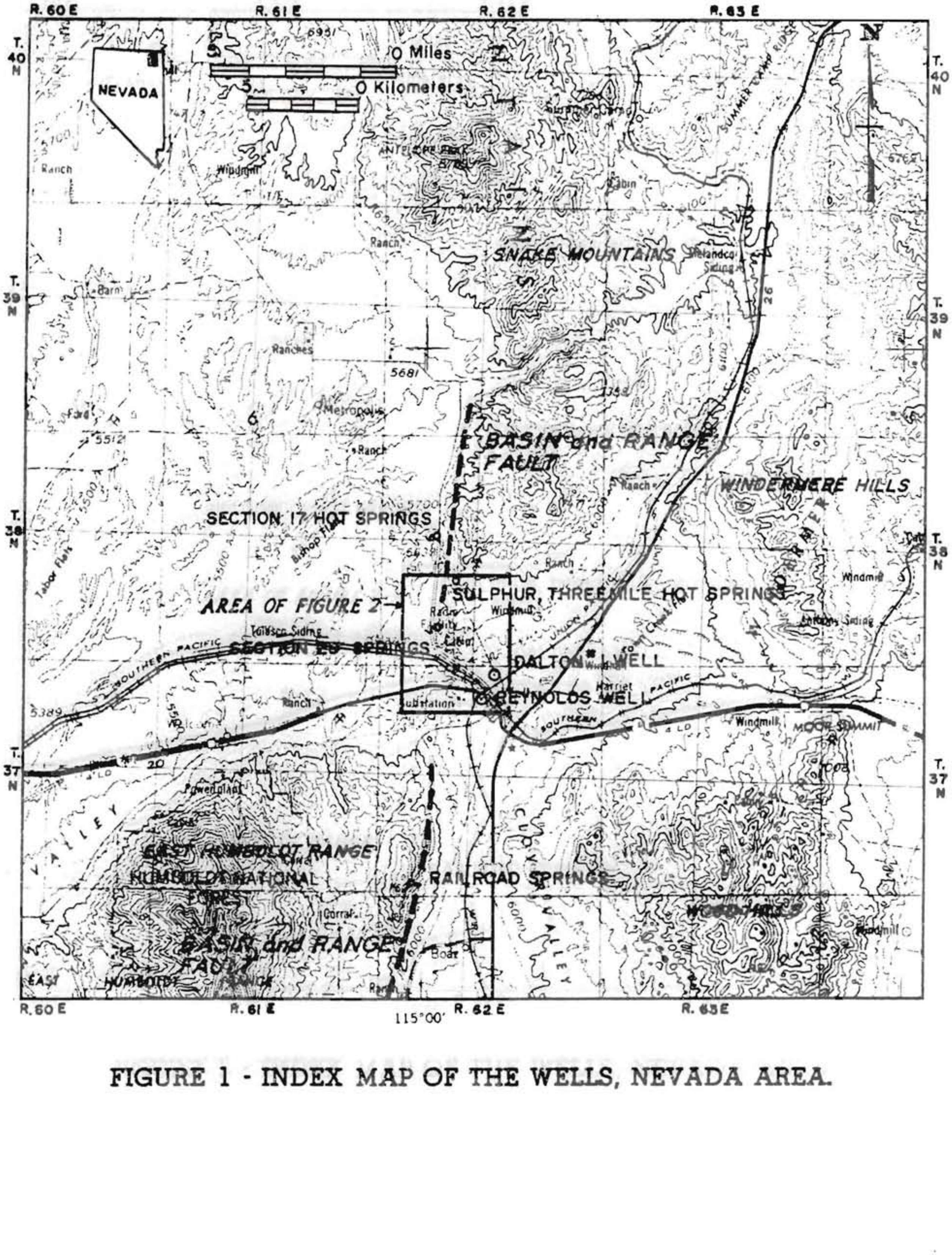

FIGURE 1 - INDEX MAP OF THE WELLS, NEVADA AREA.

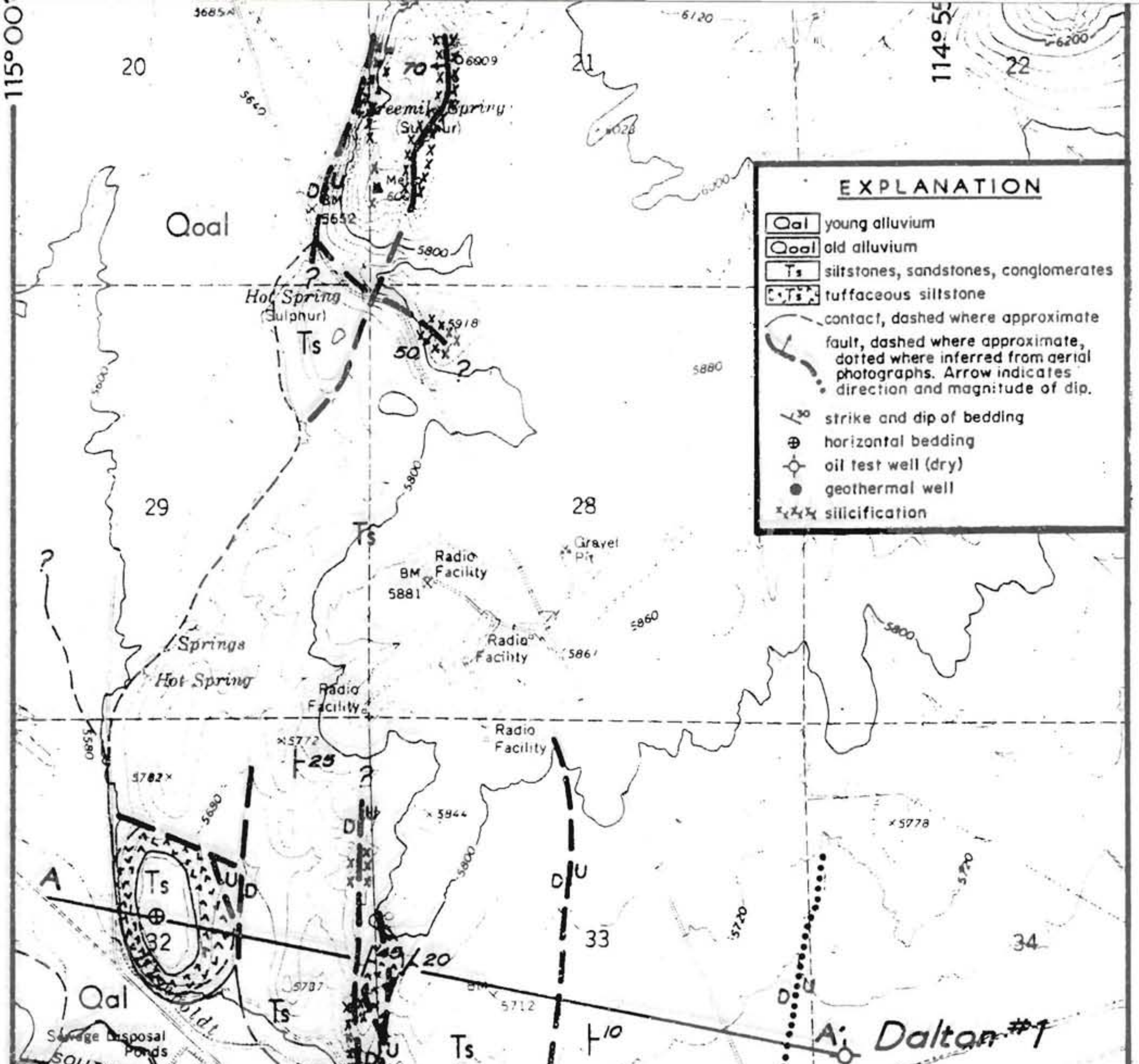

Figure 2. Geologic map of the area north of Wells, Nevada

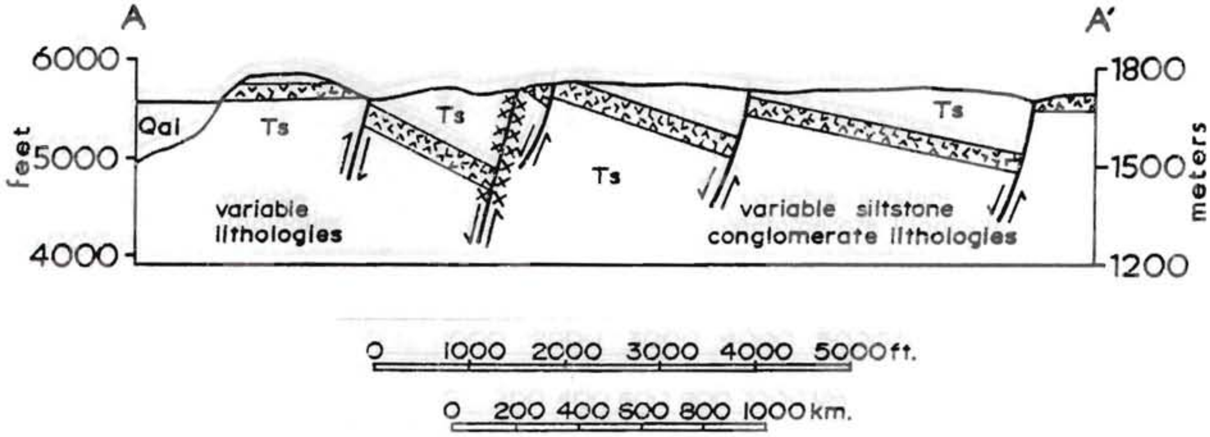

FIGURE 3 - GEOLOGIC CROSS SECTION NORTH OF WELLS, NEVADA.
LOCATION OF SECTION A-A' IS SHOWN IN FIGURE 2.
NO VERTICAL EXAGGERATION.
Symbols and unit designations as on Figure 2.

1968).

High-angle Basin and Range faulting in Sections 9 and 16, T38N, R62E (Figure 1) has exposed 1524 m (5000 ft) of the Tertiary section (Garside, 1968). Only limited portions of this section are exposed in the area of Figure 2. The best outcrops are found in railroad cuts, immediately south of the Humboldt River, where 82 m (270 ft) of the section are continuously exposed. Smaller outcrops are found over a much broader area north of the Humboldt River. No outcrops are found in the portions of Sections 4 and 5, T37N, R62E bounded by the railroad tracks and Interstate 80 (Figure 2).

Mapping for this report emphasized structural relationships rather than textural and lithologic details. Logging of cuttings from the Dalton well provided a rough picture of the overall stratigraphy, textures, and lithologies that could not be deduced by surface mapping. The stratigraphic column and brief descriptions shown on the lithologic log (Plate 1) are a condensation of the data collected.

Lithologies of the Tertiary sediments range from fine-grained siltstones and mudstones to coarse pebble conglomerates. In general, the two end members of this spectrum are dominant with much of the section having a bimodal composition of siltstone and conglomerate. The amount of clasts in the matrix of siltstone ranges from a trace to about 90 percent. Many of the clasts are quartzites and silicified conglomerates -- typical lithologies of the Mississippian-Pennsylvanian Diamond Peak Formation which crops out extensively in the Snake Mountains. A small number of siliceous volcanic clasts are also observed. In outcrop, the clasts are poorly sorted and sub-angular to well-rounded. Size ranges from very fine gravel to coarse pebble gravel (approximately 2-75 mm). The size, sorting and rounding of the clasts are undeterminable in the Dalton well cuttings because of abrasion during drilling and circulation.

The siltstones are generally fine-grained, white to buff, and commonly have a calcareous cement. A darker clay component visible in portions of the section gives the siltstones a fissile character. The siltstone grains are generally sub-angular to rounded, moderately well-sorted quartz and feldspar.

Only the most salient portions of the lithologic log shown on Plate 1 will be discussed. A very important portion of the log is the upper 70 m (230 ft) which consists of 27 m of tuffaceous siltstone overlain by 43 m of clean calcareous siltstone. The tuffaceous siltstone is composed of as much as 20% glass shards. The siltstone is unique to the entire section of the Dalton well and therefore made an excellent marker horizon with which to map the structural relationships shown in Figures 2 and 3. Garside (1968) also describes only one interval of tuffaceous sediment in the Snake Mountains. In his Tertiary stratigraphic section, a 120 m (380 ft) interval of tuffaceous sandstone is overlain by an additional 865 m (2766 ft) of sediment. A generalized comparison of Garside's section and the Dalton well section is shown in Figure 4. If one assumes that the tuffaceous siltstone is an equivalent time-stratigraphic member of the two sections, then an overall thickness of 2125-2185 m (6800-7000 ft) is established for the Tertiary sediments north of Wells. On the other hand, if the tuffaceous sediment in Garside's section and the tuffaceous siltstone found in the area of this study are the result of localized reworking of volcanic material, then correlation between the two stratigraphic sections in Figure 4 cannot be made and the exact thickness of the Tertiary section is unknown.

The remainder of the Dalton well is characterized by thick sections (up

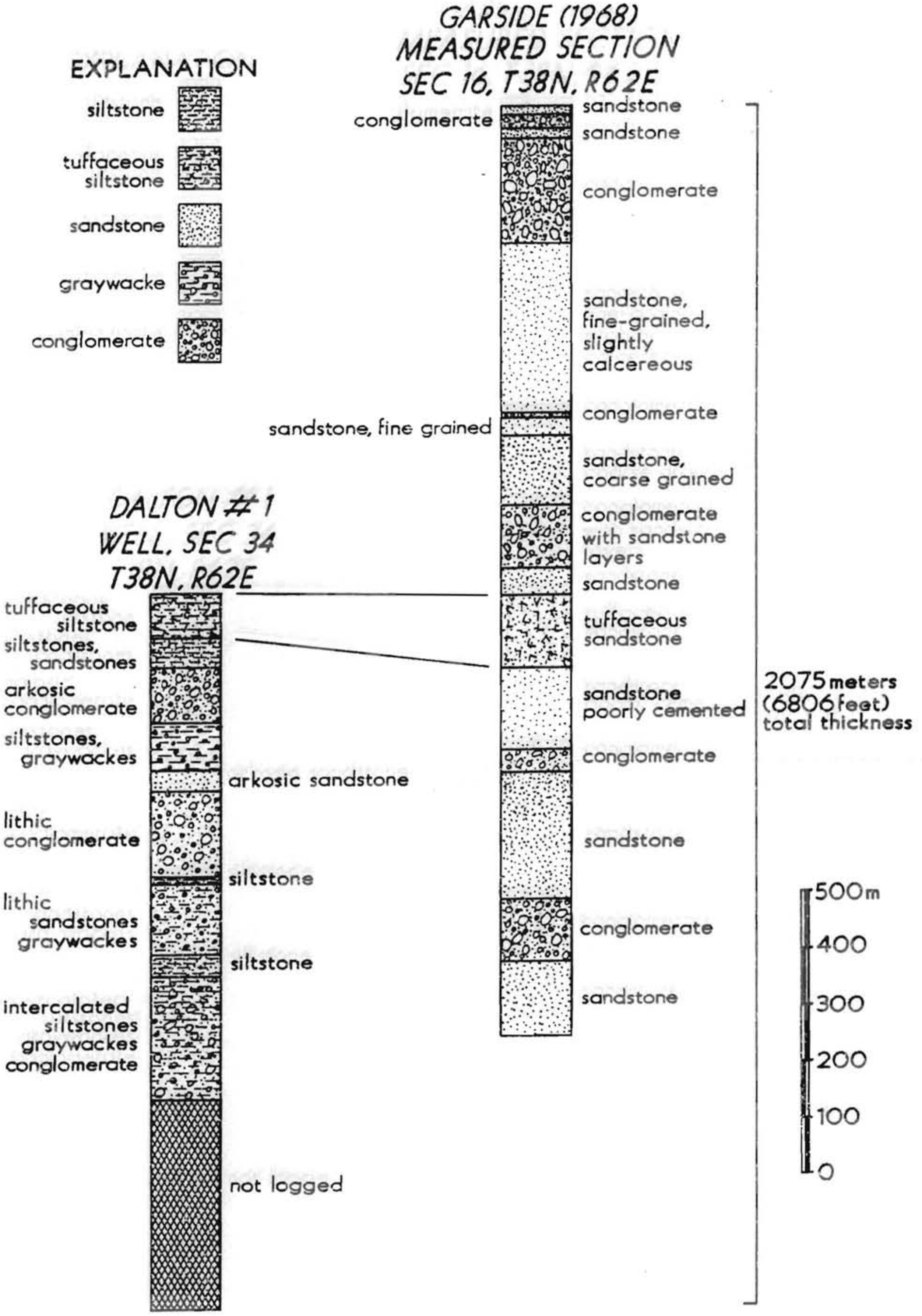

FIGURE 4 - DIAGRAMMATIC CORRELATION OF THE DALTON #1 WELL WITH GARSIDE (1968) MEASURED TERTIARY SECTION.

to 150 m) of loosely consolidated conglomeratic sediment separated by intervals of calcareous siltstones and mudstones and minor graywacke. Two cycles of deposition, each approximately 300 m (984 ft) thick are inferred from the lithologic and gamma ray logs (Plate 1). Each cycle is characterized by increasingly clay-rich, radioactive sediments toward the bottom.

Mapping in the Wells area was not extensive enough to define lateral variations of specific lithologies. Figure 4 suggests that facies change dramatically over a distance of several kilometers. Van Houten (1956) characterizes the Tertiary sediments of northeastern Nevada as having a lacustrine origin, a conclusion that has been substantiated by subsequent workers in the area (e.g., Solomon et al., 1979).

Quaternary Alluvium

Unconsolidated Quaternary sands and gravels are the youngest geologic units in the Wells area (Figure 2). The best exposures were observed in railroad and highway cuts near the Humboldt River drainage. Two Quaternary units are recognized. An older alluvium (Qoal) is mapped along the west side of the Snake Mountains. It is characterized by gentle topography which has been dissected by minor drainages. The alluvium constitutes the valley fill west of the Snake Mountains and as such probably has a considerable thickness. A young Quaternary alluvium (Qal) represents the most recent deposits in the area. It is undissected and largely confined to the low-lying areas of the Humboldt River drainage. Since the Humboldt River is downcutting the Tertiary sediments between the uplifted East Humboldt Range and Snake Mountains fault blocks, alluvium deposited by the river is probably very thin.

Structure

The structure of the rocks north of Wells is dominated by high-angle

Basin and Range faulting. Of particular importance is the western range front fault of the Snake Mountains which manifests itself as highly silicified, parallel faults along the Section 20-21 boundary and the Section 32-33 boundary (Figure 2). Poor exposures and silicification which obscures bedding have made exact determination of the fault traces and the amount of displacement impossible.

The Basin and Range faults mapped in this study appear to control Threemile Hot Springs, Sulphur Hot Springs, and the hot springs in Section 17. The faults are on the trend of the eastern Basin and Range fault of the East Humboldt Range which, in turn, appears to control Railroad Springs (Figure 1). If the two faults are connected at depth, then additional geothermal fluids may exist west of Wells where the fault is poorly exposed or covered by alluvium. Further discussion of this hypothesis is given below.

Geologic mapping for this study revealed a series of step faults that parallel the silicified Basin and Range faults (Figure 2). Step faults in the northeast quarter of Section 32 and the middle of Section 33 are mapped on the basis of linear drainage patterns and changes in the dip of the sediments. Both faults trend N5°E. A third step fault is inferred on the basis of a linear drainage between Sections 33 and 34. The general decrease of the dip of the sediments in each succeeding fault block from west to east and the parallel north-trending nature of the faulting suggest that the step faults are genetically related to the Basin and Range fault to the west. If so, the sediments in the vicinity of the Dalton well are probably flat-lying.

A fault that strikes N66°W is mapped in the northern half of Section 32. Its eastern end terminates against the westernmost step fault. These two faults isolate a small hill capped by horizontal beds of the tuffaceous siltstone marker horizon. Another northwest-trending fault is mapped immediately southeast of Sulphur Hot Springs.

Faults unrelated to Basin and Range tectonics are more difficult to recognize. A major west-northwest-trending, right-lateral strike-slip fault of probable Mesozoic age has been postulated by Thorman and Ketner (1979) to exist near Wells. Named the Wells fault, its existence is inferred on the basis of regional stratigraphic and structural trends. In the Wells area, the course of the Humboldt River matches the hypothesized trend of the Wells fault, suggesting erosion along a zone of pre-existing weakness. The offsetting horst and graben configuration between the Snake Mountains and the East Humboldt Range may also be due to a zone of weakness caused by the Wells fault (C. Thorman, oral communication, 1980) (Figure 1). If the Wells fault exists near the Humboldt River drainage, it may provide a pathway for the geothermal fluids. The exact location of the Wells fault is speculative, however, and its existence has recently been questioned (Stevens, 1981).

An attempt was made to correlate the structure and stratigraphy of the Tertiary sediments north and south of the Humboldt River and thus establish movement of possible post-Tertiary faulting through the Humboldt River drainage. Exposures along a railroad cut in Section 5, T37N, R62E show eastward-dipping sediments cut by numerous westward-dipping faults with small displacements. These are shown as a single fault on Figure 2. Exposures in the railroad cut show 27 m (88 ft) of vitric tuff and tuffaceous siltstone that are on strike with the tuffaceous siltstones north of the Humboldt River. If these units are stratigraphically equivalent, then there has been no appreciable east-west faulting along the Humboldt River drainage since Tertiary time.

Alteration

Varying degrees of alteration of the Tertiary sediments are observed locally along the trend of the Basin and Range faults north of Wells. One form of the alteration is a pervasive green to grayish-green coloration of the siltstones and tuffaceous siltstones. The lack of this coloration in other outcrops of the study area or in the upper portion of the Dalton well indicates that this is alteration rather than a diagenetic or weathering phenomenon. Lithologic distribution of this type of alteration is irregular but appears to be most common in clay-rich sediments.

Silicification of the Tertiary sediments is the most common type of hydrothermal alteration. The general extent of observed silicification is shown in Figure 2. Textural modification ranges from minor additions of silica in the matrix to obliteration of most primary textures. Some of the sedimentary beds have nodular siliceous concretions in a matrix of moderately siliceous siltstone. Other beds have a porcelaneous luster and are brecciated. Fractures in the brecciated beds are commonly healed by secondary, euhedral quartz overgrowths.

As mentioned previously, the silicification is spatially related to the major Basin and Range fault (Figure 2). The most intense silicification is observed along the Section 20-21 boundary, just north of Sulphur Hot Springs. Immediately to the south, less intense silicification is found in conjunction with a northwest-trending fault in Section 28. Hydrothermal alteration found in a north-trending zone along the Section 32-33 boundary is extremely variable, ranging from green siltstones to brecciated porcelanite.

GEOPHYSICAL WELL LOGS

Geophysical well logs can be extremely valuable tools for interpreting subsurface geology. Caliper, density, resistivity, spontaneous potential, and natural gamma ray logs for the Dalton #1 test well were obtained from Rocky Mountain Well Log Service, Denver, Colorado. A temperature log was provided by Mr. Joseph Reynolds. A porosity log was calculated from the density log. All logs were digitized on the Earth Science Laboratory's Prime 400 computer. The resulting printout was drafted and is shown as Plate 1.

Several difficulties were encountered in interpreting and correlating these data. Atlantic International, the company that drilled the Dalton #1 well, has either gone out of business or merged since the well was spudded in late 1973. Therefore, details of the drilling history could not be obtained from a person with firsthand knowledge of the project. Also, there apparently are no available drilling rate, acoustic, or neutron porosity logs, all of which could have aided in the interpretation of the well. A brief discussion of the available well logs follows.

Temperature Log

The temperature log is the most difficult of the logs to interpret for several reasons. First of all, the Dalton well was drilled for oil rather than geothermal fluids. Therefore, upon completion of the well, the borehole temperature was not given sufficient time to equilibrate before the logging was performed. Although not specified, the temperature log was probably run at the same time as all the other well logs, 8-12 hours after final circulation. Several temperature logs run at intervals up to a month or more following circulation are common in geothermal exploration and can aid greatly in interpretation of a potential geothermal reservoir (Glenn and Hulen, 1979).

The temperature log was not run in the upper 55 m (180 ft) of the Dalton well, so the temperature profile in this interval is a matter of speculation. Temperature profiles in the upper portions of other well bores are extremely erratic (e.g., Glenn and Hulen, 1979; Glenn et al., 1980) and often reflect surface temperature and shallow groundwater conditions.

The temperature profile below 55 m seems to represent two subsurface thermal regimes. The interval between 55 and 1067 m (180 and 3500 ft) shows a fairly uniform temperature gradient of 56°C/km (3.1°F/100 ft) with a noticeable temperature increase at 168 m (550 ft). Since the Reynolds well is flowing artesian at approximately the same depth and temperature (49°C) as this portion of the Dalton well, this disturbance probably indicates a hot water entry horizon.

From 1067 m to the bottom of the hole, the temperature gradient is approximately 85°C/km (4.7°F/100 ft.). The reason for this higher gradient is seen in the porosity log which shows variable but generally unporous lithologies in the 1067 m to total depth interval. A decrease in rock porosity causes a corresponding decrease in thermal conductivity which in turn increases the geothermal gradient (Olmsted et al., 1975). Geothermal gradients of 56-85°C/km are considered fairly high for the northern Basin and Range Province, although they are not anomalous for the Battle Mountain heat flow high (C. Smith and D. Nielson, oral communication, 1981).

Caliper Log

Caliper logs show the diameter of a completed well and are valuable in describing the drilling history of a hole, as well as lithology and possible fracture zones (Keys and MacCary, 1971). The caliper log is shown on Plate 1 along with casing diameter and drilling bit size. Between 98 m (the depth of the casing) and 350 m, the irregular caliper log is probably caused by variable lithologies and variations in degrees of sediment consolidation. A large washout indicated between 350 and 448 m (1150 and 1470 ft) reflects a thick interval of poorly consolidated conglomerates. The remainder of the caliper log is relatively uniform and probably indicates that the Tertiary sediments are well-cemented or highly lithified.

Density/Porosity Log

The density log was used to compute the porosity log (Plate 1), according to the equation

$$\phi = (\rho_b - \rho_g)/(\rho_f - \rho_g)$$

where ϕ is the porosity, ρ_b is the bulk density from the density log, ρ_f is the fluid density, and $\rho_g = 2.65$ g/cm^3 (the density of quartz and feldspar) (Glenn and Hulen, 1979). As a result of this equation, the density and porosity logs have a reciprocal pattern.

The density log shows irregular but steadily increasing densities to a depth of about 915 m (3000 ft), indicating increasing sediment compaction and decreasing pore space with depth. Between 915 and 1006 m (3000 and 3300 ft) there is a marked density decrease. The cause of this low-density interval is unknown due to the lack of a lithologic log below 869 m. The 915-1006 m interval also shows anomalously high resistivity and natural gamma values, the interpretations of which are discussed below. Below 1006 m the porosity values locally approach zero. Porosity below 1006 m is variable, but often approaches zero.

Resistivity Log

Two resistivity curves obtained from a Dresser Atlas Induction Electrolog are shown on Plate 1. The traces are from the 16" normal spacing (solid line) and the 40" induction resistivity spacing (dashed line). No correction has been made for temperature, although a rigorous, quantitative analysis requires that this be done (Keys and MacCary, 1971). A qualitative examination of the log reveals several features. Resistivity is irregular in the upper 350 m of the hole and may indicate variable lithologies and amounts of water within the strata. Resistivity is generally low from 350 to 884 m (1150 to 2900 ft), with locally high resistivity, high porosity zones at 534 m (1750 ft), 625-655 m (2050-2150 ft) and 777-835 m (2550-2750 ft). A thick, porous zone between 915 and 1006 m (3000 and 3300 ft) is highly resistive. Below 1006 m, the resistivity log is variable and probably reflects diverse, impermeable lithologies. Throughout much of the resistivity log, there is an inverse relationship between resistivity and porosity, indicating that the porous sedimentary rocks contain appreciable amounts of water (Key and MacCary, 1971).

Spontaneous Potential (SP) Log

The SP log shown in Plate 1 is from the same Induction-Electrolog as the resistivity log. Assuming that the formation water is more saline than the mud used to drill the hole, then SP deflections to the left represent impermeable shale while deflections to the right represent permeable sandstones and conglomerates. A shale base line is drawn on Plate 1 to allow qualitative interpretations to be made; the exact value of the shale line has no particular significance (Schlumberger, 1972). The SP curve shows very little character in the upper 945 m (3100 ft) of the hole. Between 945-1006 m (3100-3300 ft) there is a pronounced shift towards the shale line. This interval corresponds to a zone of high porosity and resistivity which was mentioned above. Combined interpretation of the density, resistivity, and SP logs suggests that the 945-1006 m interval is a porous, but not necessarily permeable, shale horizon. Below 1006 m there is a gradual but pronounced shift towards the shale line. This seems to be further confirmation that the 1006 m to total depth interval of the hole is composed of compacted, nonporous sediments.

Natural Gamma Ray Log

A natural gamma ray log measures varying amounts of radiation from uranium, thorium, and potassium in the rock. In sedimentary rocks such as those of the Dalton #1 well, a higher radiation response would be expected from strata containing volcanic ash, organic material, or certain types of clay minerals. The gamma log on Plate 1 shows relatively good correlation with the geologic log. The tuffaceous sedimentary horizon mentioned previously shows as an anomaly of about 90 API units. Between 78 and 350 m (250 and 1150 ft) there is a steady increase in gamma ray values. At 350 m, a sharp drop-off seems to correspond to a zone of loosely consolidated conglomerate seen in the geologic log and the large washout observed in the caliper log. The 350 m depth also marks the end of the first depositional cycle of the Tertiary sediments which was discussed above. The gamma ray log shows steadily increasing but highly irregular values from 350 to 1006 m (1150-3300 ft). The 945-1006 m interval is the most radioactive of the entire hole (average values of 200 API units). Below 1000 m radiation values drop sharply, indicating the bottom of the second depositional cycle.

Summary

The Dalton well logs reflect the nature of the Tertiary sediments and their bearing on the geothermal potential of the Wells area. A hot-water entry zone is hypothesized at 168 m (550 ft) depth. The porous, unlithified nature of the sediments between 168 and 350 m (550-1150 ft) does not preclude the possibility of a number of hot or cold water entry points which were not significant enough to individually register on the temperature log but which do show up as resistivity lows. A very thick, porous zone of conglomerate between 350-448 m (1150-1470 ft) appears to have little bearing on the geothermal system. Sediments between 448 and 1006 m are porous but well-cemented and probably contribute only minor amounts of fluid to the system. Sediments below 1006 m are non-porous, non-transmissive strata which show a higher conductive temperature gradient than the rest of the hole.

GEOTHERMAL RESOURCES

Surface Manifestations

As mentioned previously, the Reynolds geothermal well and the anomalously warm Dalton oil test well constitute the known geothermal manifestations in the immediate vicinity of Wells. In addition, several shallow cold water wells have been drilled closer to the city center (Figure 5). The depths, bottom hole temperature, and static water level (if known) are given in Table 1.

A number of warm springs are found along the western flank of the Snake Mountains in T38N, R62E (Figure 1). From north to south these are the hot springs in the northwest corner of Section 17 (hereafter referred to as Section 17 Hot Springs), Threemile Hot Springs in the northeast corner of the southeast corner of Section 20, and the hot springs in the extreme southeast corner of Section 20 (hereafter referred to as Sulphur Hot Springs). Hot springs are shown in the southeast quarter of Section 29 on U.S. Geological Survey topographic maps, although only cold water springs were found at this location by the author. Railroad Springs along the east flank of the East Humboldt Range (not to be confused with Railroad well in the town of Wells)

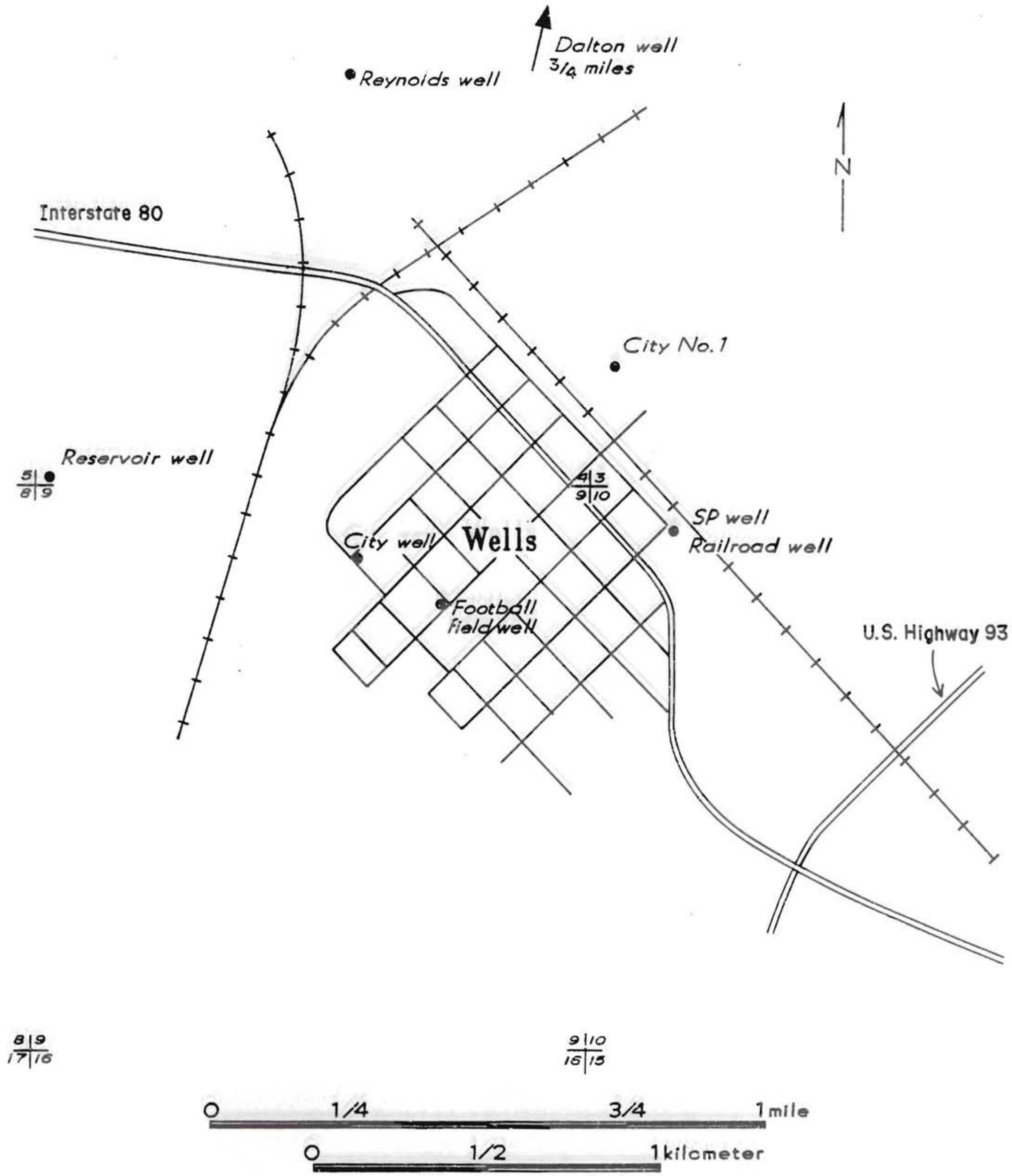

FIGURE 5 - Location of shallow water wells in and around Wells Nevada (T37N, R62E)

TABLE 1. Data for wells in the Wells, Nevada area.

Name	Elevation m (ft)	Depth m (ft)	Bottom temp. °C (°F)	Static level (below surface collar) m (ft)	Static level (true elevation m (ft)
Reynolds Well	1710 (5610)	168 (550)	49 (120)	Flowing artesian	Flowing artesian
Dalton well	1725 (5660)	1282 (4205)	113 (236)	2 (?) (6)	1723 (5654)
Section 34 shallow well	1718 (5635)	79 (260)	"cold"	2 (6)	1716 (5629)
Railroad well (SP well)	1714 (5622)	62 (202)	---	8 (25)	1706 (5597)
Football field well	1718 (5636)	105 (343)	"warm"	7 (22)	1711 (5614)
Reservoir well	1744 (5722)	111 (365)	14 (58)	35 (115)	1709 (5607)

are reported to be warm (Oesterling, 1960). A brief field check revealed only cold water at this location. Temperatures, flow rates, and water chemistry measurements are presented in Table 2 for all of these springs and the Reynolds well.

Warm water is reported from a mineral exploration hole drilled in Tertiary sediments along the west flank of the Snake Mountains north of the Section 17 Hot Springs. Due to the proprietary nature of the hole, its exact location and temperature are unknown. This area was not mapped by the author, so the lithology, porosity, alteration and structure of the rock associated with the warm water were not determined. However this report of warm water suggests that thermal fluids may be common in the uplifted fault block of the Snake Mountains.

Chemistry

The chemical analyses of Table 2 are plotted on the Piper diagram of Figure 6. The Piper plot seems to roughly define a thermal and nonthermal field with the thermal water characteristically having a higher (Na+K)/(Ca+Mg) ratio than the nonthermal water. The chemical analysis of the Reynolds well lies between the thermal and nonthermal values and suggests that this water has both thermal and nonthermal components.

Geothermometers were calculated for the Reynolds well and all hot springs with published chemical analyses (Table 3). As with all geothermometry calculations, it is assumed that chemical equilibration was achieved between water and wallrock at depth, that there was an adequate supply of reactants, and that there was no reequilibration during ascent of the hot water (Fournier et al., 1974). Note that although mixing has been hypothesized for thermal water in the Reynolds well, silica geothermometers from the Reynolds well are

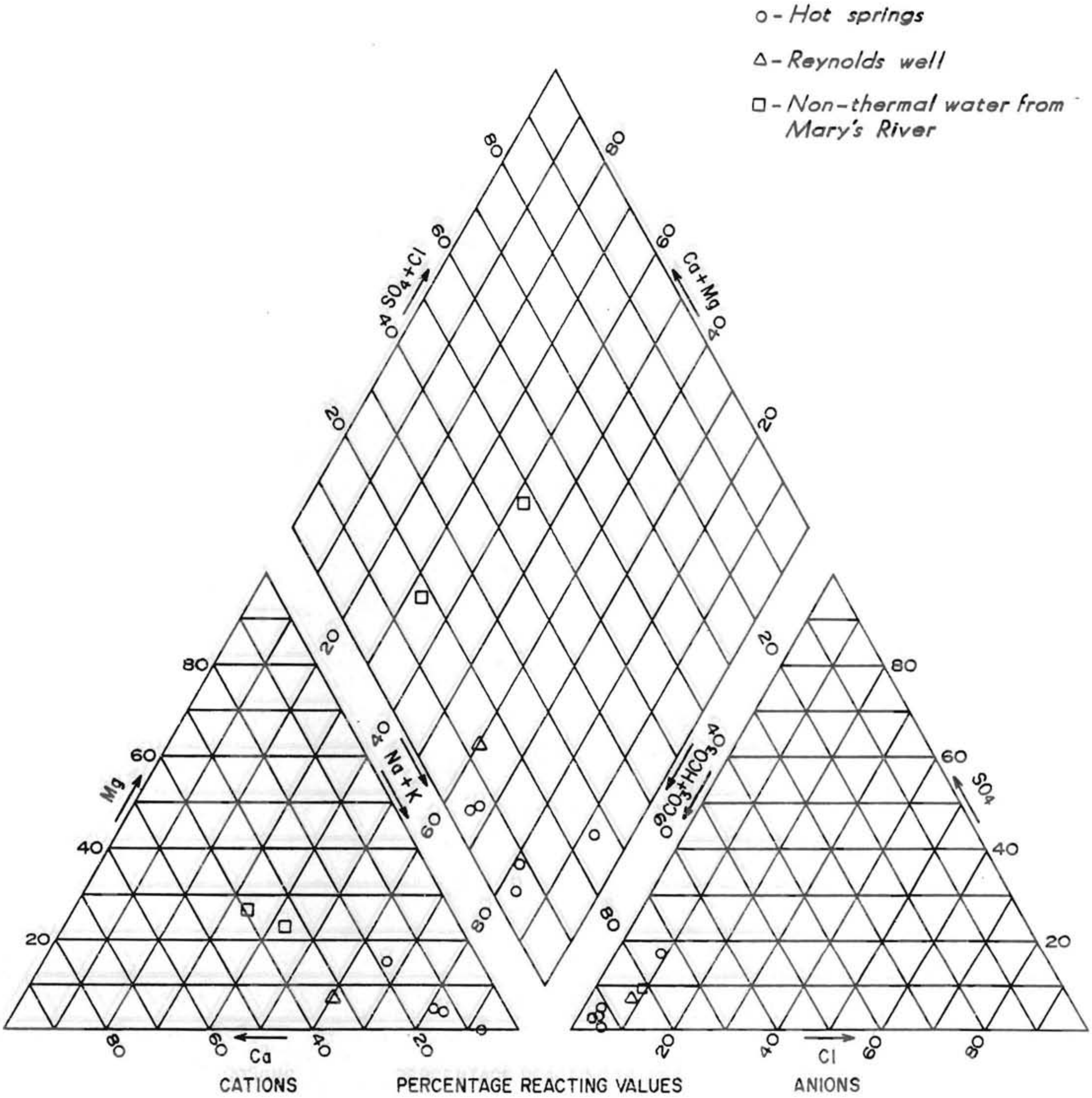

FIGURE 6 - PIPER PLOT OF THERMAL AND NON-THERMAL WATERS IN THE WELLS, NEVADA AREA.

TABLE 2. Chemistry of the thermal water near Wells, Nevada.

Name	Temp. °C	(°F)	Flow Rate l/m	(gpm)	SiO_2 ppm	Na ppm	K ppm	Ca ppm	Mg ppm	HCO_3 ppm	SO_4 ppm	Cl ppm	TDS ppm	Reference
Reynolds Well	49	(120)			88	58	20	33	5	259	20	16	270	ESL analysis (see Appendix A)
Sulphur Hot Springs (SE Sec. 20)	60	(140)			110	300	30	78	36	1210	24	26		Garside and Schilling (1979)
	50	(122)			165	160	16	12	0.3	345	61	22		
3-mile Hot Springs (SE Sec. 20)	36	(97)	189	(50)	76	340	36	51	13	1150	29	34		GEOTHERM
	46	(115)	4	(1)										Garside and Schilling (1979)
Sec. 17 Hot Springs	50	(122)	38	(10)										
	55	(131)	57	(15)	86	370	46	48	13	1230	12	37		Garside and Shilling (1979)
	61	(142)			105	300	31	75	37	1135	32	27		
12-mile Hot Springs, Sec. 27 T37N, R62E	39	(102)	3028	(800)										Garside and Schilling (1979)
Railroad Springs					18	27	6	48	15	234	27	21	239	ESL analysis
Spring, Sec. 29	15	(60)			19	384	6	7	6	1040	13	39	1172	ESL analysis
Water from irrigation well (Sec. 25)	Cold				53	34	9	36	16	234	20	17	342	ESL analysis
Humboldt wells (Sec. T27N, R62E)	Cold				46	93	12	68	30		55	136	708	ESL analysis

TABLE 3. Geothermometers of the thermal water near Wells, Nevada. Given as °C (°F).

Name	Surface Temp.	Chalcedony	Quartz (conductive)	Quartz (adiabatic)	Na-K-Ca	Na-K-Ca (Mg corr.)
Reynolds well	49 (120)	103 (217)	130 (266)	127 (260)	228 (442)	137 (279)
Sulphur Hot Springs (Sec. 20 T38N, R62E)	60 (140) 50 (122)	116 (241) 144 (291)	143 (289) 162 (324)	137 (279) 158 (316)	178 (352) 184 (363)	41 (106) 184 (363)
3-mile Hot Springs (Sec. 20)	37 (97)	94 (202)	122 (252)	120 (248)	187 (369)	92 (198)
Sec. 17 Hot Springs	55 (131) 61 (142)	101 (214) 114 (237)	129 (264) 140 (284)	126 (258) 135 (275)	199 (390) 181 (358)	100 (212) 40 (104)

in good agreement with those of the hot springs. All Na-K-Ca geothermometers are variable, particularly when the Mg correction is calculated. The reason for this variability is unknown and beyond the scope of this study.

Using an average value of a specific geothermometer from the nearby hot springs (see Table 3), and assuming that the geothermal gradients determined for the Dalton well apply throughout the area, calculations can be made concerning possible depth of circulation of the thermal water near Wells. The chalcedony or Na-K-Ca geothermometers are the most appropriate for calculations in moderate-temperature (<150°C) geothermal systems (Fournier, 1973; Fournier and Truesdell, 1973). However, the wide range of values for the Mg-corrected Na-K-Ca geothermometer precludes its use. Assuming that initial water temperature equaled mean annual surface temperature (7.2°C), the depth of circulation is approximately 1.7 km as calculated from an average of the chalcedony geothermometers of Threemile and Sulphur Hot Springs, the nearest surface thermal waters. This is somewhat shallower than the 2-6 km considered typical of Basin and Range geothermal systems (Olmsted et al., 1975, p. 51).

Hydrology and Hydrothermal Models

The central question concerning the geothermal resources north of Wells is whether the hot springs along the western edge of the Snake Mountains are related hydrologically to the warm wells immediately north of the city or whether the hot springs and wells are separate hydrothermal systems. Answers to this question would help define the depth and extent of geothermal exploration targets in the Wells area. Figures 7, 8, and 9 portray possible subsurface hydrothermal regimes. It must be emphasized that these three models are not mutually exclusive. A combination of features from any of them

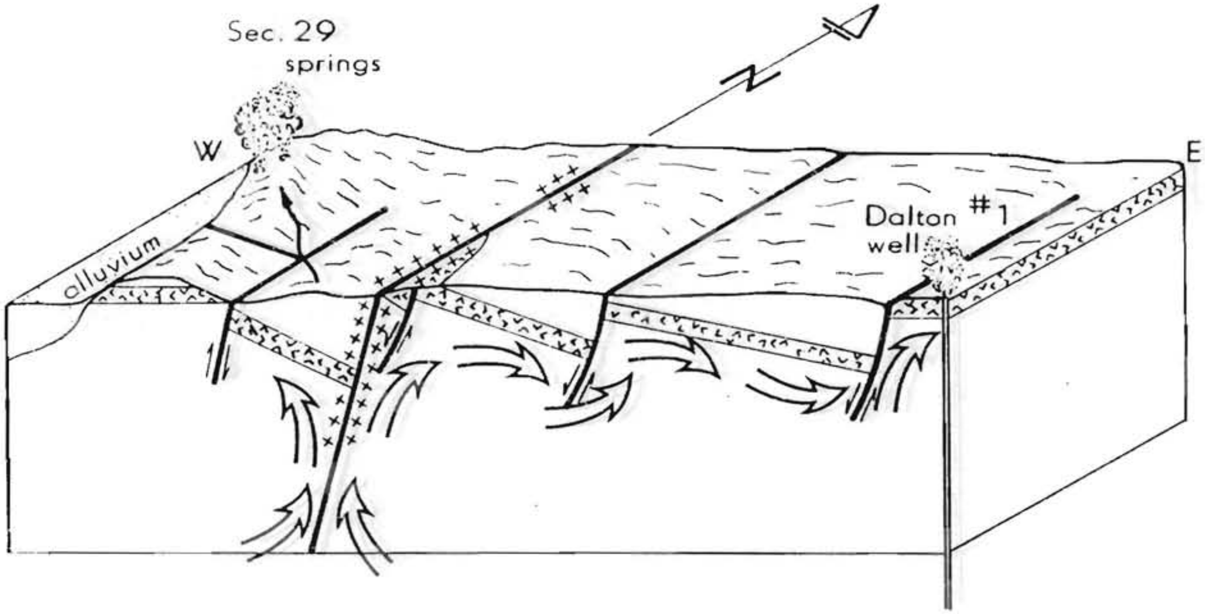

Figure 7. Subsurface model in which thermal water rises along a Basin and Range fault and migrates laterally beneath a confining aquitard. Symbols and unit designations as in Figure 2.

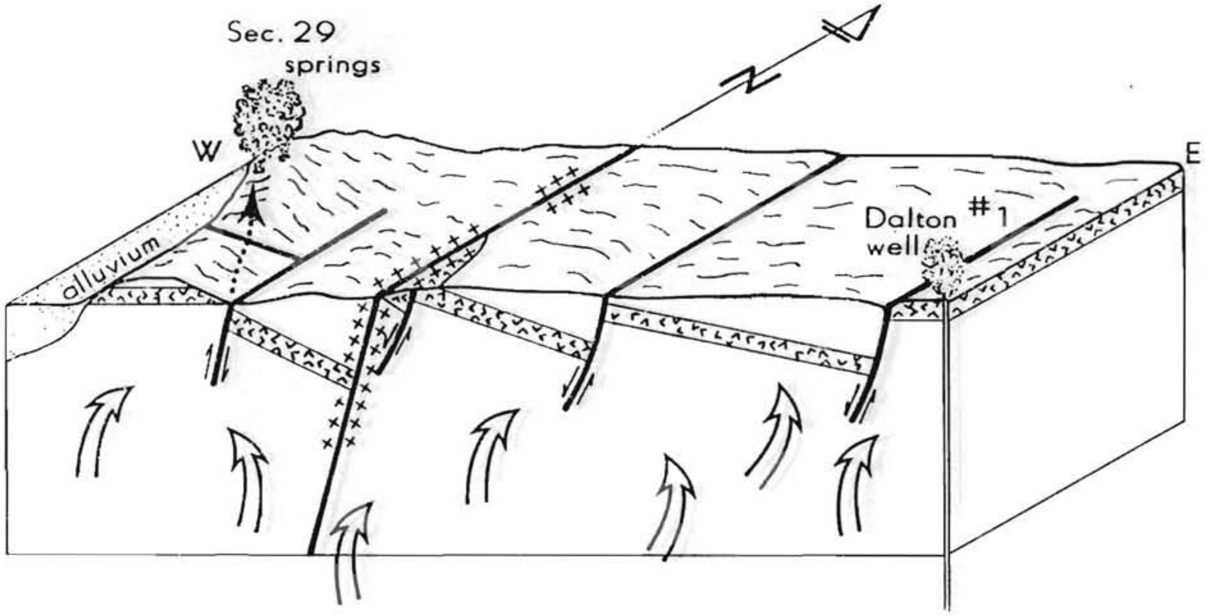

Figure 8. Subsurface model in which thermal water rises vertically throughout the Tertiary sediments. Symbols and unit designations as in Figure 2.

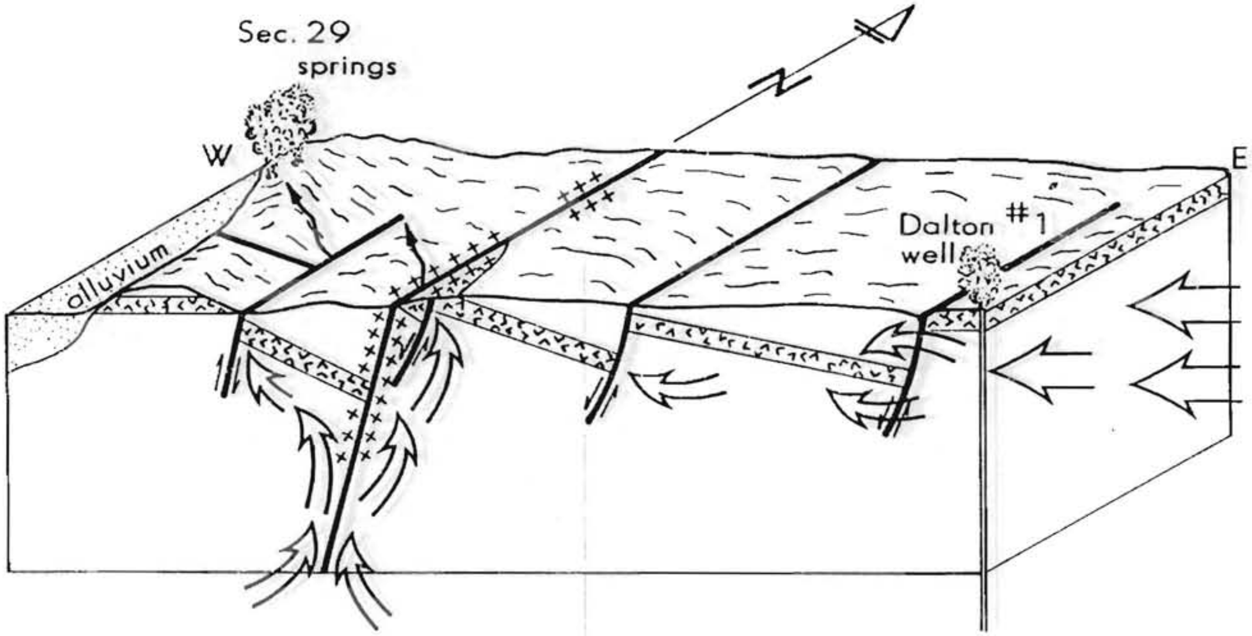

Figure 9. Subsurface model in wich separate sources are hypothesized for the thermal water. Hot springs are controlled by a Basin and Range fault. Water in the Dalton and Reynolds wells comes from an unknown source to the east. Symbols and unit designations as in Figure 2.

might be possible.

In Figure 7 hot water is hypothesized to rise up the Basin and Range fault after being heated at a depth of approximately 1.7 km. This Basin and Range fault exhibits hydrothermal alteration and an undetermined amount of displacement. (The amount shown in Figure 7 is speculative). Cooling of the hydrothermal fluids in the upper portion of the fault has resulted in silica deposition and formation of a relatively impermeable zone. Upon encountering this relatively impermeable zone, the water is forced to migrate laterally. A possible path for migration would be a porous conglomerate aquifer immediately beneath the zone of hydrothermal alteration. The tuffaceous siltstone which overlies these conglomerates is believed to form an aquitard which prevents the thermal water from escaping to the surface.

The thermal water migrates through fault blocks to the east and west (Figure 7). Although displacement along each step fault is estimated to be about 150 m (492 ft), the large thicknesses and abundance of the conglomerates relative to less permeable sediments permit the water to be transmitted between fault blocks. The thermal water that travels to the east moves down dip through successive fault blocks, contrary to the shallow, east-to-west flowing ground water regime of the Humboldt River. On the other hand, the thermal water that travels to the west moves up dip, parallel to the shallow ground water regime. The result is a stronger hydraulic head for the geothermal water moving west than for the water moving east. The variable hydraulic head may explain the lack of hot springs east of the Basin and Range fault.

A second hydrothermal model (Figure 8) shows thermal water rising from depth throughout the area north of Wells. The movement of the water is not structurally controlled. Instead, the generally unporous lithologies of the Tertiary sediments allow vertical transmission of the thermal water. The tuffaceous siltstone horizon acts as aquiclude and prevents much of the hot water from reaching the surface.

The third hydrothermal model presumes that thermal water for the hot springs and the two wells were derived from separate sources (Figure 9). Hot springs are derived from thermal water flowing up the Basin and Range fault (Figure 2). Thermal water from the Dalton and Reynolds wells originates from an eastern source which has no known surface manifestations. Note that in this model, circulation of the thermal water conforms to the shallow ground water gradient of the Humboldt River.

Legitimate objections can be raised to each of these models. The first model implies that the thermal water flows in a director opposite to the shallow ground water. The second model requires that the hot water move vertically through diverse lithologies, some of which (particularly those below 1060 m) are non-permeable siltstones. The third model is weak because the nearest hot springs to the east of Wells are located 40 km (25 miles) away (Trexler et al., 1979) in a different hydrologic basin (Eakin and Lamke, 1966). All three models suggest the possibility of warm water circulation in the step faults. That no hot springs are seen along these faults is due to the fact that the upper portions of these structures are found in the uplifted Snake Mountains fault block where they are above the potentiometric surface.

Another hydrologic enigma is the general absence of warm water in and around the town of Wells (Table 1, Figure 5). Two possible explanations are offered. First, the deepest of the domestic wells in the town is 111 m (364 ft), nearly 57 m (187 ft) above the postulated hot water entry zone in the

Reynolds and Dalton wells. A deeper well within the city limits might show the presence of warmer water. Secondly, the town is closer to the foothills of the East Humboldt Range and farther away from the hypothesized Basin and Range fault than is the Reynolds property. Runoff from the East Humboldt Range, therefore, makes the ratio of cold water to hot water higher at Wells than at the Reynolds property.

Suggested Exploration Techniques

Several geothermal exploration techniques could be applied to locate additional geothermal resources or to test the subsurface models hypothesized in the previous discussion. The specific methods applied would depend on the exploration budget and the nature of the geothermal target.

Possibly the most cost-effective technique would be temperature profiling of the existing wells. A temperature profile of the Reynolds well would be very helpful in defining the source of the geothermal water, provided the flowing artesian well could be shut in and allowed to achieve thermal equilibrium. If the Dalton well has not caved, then a new temperature log would make an interesting and cost-effective companion to the temperature log shown in Plate 1. Temperature profiles of the shallow wells in Wells might also be valuable in evaluating the thermal ground water regime near the city.

An additional extremely viable exploration technique is a temperature survey using shallow, narrow diameter boreholes. Similar surveys have been used in other geothermal areas of Nevada and the western United States. Excellent accounts of the advantages and limitations of this technique are given by Olmsted (1977) and Murphy and Gwynn (1979).

Systematics of a shallow borehole survey are relatively straightforward. A narrow-diameter hole is drilled to predetermined depth and PVC pipe is inserted, capped, filled with water, and allowed to equilibrate thermally. A temperature probe is then run down the PVC pipe. The depth to which the holes are drilled depends upon the type of geology of the target area and the hypothesized temperature of the geothermal resource. In general, shallow bore surveys are most effective where the underlying thermal anomaly is large and the perturbing influence of shallow ground water is small. Reasonably good results have been obtained from surveys as shallow as 1 meter, although deeper surveys generally give better results (Olmsted, 1977). The technique might be very useful for defining the presence of a thermal anomaly below the silicified zone mapped between Sections 32 and 33 (Figure 2) or for any exploration in the foothills of the East Humboldt Range. Caution should be used in applying it near the Reynolds well since the Humboldt River probably dominates the ground water regime in the Quaternary alluvium and therefore masks any thermal anomaly.

Additional geophysical methods could be brought to bear on the Wells geothermal resource although their use in this type of geologic setting is somewhat restricted. Resistivity surveys are sometimes useful in recognizing subsurface aquifers or stream channels. A good account of a case history involving the successful application of the technique is given in Zohdy et al. (1974). Gravity surveys are also popular in geothermal exploration, but their use is largely restricted to delineating hidden faults. The technique might be useful in the Wells area where the trace of the Basin and Range fault is marked by a density contrast such as would be observed between Quaternary alluvium and the Tertiary sediments.

An active seismic survey was completed prior to drilling the Dalton #1 hole. Such surveys can sometimes be used to delineate deep subsurface faults. It is possible to obtain these seismic data, although it is questionable whether benefits would justify the quoted cost of $8400/line-mile.

SUMMARY AND RECOMMENDATIONS

The Wells geothermal system resembles many Basin and Range systems. It is controlled by a major high-angle fault, located in an area of high heat flow, and has geothermometer temperatures which indicate a moderate-temperature (90-150°C) resource at depth. It differs from other geothermal systems in that some of the resource may be moving in the opposite direction of the prevailing hydraulic gradient and the calculated depth of fluid circulation is only 1.7 km.

The following steps (not necessarily given in order of importance) may better define the resource:

1) Deepen an existing well within the Wells city limits or drill a new well to a depth of 180-240 m (590-787 ft). This would establish whether or not the 168 m hot water entry horizon hypothesized in the Reynolds and Dalton wells extends to the south.

2) Run a suite of temperature, electric, and neutron logs on all existing wells, warm and cold, in the Wells area.

3) If exploration on a wider scale appears justifiable, a shallow probe temperature survey aimed at defining the major Basin and Range fault might be a cost-effective exploration technique.

ACKNOWLEDGEMENTS

Several co-workers at the Earth Science Laboratory made valuable comments and suggestions during the course of this study. I particularly wish to acknowledge the help and fresh ideas provided by Debbie Struhsacker, Christian Smith, and Duncan Foley. Additional constructive comments were offered by Ted Glenn and Dennis Trexler. Analytical work on water samples was done by Ruth Kroneman. Patrick Daubner drafted the figures. Georgia Mitoff and Holly Baker typed the manuscript and its revisions. Personnel from petroleum and mining companies working in the Wells area contributed ideas and some data. The conclusions and speculations presented in this report are strictly those of the author, however.

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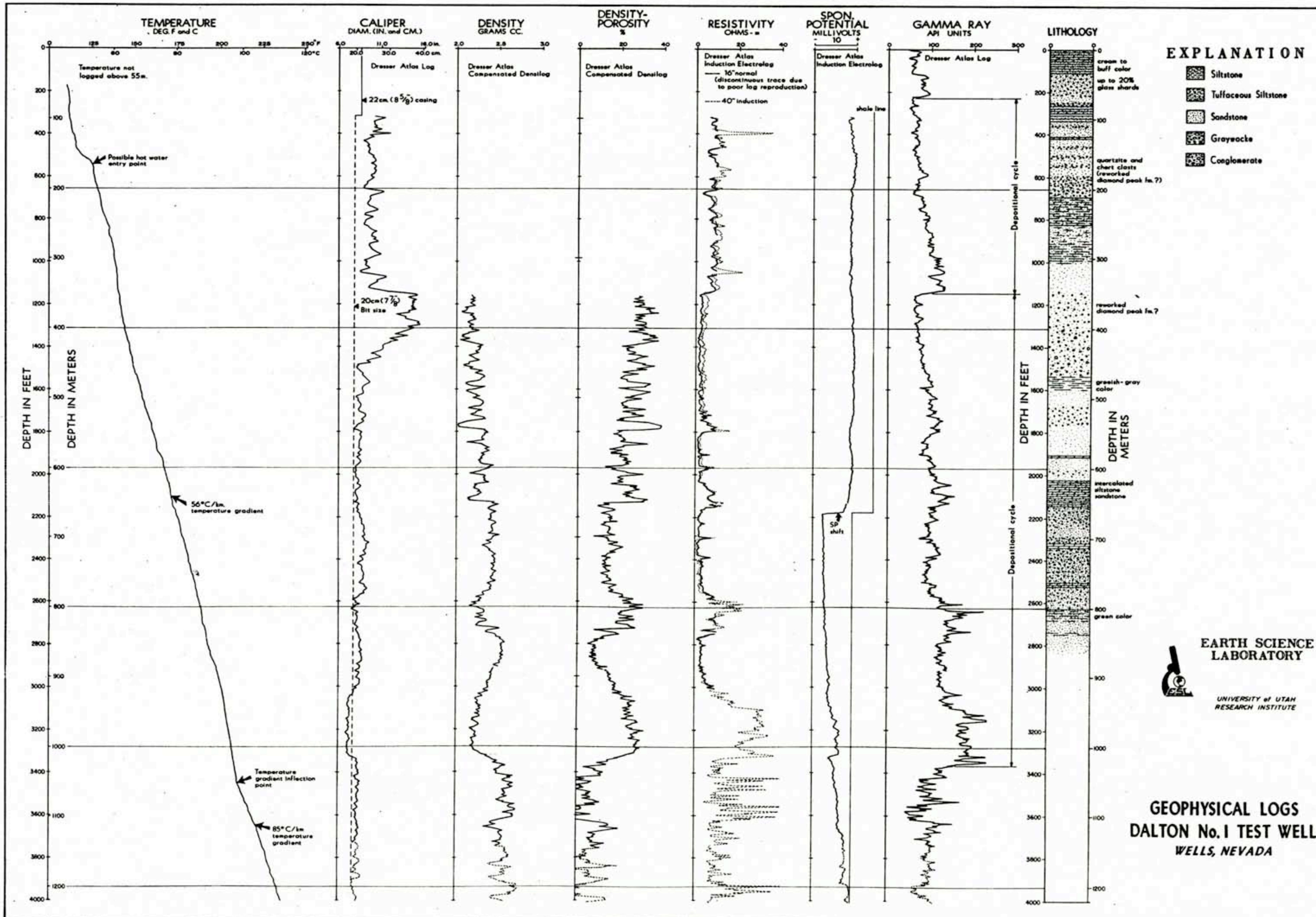
Appendix A. Major and trace element chemical analysis of water from the Reynolds well, Wells, Nevada.

103 NV-WIS-1

ELEMENT	CONCENTRATION (PPM)
NA	58
K	20
CA	33
MG	5
FE	< 0.025
AL	< 0.625
SI	41
TI	< 0.125
P	< 0.625
SR	0.31
BA	< 0.625
V	< 1.25
CR	< 0.050
MN	< 0.250
CO	< 0.025
NI	< 0.125
CU	< 0.125
MO	< 1.25
PB	< 0.250
ZN	< 0.125
CD	< 0.125
AG	< 0.050
AU	< 0.100
AS	< 0.625
SB	< 0.750
BI	< 2.50
U	< 6.25
TE	< 1.25
SN	< 0.125
W	< 0.250
LI	< 0.050
BE	< 0.005
B	0.1
ZR	< 0.125
LA	< 0.125
CE	< 0.250
TH	< 3.75
TDS	270
Cl^-	16
F^-	0.8
$So_4^=$	20



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GEOPHYSICAL LOGS
DALTON No. 1 TEST WELL
WELLS, NEVADA