An evaluation of exploration methods for low-temperature geothermal systems in the Artesian City area, Idaho

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ABSTRACT

Numerous wells and a few springs around the perimeter of the Rock Creek Hills (South Hills) south of Artesian City, Idaho, produce water as warm as 49 °C. Warm-water samples throughout the study area share similar chemical characteristics, suggesting a common source of recharge and similar flow systems. Precipitation in the Rock Creek Hills probably infiltrates to depths in excess of 650 m along numerous normal faults and within permeable horizons of the Idavada Volcanics. Underlying Paleozoic rocks are relatively impermeable, except where fractured by recent tectonism, and probably direct the infiltrating ground water toward the lowland of the Snake River Plain. The volcanics have buried a Miocene topographic high that at present separates the warm ground water into two flow systems. Heavy pumping at the edge of the Snake River Plain at present captures the warm-water flow at depth and encourages the infiltration of irrigation water through the Quaternary alluvium and basalt flows of the plain into the underlying Idavada Volcanics.

Several common geotechnical methods proved effective for the reconnaissance exploration of this low-temperature hydrothermal system. Measured temperatures of well and spring water located areas appropriate for study. The measurement of ground-water levels and hydrothermal gradients as defined herein enable the characterization of the warm-water flow systems and the identification of zones of warm-water production. A geochemical survey distinguishes waters with unique chemistries and recharge areas. Reconnaissance geologic mapping and drillers'-log interpretation identify the stratigraphic and structural framework controlling the flow systems.

INTRODUCTION

This study is a multidisciplinary effort to evaluate reconnaissance exploration techniques for use in the search for low-temperature geothermal systems. The report describes the results of several geotechnical methods employed to characterize the warm-water flow systems in the vicinity of Artesian City, Twin Falls and Cassia Counties, Idaho (Fig. 1). The discussion focuses on the suitability of those methods for reconnaissance exploration purposes. The selection of methods for low-temperature geothermal exploration is economically constrained by the low potential return on investment from such resources, thereby eliminating from consideration herein a number of techniques commonly used in the exploration for high-temperature geothermal systems. Because we have restricted our study to those techniques appropriate for reconnaissance exploration, the methods must meet the time constraints of this phase of exploration. The models resulting from this preliminary work should be of sufficient detail to discriminate the best targets for the low-temperature geothermal systems and to aid in the selection of detailed studies to delineate a productive system. The availability of a considerable geochemical, hydrologic, and geologic data base in the public domain made the Artesian City study area a suitable place in which to test several exploration techniques.

Numerous wells and a few springs around the perimeter of the Rock Creek Hills (South Hills) south of Artesian City produce water as warm as 49 °C. The area of warm water extends from Oakley on the southeast, northwestward to Twin Falls, and to Nat-Soo-Pah Warm Spring on the southwest (Fig. 1). Three ranges of ground-water temperature were determined empirically (Fig. 2): "cold" water below 20 °C, "mid-range" water between 20 and 28 °C, and "warm" water above 28 °C. These local definitions of "cold," "mid-range," and "warm" appear appropriate for the study area and are not implied to be necessarily applicable elsewhere.

The study area is restricted to Townships 11 to 13 South and Ranges 18 to 21 East and includes the lower drainages of McMullen, Rock, Dry, Buckhorn, and Cottonwood Creeks on the northern and northeastern flanks of the Rock Creek Hills (Fig. 1). A portion of the Snake River Plain occupies the northern and eastern parts of the study area. The occurrence of warm ground water around the base of the Rock Creek Hills suggests structural and stratigraphic controls of the hydrothermal system.

Previous studies of the ground water in the Artesian City area include those by West (1956), Mundorff and others (1964), and Crosthwaite (1969a). Many of the wells reported in Crosthwaite (1969a) and West (1956) have been either abandoned or deepened; their data could be used to document declines in water levels due to pumpage for irrigation, a topic not addressed in this geothermal study.

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***Note:* Tables 2 through 5 of this article are retained in the GSA Data Bank (no. 83-1). Copies may be secured free of charge by request.**

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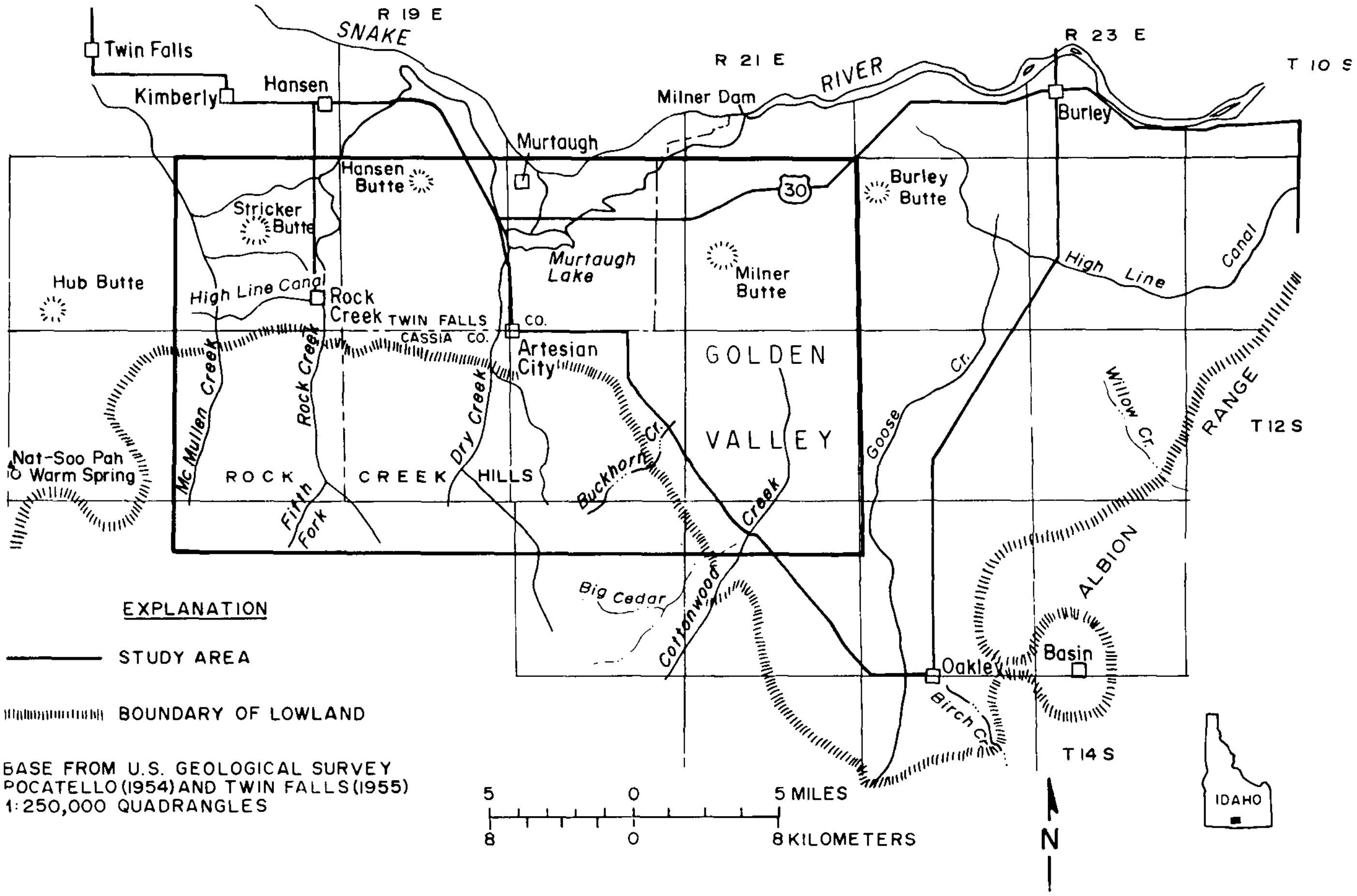

Figure 1. Location map of the Artesian City study area.

West (1956) and Crosthwaite (1969a) developed a conceptual model for the recharge and discharge of warm and cold waters in the study area. This work refines their model. Reconnaissance geologic mapping reveals the major structures and the stratigraphy affecting ground-water flow within the study area. Ground-water level and temperature data identify aquifer systems and areas where warm water can be produced. Chemical analyses of water samples from wells and springs suggest that the Rock Creek Hills are the recharge area for the warm water. The study develops an exploration strategy for low-temperature geothermal systems like the one around the northern perimeter of the Rock Creek Hills.

METHODS

Published geologic information has indicated a need for more detailed geologic mapping to distinguish deep-seated fracture systems and permeable stratigraphic horizons that might control recharge to and discharge from the system. The mapping effort at a scale of 1:20,000 focused on the Rock Creek Hills, although the examination of photo linears and fault trends extended into the lowlands. Geologic mapping in the lowlands is that of Crosthwaite (1969a) and Rembert and Bennett (1979) with minor modifications. The map included in this report is a simplification of the existing and new data at a scale of 1:100,000 (Fig. 3). Due to the abundance of good vertical exposures, the aerial photographs were used extensively to map resistant horizons in the Idavada Volcanics and to construct cross sections (Fig. 4). Well logs, obtained from the Idaho Department of Water Resources (IDWR, Open-file), provided valuable information about the stratigraphy and faults encountered in wells drilled in the lowland area. The logs permitted the construction of a contour map of the top of Idavada Volcanics concealed beneath the Quaternary cover of the lowlands (Fig. 5). Because all of the wells lie south of the Boise baseline and east of the Boise meridian, the well locations have been abbreviated to the form 12.20.1.bdd from 12S-20E-1bdd. Table 1 summarizes our observations of the lithologic and hydrologic character of the rock units and incorporates the earlier studies of West (1956), Crosthwaite (1969a), and Mundorff and others (1964).

The hydrologic field work consisted of visiting nearly every accessible water well, measuring water temperatures and levels if

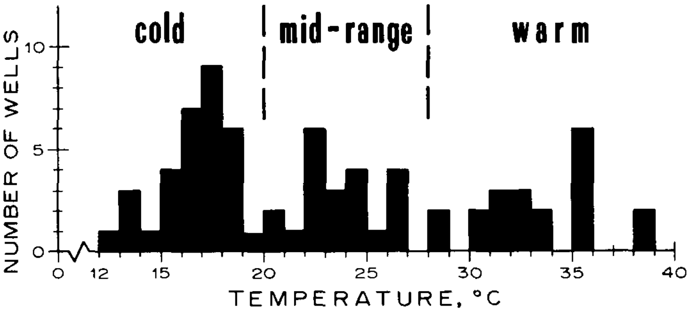

Figure 2. Histogram of measured well-water temperatures.

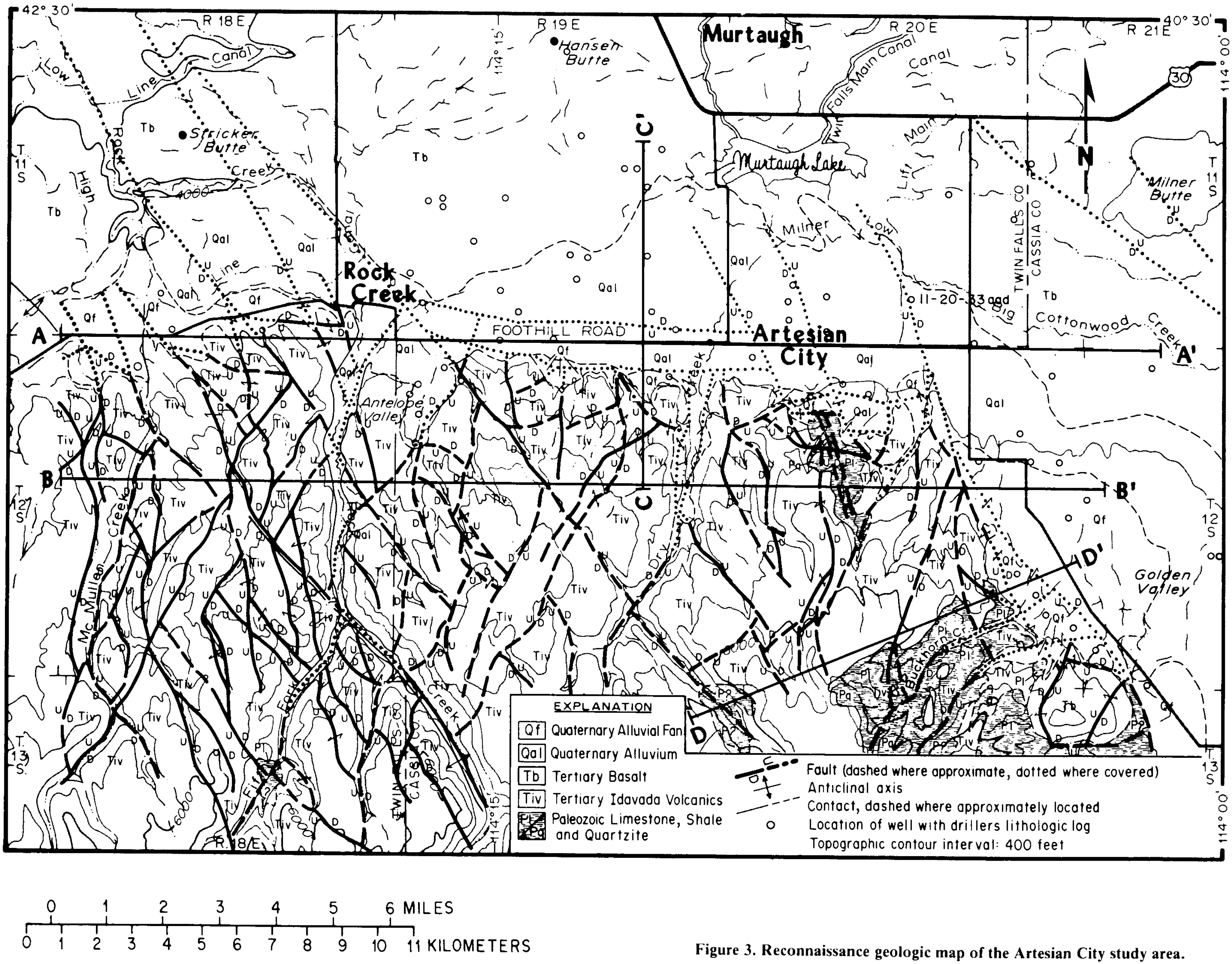

Figure 3. Reconnaissance geologic map of the Artesian City study area.

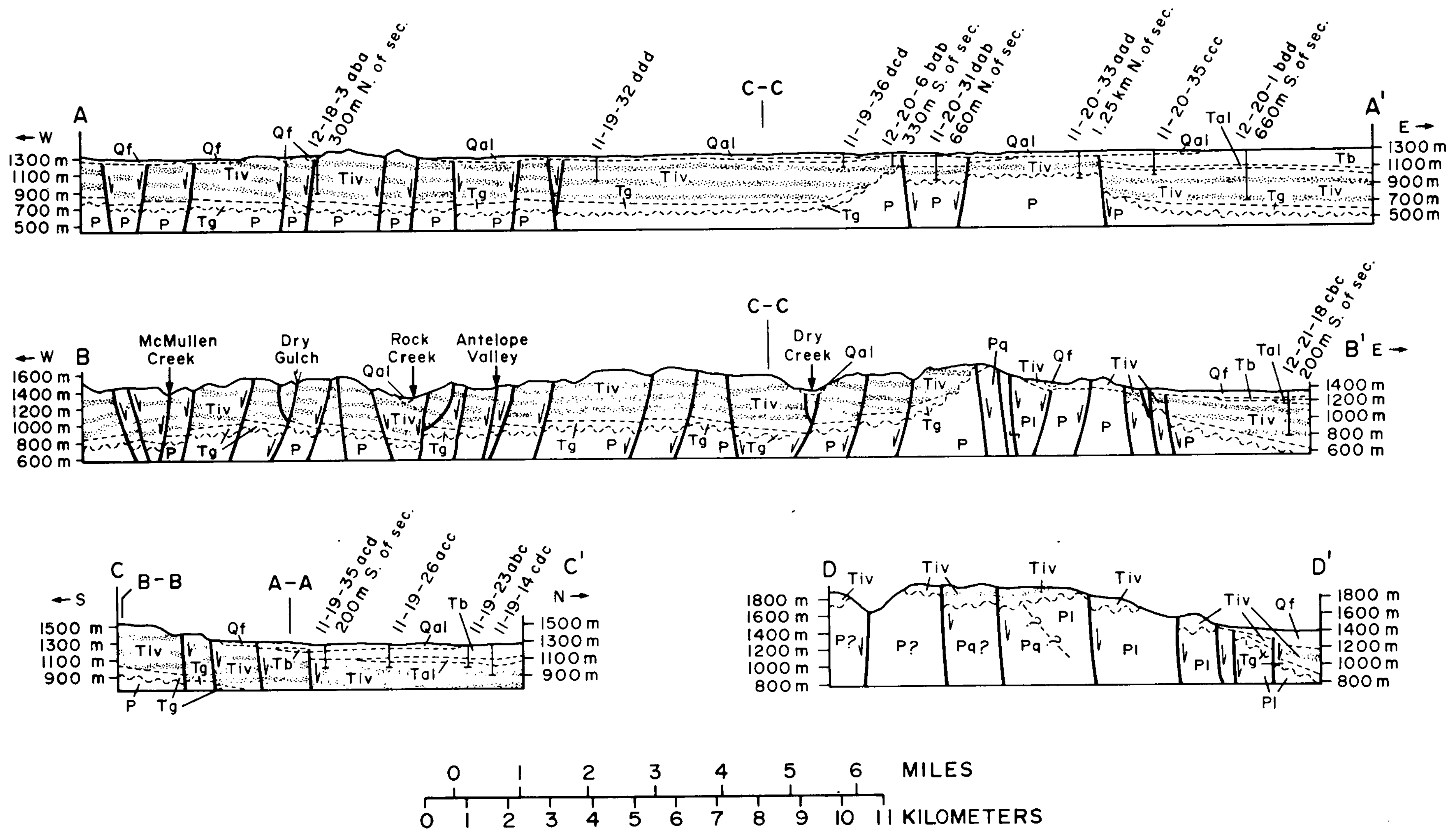

Figure 4. A. East-west cross section of the lowlands along Foothill (2900 North) Road. B: East-west cross section of the Rock Creek Hills symbols as in Figure 3 except for stippling of major tuffaceous sedimentary horizons (not used where surface control lacking). Tg (Miocene gravel observed mainly in drill records), and Tal (Pliocene-Quaternary alluvium). Locations of cross sections shown on Figure 3. C: North-south cross section of the northern margin of the Rock Creek Hills west of Dry Creek. D: Cross section of the northeast margin of the Rock Creek Hills at Buckhorn Canyon.

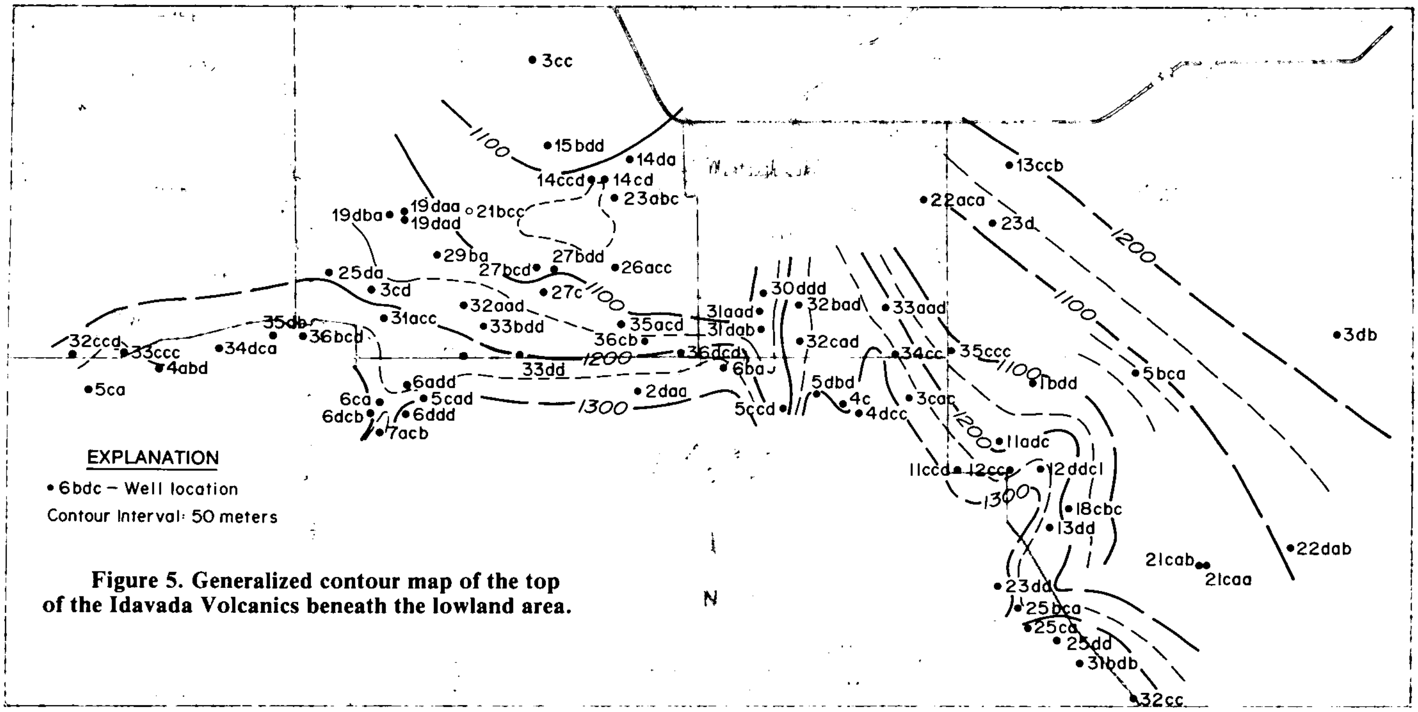

Figure 5. Generalized contour map of the top of the Idavada Volcanics beneath the lowland area.

TABLE 1. LITHOLOGIC AND WATER-BEARING CHARACTERISTICS OF GEOLOGIC UNITS

Period	Epoch	Rock units	Thickness	Lithologic characteristics	Water-bearing characteristics
Quaternary	Holocene and Pleistocene	Alluvium	0-90+	Alluvium and windblown deposits (loess). Clay, silt, sand, and gravel form unconsolidated to well-compacted, lensoid horizons.	Sand and gravel beds yield small to moderate supplies of water to wells under water-table and perched-aquifer conditions. Hydraulically connected with underlying basaltic rocks.
	Pleistocene? and Pliocene	Basalt (locally called lava) of the Snake River Group	0-180+	Olivine basalt flowsare light to dark gray and porphyritic to aphanitic. Plagioclase and olivine phenocrysts are common in most flows. Some flows contain small intergranular, diktytaxitic and abundant vesicles of varying size. The flows range from less than three to several tens of metres thick and display blocky to crude columnar jointing. Horizons of cinders and blocky rubble with clay lenses are commonly interbedded with the flows.	Heterogeneous but generally transmissive basalt yields small to large quantities of unconfined cold and mid-range temperature water. Flow contacts, rubble zones, joints, caverns, and scoriaceous horizons are best water producers. Interbedded sediments yield small quantities of water.
Tertiary	Pliocene	Alluvium	0-105+	Stream and lake deposits of clay, silt, sand, and gravel lying beneath and interbedded with the Quaternary basalt.	
	Pliocene and Miocene	Idavada Volcanics (locally called rhyolite)	400+	Welded ash-flow tuffs with interbedded sediments. The ash flows are generally rhyolitic in composition (Williams, 1981) and contain sparse to abundant phenocrysts of plagioclase, sanidine, clinopyroxene, and rare olivine. Magnetite is the common accessory mineral. Resorbed quartz phenocrysts distinguish the interval (Fig. 3) between elevations of 1,555 to 1,645 m. Simple cooling units range from 10 to 20 m in thickness. They usually include the resistant densely welded to partly welded interior and the more easily weathered nonwelded base, vitrophyre, and upper nonwelded horizons. Compound cooling units exceeding 30 m in thickness contain several densely to partly welded horizons which form the major cliffs in the canyons. These horizons contain vertical joints spaced at 0.3 to 1 m intervals with irregularly developed zones of horizontal joints parallel to the eutaxitic structure. Pumice clasts are often flattened and leave large cavities upon weathering. Lithic fragments are common in many horizons. The prominent densely welded horizons appear to extend continuously throughout the Rock Creek Hills.	The rhyolitic rocks produce small to large quantities of warm water from joints, fractures, and vitrophyre horizons in welded tuffs and flows. Fine-grained sedimentary and nonwelded ash-flow form leaky confining beds that sustain weak artesian pressure within the more transmissive welded units.

possible, and interviewing residents and well owners. Unless noted otherwise in Table 2[1], water levels were measured in August and September 1980, using a steel tape lowered into wells that were not pumping. Surface elevations were inferred from U.S. Geological Survey topographic maps to the nearest 1.5 m. Producing intervals were obtained from drillers' logs. Water temperatures from pumping wells were measured with mercury thermometers. Water samples for chemical analyses were collected from selected pumping wells.

The bulk of the downhole information presented in Table 2 was gathered from drillers' logs filed at the Idaho Department of Water Resources, from well schedules of observation wells, and from preliminary results of the Snake River Plain Regional Aquifer System Assessment Program of the U.S. Geological Survey, Water Resources Division. Plat sheets in the Twin Falls and Cassia Counties Tax Assessors' offices provided information on the geographical distribution of land ownership.

Water levels (Fig. 6) and temperatures (Fig. 7) are the basic hydrologic data in a low-temperature geothermal area. They provide information about the direction of ground-water flow and the areas of production of warm water. Hydrologic data for selected wells in the Artesian City area are included in Table 2; the locations of these wells are shown in Figs. 6 and 7. However, at Artesian City, where there are abundant well data, the map of water temperature may be supplemented by a map of the "hydrothermal gradient," defined herein as the ratio of produced water temperature to the depth from which it is produced (Fig. 8). The hydrothermal gradient is computed with the formula

$$HG = \frac{T - Ta}{\frac{t - b}{2}} \times 1{,}000 \qquad (1)$$

where HG = Hydrothermal gradient (°C/km)

T = Produced water temperature (°C)

TABLE 1. (*Continued*)

Period	Epoch	Rock units	Thickness	Lithologic characteristics	Water-bearing characteristics
				Three lava flow-like sequences occur in the section depicted in Figure 3. They display prominent flow banding and lack pyroclastic textures. Strong platy jointing has developed parallel to the flow banding and is broken by thin vertical joints spaced at 0.1- to 1-m intervals. Williams (1981) interprets these to be densely welded ashflow tuffs that were subjected to secondary flowage tuffs that were subjected to secondary flowage upon deposition. Four widespread sedimentary horizons occur within the volcanic pile. The sediments contain lenses of clay, sand, and gravel with thin interbeds of nonwelded ash-flow and air-fall tuffs. The thickest sedimentary horizon in the Rock Creek section is about 45 m thick, but the thicknesses of this and other horizons vary considerably throughout the study area. The soft sedimentary horizons form distinct breaks in the steep slopes of the canyons.	
	Miocene gravels		0-45	A layer or pockets of gravel and boulders mixed with sand and clay. Probably alluvial fans and slope wash deposited along base of Miocene fault blocks.	The hydraulic properties of the early Tertiary luvium are unknown. Fine-grained sequences can be expected to yield small quantities of water, but coarse sands and gravels may form a major ground-water flow system.
Paleozoic		Sedimentary rocks. Permian Phosphoria and Pennsylvanian Oquirrh Formations? (Mytton, unpub. data)	Unknown	Limestone, shaley limestone, and quartzite. The limestone is commonly light to dark gray and fine to medium grained. The limestone forms massive beds up to several metres thick with common interbeds of shale and chert. Some horizons are dolomitic. Abundant fractures produced by several periods of tectonism are often healed with calcite. Small solution cavities occur in some areas but are generally rare. Bedding horizons dip steeply to the east-southeast in the Buckhorn Canyon to Artesian City area. The quartzite is buff to reddish in color, generally fine grained, and contains interbeds of sandstone, limestone, shale, and chert. This rock is also intensely fractured but the healing of the fractures seems less complete than that of the limestone. A near-vertical north-northwest-trending contact separates quartzite on the west from limestone on the east between the upper reaches of Buckhorn Canyon and Artesian City.	Production of mid-range temperature water is generally limited to joints, solution cavities, and active fault zones. Massive units may act as barriers to ground-water flow at the Tertiary-Paleozoic unconformity. Pre-Tertiary weathering may enhance permeability and permit some ground-water flow along and just below the unconformity.

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[1] Tables 2 through 5 are retained in the GSA Data Bank. For free copies, send written request or telephone Publications Department. Ask for documents no. 83-1.

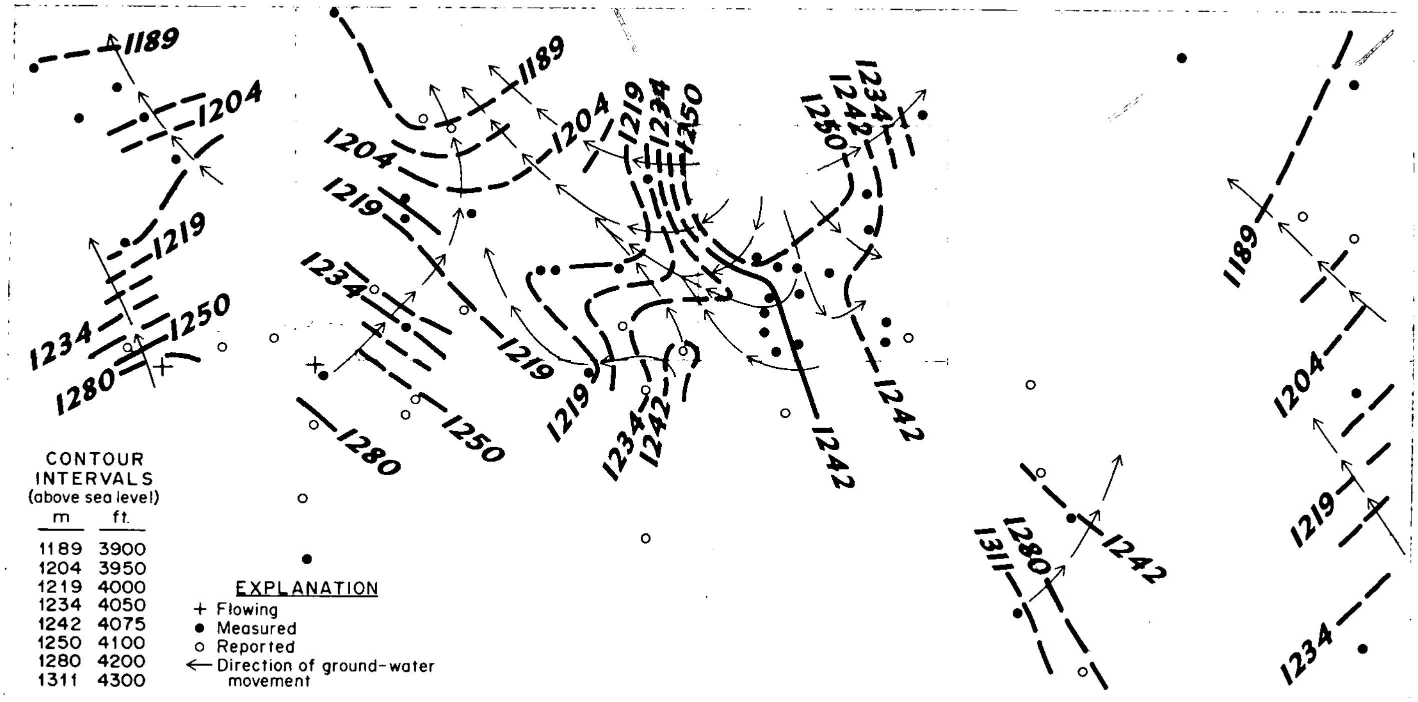


Figure 6. Map of elevation of standing water in wells, August-September 1980.

Ta = Mean annual air temperature (9.4 °C) (Mundorff and others, 1964)
t = Depth to top of producing interval (m)
b = Depth to bottom of producing interval (m)

These data normalize the observed temperatures by removing the effects of different completion depths. They reflect the convective transport of heat by ground water and are not conductive thermal gradients. In regions where downhole temperature-depth profiles are unavailable, the map of hydrothermal gradients may be the best indicator of areas where ground water is anomalously warm for the depth from which it is produced (Fig. 8).

In areas where cold water occurs above a deeper aquifer that contains a viable low-temperature geothermal resource, conductive heat loss or leakage from the deeper aquifer may contribute enough heat to the shallow aquifer to increase significantly the shallow hydrothermal gradient. The shallow water may be "cold," but the map of hydrothermal gradients may suggest areas where a deeper hydrothermal system exists.

The hydrothermal gradient is an exploration tool that must be used in conjunction with other data. It is most effective in areas where existing wells produce water that is cooler than is required by the intended use and where wells are completed to a wide range of depths. While hydrothermal-gradient data may be used successfully to estimate the depth intervals which are more likely to contain warm water, they neither replace temperature-depth data (Fig. 9) nor predict whether deeper strata can yield the needed quantity of sufficiently hot water.

The purpose of the geochemical phase of the study was to determine the recharge area, define the flow system, and estimate the probable reservoir temperatures of the thermal water. To implement this study, it was necessary to compile chemical analyses of both thermal and nonthermal wells and springs in the Artesian City area. These data are listed in Table 3 (see footnote 1), and their locations are shown in Figure 10. Analyses of water from the Oakley area, located southeast of the Artesian City study area, were also included in the compilation (Table 4; see footnote 1 above) to determine if warm water from this area has the same source as the warm water at Artesian City. The chemical compositions of all wells and spring waters were then examined on a trilinear diagram (Fig. 11) to distinguish compositional trends. Comparison of these compositional trends within the physiologic, lithologic, and hydrologic frameworks described herein allows the prediction of a source region and subsequent flow paths for the thermal waters. The methodology employed in this study is similar to that used in other low-temperature geothermal systems by Norton and Panichi (1978), Glenn and others (1980), and D. Cole (unpub. data).

The chemical analyses of water from wells and springs reported in this study include analyses compiled from the literature as well as analyses of water samples collected as part of the hydrologic study. Collection dates for these samples range from 1921 to present, and span all seasons. Cole (unpub. data) has demonstrated that there can be significant fluctuations in element concentrations in low-temperature thermal waters sampled through time, both on a yearly and seasonal level. The lack of analyses repeated with time from individual wells and springs precludes an assessment of such fluctuations within the study area.

Water samples collected during the hydrologic study were stored in polyethylene containers that had been precleaned by soaking in 20% nitric acid and rinsed in deionized water. Chemical analyses of these samples were completed as follows: pH and bicarbonate concentrations were determined on untreated samples using a selective ion meter with an Ag/AgCl combination electrode and sulfuric acid titration as discussed by Presser and Barnes (1974); fluoride, chloride, and total dissolved solids were determined on

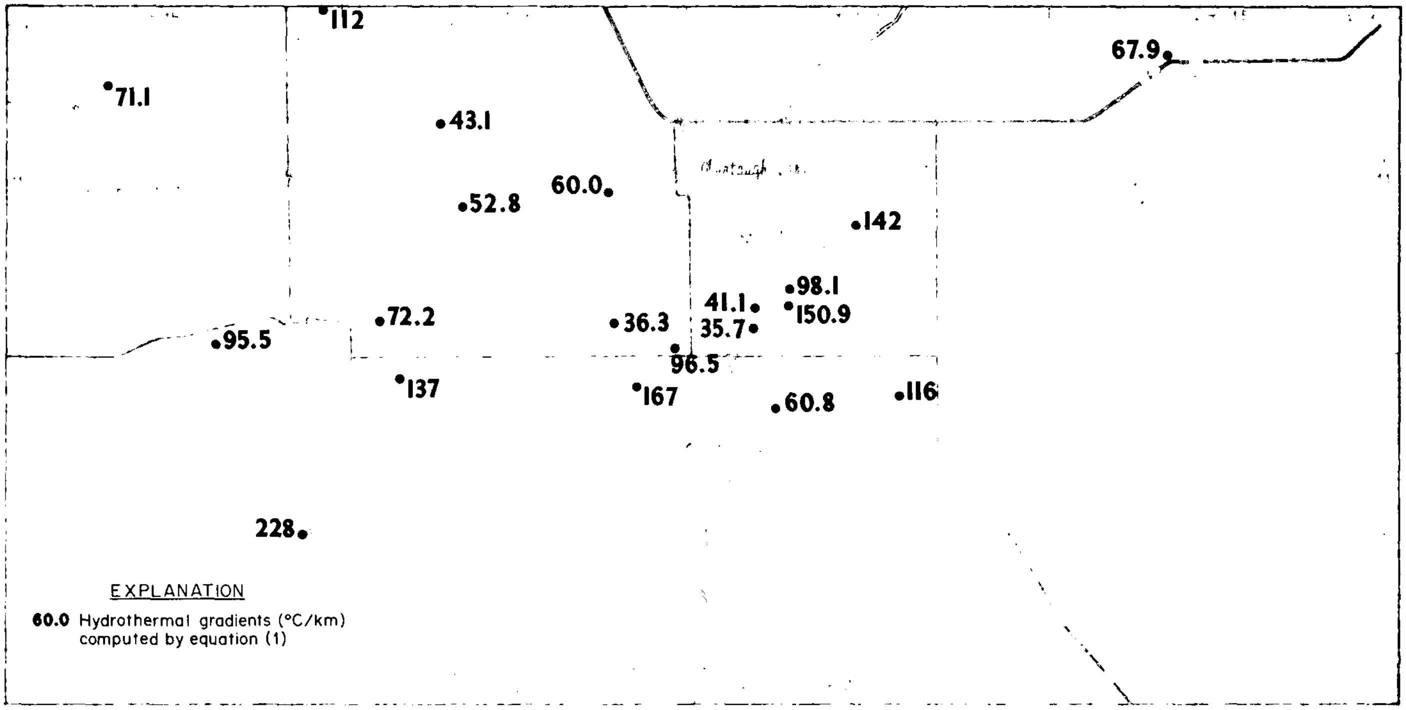


Figure 7. Map of well-water temperatures.

filtered (0.45 μm) samples employing specific ion electrode, silver-nitrate titration, and gravimetric methods, respectively (Brown and others, 1970); sulfate was determined gravimetrically on samples filtered to 0.45 μm and treated with 1% hydrochloric acid in the field; all other elements were determined with an Inductively Coupled Plasma Quantometer (Christensen and others, 1980) on samples filtered to 0.45 μm and diluted by 20% with concentrated nitric acid in the field.

GEOLOGY

The Artesian City study area lies on the southern margin of the central Snake River Plain and at the northern edge of the central Basin and Range province (Fig. 1). A lowland of loess- and alluvium-covered basalt flows extends 9.7 km southward with a minimum elevation of 1,200 m from the deeply incised canyon of the Snake River. Three shield volcanoes rise to 90 m above the

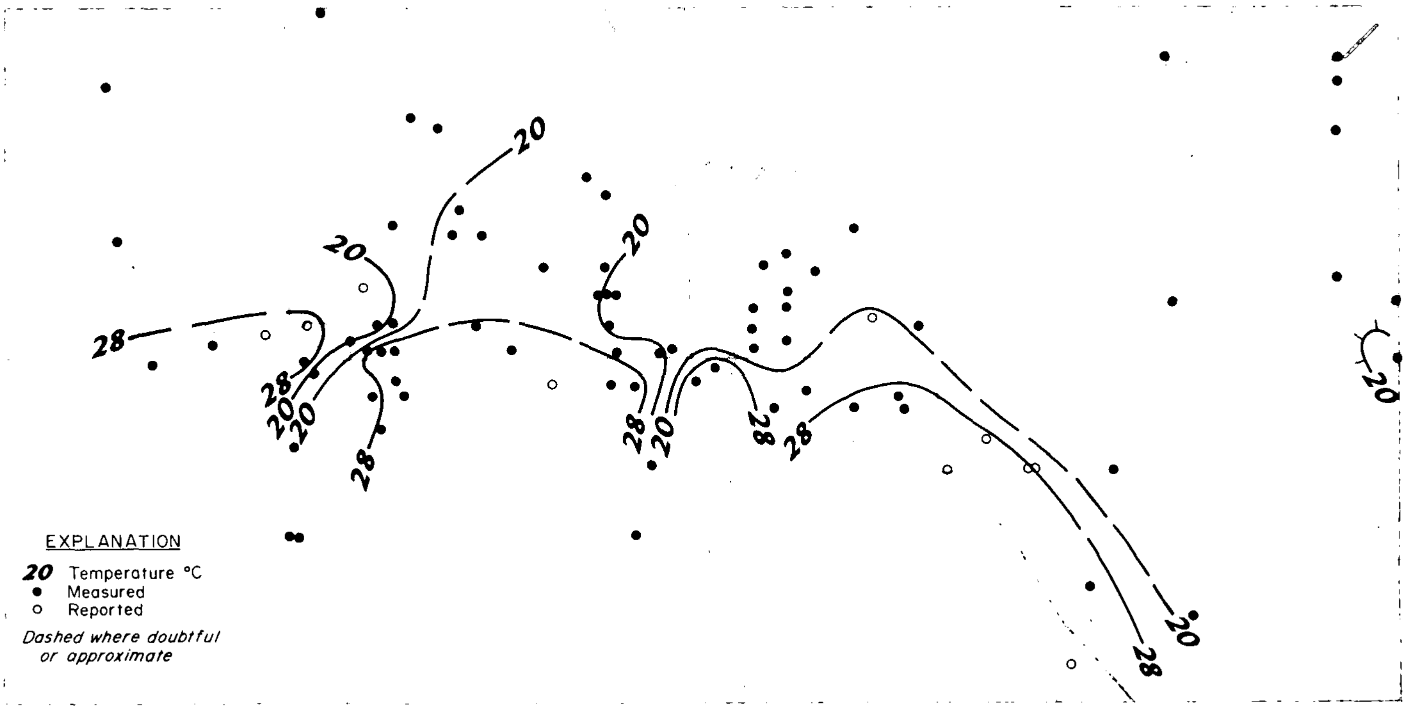


Figure 8. Map of calculated hydrothermal gradients.

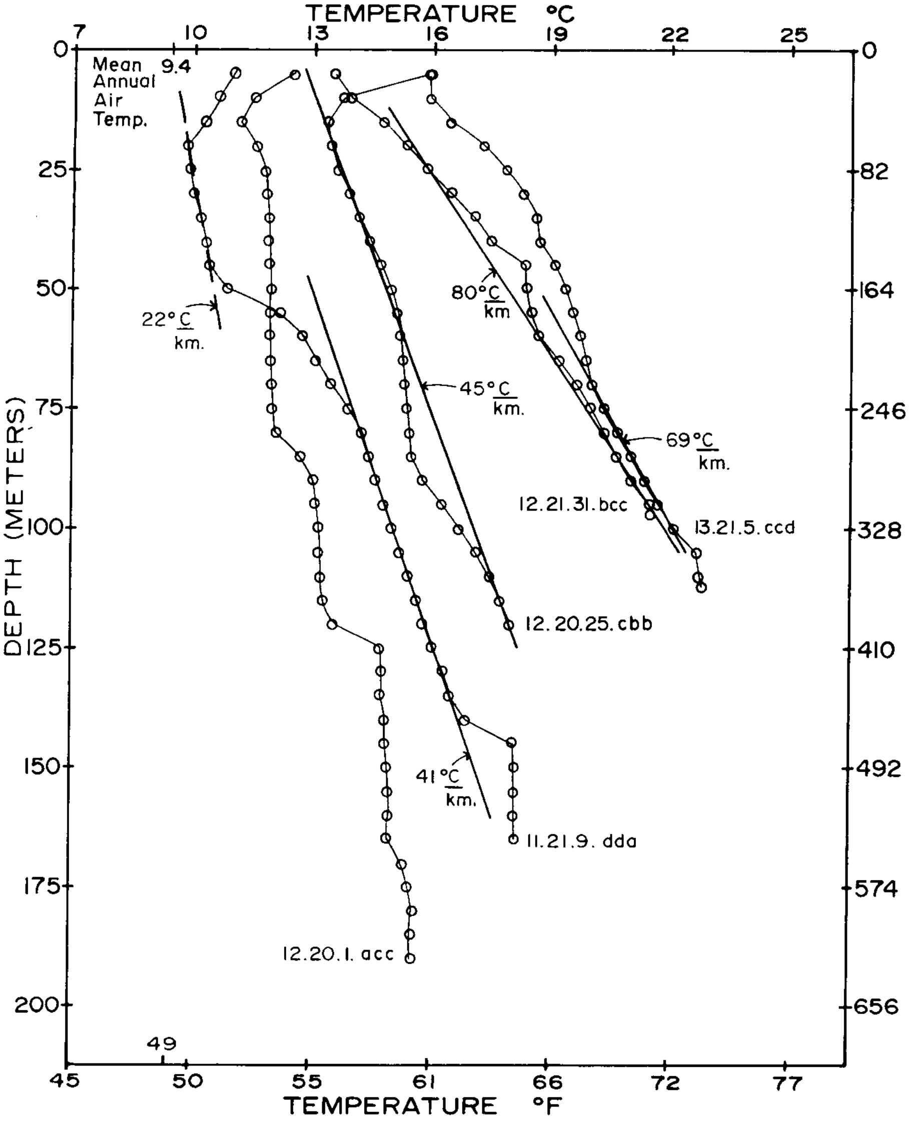


Figure 9. Thermal gradients inferred from straight line fits to temperature-depth profiles, Rock Creek Hills area: from Brott, Blackwell, and Mitchell (1976), IDWR Bulletin 30, Pt. 8.

lowland within the study area. The east-west-trending front of the Rock Creek Hills, locally known as the South Hills, and also known as the Cassia Mountains, rises from the lowland. This dome-shaped upland achieves a maximum elevation in excess of 2,400 m about 29 km south of the lowland. A thick sequence of Tertiary rhyolitic ash-flow tuffs (Williams, 1981) and sediments forms a faulted and dissected mesa (Fig. 3) that dips gently toward the lowlands in all directions (Fig. 4). Young normal faults bound the northeastern, northern, and northwestern margins of the upland. The Tertiary volcanic rocks lie unconformably on late Paleozoic marine limestone, shale, and quartzite (Fig. 4).

Stratigraphy

Paleozoic Rocks (Pls, Pqz). Paleozoic rocks underlie the Tertiary volcanic rocks and are exposed south of Artesian City (Fig. 3). The Paleozoic-Tertiary unconformity is mountainous, with as much as 600 m of relief. The pre-volcanic upland appears to have been elongated to the north and may have been the product of pre-volcanic Basin and Range faulting. This buried upland forms two ridges beneath the northern flanks of the Rock Creek Hills. The volcanic sequence exposed in the deeply incised canyons of Rock and Dry Creeks indicates that a volcanic-filled depression more than 400 m deep lies between the ridges. Well 12.20.1.bdd bottoms in the Idavada Volcanics at a depth of 580 m, indicating a greater depth to the Tertiary-Paleozoic unconformity northeast of the Rock Creek Hills (Fig. 4, A).

Water levels in the fractured limestone along the northeast margin of the Rock Creek Hills failed to recover after several seasons of pumping (Crosthwaite, 1969a). Also, many of the cold springs in the Rock Creek Hills occur near the contact of the Paleozoic and Tertiary rocks, suggesting that infiltrating precipitation flows preferentially along or above the unconformity rather than deeply into the Paleozoic section. These observations indicate that the Paleozoic rocks are unable to freely accept recharge except along faults, and generally have a low intergranular permeability.

Tertiary Rocks. *Miocene Gravel (Tg).* A layer of gravel mixed with sand, clay, and boulders occurs at the Paleozoic-Tertiary unconformity (Fig. 4, A). The distribution and thickness of the gravel unit is irregular due to the mountainous character of the unconformity. The maximum observed thickness of 100 m is recorded in the driller's log from a well southeast of Buckhorn

Creek. Other wells, near Buckhorn Creek and near Artesian City, penetrate about 30 m of gravel at the unconformity. These gravels are probably alluvial fans and slope wash (Williams, 1981) deposited in response to Miocene Basin and Range tectonism.

Little is known about the water-bearing properties of the Miocene fan gravels that irregularly overlie the Paleozoic rocks. They presumably are highly permeable and may form a major, relatively untapped aquifer above the less permeable Paleozoic rocks. If present at the base of the volcanic-filled depression of the Rock Creek Hills, the Miocene gravels may transmit deeply infiltrating rain and snow-melt.

Late Miocene–Early Pliocene Idavada Volcanics (Tiv). The volcanic cover of the Rock Creek Hills is part of the regionally extensive Idavada Volcanics (Crosthwaite, 1969a), informally named the Artesian Formation by West (1956). The Idavada Volcanics cover most of the Rock Creek Hills within the study area and dip northward beneath the basalts and alluvial deposits of the Snake River Plain (Figs. 4 and 5). The volcanic rocks are predominantly rhyolitic ash-flow tuffs. They attain thicknesses in excess of 400 m in the paleovalleys underlying the Dry Creek–Rock Creek area and the Golden Valley area east of Buckhorn Creek (Fig. 4, B). The sequence pinches out southward against the Paleozoic rocks at the crest of the Rock Creek Hills and thins to about 30 m on the paleo-ridge at the head of Buckhorn Creek. It also appears to thin westward from Rock Creek against a paleotopographic high, although exposures and drill-hole data are insufficient to confirm this. Potassium-argon dates reported by Armstrong and others (1980) indicate ages of 10 to 11 m.y. for these rocks.

The thickest exposure of the Idavada Volcanics occurs in the Canyon of Rock Creek in sec. 31, T. 12 S., R. 19 E. The section of Idavada Volcanics at this locality is 370 m thick and contains a minimum of ten simple and compound ash-flow tuff cooling units with interbedded tuffaceous sedimentary rocks. Resistant welded tuff horizons and soft sedimentary horizons provide useful marker horizons for the purposes of mapping geology and structure.

Many of the warm-water wells produce from a highly fractured welded tuff that lies below a 45-m-thick section of tuffaceous sediments and nonwelded tuffs which forms a confining layer. This aquifer is more than 120 m below the top of the Idavada Volcanics.

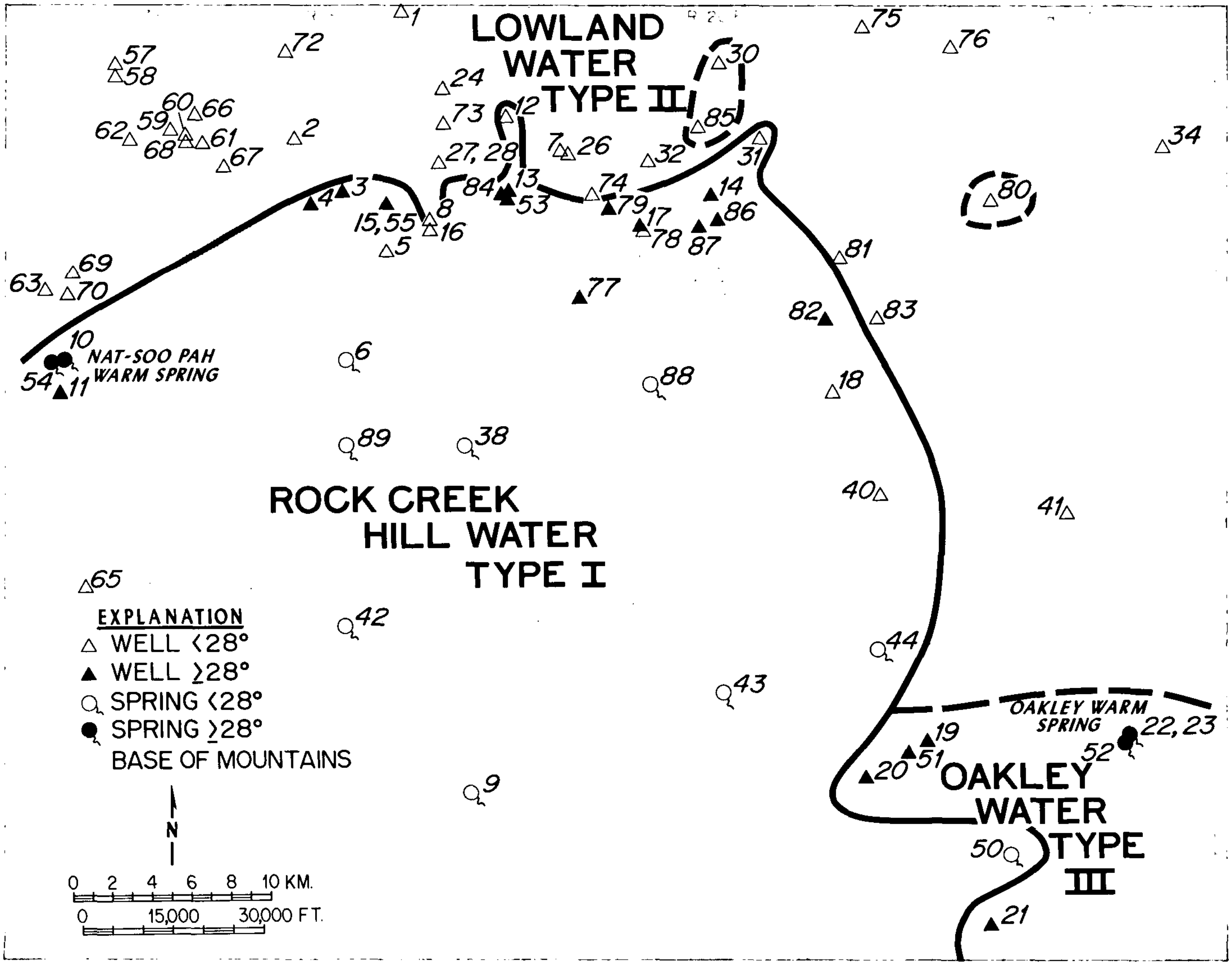


Figure 10. Artesian City area well and spring locations with available water analyses.

Most of the artesian production of warm water is reported to come from the densely welded vitrophyre zones; the necessary porosity and permeability in these zones is probably due to the high susceptibility to fracturing of the glassy material. It is likely that some of the shallow ground-water may be perched above the tuffaceous sediments and, therefore, move horizontally to emerge as cold springs in the canyons.

Pliocene Alluvium (Tal). Drillers' logs indicate that a widespread sedimentary layer of clay, silt, sand, and gravel lies above the Idavada Volcanics in the lowland area (Figs. 4A, 4B). West (1956) and Crosthwaite (1969a) suggest that fluvial, lacustrine, and fan deposits comprise the section which interfingers with overlying Quaternary basalt flows. The sediments pinch out toward the Rock Creek Hills. The unit attains thicknesses of at least 105 m east of Buckhorn Canyon and 60 m north of the Rock Creek Hills.

Tertiary-Quaternary Rocks. *Basalt (Tb).* Shield volcanoes deposited as much as 240 m of olivine basalt in the lowlands north and east of the Rock Creek Hills during the mid-Pliocene to early Quaternary (Armstrong, 1975). Hub Butte, Stricker Butte, Hansen Butte, and Milner Butte (Fig. 1) were vents for the basalt flows in the study area (Covington, 1976). Crosthwaite (1969a) identified these flows as lavas of the Snake River Group. The flows crop out widely in the northern part of the study area. The geologic map (Fig. 3) depicts the extent of the basalt at the surface and at depths less than 9 m as indicated by drillers' logs. The flows thin gradually from the vent areas toward the base of the Rock Creek Hills with an abrupt thinning occurring just north of the Foothill Road, perhaps due to the presence of a buried fault scarp (Fig. 4C). The basalt east of the Rock Creek Hills thins gradually southward along the mountain front and away from Milner Butte. Basalts of the Snake River Group are heterogeneous but are generally highly permeable. The basalt and interbedded alluvium form an unconfined aquifer at the base of the foothills.

Alluvium and Loess (Qal). A veneer of alluvium and loess covers most of the lowland area (West, 1956; Crosthwaite, 1969a). As much as 15 m of loess covers the slopes of the shield volcanoes, obscuring the lava flows in much of the study area. Clay, silt, sand, and gravel form unconsolidated to well-compacted, lensoid horizons generally derived from streams draining the Rock Creek Hills. Alluvial deposits at the mouths of the major canyons often exceed 60 m in thickness. All steeply sloping drainages have produced alluvial fans (Qf) at the base of the mountain front. Where saturated, the alluvium above the basalt yields water to wells.

Structure

Mapped crosscutting relationships distinguish three generations of structures within the Artesian City study area. The oldest structures, occurring exclusively within the Paleozoic rocks, include low-angle faults and folds related to Paleozoic and Mesozoic tectonism. The Paleozoic rocks display pervasive shattering by closely spaced fractures (West, 1956) as a result of these tectonic episodes.

High-angle faults of the second generation exposed within the Paleozoic rocks between Artesian City and Buckhorn Creek do not appear to extend upward into the Idavada Volcanics, suggesting that they predate the volcanic rocks. These faults range in strike from N40° E to N50° W but most commonly strike from N5° E to N20° W. Prominent exposures of these faults occur at the mouth of Buckhorn Creek south of Artesian City. Movement on numerous fault planes has produced zones of brecciation as much as 90 m wide.

Two sets of normal faults of the third generation traverse the Miocene-Pliocene volcanic sequence and strongly control the drainage patterns cut into the Rock Creek Hills (Fig. 3). A swarm of N20° W-N40° W-trending near-vertical faults extends from the crest of the Rock Creek Hills to the margin of the Snake River Plain. A set of N20° E-N40° E-trending near-vertical faults is similarly extensive. The maximum offset on any of these faults does not appear to exceed 150 m. Photo linears and offsets of the Idavada Volcanics indicated in drillers' logs suggest that the northwest-trending faults extend into the Snake River Plain. These faults appear to displace the youngest basalt flows in this area as much as 15 m; however, they do not disrupt the surficial deposits of loess and alluvium. Although displacements downward to the southwest prevail, a fault with displacement down to the northeast passes through Artesian City. This fault forms the western margin of a 1.6-km-wide by 135-m-deep graben that extends northwestward from the edge of the Rock Creek Hills. Drillers' logs of wells from the Artesian City area (IDWR, Open-file) provide control on the suballuvial geometry of the graben (Figs. 3, 4, and 5). Several northwest-trending faults on the west side of McMullen Creek also displace the Idavada Volcanics downward to the northeast; the volcanic rocks here form the southwestern limb of a broad, gentle, northwest-plunging anticline that lies between McMullen Creek and Rock Creek (Fig. 4B).

A set of north-south-trending normal faults, also of the third generation, transects the front of the Rock Creek Hills in the Dry Creek area. Displacements on these faults are generally less than 90 m.

Outcrops reveal numerous normal faults of small displacement paralleling the mountain front. Drillers' logs and photo linears indicate that at least two east-west- to west-northwest-trending normal faults displace the Idavada Volcanics downward at the edge of the Snake River Plain (Figs. 3, 4B, and 5). The data suggest the presence of an east-west-trending fault with about 90 m of displacement near Artesian City about 0.8 km north of the Foothill Road (2900 North Road). The faults controlling the mountain front may terminate against or merge with the northwest-trending faults near Antelope Valley and the mouth of Rock Creek. Most of the fault blocks controlled by these range-front faults dip toward the north, contributing to the downwarp of the Idavada Volcanics into the developing tectonic depression of the Snake River Plain, as suggested by Kirkham (1931). The only evidence for recent movement on faults at the base of the northern mountain front is a very subdued scarp southeast of Artesian City.

The fault zone controlling the northeast margin of Rock Creek Hills has a total displacement along the fault zone ranging from 330 m on several fault planes at the mouth of Buckhorn Creek to less than 150 m on one or two fault planes farther to the north along the mountain front. Drillers' logs and photo linears indicate that this fault extends northwestward from the Rock Creek Hills toward Murtaugh Lake. Subdued scarps parallel to the mountain front north of the mouth of Buckhorn Creek suggest recent fault movements. These scarps may, however, be the result of subsidence due to ground-water withdrawal.

Surficial evidence of warm-water flow along faults is lacking except on the Fifth Fork of Rock Creek and on the northeast edge of the Rock Creek Hills, where active and recently active mid-range temperature springs appear to tap northwest-striking fault zones in Paleozoic rocks. However, abandoned wells at the mouth of Buckhorn Creek formerly produced warm water from the range-front fault zone. A well adjacent to the subdued east-west-trending fault scarp southeast of Artesian City appears to produce from an intercept of the fault in Paleozoic rocks at depth. In these instances, repeated brittle fracture and silicification of the Paleozoic rocks may have created permeability adequate for sustained but moderate ground-water flow.

The numerous faults cutting the Idavada Volcanics form a dense polygonal pattern that probably enhances hydraulic continuity between the several water-bearing horizons within and beneath the volcanic section. The communication between individual water-bearing horizons may allow the hydrostatic heads in each horizon to be the same beneath the Rock Creek Hills. However, the variable permeability of the volcanic country rock may cause local perturbations in the hydrostatic head along a given fault zone.

Hydrothermal Alteration

The most intense hydrothermal alteration encountered in the study area occurs in the wide fault breccia zones in Paleozoic rocks exposed at the mouth of Buckhorn Creek and southeast of Artesian City. Jasperoid with crosscutting carbonate veins replaces limestone and dolomite within and adjacent to the breccia zone. Shale horizons are pervasively silicified or altered to a light green clay. This alteration may predate the Idavada Volcanics and is probably related to Basin and Range faulting.

West (1956) reported altered volcanic rocks in drill cuttings from wells north and east of Artesian City. The Idavada Volcanics and Tertiary basalts adjacent to faults are locally altered to jasperoid or clay with lesser amounts of carbonate and pyrite. The alteration in the Idavada Volcanics is no older than late Miocene, whereas that in the basalts can be no older than Pliocene. The intensity of alteration suggests that water hotter than that of the modern flow systems produced the observed alteration minerals.

Although the observed alteration minerals in the volcanic rocks do not appear to be related to the modern hydrothermal system, they probably restrict ground-water flow by locally decreasing the permeabilities of fault zones and adjacent country rock. By contrast, the silicification of Paleozoic limestone and shales has probably rendered portions of those units adjacent to fault zones more capable of sustaining fracture permeability.

HYDROLOGY

Hydrologic Setting

The potential for shallow warm-water production is limited to the foothills of the Rock Creek Hills and the area of present production along the base of the foothills. The warm water is confined and occurs in the Tertiary Idavada Volcanics. The first wells to tap the Idavada Volcanics flowed at the surface; subsequent development has lowered artesian heads as much as 90 m. It is possible that warm water could also be tapped within a relatively undeveloped area southeast of Murtaugh Lake. Water levels measured in 1980 mimic the topography except near Murtaugh Lake, which acts as a source of recharge to the shallow basalt–alluvial cold-water aquifer (Fig. 6).

Unconfined and perched cold water occurs in the Rock Creek Hills. Within the highly transmissive but heterogeneous basalt-alluvial aquifer, cold water (Fig. 2) occurs in three distinct areas: north of the canals that divert Snake River water, and downstream of the mouths of Rock and Dry Creeks (Fig. 7). Mid-range water (Fig. 2) is found in Paleozoic rocks along the southeast flank of the Rock Creek Hills. It also appears in the unconfined basalt-alluvial aquifer in the part of T. 11 S., R. 19 E. that is both above the elevation of the irrigation canals and unaffected by the cold recharge from Rock and Dry Creeks.

Water Level. The term "water level" is used in preference to the more rigorous term "potentiometric surface" throughout this study due to the diversity in the sources of data on static water levels and the observation that most of the wells are open to more than one water-bearing zone. Static water levels in these wells do not reflect a potentiometric surface, but rather some sort of average of several potentiometric surfaces. As a result, the water levels shown in Figure 5 are the static water levels in wells that tap a variety of aquifers at a wide range of depths. They represent a reconnaissance picture of the general patterns of ground-water flow and do not reflect a rigorous attempt to depict the direction of ground-water movement within individual aquifers. The details of the flow system can be known only by drilling piezometers and measuring their potentiometric surfaces. This is impractical for reconnaissance low-temperature geothermal surveys. The water levels shown in Figure 5 provide an adequate framework for understanding where and which way ground water flows in the Artesian City area.

Water levels in wells penetrating the Idavada Volcanics several kilometres upstream of the mouths of Rock and Dry Creeks are artesian and higher than they are at the base of the foothills (Fig. 6). The sparse data suggest that the water level within the foothills slopes gently to the northeast. The water tapped by these wells is warm. At the edge of the foothills, this water is produced from the numerous wells along or near the "Foothill Road."

Water levels on the eastern margin of the area shown in Figure 6 are highest in the south and decrease to the northwest. Recharge from the area of Buckhorn Canyon on the northeast flank of the Rock Creek Hills flows northeast and then joins the north-northwest ground-water flow system in the Oakley Valley.

On the western edge of the study area, the direction of ground-water flow is also to the north-northwest. The gradient is steepest in the alluvial fans at the base of the Rock Creek Hills and flattens to the north, where diverted Snake River water is used for irrigation. Infiltration of irrigation water and the high transmissivity of the basalt probably cause the observed flattening of the gradient.

Surface water and underflow at the mouth of Rock Creek flow to the north-northeast; underflow at the mouth of Dry Creek flows to the north and north-northwest. A minor ground-water trough is present between the areas at the mouths of the creeks (Fig. 6). This trough suggests that the recharge from the creeks flows to the northwest.

Murtaugh Lake is the holding facility for the canals of the Twin Falls South Side Project. Seepage losses from Murtaugh Lake cause high water levels that decline steeply to the west and southwest. Seepage losses from fields below the Milner Low Lift Canal may cause the water levels to decline less steeply to the east and south. The pronounced flattening of the gradient southeast of Murtaugh Lake suggests that the seepage losses may be preferentially flowing to the southeast.

A linear north-northwest–trending break in water level is sustained from the base of the Rock Creek Hills to the recharge mound at Murtaugh Lake. Because water levels are higher on the east of the linear break than on the west, Dry Creek cannot be the source of recharge that sustains the high water levels. The linearity of the break suggests that differences in the quantities of ground water pumped for irrigation are not responsible for the abrupt change in water level. It is possible that seepage from Murtaugh Lake sustains perched water at abnormally high water levels. The few data in R. 20 E. are too scattered to define the eastern and northern extents of the high water levels or to discriminate possible perched water above the water table.

Water Temperature. As noted by West (1956) and Crosthwaite (1969a), a band of warm water extends along the base of the Rock Creek Hills (Fig. 7). Within the band of warm temperatures, mid-range temperature water is produced by shallow wells drilled in the alluvial fans at the mouths of Rock and Dry Creeks. These mid-range temperatures are probably the result of mixing of cold surface water infiltrating the fans and warm water from the Idavada rocks.

An area of mid-range temperature water in T. 11 S., R. 19 E. lies north of the band of warm temperatures, east of the cold outflow from Rock Creek, and west of the cold outflow from Dry Creek and Murtaugh Lake. Since the elevation of this area is higher than the levels of the canals, canal water cannot be used for irrigation. All irrigation water is ground water pumped from the basalt-alluvial and Idavada aquifers. The heavy pumping causes the water levels to be deeper than they are in the flanking areas. Wells are accordingly deeper. The temperature map cannot be used to determine whether the mid-range temperatures are a product of increased well depths or of leakage from the band of warm water to the south.

Mid-range temperatures are obtained from wells in T. 12 S., R. 20 E., Sec. 5, south of Artesian City that penetrate Paleozoic rocks that are part of the paleo-upland buried by the Idavada volcanic rocks (Fig. 4A). Water in the Paleozoic rocks in this area is colder than water at shallower depths in neighboring wells that penetrate the Idavada Volcanics. The available hydrologic data alone do not explain this decrease in water temperature with stratigraphic position. It can be inferred that the ground-water flow system that allows warm water to occur at shallow depths within the jointed volcanic rocks is not present within the buried range of Paleozoic rocks.

The regional temperature patterns include areas of cold water in the northeastern and northwestern corners of the area shown in Figure 7. Data are too sparse in the north-central portion of the map to conclude that these areas are connected. Although the temperatures of water in both northern corners of the map are "cold," they average nearly 8 °C above the mean annual air temperature. In both areas, fields are irrigated with water diverted from the Snake River by an extensive network of canals. Water ponded in the fields and flowing in the canals is exposed to the atmosphere and accordingly warmed during the summer irrigation season. Irrigation water that is not lost to evaporation or consumed by crops percolates down to the basalt-alluvial aquifer. Even though the rate of downward infiltration is unknown, it is unlikely that the water cools to the mean annual air temperature during the time it takes to reach the water table. A survey of water temperatures during the spring would test whether solar-heated infiltrating irrigation water causes the elevated water temperatures.

The 20 °C contour west of Dry Creek passes through three wells less than 45 m apart in T. 11 S., R. 19 E., Sec. 26. Two of these wells produce cold water and are approximately 227 m deep (Table 2); the third well with the "mid-range" temperature is 339 m deep. These data reveal a major shortcoming of water-temperature maps: they fail to document the effect of well depth on water temperature.

Hydrothermal Gradients. The map of hydrothermal gradients (Fig. 8) can be used to distinguish areas where ground water is anomalously warm for the depths from which it is pumped. Table 2 reveals that there are relatively few wells in the study area for which both water temperature and producing interval are known. More drillers' logs than those included in Table 2 are known to exist but were not available for this study; the data in Figure 8 are accordingly incomplete. However, they are sufficient to reveal areas with both light and low hydrothermal gradients.

The band of warm water at the base of the Rock Creek Hills is also a band of high hydrothermal gradients. The northern limit of high gradients appears to lie in the southern tier of sections in T. 11 S., R. 18–20 E., less than 1.5 km north of the "Foothill Road." The high gradient for a well in Rock Creek Canyon (12.18.24.bab) suggests that the warm water occurs at shallow depths within the foothills as well as at their base. The combination of warm temperatures and high hydrothermal gradients argues that all wells drilled south of the "Foothill Road" in this area are likely to tap warm water within the artesian aquifer system in the Idavada Volcanics.

The northern limit of the band of high gradients at the base of the foothills indicates that anomalously warm water is not produced by wells farther north, even by wells such as 11.19.23.abc that tap the Idavada Volcanics. In the 1950s, wells farther north did produce warm water (West, 1956). Hence, it is possible that production within the band of warm water during the past 30 years has drawn the water levels down so severely that it has captured water that once leaked into the basalt-alluvial sequence from the Idavada Volcanics. However, there are no data to suggest unequivocally that warm water can be produced in the lowlands. Efforts to obtain warm water in the lowlands may require the drilling of wildcat test wells through the entire Idavada sequence.

In the northern corners of the study area, where water temperatures in the shallow basalt aquifer are 8 °C above the mean annual air temperature, the hydrothermal gradients are high. This probably reflects the infiltration of irrigation water rather than the presence of geothermal water at depth.

The band of high hydrothermal gradients extends as far east as T. 12 S., R. 20 E., Sec. 5, where one of the wells that produces from Paleozoic rocks has a low gradient, suggesting that the mid-range water in the Paleozoic section is not unusually warm for the depth from which it is produced.

Wells in Artesian City that produce from the basalt-alluvial aquifer within a north-northwest–trending graben (Fig. 3) have consistently low hydrothermal gradients. East of the graben, hydrothermal gradients are high for wells that produce from a horst of Idavada Volcanics. The linear break at the graben margin suggests that there is no apparent leakage of warm water from the horst into the basalt-alluvial aquifer within the graben. Along the trend of the horst, hydrothermal gradients are high, but water temperatures are cold. The high hydrothermal gradients extend from Murtaugh Lake to the base of the Rock Creek Hills. Since Murtaugh Lake contributes water to the basalt-alluvial aquifer, it is possible that solar-warmed seepage losses cause the high hydrothermal gradients along the trend of the horst. Other possible causes for the high gradients may be warm water leaking out of the Idavada Volcanics within the horst block or the conductive heat loss from a deeper, warm aquifer.

The area with mid-range temperature water in T. 11 S., R. 19 E. has low hydrothermal gradients, indicating that it is unlikely that warm water can be tapped at shallow depths. If there were anomalously warm water in this area, it must be confined at some depth greater than the deepest well for which hydrothermal gradients have been calculated, 335.8 m. Crosthwaite (1969a) reported that confined water from the Idavada Volcanic rocks leaks upward into the basalt-alluvial aquifer. Hydrothermal gradients north of the "Foothill Road" suggest that vertical leakage from deeper aquifers is not as significant in 1980 as it was in the late 1960s.

GEOPHYSICS

Previous Work

Aeromagnetic and Gravity Surveys. Geophysical data from the Rock Creek Hills area are limited to two regional aeromagnetic (U.S. Geological Survey, 1978) and gravity (Mabey and others, 1974) maps and to five temperature-depth profiles made in large-diameter water wells (Brott and others, 1976). The aeromagnetic data were collected at 3,800-m elevation along east-west flight lines 16 km apart. Terrane clearance ranged from 2,400 m to 1,200 m. Only five gravity stations are shown within the Rock Creek Hills. Neither regional map has sufficient detail to contribute significantly to an understanding of the structural patterns in the Rock Creek Hills. Both have a strong regional east-west gradient passing through T. 11 S., north of the Rock Creek Hills. The east-west grain reflects crustal structure but obscures local detail.

Thermal Gradient Survey. Temperature-depth data obtained by Brott and others (1976) do not reliably indicate conductive heat flow within the study area. Figure 9 shows the temperature-depth profiles presented by Brott and others (1976) for five wells in the eastern part of the study area. All contain temperature disturbances—isothermal intervals and abrupt temperature kicks induced by the convective transport of heat in flowing ground water—which preclude reliable inferences about terrestrial heat flow (Brott and others, 1976). To be reliable, estimates of heat flow must be made from thermal gradients measured in holes that do not intercept flowing ground water.

Thermal gradients for these wells are inferred from the straight line fits to the temperature-depth data and are shown by the bold lines in Figure 9. The straight lines all follow or connect relatively linear sections of the profiles below the depth of the annual wave. The four estimated values are 41, 45, 69, and 80 °C/km. This range in values may be due partially to the different lithologies encountered in the wells, but it is unlikely that lithologic or porosity variations could cause the twofold change. The land-surface projections for each of the four inferred gradients are above the mean annual air temperature, 9.4 °C, suggesting that none of the four are in equilibrium with the ambient conditions. The wide range of estimated thermal gradients, the isothermal intervals, the temperature kicks, and the imbalance with ambient conditions all indicate that the temperature-depth data reveal more about the convective transport of heat by ground water than they do about terrestrial heat flow.

The temperature-depth data from the deepest well (12.20.1.acc) contain four distinct isothermal intervals which probably reflect four cold-water-bearing zones within the basalt-alluvial sequence. The second deepest well (11.21.9.dda) appears to intersect an isothermal water-bearing zone at a depth of 145 m. The linear gradient above the aquifer may be influenced by the flow of relatively cool water in highly transmissive basalt. The dashed line above a depth of 50 m in this well intersects the land surface at the mean annual temperature. The thermal gradient that can be inferred from the dashed line, 22.4 °C/km, may be the result of air circulating in cavernous basalt above the 145-m-deep aquifer. The data from the well drilled in the alluvial fan below Buckhorn Creek (12.20.25.cbb) show a cooling trend that is probably caused by downward-flowing cold water within the fan materials.

The two warmest and shallowest wells (12.21.31.bcc and 13.21.5.ccd) are reported to have produced mid-range temperature artesian water from fractured Paleozoic rocks (Crosthwaite, 1969a). They were abandoned because water levels dropped severely and failed to recover after several years of heavy pumping. Mid-range temperature water within the Paleozoic rock near the bottoms of these holes is likely to cause both the observed higher temperatures and the inferred high thermal gradients. The sharp kick at a depth of 45 m suggests that well 12.21.31.bcc may intersect a fracture containing mid-range temperature water.

Since ground water may depress the temperatures in the two wells with thermal gradients near 40 °C/km and elevate the temperatures in those with 69–80 °C/km gradients, it is likely that a thermal gradient representative of the background conductive heat flow lies between these values. This range of calculated thermal gradients permits the calculation of probable maximum and minimum depths of 951 m and 488 m for the circulation of 0 °C melt water warmed to the maximum observed temperature of 39 °C. The mean of these gradients, 60 °C/km, produces an estimate of the depth of circulation of 650 m.

GEOCHEMISTRY

Ground-Water Chemistry

The proportions of cations and anions in ground water from the Artesian City area, plotted on a trilinear diagram (Fig. 11), exhibit three distinct water types. These compositional groupings also define three clear geographic regions, displayed in Figure 10, which include the Rock Creek Hills (type I), Lowlands (type II), and Oakley (type III) areas. A contour of water temperatures on this trilinear diagram (Fig. 12) indicates that these water types are further characterized by temperature. Type I water includes both thermal and nonthermal waters with temperatures ranging from 4 to 39 °C, type II contains only cold or mid-range waters (less than 28 °C), and type III contains only thermal water with temperatures greater than 40 °C.

Type I (Rock Creek Hills) water includes all Artesian City area warm wells and springs sampled (28 to 39 °C), several nonthermal wells (11 to 27 °C), and all cold springs (4 to 26 °C) (Fig. 12 and Table 3). These waters, although having similar proportions of anions and cations, become more concentrated in total dissolved solids with increasing temperature (Fig. 13). They are dilute, near-neutral bicarbonate ground waters with average total dissolved solid contents varying from 141 mg/l in cold springs to 200 mg/l in thermal wells. The pH also changes with temperature from a low of 6.2 in the coldest, 4 °C, water to 7.9 in the hottest, 39 °C, water (Fig. 14). Sulfate and chloride are both present in consistently low concentrations at less than 20 mg/l. Calcium followed by sodium, both ranging in concentrations from 3 to 43 mg/l, are the dominant cations present in the majority of Rock Creek Hills water samples.

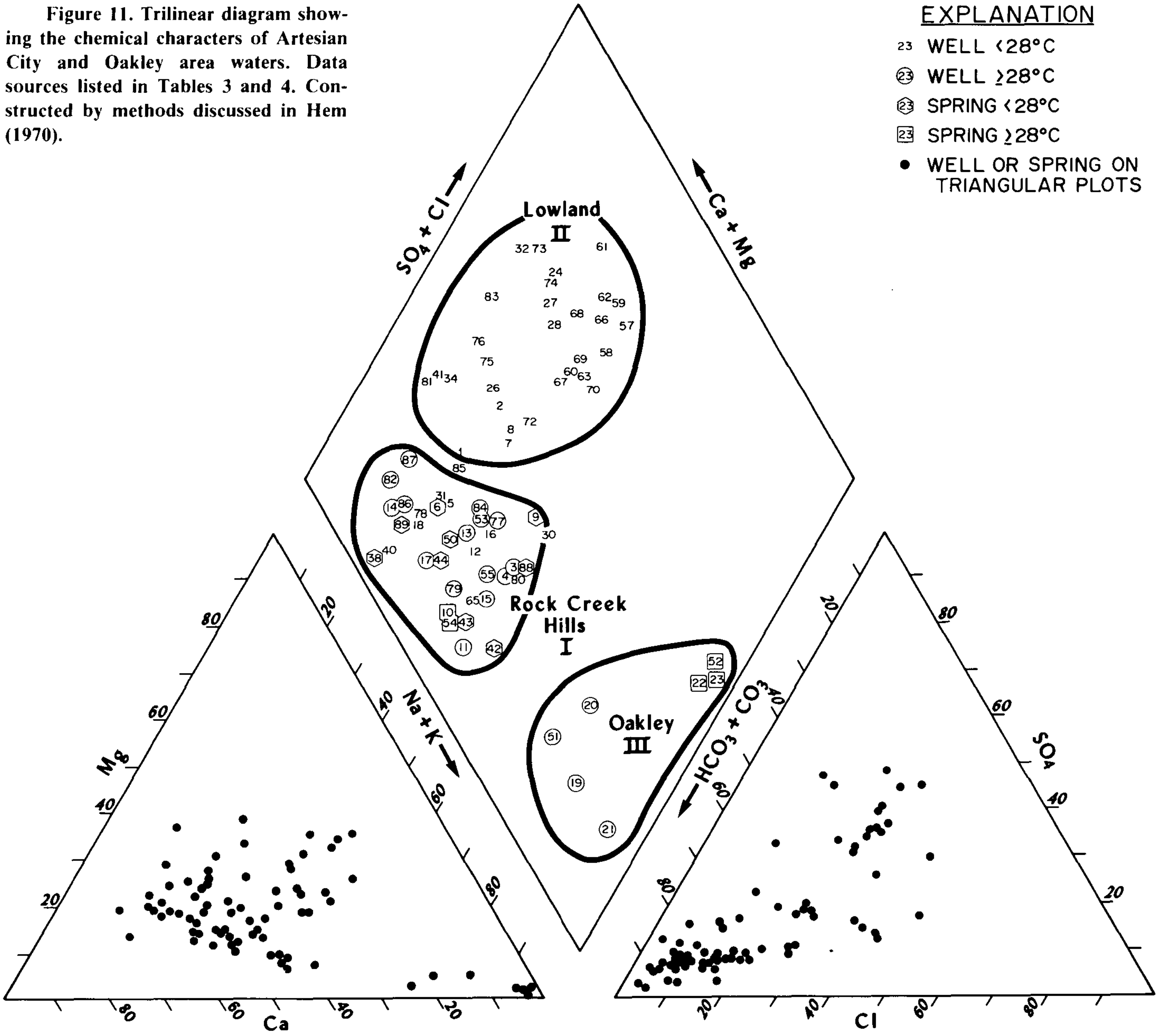
Type II (Lowland) water includes the majority of wells sampled in the lowlands north and northeast of the Rock Creek Hills area (Fig. 10). This water is nonthermal and exhibits a large variation in composition, ranging from slightly basic calcium or sodium bicarbonate to calcium or sodium bicarbonate-sulfate or bicarbonate- chloride ground water. In contrast to the Rock Creek Hills water, 90% of the Lowland water samples have temperatures under 20 °C. It also has higher total dissolved solid concentrations and pH values, averaging 518 mg/l and 7.7, respectively. Concentrations of sulfate and chloride in the Lowland water average 137 and 86 mg/litre, respectively.

Oakley thermal water (type III) is found around the Oakley Warm Spring, southeast of the Artesian City study area (Fig. 10). This water has a sodium bicarbonate to sodium bicarbonate-chloride composition. It differs from both the Rock Creek Hills and Lowland waters by having higher temperatures ranging from 41° to 49 °C; higher pH values and sodium concentrations, averaging 9.0 and 73 mg/l, respectively; and lower calcium, averaging 6 mg/l. Fluoride is also characteristically higher in the Oakley thermal water, averaging 5.8 mg/l, in contrast to an average of 0.7 mg/l in the Rock Creek Hills thermal water. The chemical compositions of the Oakley and Rock Creek Hills waters, shown on Figure 11, indicate that they are probably not related, and therefore the Oakley waters will not be considered further in this report. The different water chemistries may reflect the marked difference in the character of the lithologies encountered by the drainages in these two areas (Crosthwaite, 1969a). The Rock Creek Hills in the Artesian City area are predominantly silicic volcanics, whereas in the Oakley area they have a complex Mesozoic and Paleozoic stratigraphy beneath a volcanic veneer.

Source Regions and Flow Systems of Artesian City Area Thermal Water

The similar chemical compositions of the Rock Creek Hills ground-water samples, independent of temperature, suggest a common source in the rain and melt water from snowpack in the

Figure 11. Trilinear diagram showing the chemical characters of Artesian City and Oakley area waters. Data sources listed in Tables 3 and 4. Constructed by methods discussed in Hem (1970).



Rock Creek Hills (West, 1956; Crosthwaite, 1969a). Rain and melt water in equilibrium with atmospheric carbon dioxide pressure will be slightly acidic (approximate pH ranging from 5 to 7) and very dilute (total dissolved solids of less than 10 mg/l) (Feth and others, 1964; Garrels and MacKenzie, 1971). Infiltration of the water through the soil zone produces an increase in the carbon dioxide pressure, which will cause the pH of the water to become even more acidic (Paces, 1972), with a pH ranging from approximately 4 to 5 (Helgeson and others, 1969; Capuano, 1977). As this very dilute acid water flows through and reacts with the silicic volcanics of the Rock Creek Hills, it will increase in pH and total dissolved solids as the result of feldspar dissolution reactions (Helgeson and others, 1969). The deeper this rain and melt water infiltrates, and, therefore, the longer it reacts with the host rock, the higher its pH and concentration of total dissolved solids will become as it approaches chemical equilibrium with the host rock (Helgeson and others, 1969; Paces, 1972; Capuano, 1977). In addition, the deeper this water infiltrates, the higher its temperature will become as a result of the geothermal gradient.

The pH of the Rock Creek Hills water, although increasing with increasing temperature, appears to be buffered at just below 8 (Fig. 14; Table 3). This observation agrees with equilibrium calculations by Helgeson and others (1969) and Paces (1972) which indicate that the pH of rain interacting with feldspar-bearing rock is buffered between 8 and 9 by the production of kaolinite and montmorillonite.

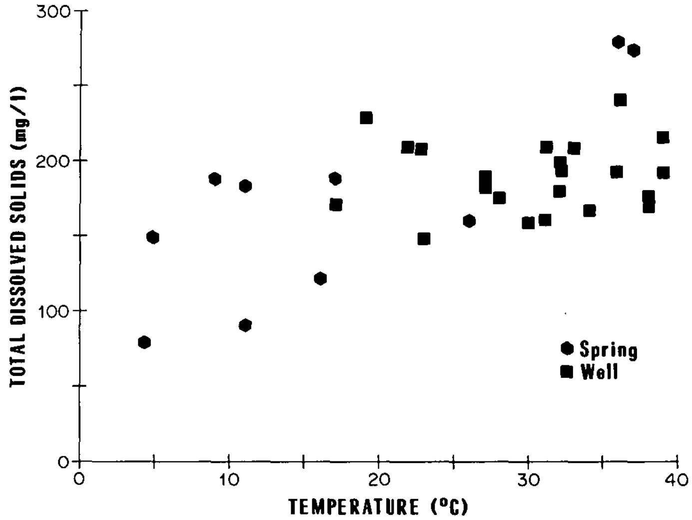


Figure 13. Total dissolved solids versus temperature diagram of Rock Creek Hills water.

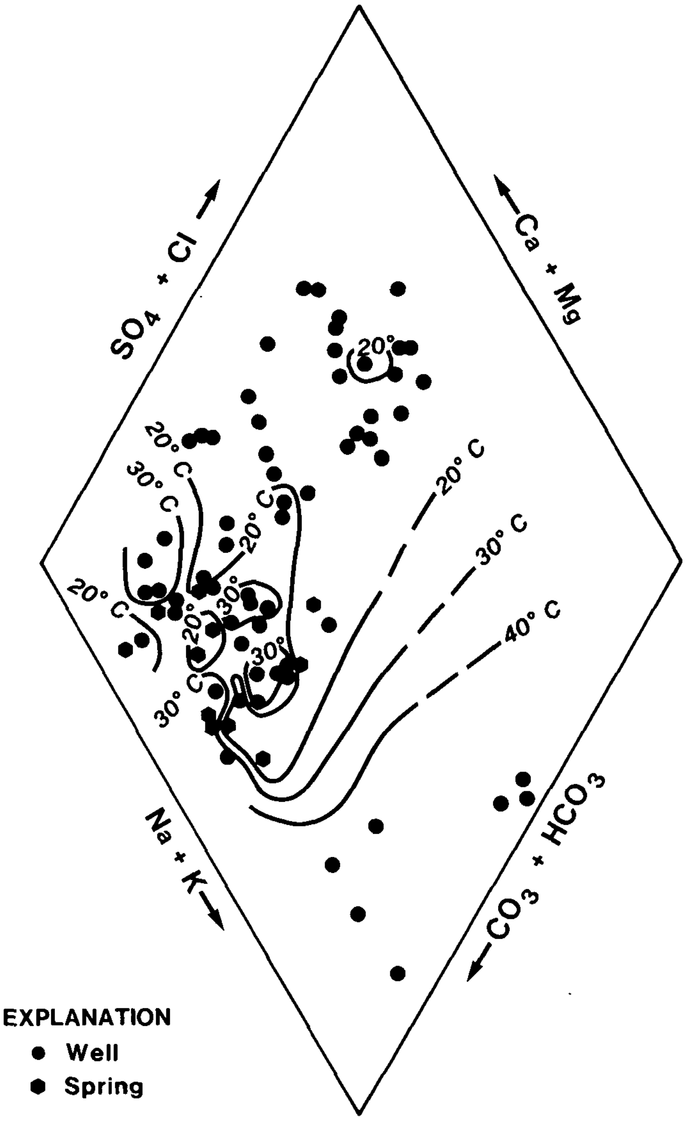


Figure 12. Contour of water temperatures on a trilinear diagram.

The similar chemical character of both the cold and warm Rock Creek Hills waters suggests a common set of reactions with the dominant silicic volcanic rock type in the Rock Creek Hills. Also, the increase of pH (Fig. 14) and total dissolved solids (Fig. 13) with increasing temperature implies longer reaction times and, thus, deeper infiltration of the warm water. These data, therefore, suggest a hypothetical flow system for the warm water in the Artesian City area that has its source as rain and melt water high in the Rock Creek Hills and travels through the rhyolite to wells and springs at the base of the hills (Fig. 16), as indicated by the previously discussed hydrologic and geothermal gradient data.

Irregularities in the boundary between the Rock Creek Hills water and the Lowland water, shown in Figure 10, are probably the result of a combination of factores. These include: (1) differing well depths; (2) possible changes in water compositions during the 30 years these samples were collected, which would in part be the result of increased irrigation with both Snake River and local ground

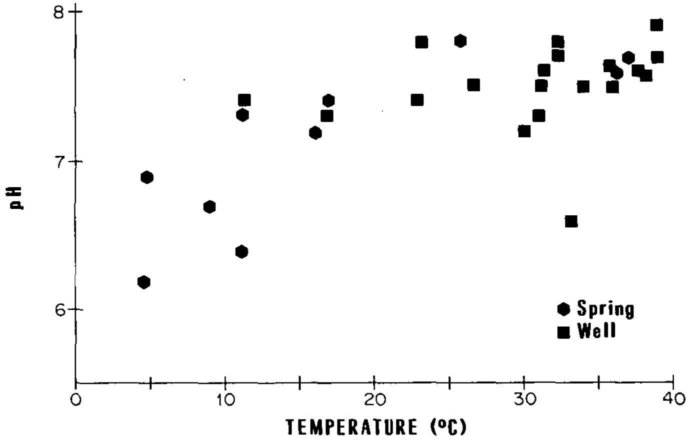
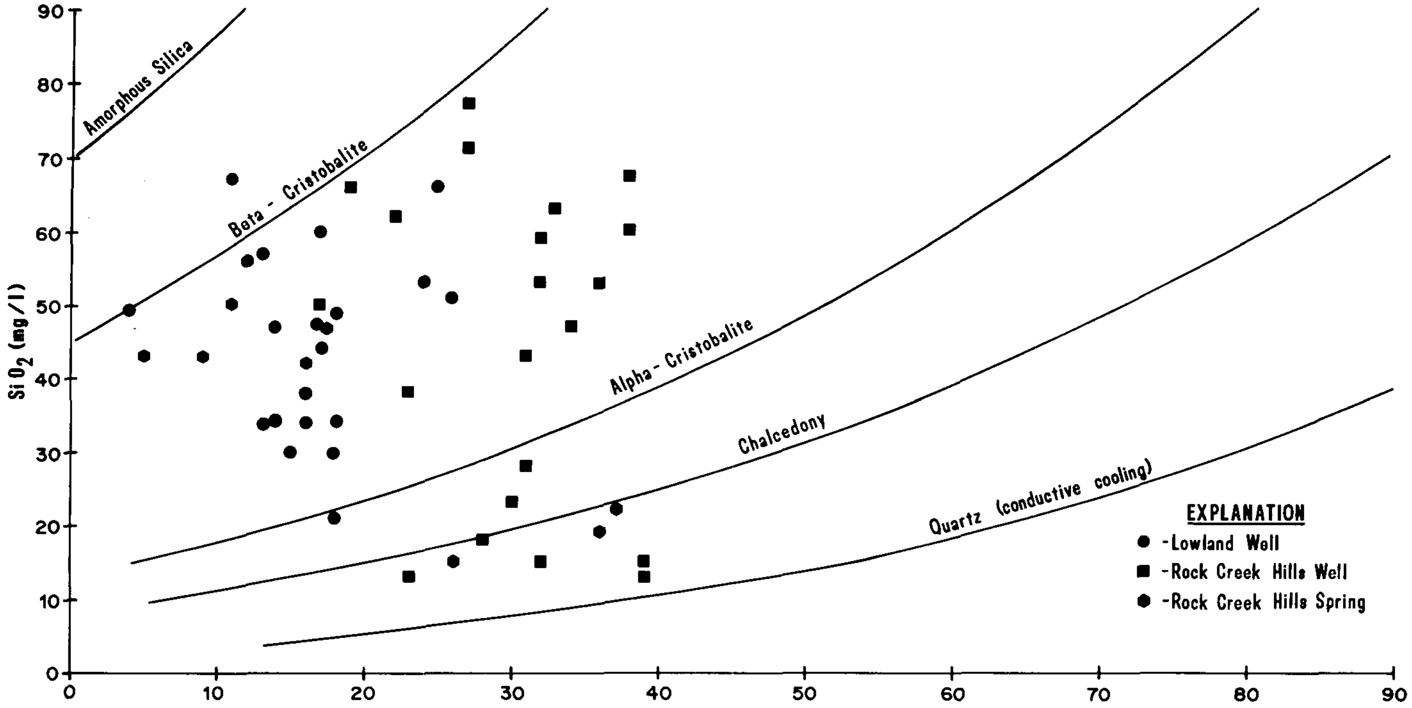


Figure 14. Hydrogen ion concentration versus temperature diagram of Rock Creek Hills water.



CAPUANO, 1980

Figure 15. Silica concentration versus temperature diagram of Lowland and Rock Creek Hills water. Mineral solubilities taken from Fournier (1977).

water; and (3) variations in water compositions dependent on the season of sample collection.

Of the water samples collected, two, wells 30 (11.20.10.dcd) and 85 (11.20.21.dcd) do not fit clearly into either the Rock Creek Hills or Lowland water types. Although these samples have chemistries similar to that of the Lowland water, their high bicarbonate concentrations, of 420 and 435 mg/l, set them apart from this water type. Another water sample which also does not fit well into these water divisions is that collected from well 80 (12.21.1.aaa). This water appears similar in composition to Rock Creek Hills water; however, it is separated from other Rock Creek Hills water wells by over 10 km and occurs in the region where wells tap Lowland water. Well 80 lies on the projection of the Churchill fault, which cuts the Idavada volcanics east of the study area and may carry warm water upward.

Subsurface Temperatures

Geothermometers based on temperature-dependent mineral-fluid equilibria are routinely used to approximate subsurface temperatures of thermal fluids (for example, see Fournier, 1977). The utility of these geothermometers is contingent on the attainment of equilibrium between thermal fluid and the host rock. Achievement of equilibrium conditions between the thermal fluid and host rock is dependent on mineral abundances, their exposed surface area, the kinetics of the dissolution reactions, and duration of water-rock interaction. Calculated geothermometer temperatures can be misleading if the conditions are such that chemical equilibrium is not achieved, the thermal fluid mixes with nonthermal ground water, or, as the fluid cools, it re-equilibrates at the lower temperature. Slow reaction rates at low temperatures, therefore, suggest that these geothermometers may not be applicable in a low-temperature (less than 90 °C as defined by White and Williams, 1975) geothermal system (Fournier, 1973, 1979). If, however, the low-temperature system is a surface expression of cooled waters (nonmixed, nonboiled) from an intermediate- to high-temperature geothermal system, then calculated geothermometer temperatures could be more useful, as in the Icelandic study of Arnorsson (1975).

In this study, geothermometer temperatures were calculated from all water analyses and compared with the hydrologic and geologic data for the area to determine the applicability of these calculated temperatures in estimating subsurface temperatures for these waters. Calculated geothermometer temperatures are listed in Tables 3 and 4. Cation geothermometers employed in this study include the Na-K-Ca (Fournier and Truesdell, 1973, 1974) and Na-K-Ca-Mg (Fournier and Potter, 1979). As suggested by Fournier and Potter (1979) for fluids in which the Mg correction was applicable, the Mg-corrected temperature was used in preference to the Na-K-Ca temperature. Silica geothermometers (Fournier, 1977) have been developed to consider fluid equilibrium with five of the most important SiO_2 polymorphs because of their different solubilities. These include quartz, chalcedony, alpha-cristobalite, beta-cristobalite, and amorphous silica. The temperature dependence of their solubilities is displayed on Figure 15, which is a plot of aqueous silica concentration against temperature. Silica concentrations of well and spring water samples plotted against their collection temperatures are also included on Figure 15. It is apparent from this diagram that the majority of the samples analyzed are supersaturated with alpha-cristobalite, chalcedony, and quartz, while undersaturated with beta-cristobalite and amorphous silica. The silica geothermometer employed for each sample was that of the least supersaturated polymorph, which will predict a minimum geothermometer temperature.

The silica geothermometer temperatures determined in this manner agreed closely with calculated Na-K-Ca(-Mg) temperatures. The agreement between calculated Na-K-Ca(-Mg) and SiO_2 temperatures is within 10 °C for 47% of the samples and within 20 °C for 90% of the samples. The range in geothermometer temperatures for each water group are listed in Table 5 (see footnote 1).

Measured temperatures for all of the water samples collected from the Artesian City area are below 100 °C; therefore, their estimated geothermometer temperatures are suspect, despite the apparent agreement between predicted temperatures of the two geothermometers. Review of the chemical character of these waters in the light of the proposed hydrologic regime of each water type further supports the questionable reliability of these predicted temperatures.

Hydrologic and geochemical data strongly suggest that Rock Creek Hills cold springs produce shallow circulating rain and melt water from the Rock Creek Hills. The low concentration of total dissolved solids in these waters, ranging from 31 to 192 mg/l, supports this suggestion of shallow circulation and, thus, short residence time within the host formation. Therefore, the estimated Na-K-Ca(-Mg) temperatures of as much as 72 °C and SiO_2 temperatures as much as 65 °C are probably too high. The enriched silica concentrations in the cold-spring samples that yield high estimated SiO_2 temperatures are probably the result of rapid dissolution of volcanic glass, characteristically comprised of alpha-cristobalite (Deer and others, 1966), present in the silicic Idavada Volcanics. This is similar to the trend found by Paces (1972) in shallow-circulating cold ground water in granitic rocks. The anomalously high Na-K-Ca(-Mg) temperatures could be due, on the other hand, to nonequilibrium in the cold-spring water as a result of the short residence time of that water within the formation.

Water compositions (except SiO_2), fluid sources, and the range of predicted temperatures (Table 3) of thermal and nonthermal Rock Creek Hills well water are similar to those of the cold spring water. Thus, Na-K-Ca(-Mg) temperatures calculated for the Rock Creek Hills well waters, of as much as 76 °C, may also be too high.

The estimated SiO_2 temperatures for the Rock Creek Hills thermal and nonthermal wells are also suspect. In this case, SiO_2 concentrations in the well waters are believed to be controlled by equilibrium with clay minerals rather than an SiO_2 polymorph as considered by the geothermometer. This is supported, as previously discussed, by the tendency of the pH of this water to be buffered just below 8, a possible result of kaolinite and montmorillonite equilibrium.

Geothermometer temperatures for Lowland water are questioned because their main source of recharge is suggested by hydrologic data to be downward infiltration of irrigation water. This downward-percolating water is most likely not in equilibrium with the formation rock because of concentration by evaporation, reaction with the soil layer, and short residence time in the formation. These conditions could therefore result in the predicted temperatures being too high. Without isotopic data and equilibrium calculations, this interpretation cannot be confirmed.

In conclusion, the estimated temperatures as high as 73 °C for the Artesian City area thermal water and as much as 77 °C for nonthermal water are misleading. Hydrogeologic data indicate that the convergence of the cation and silica geothermometer data is coincidental and does not reflect temperature conditions at depth within the ground-water systems. These waters probably have cooled from temperatures not much higher than their discharge temperatures.

INTEGRATED MODEL OF THE ARTESIAN CITY GEOTHERMAL SYSTEM

The previously discussed geologic, hydrologic, and geochemical data support a hydrogeologic model for the low-temperature geothermal system on the northern perimeter of the Rock Creek Hills. Figures 16A and 16B schematically illustrate this model.

Water temperatures from wells with interpretable drillers' lithologic logs indicate that the warm (28 °C) water flows within the Idavada Volcanics at least 122 m below the top of the formation. Water levels indicate that the warm water moves down-gradient from the highlands of the Rock Creek Hills. The Rock Creek Hills are the only recharge area with an elevation sufficient to sustain the hydraulic head necessary for deep circulation. This deeply circulating and hence warm water contains proportions of cations and anions that are similar to those in the cold spring water of the Rock Creek Hills. These data suggest that the warm and cold waters share a common source of recharge in the Rock Creek Hills.

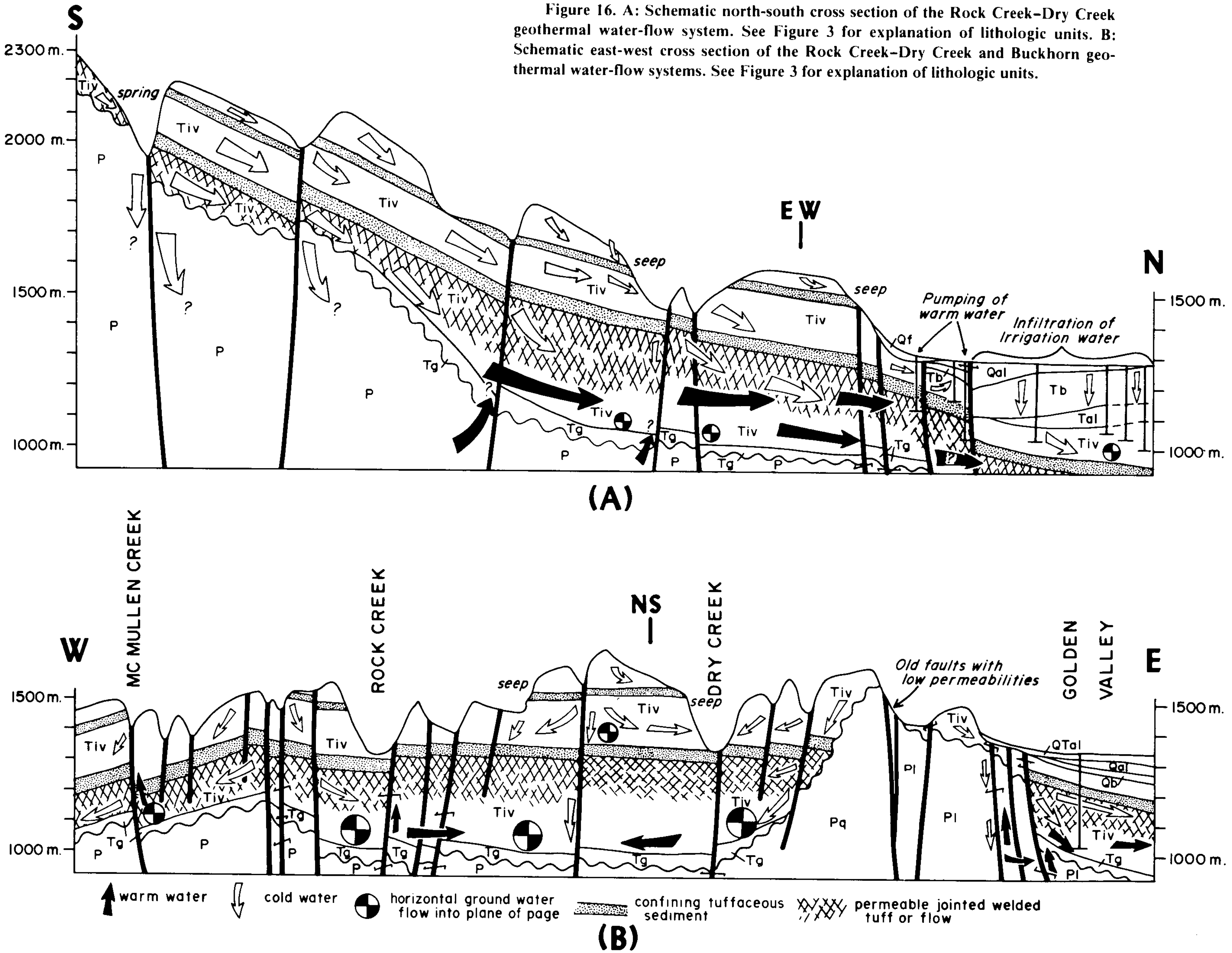
The heaviest precipitation in the Rock Creek Hills falls mostly as snow above the 2,000-m elevation (Crosthwaite, 1969). Snow melt and rain infiltrate both the Idavada Volcanics and Paleozoic rocks exposed in this area through abundant joints, faults, and permeable horizons (Fig. 16A). The relatively impermeable Paleozoic rocks cause the infiltrating water to move laterally along or near the Tertiary-Paleozoic contact. Some of this ground water emerges as cold springs supplying the creeks, whereas the remainder flows northward down the dip of the volcanic strata.

The north-northwest–trending paleomountain ridges of Paleozoic rocks isolate two warm ground-water systems: that of the Rock Creek–Dry Creek drainage area and that of the Buckhorn Creek drainage (Figs. 1 and 16). The ultimate thickness of the Idavada Volcanics, although unknown in the two ground-water systems, is probably sufficient to accommodate circulation to the 540-m depth required to warm water to 39 °C at the inferred local mean thermal gradient of 60 °C/km.

The migration, circulation, and subsequent warming of the ground water probably occur throughout the Idavada Volcanics section and in zones of Paleozoic rocks brecciated by major normal faults. However, the total volume of water flowing within the fault zones is probably much smaller than that flowing in the strata-bound aquifers of the Idavada Volcanics.

The warm-water artesian aquifer appears to be laterally continuous within the Idavada Volcanics along the northern edge of the Rock Creek Hills. Extensive permeable volcanic horizons and numerous vertical northwest- and northeast-striking faults sustain the continuity of the aquifer at least as far north as the east-west–striking range-front faults. Farther north, wells penetrating the Idavada Volcanics beneath the lowlands, both down-dip and down the hydraulic gradient from the east-west faults, do not encounter

Figure 16. A: Schematic north-south cross section of the Rock Creek–Dry Creek geothermal water-flow system. See Figure 3 for explanation of lithologic units. B: Schematic east-west cross section of the Rock Creek–Dry Creek and Buckhorn geothermal water-flow systems. See Figure 3 for explanation of lithologic units.



warm water and do not have high hydrothermal gradients. Although the east-west range-front faults may be acting as vertical conduits for upwelling warm water, high rates of ground-water withdrawal along the mountain front probably cause the lack of warm water within the Idavada Volcanics at shallow depth beneath the lowlands north of the Rock Creek Hills.

The shallow, cold ground water derived from the infiltration of irrigation water in the lowlands has different chemical characteristics from the Rock Creek Hills water and is unrelated to the geothermal system. This ground water includes components of Snake River water infiltrating from the distribution canals as well as water distributed on the fields from wells tapping aquifers in the Idavada Volcanics, the Tertiary basalt, and Quaternary alluvium.

DISCUSSION OF EXPLORATION METHODS

The study of the Artesian City geothermal system utilized several exploration techniques that proved to be effective in defining the hydrogeologic character of the system. Each of the techniques, as used in this study, had shortcomings and may or may not be suitable for the study of other low-temperature geothermal systems. The following comments highlight the strengths and weaknesses of the techniques used or considered in this study.

The reconnaissance nature of the Artesian City study required the rapid acquisition of structural and lithologic data from the literature and the field. Exposures in the upland provided the best opportunity to recognize structures important to the recharge mechanism and others that control the shallow flow and discharge of thermal water. The persistent marker horizons and good exposures within the Idavada Volcanics permitted rapid mapping of three 7.5-minute quadrangles with aerial photos and field checks. These data greatly augmented our ability to interpret the lithologies and structures reported in the drilling records. The stratigraphic model is necessarily general with this reconnaissance approach, but the structural model is fairly complete. However, the geologic data are insufficient for the purposes of selecting drilling sites without a more detailed knowledge of the structure in both the upland and the lowland areas.

Investigations of other geothermal systems will require different amounts of geologic mapping effort, depending upon the complexity of the geology and the extent of previous work in the area. Any study should have sufficient detail to provide a firm understanding of the stratigraphic and structural framework controlling the geothermal system.

The drillers' logs of irrigation wells provided invaluable lithologic and structural information. The drillers' identifications of rock types were generally consistent and interpretable due to the distinct characters of the major rock units. The interpreted drillers' logs were used to construct a contour map (Fig. 5) of the top of the Idavada Volcanics to aid in the structural interpretation of the lowland area. The degree of stratigraphic control on the map is laterally variable due to the irregular distribution of the wells and post-Idavada erosion of the volcanic pile.

The hydrologic data acquired from well records and new observations provide the basic evidence for the size and dynamics of the geothermal system. The production-level data are readily available at minimal cost from drilling records at the Idaho Department of Water Resources. The acquisition of temperatures and water levels requires more careful planning.

The hydrologic data presented in Table 2 were collected largely during August and September 1980 at the end of the irrigation season. This timing was made necessary by contractual commitments and is not optimal for data collection. Water levels could not be measured in pumping wells nor could temperatures be measured in wells already shut down. Farmers were busy with their harvest and less available for comment than at other times of the year. It is recommended that future field studies in this agricultural area be conducted during March or April, before the pumping starts. Water levels would be less disturbed by pumping withdrawals and could be measured in more wells than were available during August and September.

During the collection of water-level data, efforts should be made to collect temperature-depth profiles of existing wells. Isothermal intervals or kicks in the temperature data may indicate producing horizons. These data would circumvent the need to calculate hydrothermal gradients. A hydrothermal gradient map may isolate areas where warm water can be tapped. In addition, the expanded data base could allow for a statistically meaningful estimate of the background thermal gradient. After the water levels and temperature-depth profiles are collected and pumping begins, a second pass through the area to collect water temperatures and samples at the same locations could be made. Downhole temperature data from existing wells appear to be the most useful and cost-effective set of geophysical data in the Rock Creek Hills area. Because ground water may affect the temperature-depth data from all wells in the Rock Creek Hills area, and because there are literally hundreds of wells in the area, no particular gain can be expected from drilling holes specifically for thermal-gradient data.

Long-term variations in water withdrawal demand caution when comparing older water-level and temperature data with newer data. The data obtained prior to the extensive well drilling and ground-water withdrawals that commenced in the 1950s represent a hydrologic setting somewhat different from the present one.

Regional geophysical techniques appear to have little potential to contribute to the conceptual model of the Artesian City geothermal system. The resolution of the published regional gravity and aeromagnetic surveys was insufficient to identify the important structural and lithologic features in the study area.

Detailed gravity data in the foothills and the lowlands may show the trend of and depth to the buried mountain range, where the Paleozoic rocks are more dense than the Idavada tuffs. It is also possible that the susceptibility contrasts between the tuffs and marine rocks would be large enough to warrant a magnetic survey. Even if gravity and magnetic surveys were run, their results would serve only to eliminate certain areas from future study; no wells have tapped warm water in the Paleozoic rocks.

The temperature and salinity contrasts between the warm and cold water are not large enough to justify electrical or electromagnetic surveys. Rock-alteration patterns are not extensive, may be unrelated to the flow of warm water, and are probably indistinguishable electrically from fine-grained sediments and loess. Volcanic terranes, including the Idavada Volcanics and the basalts of the Snake River Plain, contain numerous thin reflective horizons, making seismic surveys difficult to interpret.

The geochemistry of the well- and spring-water samples from the study area were useful in discriminating the waters of differing character and in correlating the waters to different source areas identified by geologic and hydrologic techniques. The trilinear diagram (Fig. 11) is an effective empirical method for categorizing water samples according to their chemical characteristics. The contouring of the water-sample temperatures on the trilinear diagram illustrates that waters having similar chemical characteristics lie within a given temperature range. The chemical and temperature data considered together with known producing horizons in the wells and springs support the flow-system models derived from the hydrogeologic data. Stable isotope data could strengthen these models. However, such data may not be obtainable within the cost and time limitations of a reconnaissance exploration program.

The considerable scatter of analytical values within compositional groupings points to the need for caution. When interpreting the water chemistry, several factors must be considered: the length of ground-water–residence times, lithologic variability within the flow system, and the mixing of waters from different source areas. Changes in the hydrologic regime due to seasonal and long-term climatic variations or water use can also influence water chemistry. Differences in sampling and analytical techniques indicate the need for caution in comparing analyses from different laboratories and of different ages. In addition, the exposure of the ground water to atmospheric CO_2 at shallow depths or within the discharge pipe can affect an analysis for the purpose of plotting on the trilinear diagram. This method requires a large sample population collected over an area extending beyond the boundaries of the geothermal system in question to counter these difficulties and provide statistical reliability.

The silica and cation geothermometers are apparently unreliable for the prediction of the base temperature of the geothermal system at Artesian City. The trilinear diagram, coupled with hydrogeologic data, provides qualitative information as to the history of the waters sampled and, therefore, the degree to which the conditions satisfy the basic assumptions necessary for the successful use of the geothermometers. The technical complexities and time demands required to determine the validity of the various geothermometers employing mineral equilibria calculations make the method generally inappropriate for reconnaissance exploration.

In conclusion, an efficient strategy for the reconnaissance evaluation of a low-temperature geothermal resource should include: the determination of water temperatures in wells and springs to identify the area for exploration; the measurement of ground-water levels to characterize the flow system(s); the calculation of hydrothermal gradients and the collection of temperature-depth data to identify zones of warm-water production; a broad-based geochemical survey to distinguish types and distributions of waters with unique chemical characteristics; and reconnaissance geologic mapping and well-log interpretation to identify the stratigraphic and structural framework controlling the observed flow systems, thereby correlating the water types distinguished with unique source areas. The strategy clearly requires the careful collation of diverse data to develop a sound working model.

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