REPORT OF INVESTIGATION

UTAH GEOLOGICAL AND MINERAL SURVEY

DOE/ET/28393--T1

DE83 001219

No. 174

EVALUATION OF LOW-TEMPERATURE GEOTHERMAL POTENTIAL IN CACHE VALLEY, UTAH

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE. It has been reproduced from the best available copy to permit the broadest possible availability.

A507-77ET28393

by

Janet L. de Vries

November 1982

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

FOREWORD

Under contract with the U. S. Department of Energy (DOE) the Utah Geological and Mineral Survey (UGMS) has been conducting research to advance the utilization of low-temperature geothermal resources in the State of Utah. Activities related to the contract (originally EG-77-5-7-1679 but later changed to DE-AS07-77ET 28393) began on July 1, 1977.

As part of this ongoing Utah Geological and Mineral Survey study, Janet L. deVries was funded to evaluate low-temperature geothermal potential in the Cache Valley, Utah from the period June 1, 1981 to June 1, 1982. This work was done for partial fulfillment of the requirements of a Master of Science degree in geology at the Utah State University.

Robert H. Klauk
Principal Investigator

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

EVALUATION OF LOW-TEMPERATURE GEOTHERMAL POTENTIAL IN CACHE VALLEY, UTAH

Janet L. de Vries

ABSTRACT

The purpose of this research was to continue the assessment of the low-temperature geothermal resources of Cache Valley, Utah initiated by the Utah Geological and Mineral Survey under U. S. Department of Energy (DOE) contract DE-AS07-77ET 28393. Field work consisted of locating 90 wells and springs throughout the study area, collecting water samples for later laboratory analyses, and field measurement of pH, temperature, bicarbonate alkalinity, and electrical conductivity. Na^+, K^+, Ca^{+2}, Mg^{+2}, SiO_2, Fe, SO_4^{-2}, Cl^-, F^-, and total dissolved solids were determined in the laboratory.

Temperature profiles were measured in 12 additional, unused wells. Thermal gradients calculated from the profiles were approximately the same as the average for the Basin and Range province, about 35°C/km. One well produced a gradient of 297°C/km, most probably as a result of a near-surface occurrence of warm water.

Possible warm water reservoir temperatures were calculated using both the silica and the Na-K-Ca geothermometers, with the results averaging about 50-100°C. If mixing calculations were applied, taking

into account the temperatures and silica contents of both warm springs or wells and the cold groundwater, reservoir temperatures up to about 200°C were indicated.

Considering measured surface water temperatures, calculated reservoir temperatures, thermal gradients, and the local geology, most of the Cache Valley, Utah area is unsuited for geothermal development. However, the areas of North Logan, Benson, and Trenton were found to have anomalously warm groundwater in comparison to the background temperature of 13.0°C for the study area. The warm water has potential for isolated energy development but is not warm enough for major commercial development.

EVALUATION OF LOW-TEMPERATURE GEOTHERMAL POTENTIAL IN CACHE VALLEY, UTAH

STATEMENT OF THE PROBLEM

The last decade has seen a massive increase in research directed towards alternate forms of energy. The area of geothermal resources is one of those areas which has gained renewed attention. The Utah Geological and Mineral Survey is presently conducting an inventory and assessment of the state's low-temperature geothermal resources, and this report is a continuation of that project.

The following objectives were accomplished in the process of evaluating the low-temperature geothermal occurrences in Cache Valley, Utah for energy development:

1. Collection and chemical analyses of 90 water samples from wells and springs distributed throughout the study area;
2. Measurement of temperature profiles and calculation of thermal gradients for 12 irrigation and culinary water wells;
3. Use of Na-K-Ca and silica geothermometers, Na-K-Ca ratios, and mixture calculations as tools in evaluating the low-temperature geothermal potential of the study area; and
4. Development of models to explain the occurrences of warm water in certain areas.

STUDY AREA

Cache Valley, Utah is located in the north central portion of the state (Fig. 1) and is bounded by the Idaho border on the north, the Wellsville Mountains, Junction Hills, and Malad range on the west, and the Bear River range on the east. Cache Valley lies in both Utah and Idaho; however this research deals only with the Utah portion of the valley. The approximate boundary of the valley floor was defined by Bjorklund and McGreevy (1971, Plate 2).

Cache Valley, Utah is approximately 56 kilometers long and 26 kilometers wide at the state boundary, covering about 1,165 square kilometers (Williams, 1958; Williams, 1962). It lies completely within the boundaries of Cache County, Utah.

Agriculture and associated businesses are the primary industries in the valley. Much of the land below the Lake Bonneville shoreline, elevation 1,565 meters (5,135 feet), is farmed (Williams, 1958). Cheese production, vegetable canning, trout fishing, and Utah State University also play important roles in the local economy. Logan is the largest city in Cache Valley, Utah.

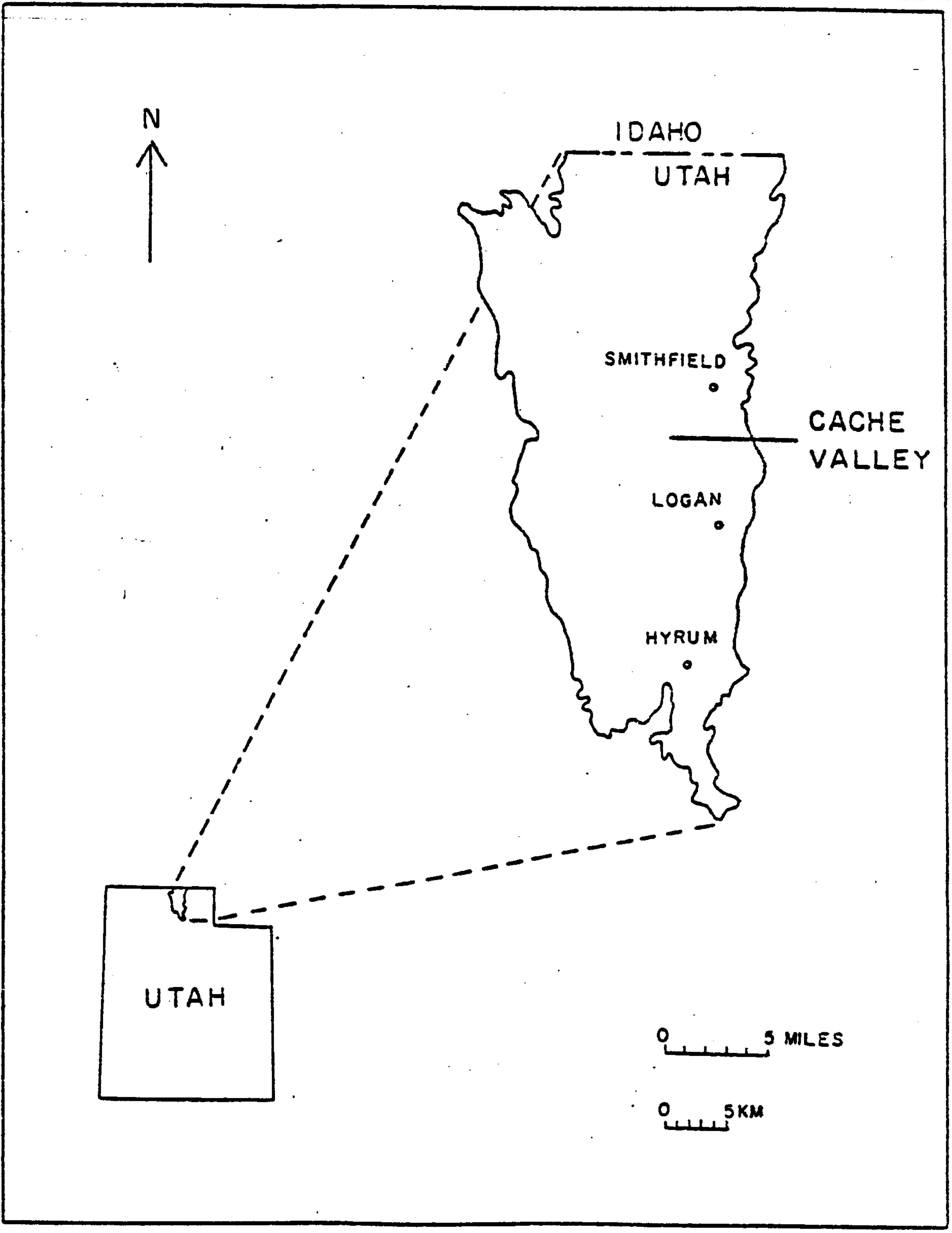


FIG. 1.—Location of study area, Cache Valley, Utah (adapted from Beer, 1967).

PREVIOUS WORKS

The literature review involved compiling information pertinent to the hydrology and geothermal occurrences of Cache Valley, Utah. Other reports, especially Klauk et al. (1981) and personal communications (Darling; Klauk; Kroneman; and Kolesar) concerning analogous investigations were reviewed to establish methods of investigation, presentation, and interpretation.

The groundwater conditions of Cache Valley, Utah have been described by several workers. Peterson (1946) studied the groundwater supply in Cache Valley, Utah and collected data on 1,065 wells in Cache Valley from 1925 to 1943. Data included owners, locality, year in which the well was drilled, depth of the well, size of the pipe, flow rate, height of head, and elevation. Israelson (1952) studied drainage in the Lewiston area of Cache Valley. Williams (1962) mentioned groundwater briefly in his description of the Quaternary geology of Cache Valley, Utah. Beer (1967) conducted extensive research on the groundwater hydrology of southern Cache Valley, Utah, made interpretations about the source and recharge to the Cache Valley groundwater basin, water-level patterns and fluctuations, and calculated a water budget of Cache Valley. McGreevy and Bjorklund (1970) published selected hydrologic data from Cache Valley, Utah and Idaho, and Bjorklund and McGreevy (1971) published an interpretive report providing information for water users and managers in Cache Valley to develop, conserve, and administer their water resources. Stanley (1971) made an integrated geophysical study (gravity, magnetic, seismic reflection, and DC resistivity techniques) related to groundwater conditions along the Utah-Idaho state line in Cache Valley.

Milligan et al. (1966) and Mundorff (1970) studied mineralized and thermal springs in Utah respectively. Milligan et al. (1966) mentioned three springs just north of the Idaho-Utah state line. Energy Services, Inc. (1980) and the Idaho Department of Water Resources (Eastlake, personal communication) have described those hot springs and wells for the purpose of developing the geothermal resources for space heating in the city of Preston, Idaho. Beer (1967) and Bjorklund and McGreevy (1971) briefly discussed groundwater temperatures in Cache Valley in their respective reports. Goode (1978) published a comprehensive report on thermal waters in Utah, with data from 454 wells and 80 springs in Cache Valley. He noted 24 wells with temperatures of 20 to 28°C in the areas of Amalga, Benson, and northwest of Logan, and 50 wells in the Benson area and northwest of Logan having temperatures of 16 to 19°C. One well south of Trenton was reported to have a temperature of 49°C at a depth of 1,587 meters (5,208 feet). Utah Geological and Mineral Survey (1980) located and measured water temperatures of 326 wells and springs in Cache Valley, Utah as their initial assessment of the geothermal potential in the area. The following report is a continuation of that study.

GEOLOGY OF CACHE VALLEY

Cache Valley is a narrow, north-trending basin which lies in north central Utah and southeastern Idaho, on the northeastern edge of the Great Basin. Structurally, the valley is a graben bounded by high-angle normal faults similar to those of the Basin and Range province (Williams, 1962). Cenozoic rocks and sediments up to 2,438 meters thick cover the valley floor, and mountain ranges, formed by the uplifted blocks of Paleozoic rocks, surround the valley.

Williams (1958, 1962) summarized the regional and local geology of Cache Valley. The evolution of the present features of the valley apparently began in the Middle Tertiary and has continued since then, although earlier folding and faulting in the surrounding mountains is assumed (Williams, 1962). Cache Valley was born during the Late Mesozoic Laramide orogeny as a sinking, faulted area between adjacent blocks that continued to stand relatively high. The present valley is underlain by marine and non-marine Paleozoic sedimentary rocks.

The Paleozoic section in the mountains adjacent to Cache Valley, Utah is over 9,144 meters thick and contains no Permian units. Most of the Tertiary and Quaternary deposits in the valley were derived from these rocks, with sandstone, limestone, and dolostone being the most abundant rock types in the Paleozoic section. A considerable thickness of Triassic and Jurassic rocks was eroded as northwest Utah rose during the Late Jurassic, leaving little or no Mesozoic sediments behind in the valley or on the adjacent mountain blocks (Williams, 1962).

Peterson and Oriel (1970) estimated that 2,134 to 2,438 meters of Cenozoic fill lie in two fault-bounded troughs in Cache Valley near the Idaho-Utah state line. Two oil and gas wells show depths to pre-Cenozoic rocks of 1,486 and 1,586 meters (Bjorklund and McGreevy, 1971).

The Tertiary system includes the Wasatch and the Salt Lake Formations. The Early Tertiary Wasatch Formation is unimportant in groundwater considerations in the valley, and is exposed in only a few small areas on the western side of the valley. The Late Tertiary Salt Lake Formation, composed of a lower conglomerate unit, middle tuff unit, and an upper conglomerate and sandstone unit, is widely exposed on the edges of the valley and serves as a confining layer on the sides and bottom of the groundwater basin.

The Quaternary age sediments, predominantly sediments of Lake Bonneville and younger alluvium, serve as groundwater aquifers and as sources of recharge to the groundwater system of Cache Valley. Pre-Lake Bonneville deposits of alluvial fan gravels and landslides are exposed at the edges of the valley. About 100 meters of fluviatile and lacustrine sediments, indicated by well logs, are located in the basin interior, underlying the Lake Bonneville Group. These thick, clay zones are interbedded with gravel and sand zones.

The Lake Bonneville Group consists of the Alpine and Bonneville Formations, undifferentiated, and the Provo Formation, each representing different stages of deposition by Lake Bonneville. The Alpine

Formation consists of lacustrine gravel, sand, silt, and clay, whereas the overlying Bonneville Formation is mostly gravel. The Alpine Formation was deposited while the lake was at the 1,554-meter (5,100 foot) level, and the Bonneville Formation was deposited during the 1,565-meter (5,135-foot) stage, the highest level of the lake (Beer, 1967). The outcrop pattern resembles a modified, discontinuous, concentric band, lying within the Tertiary Salt Lake Formation (Beer, 1967, p. 24). This pattern is modified by the overlying alluvial deposits occupying the central part of the valley along active streams. The Alpine and Bonneville gravels are found as local, discontinuous patches along both sides of the basin, deposited as shore-terrace embankments. The finer sand, silt, and clay formed current-built embankments between the Provo and Bonneville stages of Lake Bonneville.

The youngest formation in the Lake Bonneville Group is the Provo Formation, which was deposited during the Provo stage of Lake Bonneville. It is the most extensively exposed Quaternary formation in Cache Valley and is composed of two informal members, the sand and gravel member and the silt and clay member, which are intertonguing and intergrading lithofacies units of approximately the same age. The gravel and sand member forms many deltas, bars, and spits near the valley's edges. These deltas form important groundwater recharge zones, cover an area of 38.8 square kilometers (15 square miles), and are up to 21 meters (70 feet) thick (Williams, 1962). The silt and clay member was formed by sediment settling from suspension onto the lake bottom, and is exposed mainly in the lowland areas of the valley, especially along the flood plain of the Bear River.

Post-Lake Bonneville deposits, the youngest Quaternary deposits in the valley, include fan gravels, flood-plain alluvium, alluvial sand, and spring tufa cones. The fan gravels are coarse, angular, poorly sorted sediments which have been deposited along the mountain fronts, overlying the silt and clay member of the Provo Formation (Williams, 1962). The flood-plain alluvium, generally sandy, is exposed along the major streams of the valley. The alluvial sand deposits are exposed in the natural levees of the Bear River and constitute some of the best farm land. The spring tufa cones, located west of Trenton, were deposited by warm springs aligned along the face of Little Mountain (Newton Hill) and trend north-northwest for about 1.6 kilometers (1 mile) (Williams, 1962) (Fig. 9). The alignment is probably associated with the Dayton fault zone.

Structural Geology

Williams (1962) inferred Cache Valley to be a graben bounded by north-striking, high-angle normal faults (Plate 1) similar to those of the Basin and Range physiographic province produced by Middle Tertiary faulting. Along the west side of the valley, the Wellsville fault and the Dayton fault zone were located using physiographic evidence (Williams, 1958) and gravity survey data (Peterson and Oreil, 1970). The Wellsville fault is located in the southwestern part of the valley along the mountain front. The Dayton fault zone extends south from Red Rock Pass in Idaho and borders on Bergeson

Hill and Little Mountain (Newton Hill) near Trenton. The Clarkston fault zone is located in the west-central part of the valley at the base of Cache Butte and trends north to Cutler Reservoir.

The East Cache Valley fault zone, composed of north-striking, high-angle normal faults (Williams, 1962), extends along the full length of the east side of the valley. It is inferred to be a graben boundary fault.

Mullens and Izett (1963) mapped a small fault and the axis of an anticline on the Hyrum Bench on the southwestern edge of the valley. These structures do not appear to be part of the East Cache Valley fault zone.

GROUNDWATER OF CACHE VALLEY, UTAH

The Lake Bonneville Group and pre-Lake Bonneville sediments of Quaternary age constitute the groundwater reservoir of Cache Valley. The groundwater basin is lined with more highly consolidated and less permeable rocks of the Tertiary Salt Lake Formation. The two principal aquifers, composed of sand and gravel in the form of ancient deltas and fans, are separated by relatively impermeable lake-bottom clays and silts. These confining layers cause widespread artesian conditions.

The confining beds extend from the center of the valley to the sides, and retard upward movement of the groundwater. Because the confining layers are thin or discontinuous in some areas, leaky aquifer conditions exist. Unconfined aquifers are located along the margins of the groundwater basin where the confining layers are absent. Because the water table is very close to the ground surface and the hydrostatic pressure pushes water through the semi-confining layers, water-logged soil conditions also occur, especially in the central part of the basin. Two thirds of the valley is under artesian conditions (confined aquifer), and the remaining one third has water-table conditions (unconfined aquifer) (Beer, 1967). Local perched groundwater bodies are also common in many parts of the valley (Bjorklund and McGreevy, 1971).

Recharge of the principal groundwater reservoir occurs by inflow from the bedrock aquifers of the watershed, infiltration from streams, canals, and irrigation ditches, and from precipitation. The most important recharge area is along the valley margins where confining layers do not exist. Water entering along the mountain front of the Bear River range moves westward toward discharge areas in the lower part of the valley. Water entering the valley fill along the southwestern margin discharges from large springs near Wellsville and Mendon (Bjorklund and McGreevy, 1971).

The valley is generally an overflowing basin with apparently stabilized water levels. The equilibrium water-level configuration is saucer-shaped and generally parallels the valley perimeter. This shape reflects the variability of the aquifer permeability and the rate of recharge (Beer, 1967). Seasonal fluctuations in the groundwater level occur due to irrigation and snow melt, although the change from abnormal to equilibrium conditions is rapid.

Groundwater Districts

Bjorklund and McGreevy (1971) divided Cache Valley, Utah and Idaho into 11 areas where groundwater conditions are generally similar. Seven of those districts are located in the study area and will be described here. Outside the individually discussed areas, groundwater occurs in slope wash and alluvium, in the sandstone and conglomerate of the Salt Lake and Wasatch(?) Formations, and in fractures and solution openings in older rocks.

A single, complex aquifer system in the Smithfield-Hyrum-Wellsville area (Area 1, Fig. 2) was formed by coalescing coarse fan and delta deposits of Summit Creek, Logan River, Blacksmith Fork,

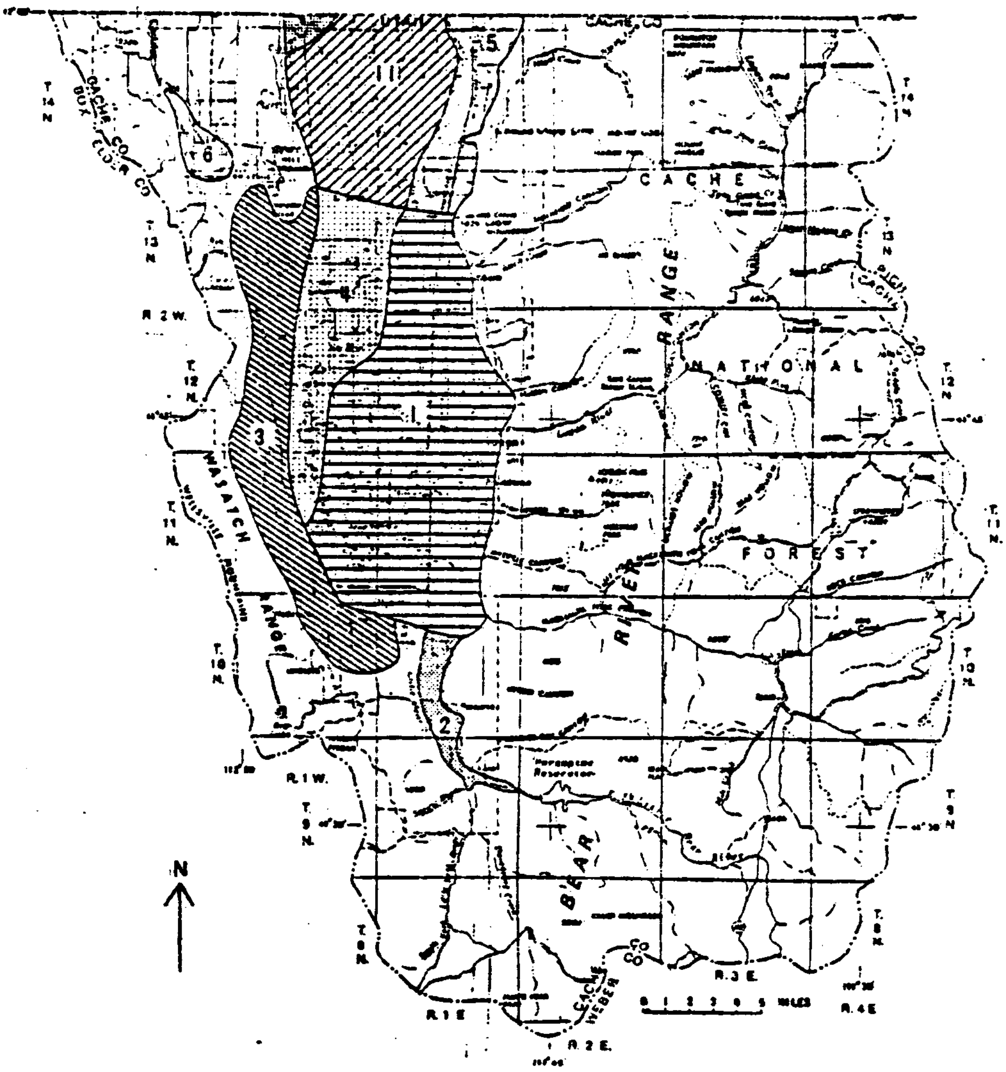


FIG. 2.--Groundwater districts in Cache Valley, Utah. Numbers correspond to areas discussed in the text. Areas 7-10 are located in Cache Valley, Idaho (Bjorklund and McGreevy, 1971).

and Little Bear River. Near Logan the aquifer is almost 305 meters thick, with coarse materials near the mountain front becoming finer toward the center of the valley. This aquifer system is the largest and most productive in Cache Valley and has exhibited little long-term change over 34 years of record (Bjorklund and McGreevy, 1971), although seasonal fluctuations do occur as a result of irrigation. The quality of the water is generally good.

The Little Bear River Area (Area 2, Fig. 2) is located along the flood plain and terrace of the Little Bear River, south of Hyrum. Thin deposits of gravel, less than 10 meters thick, overlie fine-grained material, and these unconfined aquifers are recharged by seepage from streams and canals and from irrigation. The chemical quality of the water is good.

The groundwater conditions from Wellsville to Newton (Area 3, Fig. 2) on the west side of the valley are poorly known. The Quaternary fill, of variable thickness, is mostly underlain by Tertiary rocks. The fill is generally fine grained with low permeability and yield. Groundwater is both confined and unconfined.

Area 4 (Fig. 2) covers the central part of the valley along the lower part of the Little Bear River, the Benson area, as well as the Barrens. The Quaternary sediments are primarily clay and silt with some thin, confined beds of sand and gravel. Most wells in the Benson area produce from a depth of 91 to 283 meters and have high artesian pressures (up to 19 meters above the ground surface). Total dissolved solids (TDS) in the Little Bear River area range from 400 to 800 mg/1, similar to that of the Wellsville to Newton area. In the

Benson and Barrens areas, the concentration of TDS is as high as 1,200 mg/l.

The Cub River subvalley (Area 5, Fig. 2) aquifer system extends along the Cub River from Franklin, Idaho to Richmond, Utah. The Quaternary deposits of interbedded clay, silt, sand, and gravel overlie Tertiary conglomerate in most of this area. The gravel and sand beds are thin and moderately permeable. The groundwater is mostly confined, and water levels are fairly stable.

The sand and gravel deposits in the Clarkston area (Area 6, Fig. 2) yield water to very few wells. Little is known about the water-bearing materials.

The principal water bearing materials in the Fairview-Lewiston-Trenton area (Area 11, Fig. 2) are reworked sands and silts from the Bear River delta. Groundwater is unconfined and near the land surface, necessitating the installation of drains at some locations. Many shallow wells were once used for culinary water, but most have been destroyed in favor of public-water systems.

DATA COLLECTION

Purpose

Chemistry.--Water samples were collected from wells and springs throughout Cache Valley, Utah (Plate 1) for the purpose of chemical analysis. The chemistry of the water may be used as a tool in evaluating low-temperature geothermal occurrences for energy development by applying the silica and Na-K-Ca geothermometers. Previous chemical analyses of groundwater in Cache Valley are available (McGreevy and Bjorklund, 1970), however, these data are inconsistent in their collection and analytical procedures.

Thermal gradients.--Because there were no thermal gradient data available for Cache Valley, Utah and because heat flow data is useful for geothermal evaluation, thermal gradients were measured in selected wells in various parts of the valley (Plate 1). The thermal gradient data collected in Cache Valley, Utah will provide some insight into local thermal gradients.

Field Sampling Procedures

Wells and springs chosen for sampling were selected primarily on the basis of two factors: (1) known temperatures; and (2) data collected by the Utah Geological and Mineral Survey during 1980 for the initial assessment of groundwater temperatures with regard to geothermal potential in Cache Valley, Utah. The warmest wells found in the 1980 survey were selected for sampling in this study. Water sampling and on-site analyses were done in accordance with Utah Geological and Mineral Survey field procedures (Darling, 1981; Kroneman, 1981) in order to insure consistency with the on-going investigation of low-temperature geothermal resources in the state of Utah presently being carried out by the Utah Geological and Mineral Survey.

Samples were collected as close as possible to the wellhead or spring orifice. In the case of wells, care was taken to assure that the water was fresh from the aquifer, avoiding water which had been standing in the casing for a long period of time. A total of 90 samples was collected.

The on-site analyses and data collection consisted of: (1) pH; (2) alkalinity; (3) temperature; (4) conductivity; and (5) Eh.

Pressure filtration of the water was accomplished with a GeoFilter Peristaltic Pump, Model #004, using a 0.45 micron pore size filter membrane. Three 570 ml polyethylene bottles were filled with filtered water at each location. One bottle was acidified with reagent grade HNO_3 to a final concentration of 20% HNO_3 for later analysis of Na^+, K^+, Mg^+, and Fe; a second bottle was acidified with concentrated HCl to a final concentration of 1% HCl for Ca^{+2} and SO_4^{-2} analyses; the third bottle, used for Si, Cl^-, F^-, and total dissolved solids (TDS) determinations, had no additives. The concentrations of the additives were consistent with those required by the Earth Science Laboratory (ESL), Salt Lake City, Utah, where the Utah Geological and Mineral Survey water samples are analyzed (Kroneman, 1981).

A Markson Digital pH/Temperature Meter and an Orion gel-filled combination pH electrode, Model 91-05, were used to measure pH. The average of three readings was recorded as the final value.

Alkalinity in water is the ability to neutralize acid and is reported in terms of equivalent amounts of calcium carbonate ($CaCO_3$) when using the Hach Titration Method of Alkalinity (Hach Chemical Company, 1975). Alkalinity is primarily a function of carbonate (CO_3^{-2}), bicarbonate (HCO_3^-), and hydroxide (OH^-) concentrations, although the amount of hydroxide present rarely affects alkalinity determinations (Rainwater and Thatcher, 1960).

The Hach Titration Method of Alkalinity (Alkalinity Test Kit, Model ALAP) was used to analyze for alkalinity at each location. Brom cresol green-methyl red was used as an indicator, and a standard solution of 0.030 N sulfuric acid was titrated directly into 15 ml of sample. The indicator changed from green to red when the alkalinity was neutralized, and the number of drops of acid equaled alkalinity expressed as grains $CaCO_3$ per gallons of solution, ± 5%.

The preferred expression for alkalinity is mg/l HCO_3^-. The value mg/l HCO_3^- is derived from the following relationship:

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{+2} + 2HCO_3^-$$

and is calculated as:

Alkalinity (expressed as HCO_3^-, but also including H_2CO_3 and CO_3^{-2}) =

$$\frac{\text{grains/gal } CaCO_3}{\text{volume factor}} \times \frac{17.1187 \text{ mg/l}}{1 \text{ grain/gal}} \times \frac{122.0122 \text{ g/2 moles } HCO_3^-}{100.0782 \text{ g/l mole } CaCO_3}$$

A volume factor of 2.5 was used to calculate alkalinity. A 15 ml sample, rather than the standard 6 ml sample, was required to minimize the error at the relatively low concentration levels observed, i.e., 150 to 400 mg/l HCO_3^-.

Finally, the above quantity was adjusted for the effect of pH, because the concentrations of carbonate species vary with pH (Krauskopf, 1979, p. 42). The alkalinity values in this report are expressed as mg/l HCO_3^- and have been adjusted for the pH at each location.

A YSI Model 33 Temperature-Conductivity Meter was used to measure temperature and conductivity. Measurement uncertainties due to the meter are estimated to be ± 0.6°C and 4.5% of the conductivity measurement. Conductivity (electrical conductance) is the ability of a substance to conduct an electrical current and is measured in micromhos. The presence of charged ionic species in a solution makes the solution conductive, therefore, the conductance measurement provides an indication of ion concentration (Hem, 1970). In Cache Valley, the ratio of total dissolved solids in mg/l to conductivity in mmhos is 0.6:1 (Bjorklund and McGreevy, 1971). This ratio is dependent upon the aquifer and chemical constituents in the water.

Eh measurements were taken at 42 locations using an Orion Platinum Redox Electrode, Model 96-78, with a Markson Digital pH/Temperature Meter, Model 90. A direct measurement in millivolts was recorded. Eh values are necessary for water-rock equilibrium calculations. This information was collected at only 42 of 90 locations because the equipment was not available when the research commenced.

Thermal Gradients

Temperatures in unused water wells were measured with a thermistor probe in combination with a Digital Multimeter, Model 2530-A2, essentially the same as described for the portable mode in Sass et al. (1971). The resistance (R) of the thermistor varies with temperature (°C) according to the equation:

$$\log R = A + B/T + C/T^2$$

where A, B, and C are calibration constants.

Measurement uncertainties resulting from the equipment and techniques are estimated to be ± 1 ohm and ± 0.01°C in resistance and temperature values respectively (Sass et al., 1971).

It was difficult to find deep (greater than 300 m), nonflowing, unused wells in Cache Valley, especially since most of the wells toward the center of the valley are artesian. Artesian flow causes the water to be isothermal throughout the well. All of the wells used in this investigation were drilled in Quaternary alluvium or the Tertiary Salt Lake Formation with the intention of intersecting aquifers. Perforations in the casing at the aquifers can cause disturbed water, resulting in isothermal temperature profiles.

Temperature surveys were taken in 12 unused, cased irrigation and culinary water wells throughout Cache Valley, Utah during September, 1981 and February, 1982. Temperatures were measured at 10 m intervals. The probe was allowed to equilibrate with its surroundings for 5 to 20 minutes before recording the thermistor resistance.

Laboratory Analyses and Procedures

Concentrations of Na^+, K^+, Mg^{+2}, Ca^{+2}, Si and Fe in mg/l were determined with a Perkin-Elmer Atomic Absorption Spectrophotometer, Model 303, using standard methods (Perkin-Elmer Corp., 1973). Na^+, K^+, Mg^{+2}, Ca^{+2}, and Fe were determined using an air-acetylene flame, whereas Si was determined using a nitrous oxide-acetylene flame. Fe was reported as total iron content because the oxidation state could not be determined.

Chloride.--The chloride activity of the water samples was determined using an Orion Chloride Electrode, Model 94-17, with a Markson Digital pH/Temperature Meter, Model 90. The direct measurement method was used by preparing a set of 10, 100, and 1000 mg/l Cl^- standards and plotting their electrode potentials (millivolts) on a semilogarithmic scale. One milliliter of ionic strength adjustor was added to each 50 ml of standard and sample to maintain a constant background ionic strength, and the electrode potential for each sample was recorded. Activities of Cl^- in mg/l were then determined from the curve derived from the standards.

Fluoride.--The fluoride activity in the water samples was measured using an Orion Fluoride Electrode, Model 94-90, and a Markson pH/Temperature Meter, Model 90. The method of known additions was used. The electrode potential (activity) of the free fluoride ions in the sample was measured in millivolts (mv), then 5 ml of 10 mg/l F^- standard were added to 50 ml of the sample, and the new electrode potential was recorded. The change in potential, ΔE corresponded to a concentration ratio, Q, given in the known additions table provided with the probe. The original total sample activity, C_o, was calculated as follows:

$$C_o = QC_s$$

where C_o = total sample activity in mg/l, Q = value from the known additions table, and C_s = activity of added standard.

Approximately 1 gram of ammonium citrate, $(NH_4)_2HC_6H_5O_7$, was added to 50 ml of sample as an ionic strength adjustor. The main purpose was to decomplex the fluoride, because only the electrode potential of free fluoride ions can be measured. The ammonium citrate also helped to maintain a constant background ionic strength.

Sulfate.--Concentrations of sulfate ion, SO_4^{-2}, were determined using the standard Turbidimetric Method using SulfaVer IV Sulfate Reagent by Hach Chemical Company (1975) and a Varian Series 634 UV-Visible Spectrophotometer. A 2,000 mg/l SO_4^{-2} solution was prepared by dissolving 1.4797 g of dried, anhydrous Na_2SO_4 in 500 ml of 1% HCl. A series of standards containing 10, 25, 50, 75, and 100 mg/l SO_4^{-2} was prepared by diluting portions of the original solution. A premeasured packet of SulfaVer IV Sulfate Reagent was dissolved in each sample and standard, and after 5 minutes, the absorption was measured at a wavelength of 450 nm. Absorption of each of the standards was plotted on standard graph paper, and with the measured absorption of each water sample, concentrations of SO_4^{-2} were read from the graph.

Total dissolved solids.--Total dissolved solids (TDS) were measured by evaporating 50 ml of untreated, filtered sample. Empty beakers were labeled and dried in a drying oven at approximately 110°C for an hour, cooled in a desiccator, then weighed. Fifty ml of sample were pipetted into a beaker, and the beaker was placed in the drying oven at less than 90°C until all of the water had evaporated. The beaker was then heated to approximately 110°C for another hour to insure that the glassware had not adsorbed any water. After cooling in a desiccator, the beakers were weighed. The difference in weight was the TDS expressed as grams TDS/50 ml water. This value was converted to mg/l by multiplying by 20,000.

RESULTS

Temperature

Temperatures of the 90 wells and springs sampled ranged from 9.9°C to 50.1°C, with a mean of 14.4°C. The mean of 313 wells and springs collected by the Utah Geological and Mineral Survey (1980) is 13.5°C. The temperatures of known warm springs and temperatures of questionable reliability were excluded when the mean calculations were made. The mean temperature for the data in this report is higher than that of the Utah Geological and Mineral Survey's data due to the biased selection procedure used for this study. The warmest wells and springs in each area were selected for sampling based on the Utah Geological and Mineral Survey temperatures. The background temperature for groundwater in Cache Valley, Utah is about 13.0°C. This temperature was derived from a histogram of the study data and the Utah Geological and Mineral Survey values, and it can be used for determining anomalous water temperatures. The temperature of each well or spring is listed in Appendix III; Plate 1 (p. 98) shows groundwater temperatures in the study area.

The three areas in Cache Valley, Utah with anomalous water temperatures are: (1) North Logan, where temperatures range from 16.0°C to 25.1°C; (2) Benson, where temperatures range from 13.5°C (Utah Geological and Mineral Survey, 1980) to 23.0°C; and (3) Trenton, which has evidence for past and present warm spring activity, with temperatures ranging from 22.9°C to 50.1°C.

Thermal Gradients

Gradients were calculated using linear regression, and topographic corrections were not employed. Figures 3 and 4 show the measured temperature profiles. Table 1 gives an overview of the thermal gradient data, and Appendix II includes the details of each location. The locations of the gradient wells are shown in Plate 1.

The 12 thermal gradients ranged from 15°C/km to 297°C/km. Three of the wells yielded isothermal temperature profiles, indicating primarily convective heat flow. Lower gradients (15-29°C/km) and isothermal temperature profiles appear to be grouped in the southern part of the valley (Paradise, Hyrum, Mt. Sterling, and River Heights).

The higher gradients (31-297°C/km) are located in the northern part of Cache Valley, Utah (Smithfield, Logan, Richmond, Clarkston, and Trenton). The highest gradient measured was 297°C/km in a well in Logan. This anomalous gradient correlates positively with the warm water found in the North Logan area.

The reliability of several gradients, especially those in the southern part of the valley, is questionable due to shallow depths of the wells. Water and air entering through the perforations in the casing may cause disturbances in the temperature profile, making gradient calculations difficult. These disturbances are consistent with the findings of Darling (1982), who found that thermal gradients from irrigation wells in northwestern Utah varied greatly in quality

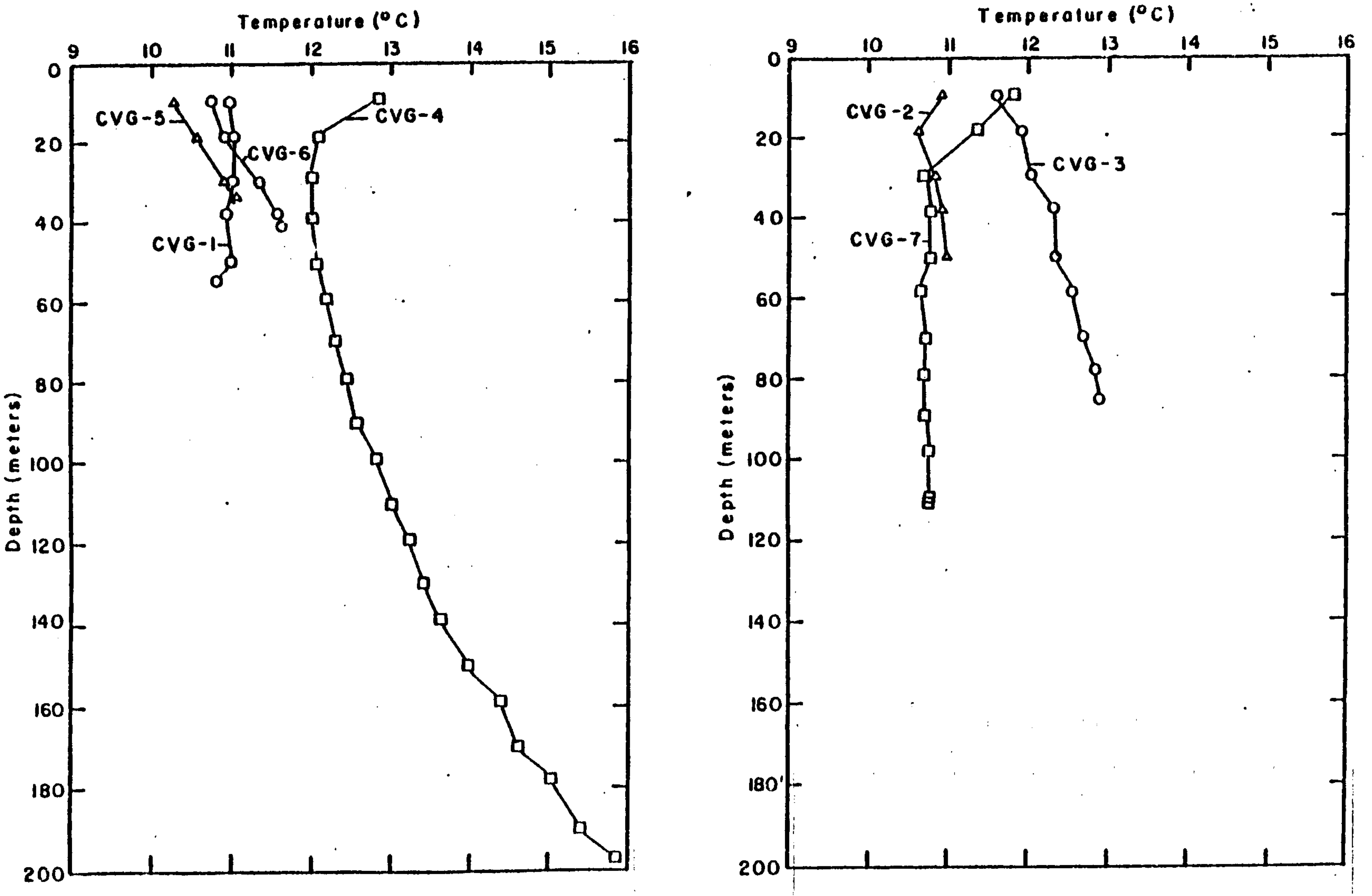


FIG. 3.--Temperature profiles of wells located in southern Cache Valley, Utah.

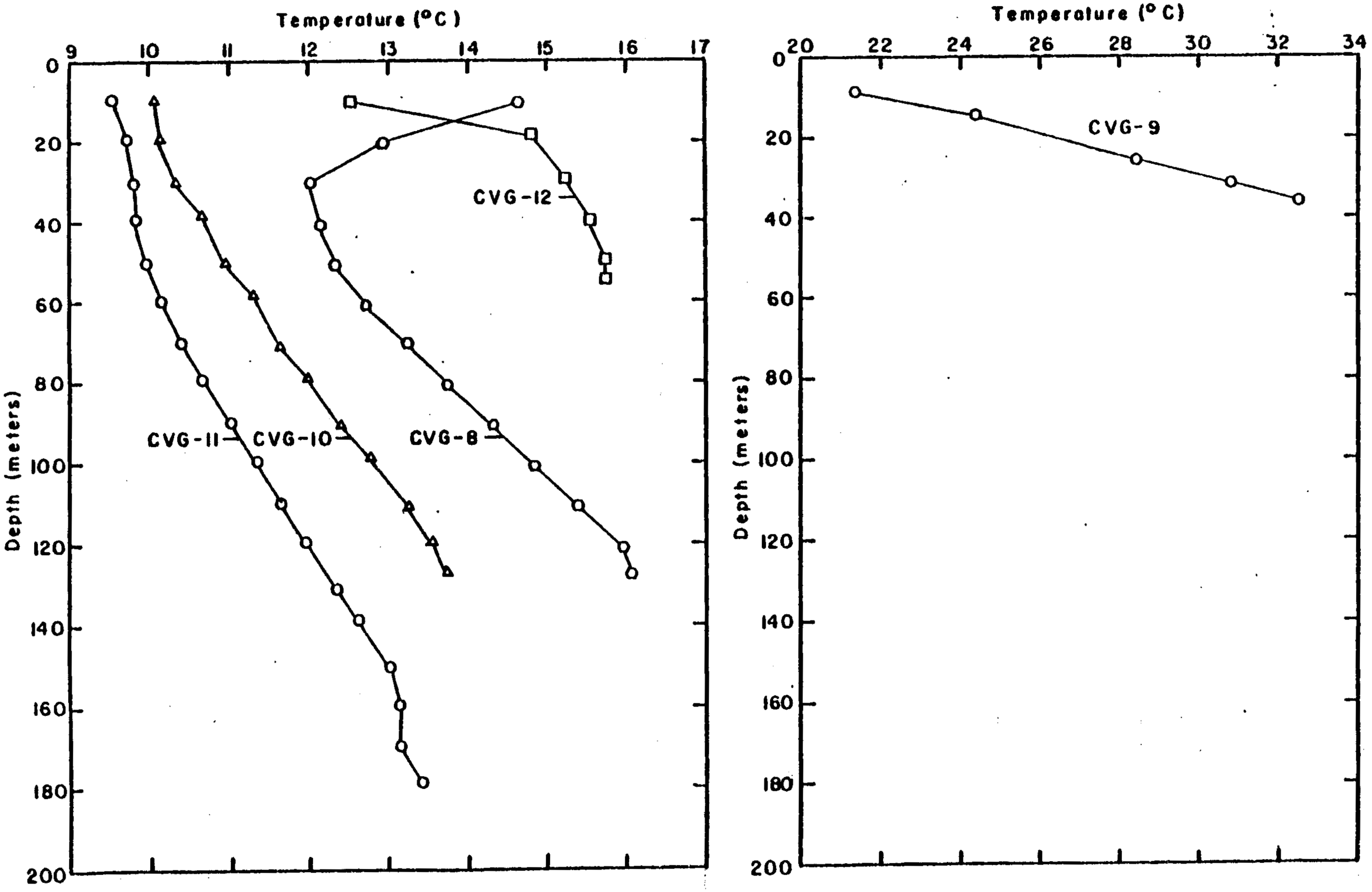


FIG. 4.--Temperature profiles of wells located in northern Cache Valley, Utah.

TABLE 1.--Thermal gradient data, Cache Valley, Utah

Locality	Site	N. Latitude	W. Longitude	Elevation (m)	Depth Range (m)	Gradient (°C/km)	Heat Flow* (mW/m^2)
Paradise	CVG-1	41°34'56.5"	111°48'44"	1591 ± 6	19-49	isothermal	--
Paradise	CVG-2	41°34'25.5"	111°48'53"	1567 ± 6	19-49	isothermal	--
Hyrum	CVG-3	41°36'36"	111°50'48"	1466 ± 3	19-79	15 ± 1	23
Millville	CVG-4	41°41'07.5"	111°48'12"	1581 ± 3	169-199	40 ± 1	60
Mt. Sterling	CVG-5	41°36'26"	111°54'24"	1466 ± 3	19-39	29 ± 2	44
Avon	CVG-6	41°32'00"	111°48'46"	1530 ± 6	19-39	32 ± 4	48
River Heights	CVG-7	41°43'24"	111°49'05"	1399 ± 6	29-109	isothermal	--
Smithfield	CVG-8	41°49'02.5"	111°48'31"	1417 ± 6	50-120	52 ± 1	78
Logan	CVG-9	41°45'23.5"	111°48'48"	1408 ± 6	23.5-37.5	297 ± 45	456
Richmond	CVG-10	41°56'27.5"	111°51'21"	1385 ± 1	29-125	36 ± 1	54
Clarkston	CVG-11	41°59'32"	112°05'23"	1588 ± 6	49-149	31 ± 1	47
Trenton	CVG-12	41°55'12.5"	111°57'56"	1392 ± 3	19-39	36 ± 1	54

*Based on an estimated thermal conductivity of 1.5 watts/m°C.

since they were sited in alluvium and were intended to intersect aquifers.

Wells CVG-1, CVG-2, and CVG-7 were isothermal, with their water temperatures generally between 10.67°C and 11.01°C. Isothermal temperature profiles (Fig. 3) indicate convective heat flow and hide the true conductive gradient. CVG-3 has a gradient of 15°C/km. This value is of questionable reliability because the well is shallow and because it is low in comparison to the average Basin and Range thermal gradient of 35°C/km, where gradients range from approximately 30 to 58°C/km (Chapman, personal communication). More gradient measurements in this area would prove useful in determining whether or not there is actually a relatively low thermal gradient in this area of the valley.

The temperature profile of CVG-4 (Fig. 3) has two inflection points, hence three apparent gradients. The gradient calculated between 169 and 199 meters, 40°C/km, is probably the most representative since it is at the deepest part of the well. Two possible explanations for the three gradients in CVG-4 are: (1) temperature measurements were made in air rather than water; and (2) the diameter of the casing is quite large (25.4 cm). Both factors make equilibration of the thermistor with the surroundings more difficult. It is unlikely that distinct aquifers are producing more than one thermal gradient because the driller's log (Appendix II) does not indicate water until a much greater depth. The lithologies cut by the well are fairly uniform, therefore this factor should not produce zones with distinctly different thermal conductivities and thermal gradients.

CVG-6, CVG-5, and CVG-12 have gradients of questionable reliability due to the small range (20 m) over which the calculations were made. All three are relatively shallow holes (< 54 m) drilled in alluvium for the purpose of irrigation and culinary use.

CVG-11, CVG-10, and CVG-8, all in the northern part of Cache Valley, Utah, have reliable thermal gradients of 31°C/km, 36°C/km, and 52°C/km, respectively, because they were all calculated over a wide depth range (Fig. 4). CVG-9, located in the North Logan warm water area, has a gradient of 297°C/km. The temperatures measured at this location range from 21.36°C to 32.54°C, higher than any other temperatures encountered in gradient holes. This result is consistent with the warm water found in the North Logan area, although this gradient is probably not the true gradient for the area.

The thermal gradient data collected in Cache Valley, Utah will provide some insight into local thermal gradients. However, definite conclusions regarding geothermal potential cannot be drawn due to the sparcity of data, the questionable reliability of some gradients, and the lack of thermal conductivity measurements for the alluvium in which the wells were drilled, which would allow for accurate heat flow determinations.

Using 1.5 watts/m°C for the average thermal conductivity of alluvium (Chapman, personal communication), heat flow values were calculated for Cache Valley, Utah based on the thermal gradients measured (Table 1). Values ranged from 23 to 78 mW/m^2 (456 mW/m^2 at CVG-9), compared to the estimated heat flow values for Cache Valley of 63 to 105 mW/m^2 (Lachenbruch and Sass, 1978) and the average Basin and Range heat flow of 90 to 100 mW/m^2 (Chapman, personal communication).

The relatively low heat flow values calculated for Cache Valley may be the result of unreliable thermal gradients or incorrect estimates for the thermal conductivity. The control points for the heat flow estimates of Lachenbruch and Sass (1978) for Cache Valley are far from the valley, so their values may not be accurate. More data must be gathered to make definite conclusions about the heat flow of the area.

Chemical Analyses

Table 2 lists the minimum, maximum, mean, and standard deviation of the chemical attributes analyzed. All of the chemical data, as well as other descriptive information about each location, are found in Appendix III. Blanks indicate that the information was not gathered or was unavailable. All chemical analyses were performed by the author unless otherwise indicated.

Chemical balance calculations were made to compare milliequivalents of cations to anions and measured total dissolved solids (TDS) to calculated TDS. These calculations were performed to double check the reliability of the analyses. A 10% difference between the values was acceptable, 15% was questionable, and greater than 15% was unacceptable without an explanation (Kroneman, personal communication). Fifteen samples with unacceptable errors were reanalyzed by Kroneman at the Earth Science Laboratory, Salt Lake City, Utah, and the results remained in the unacceptable error

TABLE 2.--General water chemistry data. All values are mg/l unless otherwise indicated. F^- and Cl^- are activities.

	Minimum	Maximum	Mean	Standard Deviation
SiO_2	4.0	69.0	21.5	15.6
Fe	0.0	4.5	0.5	0.8
Ca^{+2}	7.0	150.0	73.1	28.3
Mg^{+2}	4.0	108.0	28.7	18.3
Na^+	3.0	1500.0	89.5	225.4
K^+	0.3	130.0	7.6	18.0
HCO_3^-	124.0	842.0	270.8	107.1
SO_4^{-2}	0.0	202.0	21.1	36.7
Cl^-	5.0	2400.0	159.1	379.2
F^-	0.0	4.5	0.5	0.7
TDS	202.0	4466.0	578.8	660.3
Cond. (mmhos)	180.0	9500.0	834.4	1356.0
pH	6.7	7.8	7.1	0.2

range, which leads the author to conclude that her lab procedures were acceptable and reproducible. The high errors may be the result of one or more of the following: (1) the presence of unanalyzed ions such as nitrates and phosphates, which are common in fertilizers used in agriculture; (2) combined small errors in pH and alkalinity which produce a much larger error in the reported bicarbonate (HCO_3^-) value; and (3) the relatively small concentrations of ions in the samples which result in a comparatively large relative error. Most of the samples with high errors had greater measured total dissolved solids (TDS) than calculated TDS which supports the suggestion that there are unanalyzed ions in the water.

An effort was made to group the chemical analyses using: (1) the Piper diagram (Hem, 1970, p. 269); and (2) the Clustar cluster analysis program (Romesburg and Marshall, 1980) using the average Euclidean distance, d_{jk}.

The Piper trilinear diagram in Figure 5 is based on percentage of total milliequivalents of either anions or cations per liter. Thus, the $Na^+ + K^+$ value represents the percentage of $Na^+ + K^+$ relative to the total cation milliequivalents ($Na^+ + K^+ + Ca^{+2} + Mg^{+2}$). The $CO_3^{-2} + HCO_3^-$ value is the percentage of $CO_3^{-2} + HCO_3^-$ relative to the total anion milliequivalents per liter ($CO_3^{-2} + HCO_3^- + Cl^- + SO_4^{-2}$). The percentages referred to in the following discussion will be those calculated as described above, not percentage of the total analysis.

The Piper diagram was used to divide the wells and springs into three groups, except for wells CVV-36 and CVV-72, which do not

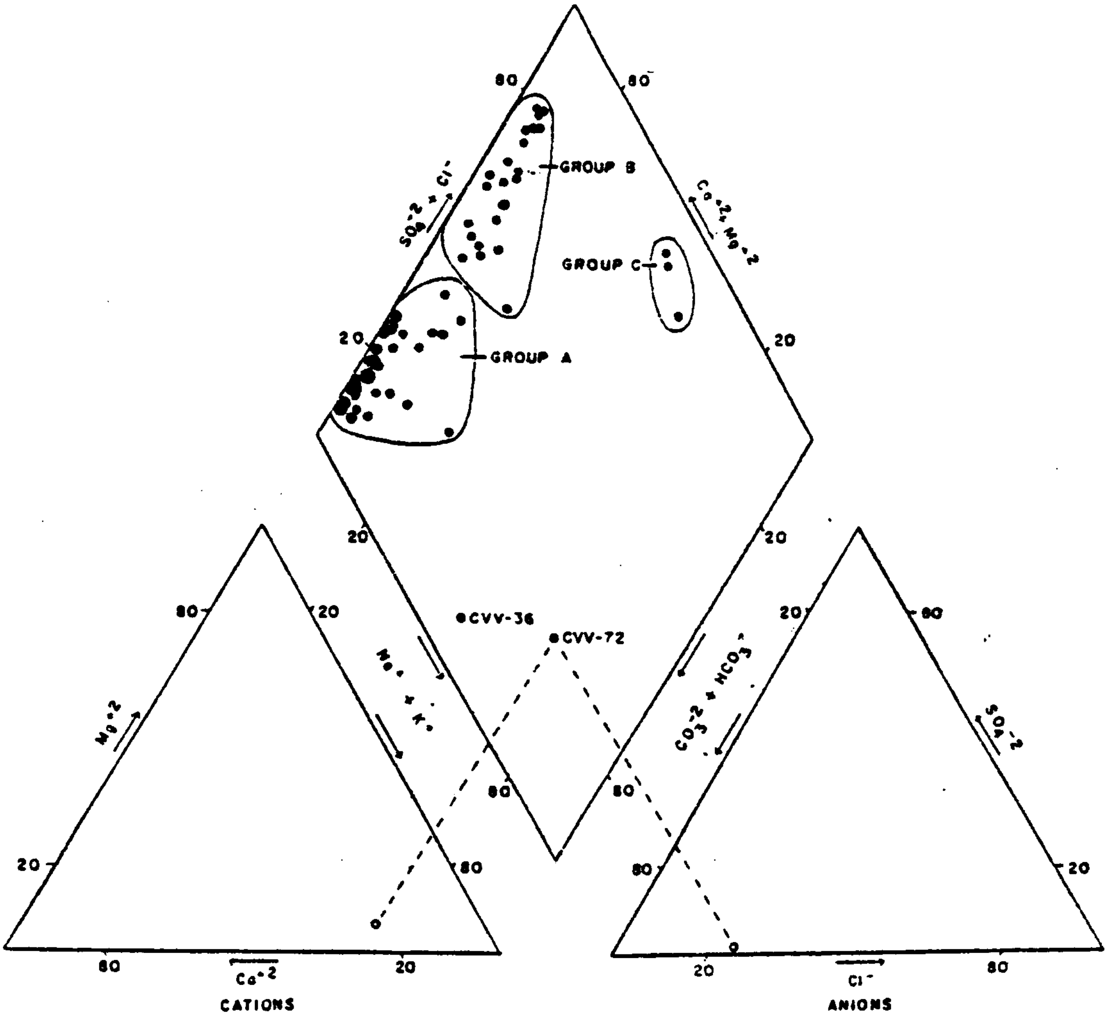


FIG. 5.--Piper diagram showing groundwater chemistry groups derived for Cache Valley, Utah. Chemical constituents are plotted as percentage of total milliequivalents. Percentage of cations for each sample is plotted in the left ternary diagram, and percentage of anions is plotted in the right ternary diagram. These points are transferred onto the central diamond as shown for sample CVV-72 (after Hem, 1970).

fall within any of the groups. Generally, the water in the Benson area, the Mt. Sterling area, and the Cornish area is in Group B. The three warm wells and springs located west and south of Trenton (CVV-30, CVV-31, and CVV-81) fall into Group C with higher percentages of $Na^+ + K^+$ than Groups A and B. Group A, the largest group, encompasses the rest of the valley, with water containing higher percentages of $CO_3^{-2} + HCO_3^-$ than the other two groups. It can be observed on the Piper diagram (Fig. 5) that most of the wells and springs plot below 20% $Na^+ + K^+$. The Group A water has more than 55% $CO_3^{-2} + HCO_3^-$.

Clustering the chemical data using the average Euclidian distance, d_{jk} (Fig. 6), proved to be useful when grouping the chemical data because it added insight into why the objects (wells and springs) had been grouped as they were. Seven attributes (Ca^{+2}, Mg^{+2}, Na^+, K^+, HCO_3^-, SO_4^{-2}, and Cl^-) were used in the cluster analysis with the average Euclidean distance, and groups similar to those found in the piper diagram were derived.

The average Euclidean distance was calculated using the relationship (Romesburg and Marshall, 1980):

$$d_{jk} = \sum_{i=1}^{n} [\ (X_{ij} - X_{ik})^2/n\ ]^{1/2}$$

where d_{jk} is the average Euclidean distance, j and k are the objects (wells and springs), n is the number of attributes (chemical constituents) or dimensions in the model (i.e. seven-dimensional in the case of seven attributes), and X is the coordinate (location

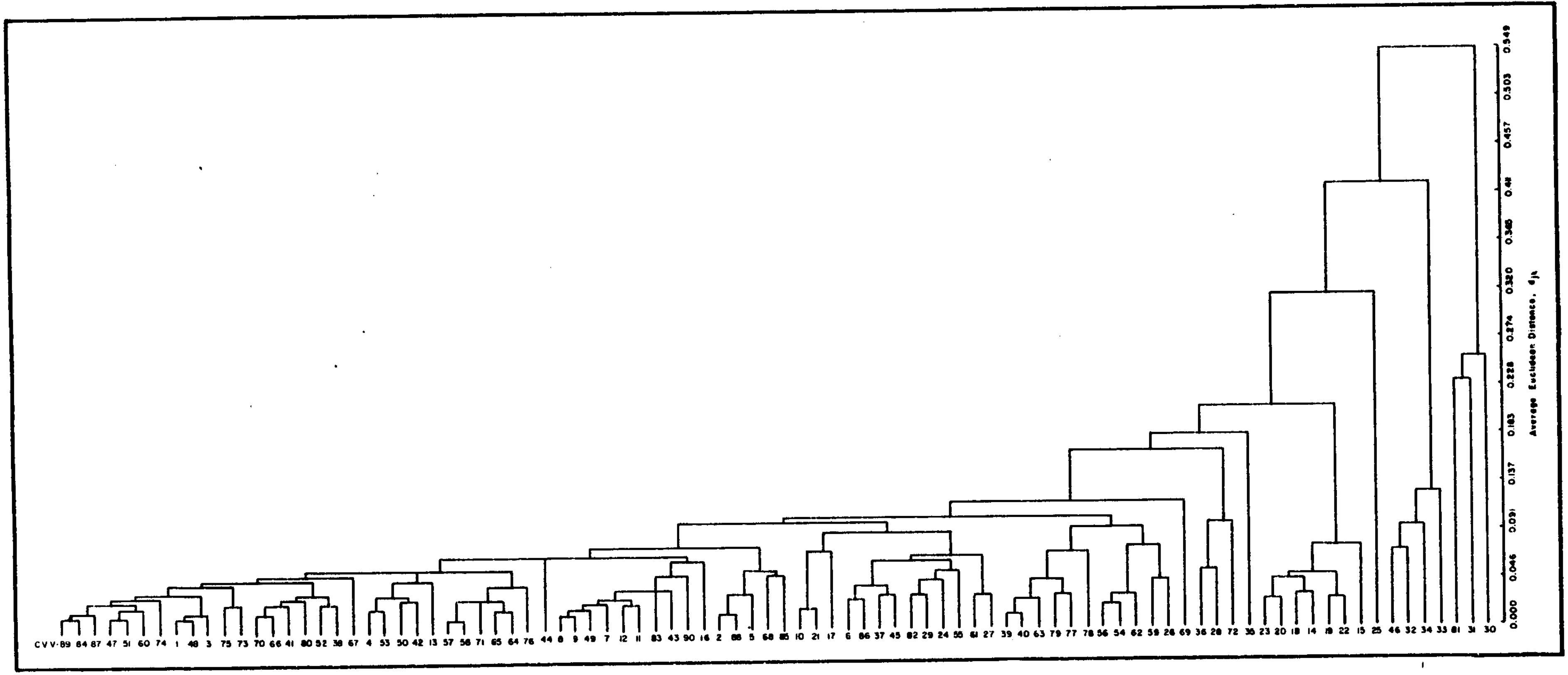


FIG. 6.--Cluster tree derived from 7 attributes using the average Euclidean distance, d_{jk}. Correlation is best at low values of d_{jk}.

in the n-dimensional model). A simplified example would involve two attributes, n, and two objects, j and k. Using the conventional rectangular coordinates (2-dimensional), the abscissa X_1 represents attribute 1 and the ordinate X_2 represents attribute 2. When the two objects are plotted, the distance between them represents their dissimilarity, i.e., the greater the distance between them, the less similar they are.

For the purposes of this study, the chemical data will be placed into one of three groups based on a combination of the above grouping techniques. Two wells, CVV-36 and CVV-72, do not fit into any of the groups. The Piper diagram in Fig. 5 shows the distribution of the chemistry groups. Plate 2 (p. 99) shows the geographic distribution of the groundwater chemistry groups.

Chemical Geothermometry

Several chemical geothermometers have been developed to assist in the exploration for, and evaluation of, geothermal resources. The last temperature of water-rock interaction can be estimated from the water chemistry using several techniques including the silica geothermometer (Fournier and Rowe, 1966) and the Na-K-Ca geothermometer (Fournier and Truesdell, 1973).

Fournier et al. (1974) made five assumptions which are applicable to both the silica and Na-K-Ca geothermometers. It is important to keep these in mind when using these chemical geothermometers and to be aware of the limitations. The assumptions are:

1. Temperature-dependent reactions occur at depth.

2. All constituents involved in the temperature-dependent reaction are sufficiently abundant in the rocks, so that their supply is not a limiting factor for the reactions.

3. Water-rock chemical equilibration occurs at the reservoir temperature.

4. Re-equilibration or change in composition does not occur at temperatures lower than that of the reservoir while the water is flowing from the reservoir to the surface. An approximate minimum flow rate of 200 l/min was suggested by Fournier et al. (1974) as an arbitrary cut-off for flow from a single, isolated spring. At a lower flow rate, re-equilibration at lower temperatures is possible, and the calculated temperature is probably lower than the actual reservoir temperature.

5. No mixing of hot water with cooler, shallow water occurs. Fournier and Truesdell (1974) developed a technique for estimating both the proportions of hot and cold water involved in a mixing situation and the hot reservoir temperature, providing there was no gain or loss of silica prior to or after mixing and conductive cooling did not occur.

Use of the Na/K ratio as an indicator of reservoir temperature was proposed by White (1965) and Ellis (1970) because this ratio is presumably controlled by albite and potassium feldspar equilibrium:

$$K^+ + \text{Na-feldspar} = \text{K-feldspar} + Na^+$$

Fournier and Truesdell (1973) observed that the Na/K geothermometer yielded unreasonable results for waters with high Ca content and concluded that Ca also enters into the silicate reactions in competition with K and Na:

$$K^{+} + \text{NaCa plagioclase} + \text{qtz} = \text{K-feldspar} + Na^{+} + Ca^{+2}$$

An equation was derived by Fournier and Truesdell (1973) for estimating reservoir temperatures based on the Na, K, and Ca content of the water:

$$T°C = 1647/[2.24 + F(T)] - 273.15$$

where $F(T) = \log (Na/K) + \beta \log(\sqrt{Ca}/Na)$, Na, K, and Ca concentrations are expressed in molality, and β is 1/3 or 4/3 if the calculated temperature is greater or less than 100°C, respectively.

Fournier and Potter (1979) observed that Mg-rich waters yielded Na-K-Ca temperatures well above 150°C and questioned their validity, so they developed a magnesium correction for the Na-K-Ca chemical geothermometer of Fournier and Truesdell (1973). The magnitude of the correction, Δt_{Mg}, depends on the Na-K-Ca estimated temperature and the Mg^{+2} concentration relative to the sum of dissolved Mg^{+2}, K^{+}, and Ca^{+2}, with concentrations expressed in equivalents. They recommended the use of the Mg correction when the Na-K-Ca estimated temperature was >70°C and when R is in the range 5-50, where $R = [Mg/(Mg + Ca + K)] \times 100$ using equivalent units of concentration. Δt_{Mg} can be calculated or read from a graph derived by Fournier and Potter (1979) and is subtracted from the Na-K-Ca estimated temperature. The Na-K-Ca geothermometer with the Mg correction was used in this research for estimating reservoir temperatures.

Coplen (1973) used the function F(T) as a geothermal exploration tool rather than for the prediction of a water-rock equilibration temperature for geothermal fluid samples. When calculated from well and spring water samples, the function may indicate areas in which there is a leakage of geothermal brine at depth into the near-surface hydrologic system. In this case, the function is not used to determine the water-rock equilibrium temperature, but only to indicate that a geothermal anomaly exists. Coplen (1973) plotted F(T) values for wells in the Imperial Valley area of California and found the Na-K-Ca geochemical exploration technique to be useful. A potential geothermal anomaly was indicated by this technique when values of F(T) were less than about 2.00. F(T) values were calculated for Cache Valley, Utah (Plate 2); their usefulness is discussed by individual warm-water areas in a later section.

Fournier and Rowe (1966) proposed that the silica content of a hot spring is controlled by crystalline-phase silica solubility at depth, not the solubility of amorphous silica found near the surface. Temperatures based on the silica content of the water as a function of quartz solubility are calculated by:

$$T°C = 1309/(5.205 - \log SiO_2) - 273.15$$

where the concentration of SiO_2 is in ppm (Fournier, 1977).

If the Na-K-Ca thermometer indicates a temperature of less than 100°C, then the silica temperature is calculated assuming that the silica content of the water is a function of chalcedony solubility (Fournier, 1977):

$$T°C = 1032/(4.69 - \log SiO_2) - 273.15$$

Reservoir temperatures in Cache Valley, Utah were also calculated using the silica geothermometer following the guidelines noted above.

Fournier and Truesdell (1974) proposed that some warm springs may be the result of hot water from depth mixing with cooler, shallow water. Under certain conditions, the original temperature of the hot water and the fraction of cold water in the mixture can be estimated by using the measured temperatures and the silica contents of the warm spring water and nonthermal water in the area. Fournier and Truesdell (1974) described graphical and analytical procedures for these estimations for warm springs with large flow rates, and Truesdell and Fournier (1977) presented a simplified graphical method for obtaining the same results. The graphical method was used in this research. The silica geothermometer is more susceptible to estimating low reservoir temperatures as a result of mixing than is the Na-K-Ca geothermometer because it is based on the actual silica content of the water rather than ratios of ions as in the Na-K-Ca geothermometer.

Sonderegger and Donovan (1981) used a similar graphical method for estimating reservoir temperatures. They used a chalcedony solubility curve rather than the quartz solubility curve used by Truesdell and Fournier (1977). Reservoir temperatures derived from the chalcedony solubility curve were lower than those derived from the quartz solubility curve. The graphical method used by Sonderegger and Donovan (1981) was also applied to this research.

DISCUSSION

Areas of Warm Water

The three areas with warm water in Cache Valley, Utah are North Logan, Benson, and Trenton. Each of these areas will be discussed individually with respect to surface temperatures, thermal gradient, chemical analysis, geothermometry, models to explain their occurrence, and geothermal potential.

The initial method for evaluating apparent surface temperature anomalies is to compare the measured surface water temperature to the calculated temperature of water coming from a certain depth, to determine if the normal thermal gradient could be responsible for the measured surface water temperature. Basic potential theory expresses this relationship as:

$$T_z = T_o + (\Delta T/\Delta Z)(Z)$$

where T_z = temperature at depth Z, T_o = mean annual temperature, $(\Delta T/\Delta Z)$ = thermal gradient, and Z = depth (Darling, personal communication). The depth is normally assumed to be the depth of the well or the depth of the perforations. The mean annual temperature in Logan, Utah is 8.3°C (Richardson, personal communication), and the thermal gradient used is the one located closest to the well in question or the normal gradient for the area if the former is anomalous. This calculation can be used to answer two questions: (1) Do the depth of the well and the thermal gradient account for the temperature of the water at the surface? and (2) To what depth must water circulate in order to reach the temperature observed at the surface? Presented in Table 3 are the measured surface temperatures, calculated temperatures using the equation above, well depths, and the depths necessary to obtain the measured temperatures for the warm water areas. In general, the depths of the wells and the gradient do not account for the warm water anomalies in Cache Valley, Utah, except in the North Logan area where the gradient itself is anomalous and misleading.

The silica and Na-K-Ca geothermometers yielded some unreasonable and questionable results for the reservoir temperatures (Table 4) because the calculated temperatures were less than measured surface temperatures. When temperatures calculated by both methods were plotted (Fig. 7), it was observed that there was a wide scattering of points, and no groups were formed. Estimated reservoir temperatures were less than 120°C for all wells and springs.

In order to explain why the chemical geothermometers did not register the same temperature, one must return to the basic assumptions made when the thermometers were developed. Commonly the flow rate of the water may be less than the recommended minimum of 200 l/min (Fournier et al., 1974), which allows re-equilibration at a lower temperature. In this case, the calculated temperature is probably lower than the actual reservoir temperature.

Kolesar and Degraff (1978) suggested that movement of hot water through the saline, valley-fill sediments of Lake Bonneville might dissolve soluble sodium- and potassium-rich minerals such as

TABLE 3.--Comparison of measured surface temperatures to calculated temperatures assuming water is rising from the bottom of the well. The depth of the well and the depth necessary to account for the measured temperature are also given (see text for explanation of North Logan area).

	Location	Measured Temperature (°C)	Calculated Temperature (°C)	Depth of Well (m)	Necessary Depth (m)
North Logan:	thermal gradient 35°/km (297°C/km)				
	CVV-1	21.1	10.1 (14,947.4)	50.3	365.7 (0.04)
	CVV-2	16.0	10.1 (15,482.0)	52.1	220.0 (0.03)
	CVV-3	25.1	11.0 (23,263.4)	78.3	480.0 (0.06)
	CVV-4	19.9	10.0 (14,501.9)	48.8	331.4 (0.04)
	CVV-7	16.4	10.5 (19.016.3)	64.0	231.4 (0.03)
	CVV-8	16.6	10.5 (18,303.5)	61.6	237.1 (0.03)
	CVG-9	32.2	8.8 (12,422.9)	41.8	682.9 (0.08)
Benson:	thermal gradient 35°C/km				
	CVV-10	15.0	14.8	187.8	191.4
	CVV-11	20.9	13.8	157.0	360.0
	CVV-12	20.9	14.0	162.5	360.0
	CVV-13	23.0	15.1	195.4	420.0
	CVV-14	18.4	13.9	160.0	228.6
	CVV-15	19.9	12.1	107.9	331.4
	CVV-16	17.5	15.0	190.8	262.9
	CVV-17	17.5	14.2	170.1	262.9
	CVV-18	17.4	14.1	166.4	260.0
	CVV-19	18.1	—	?	280.0
	CVV-20	20.0	15.9	216.4	334.3
	CVV-21	23.1	18.2	283.5	420.0
	CVV-22	17.5	16.0	220.4	262.9
	CVV-23	19.8	16.3	227.4	328.6
	CVV-24	11.4	9.9	44.8	88.6
Trenton:	thermal gradient 36°C/km				
	CVV-30	30.1	—	spring	605.6
	CVV-31	50.1	65.4	1587.4	1161.1
	CVV-81	22.9	—	spring	405.6

TABLE 4.--Estimated reservoir temperatures based on chemical geothermometers

	Location	Silica T(°C)	Na-K-Ca T(°C)	Measured Surface T(°C)
North Logan				
	CVV-1	15.3	29.9	21.1
	CVV-2	18.0	31.6	16.0
	CVV-3	27.2	45.6	25.1
	CVV-4	31.3	42.5	19.9
	CVV-7	32.8	56.1	16.4
	CVV-8	34.9	53.3	16.6
Benson				
	CVV-10	83.5	45.4	15.0
	CVV-11	78.2	42.0	20.9
	CVV-12	69.5	49.6	20.9
	CVV-13	32.8	27.5	23.0
	CVV-14	12.6	14.7	18.4
	CVV-15	29.3	15.1	19.9
	CVV-16	18.0	67.2	17.5
	CVV-17	15.3	22.4	17.5
	CVV-18	6.5	33.4	17.4
	CVV-19	9.7	38.2	18.1
	CVV-20	38.5	37.9	20.0
	CVV-21	52.0	38.3	23.1
	CVV-22	9.7	34.1	17.5
	CVV-23	36.7	33.5	19.8
	CVV-24	67.5	52.4*	11.4
Trenton				
	CVV-30	31.4	71.3*	30.1
	CVV-31	88.8	56.5*	50.1
	CVV-81	46.6	55.4*	22.9

*Magnesium correction applied to Na-K-Ca temperatures.

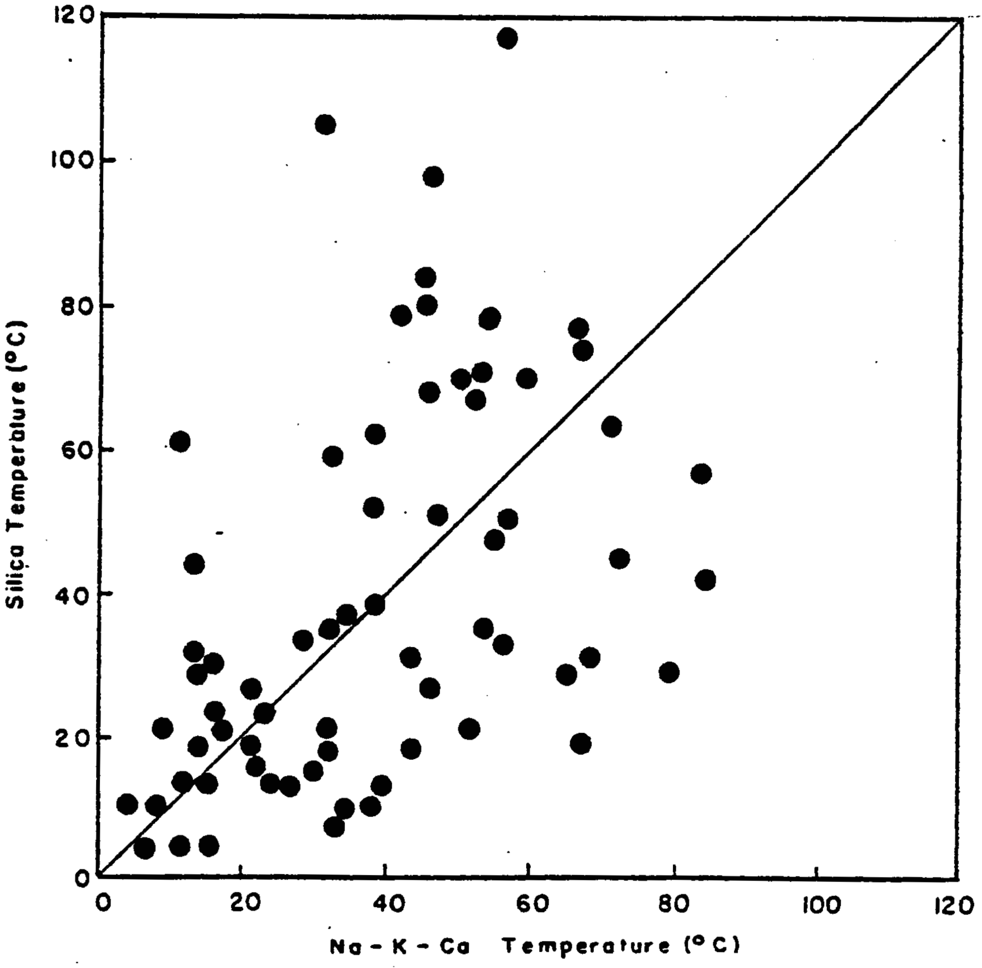


FIG. 7.--Plot of indicated silica temperature versus indicated Na-K-Ca temperature. Mg correction has been applied to the Na-K-Ca temperature where necessary. The 1:1 ratio line represents ideal agreement between the two chemical geothermometers.

halite and sylvite. This would enrich the water in sodium and potassium, making the Na-K-Ca thermometer invalid.

The silica and Na-K-Ca geothermometers were developed for high-temperature geothermal occurrences in Yellowstone Park where the source rocks of the aquifers are primarily of volcanic origin. Because the compositions of the source rocks of the aquifers in Yellowstone are vastly different than those found in Cache Valley (sandstone, limestone, and dolostone), the water-rock equilibrium equations upon which the geothermometry calculations are based may not be valid.

Finally, little research has been done on such low-temperature geothermal occurrences, so it is possible these chemical geothermometers are just not applicable to relatively low-temperature waters. Use of F(T) values may be a more useful tool in the evaluation of low-temperature geothermal resources (Coplen, 1973). Plate 2 indicates the locations of wells and springs in the study area where F(T) values indicate a possible geothermal anomaly.

In attempts to apply the mixing model of Truesdell and Fournier (1977) to the wells and springs in the warm water areas, it was found that many of the locations had temperatures and/or concentrations of silica too low for the model to be applicable. Table 5 lists the results of those wells and springs in which the mixing model could be applied.

Two types of masking effects are proposed as models for explaining the production of warm water occurrences in Cache Valley, Utah. Model 1 involves water which has migrated to depth, is warmed by the

TABLE 5.--Results of mixing calculations

	Location	Surface Temp. (°C)	Warm Spring Silica (ppm)	Cold Spring Temp. (°C)	Cold Spring Silica (ppm)	Corrected Hot Spring Temp. (°C)	% Hot H_2O	Original SiO_2 Temp. (°C)	Na-K-Ca Temp. (°C)
North Logan	CVV-3	25.1	18	14.3	14	108[1] 36[2]	10 30	27.2	45.6
	CVV-4	19.9	20	14.3	14	157[1]	5	31.3	42.5
Benson	CVV-11	20.9	57	12.5	49	168[1] 69[2]	5 10	78.2	42.0
	CVV-12	20.9	48	12.5	49	99[1]	10	69.5	49.6
Trenton	CVV-30	30.1	20	10.1	19	64[1] 30[2]	40 100	31.4	71.3
				14.8	20	64[1] 30[2]	30 100		
	CVV-31	50.1	69	10.1 14.8	19 20	200[1] 205[1]	20 20	88.8	56.4
	CVV-81	22.9	29	10.1	19	145[1] 106[2]	10 15	46.6	55.4
				14.8	20	195[1]	5		

[1] Based on quartz solubility curve (Truesdell and Fournier, 1977).

[2] Based on chalcedony solubility curve (Sonderegger and Donovan, 1981).

normal thermal gradient, rises quickly along a permeable fault zone without cooling, encounters near-surface cold water recharge and is diluted, thereby appearing cool at the surface (Fig. 8a). In Model 2, water migrates to depth, is warmed by the normal thermal gradient, rises rapidly along the fault zone and encounters a layer of less permeable sediments (confining layer). The less permeable zone causes horizontal flow and gradual cooling of the water until it reaches the surface (Fig. 8b). The models can also be combined to explain the cooling of hot water rising from depth.

North Logan.--Wells CVV-1, CVV-2, CVV-3, CVV-4, CVV-7, and CVV-8 are in the North Logan area. Water temperatures range from 16.0°C to 25.1°C. A thermal gradient of 297°C/km was calculated at CVG-9, quite anomalous when compared to the average Basin and Range thermal gradient. When gradient well CVG-9 was being pumped, the temperature of the water was 32.2°C (Huppi, personal communication), close to the present bottom hole temperature (32.54°C). The temperatures measured in CVG-9 ranged from 21.36°C to 32.54°C, unusually high compared to the other temperature profiles measured for this study, which ranged from 9.52°C to 16.03°C. Based on this high measured temperature and high calculated thermal gradient, it appears that warm water is close to the surface at CVG-9.

If the thermal gradient of 297°C/km is used to calculate the temperature of water within wells in North Logan, it is clear that the depth of each well can account for the measured water temperature (Table 3). However, 297°C/km is an extremely anomalous gradient, which probably results from the presence of warm water near the

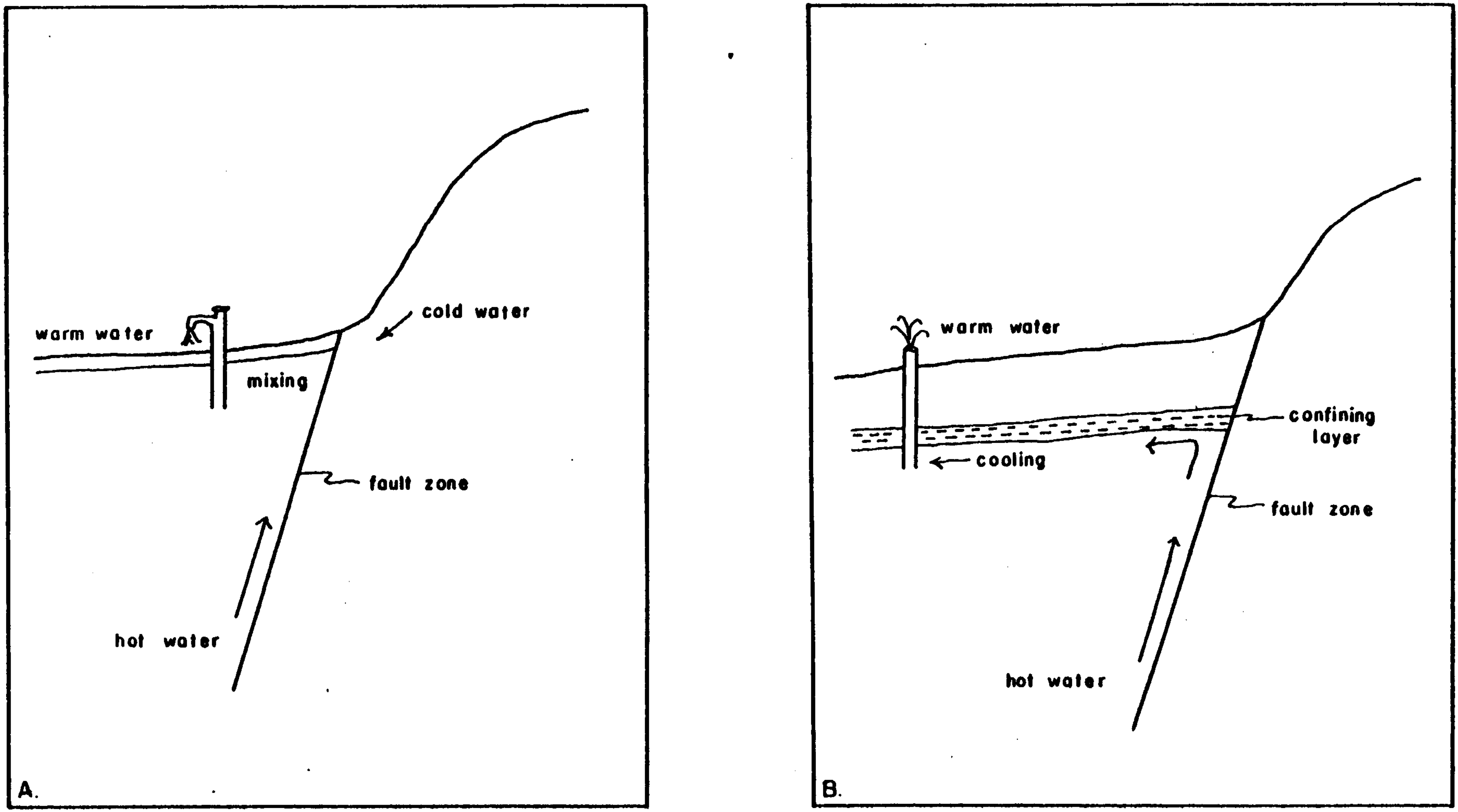


FIG. 8.--Masking models (see text for discussion).

surface. A near-surface occurrence of moving, warm groundwater, with its convective heat transfer, would mask the conductive heat transfer and preclude the determination of the actual thermal gradient in the area.

If the average Basin and Range thermal gradient of 35°C/km is used in the calculations, it can be seen (Table 3) that the well depths in North Logan are insufficient to account for the measured water temperatures.

The chemical analyses of wells in the North Logan area placed the water in Group A. According to the Piper diagram, this water has high percentages of $CO_3^{-2} + HCO_3^-$ and high percentages of $Ca^{+2} + Mg^{+2}$ indicating recharge from a carbonate terrain (i.e., Bear River range). The cluster analyses correlate the individual wells fairly closely but do not show anything striking about the water chemistry in comparison to other Group A samples. The concentrations of TDS in the North Logan area are lower than those in other warm water areas, which may be the result of shorter residence time of the recharge water in the aquifer, coarser sediments through which this water travels, or mixing with cold recharge water which could cause precipitation or dilution of the dissolved solids.

When the chemical analyses were used to calculate reservoir temperatures, the silica temperature was consistently lower than the Na-K-Ca temperature (Table 4). Estimated reservoir temperatures ranged from 15.3°C to 56.1°C, which may indicate a possible low-temperature geothermal reservoir. F(T) values calculated for the area (Plate 2) did not indicate a geothermal anomaly.

The mixing model (Truesdell and Fournier, 1977) was applied to the warm water wells in the North Logan area with some success. Corrected temperatures for the hot water component of wells CVV-3 and CVV-4 were 108°C and 157°C respectively, compared to the silica geothermometer temperatures, 27.2°C and 31.3°C, and the Na-K-Ca temperatures, 45.6°C and 42.5°C. The mixing model was not applicable to the other wells in the area because of low silica concentrations and low water temperatures.

Peterson (1946) and Utah Geological and Mineral Survey (1980) noted the warm water occurrence in the North Logan area, and both suggested similar theories as explanations. Peterson (1946, p. 33) proposed that "water issues from deep fissures on the edge of the valley and is confined to definite gravel strata." Utah Geological and Mineral Survey (1980) mentioned the intersection of two major faults which are part of the East Cache Valley fault zone and are located east of North Logan. This author proposes a combination of the two masking models discussed earlier to explain the occurrence of warm water in the North Logan area. The intersection of the two major faults increases vertical permeability, allowing the water at depth to rise rapidly, but thick layers of Quaternary sediments force the hot water to flow horizontally. Such a model can also explain the anomalously high thermal gradient, because the hot water comes close to the surface before being forced to flow horizontally. Evidence for this situation is the inverted temperature zones noted by Peterson (1946) in the wells at Logana Plunge, (A-12-1)28bba, and in a well southwest of Amalga, (B-13-1)25b. At Logana Plunge, a gravel aquifer at 44.8 m produced water at 27.8°C, and at 78.3 m another gravel aquifer produced water at 26.1°C. The well near Amalga had 37.8°C water at 324.3 m and 16.7°C water at 415.7 m. Warm water wells located close to the western branch of the East Cache Valley fault zone have temperatures which can be accounted for by their depths, but are still anomalous when compared with the background value for groundwater temperatures in Cache Valley. Cold recharge water flowing through the sediments may be mixing with the hot water rising along the fault zone, so that the water which rises in wells near the fault is only slightly warmer than normal.

Benson.--Wells CVV-10 through CVV-24 are in the Benson area. Temperatures range from 13.5°C (Utah Geological and Mineral Survey, 1980) to 23.0°C. No temperature profile was measured in the area because a suitable well was not located. The wells generally penetrate a confined aquifer at depths of 91 to 283 meters (Bjorklund and McGreevy, 1971). None of the temperatures measured in the Benson area can be completely accounted for by well depths and the average Basin and Range thermal gradient (35°C/km). It is possible that the thermal gradient in the area is greater than 35°C/km, which would account for the higher temperatures. However, this seems unlikely, as gradients measured to the north and south of Benson are 36°C/km and 29°C/km respectively.

Based on the chemical analyses, water samples in the Benson area generally belong to Group B. According to the Piper diagram, this water has lower percentages of $CO_3^{-2} + HCO_3^-$ than Group A. The cluster analyses correlate most of the wells fairly close together.

Most have higher concentrations of TDS and Ca^{+2} than the rest of Group B. CVV-16 has a lower concentration of Ca^{+2} than the rest of the wells and plotted on the far edge of the B group in the Piper diagram. Wells CVV-11 and CVV-12 are in Group A, with higher percentages of CO_3^{-2} + HCO_3^- and lower concentrations of Cl^- and TDS than other wells in the Benson area. Where Eh readings were taken, most were negative (reducing environment), which correlates positively with bad tasting water.

Some of the samples produced similar calculated reservoir temperatures when using the silica and Na-K-Ca thermometers (Table 4). These temperatures range from 12.6°C to 38.5°C. However, the 12.6°C calculated reservoir temperature for CVV-14 is lower than the measured surface temperature (18.4°C), and therefore those wells with calculated temperatures less than measured temperatures are unreasonable. F(T) values also did not indicate a geothermal anomaly in this area (Plate 2).

The mixing model of Truesdell and Fournier (1977) was not applicable to most of the wells in the Benson area because of low temperatures and low silica contents. In the two wells in which the mixing model was applicable, CVV-11 and CVV-12 had corrected hot water temperatures of 168°C and 99°C in comparison to silica thermometer temperatures of 78.2°C and 69.5°C and Na-K-Ca temperatures of 42.0°C and 49.6°C.

Whereas the depths of the wells in the Benson area and a thermal gradient of 35°C/km do not account for the warm water, a possible explanation for the occurrence of warm water is that water heated by the normal thermal gradient is rising quickly from depth along the nearby Clarkston fault zone or other unknown fault(s) and is moving horizontally towards Benson. The great thickness of Quaternary sediments, especially in the clay-sized particle range, may be causing the water to move horizontally rather than vertically. Bjorklund and McGreevy (1971, Plate 4) showed that the water in the area flows from the west side of the valley toward the center. A detailed gravity survey of the area would be helpful for locating faults to provide further evidence to support this theory. If temperature profile measurements were possible in the area, then the estimated thermal gradient could be revised if necessary.

Trenton.--Three springs and one well in the Trenton area have temperatures ranging from 22.9°C to 50.1°C. A thermal gradient of 36°C/km was calculated from a temperature profile measured within 1 kilometer of Gancheff's spring (Rock Well). Tufa deposits were found at four locations coinciding with the Dayton fault zone (Fig. 9): (1) Pitcher's spring; (2) Gancheff's spring; (3) Read's spring; and (4) the Trenton gravel pit.

Pitcher's spring has been covered with soil by a farmer who wanted to farm over it, but a swampy area with cattails and scattered chunks of tufa remain as markers. This spring is said to have erupted during the lifetime of the present owner's father, i.e., within the last 100 years (Pitcher, personal communication).

Gancheff's spring (CVV-30) orifice is about 6.1 meters in diameter, surrounded by a mound of tufa, with the water level about 3 meters below the ground surface. The water has a fairly constant

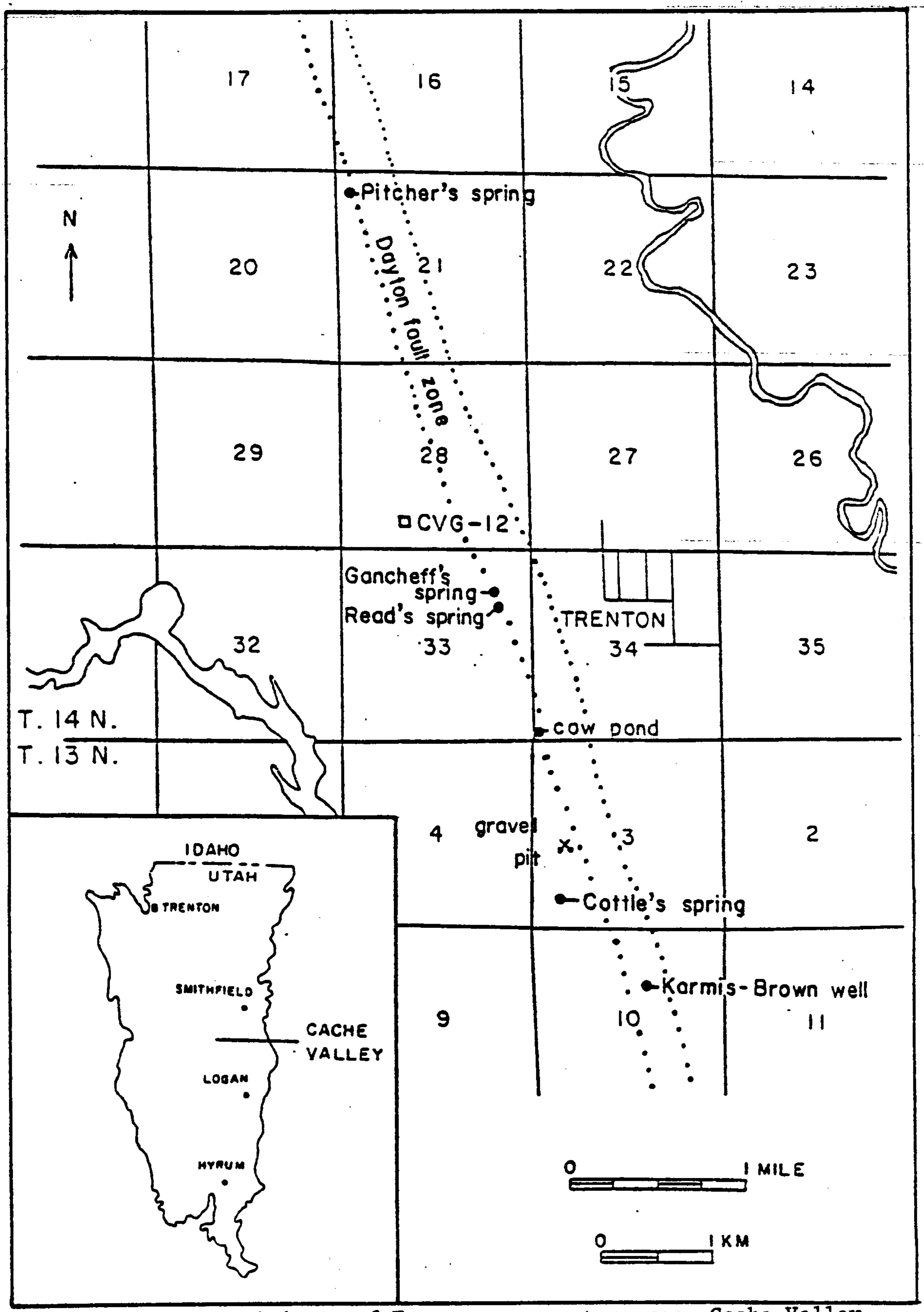


FIG. 9.--Detailed map of Trenton warm-water area, Cache Valley, Utah (adapted from Williams, 1962).

temperature of 30.1°C. A constant flow of water from both Gancheff's spring and Read's spring gushes from a horizontal well into an irrigation canal. Read's spring orifice is dry as a result. No water is flowing over the top of Gancheff's spring, therefore tufa is no longer being formed. A spring-fed cattle pond south of Gancheff's spring had a temperature of 26.5°C but contained too much sediment for sample collection.

Cottle's spring (CVV-81) had a temperature of 22.9°C and smelled like sulfur. It was used to scald pigs during the recent past (Anderson, personal communication). Warm springs are sited sporadically along the banks of the Bear River. Those near Trenton were never observed by the author because the water in the slough where they are supposedly located covered their orifices.

The Karmis-Brown gas well (CVV-31) was drilled to a depth of 1,587 meters and has a temperature of 50.1°C. This temperature can easily be accounted for using a thermal gradient of 36°C/km, even if water is entering through the perforations closest to the surface (1151 to 1155 meters). Its temperature has remained constant since it was drilled in 1957.

CVV-30, CVV-31, and CVV-81 are isolated chemically from the previously mentioned groups and form Group C on the Piper diagram. They have relatively higher percentages of both $Na^+ + K^+$ and $SO_4^{-2} + Cl^-$ than the other groups (Fig. 5). CVV-30 contains the highest concentrations of Na^+, K^+, Cl^-, and TDS, and has the highest conductivity found in the study area. These samples are closely correlated because of their high concentrations of all of the ions which were analyzed.

When the silica geothermometer and Na-K-Ca geothermometer with the Mg correction were applied, relatively high reservoir temperatures were calculated. When mixing model calculations were performed using various combinations of warm and cold springs, the reservoir temperatures for CVV-30 were higher than the temperature calculated by the silica thermometer and similar to the temperature calculated by the Na-K-Ca geothermometer. The corrected hot water temperatures for CVV-31 and CVV-81 were much higher than the Na-K-Ca temperatures (Table 4), indicating that mixing probably did occur at all three locations. The temperature of the reservoir may be between 100 and 200°C according to the mixing calculations, with circulation depths of 2.5 to 5.3 km necessary to warm the water by the normal thermal gradient.

F(T) values for these three locations indicate a possible geothermal anomaly (Plate 2). Tufa deposits and surface temperatures also indicate the presence of a geothermal anomaly. The warm springs in the Trenton area may be related to the Dayton fault zone, with water from depth rising rapidly to the surface along the fault zone, cooling little before reaching the surface. There is probably less horizontal flow and fewer masking effects in this area because the springs are closer to the fault zone, which probably displaces Quaternary sediments.

CONCLUSIONS

Chemical Geothermometry

The author found that many of the source tempratures calculated for each location from the silica and Na-K-Ca geothermometers were similar; however, some temperatures were unreasonable (i.e., measured surface temperature was greater than calculated source temperature, or calculated temperatures for the same location varied drastically). Application of the Mg correction was necessary for some of the Na-K-Ca temperatures and made significant changes in those with originally high source temperatures. Because the silica and Na-K-Ca chemical geothermometers used in this study produced some questionable results, the author feels that these geothermometers should be used with caution as tools in evaluating low-temperature geothermal resources. F(T) values (Coplen, 1973) may be of more use than questionable reservoir temperatures. The mixing model of Truesdell and Fournier (1977) was generally not applicable to this research due to low surface temperatures and low concentrations of silica.

Low-temperature Geothermal Potential in Cache Valley, Utah

The water temperatures in Cache Valley, Utah are lower than those generally considered useful as low-temperature geothermal resources, i.e., 50 to 80°C (Todd, 1980, p. 64). However, North Logan (16.0

to 25.1°C), Benson (13.5 to 23.0°C), and Trenton (22.9 to 50.1°C) have anomalously high temperatures when compared to the background temperature of 13.0°C found in the overall study area. Rinehart (1980) listed temperatures of geothermal fluids required for various uses. Those temperatures which are applicable to Cache Valley, Utah are listed in Table 6. He made the following suggestions for developing a geothermal reservoir for commercial exploitation (Rinehart, 1980, p. 175):

1. The water must be obtainable at a relatively shallow depth (< 3000 m);

2. The reservoir must be large and sufficiently permeable to allow water and steam to flow out continuously at a high rate or be stored;

3. A cap rock of low permeability must be present to inhibit the flow of water and heat to the surface;

4. There must be an adequate supply of water to recharge the reservoir; and

5. The fluid should be relatively free from excessive and corrosive chemicals.

All of the water in Cache Valley is available at shallow depths, and the total annual recharge is approximately equal to the total annual discharge. The lake-bottom sediments of clay and silt act as a confining layer or cap rock, but they allow some conductivity of the groundwater. The aquifers are generally highly permeable, and the valley sediments have high storage capacity (Bjorklund and McGreevy, 1971).

TABLE 6.--Temperatures of geothermal fluids required for various purposes (after Rinehart, 1980)

Temperature (°C)	Uses
60	Animal husbandry; Greenhouses by combined space heating and hotbed heating
50	Mushroom growing; Balneological baths
40	Soil warming
30	Swimming pools, biodegradation, fermentations; Warm water for year around mining; Deicing
20	Hatching of fish; Fish farming

North Logan water is low in TDS, but because it is on the edge of the valley, supplies may be depleted more rapidly during drought years than in other parts of the valley. Benson water has a high TDS content and is corrosive, but it has a high yield and is confined, which reduces pumping costs. Plastic pipes would possibly solve the corrosion problem. Trenton water, with the highest temperatures, also has the highest TDS and a high yield.

Although water temperatures in Cache Valley are too low for extensive development of geothermal resources, the warm water is already being utilized for fish hatching and farming, partially heating a swimming pool, and groundwater heat pumps for homes. A groundwater heat pump extracts heat energy from incoming groundwater, thereby delivering it to the home. Groundwater is a better heat source than air (Utah Water Research Laboratory, 1979).

In conclusion, the warm water in the specific geographic areas previously mentioned, North Logan, Benson, and Trenton, has potential for isolated energy development. Groundwater heat pumps for domestic use have proven to be useful in some homes in Cache Valley, Utah and should be utilized by other homeowners, especially in the warm water areas. Precautions should be taken when the water is corrosive or high in TDS as in the Benson area. Plastic pipe is a possible solution. The water in Cache Valley, Utah is not warm enough for major commercial development other than the uses suggested by Rinehart (1980) (Table 6).

Hopefully the data and conclusions of this report will provide some additional insight into groundwater conditions in Cache Valley, Utah and will help interested parties to evaluate the low-temperature geothermal potential within their own particular geographic areas.

FURTHER INVESTIGATIONS

With the groundwork which this investigation provides, more thermal gradient measurements should be made, as well as thermal conductivity measurements, so that a regional heat flow study can be performed.

Detailed gravity surveys and modeling are recommended for North Logan, Benson, and Trenton areas.

A similar assessment should be carried out in Cache Valley, Idaho so that a complete low-temperature geothermal evaluation of the entire Cache Valley can be accomplished.

REFERENCES

BEER, L. P., 1967, Ground-water hydrology of southern Cache Valley, Utah: Utah State Engineer Information Bull., no. 19, 118 p.

BJORKLUND, L. J., AND McGREEVY, L. J., 1971, Ground-water resources of Cache Valley, Utah and Idaho: Utah Dept. of Natural Resources Tech. Pub. 36, 72 p.

COPLEN, T. P., 1973, A geothermal resources reconnaissance of the Imperial Valley and surrounding area, California, utilizing the sodium-potassium-calcium geochemical exploration technique: Institute of Geophysics and Planetary Physics, University of California, Riverside, 3 p.

DARLING, R., 1981, Field water sampling procedures: Utah Geol. and Mineral Survey, internal memorandum, 14 p.

DARLING, R., 1982, Regional heat flow in northwestern Utah (Master's thesis, in preparation): Salt Lake City, University of Utah.

ELLIS, A. J., 1970, Quantitative interpretation of chemical characteristics of hydrothermal systems, in U.N. Symp. on Development and Utilization of Geothermal Resources: Spec. Issue 2, v. 2, pt. 1: Geothermics, p. 516-528.

ENERGY SERVICES, INC., 1980, Institutional/legal aspects of proceeding with technical development of the Preston area geothermal resource: Report to the City of Preston, Idaho by Forsgren-Perkins Engineering, Logan, Utah, 14 p.

FOURNIER, R. O., 1977, Chemical geothermometers and mixing models for geothermal systems: Geothermics, v. 5, p. 41-50.

FOURNIER, R. O., AND POTTER, R. W., II, 1979, Magnesium correction to the Na-K-Ca chemical geothermometer: Geochim. et Cosmochim. Acta, v. 43, p. 1543-1550.

FOURNIER, R. O., AND ROWE, R. J., 1966, Estimation of underground temperatures from the silica content of water from hot spring and wet-water wells: Am. Jour. Sci., v. 264, p. 685-697.

FOURNIER, R. O., AND TRUESDELL, A. H., 1973, An empirical Na-K-Ca geothermometer for natural waters: Geochim. et Cosmochim. Acta, v. 37, p. 1255-1275.

FOURNIER, R. O., AND TRUESDELL, A. H., 1974, Geochemical indicators of subsurface temperature--part 2, estimation of temperature and fraction of hot water mixed with cold water: U.S. Geol. Survey Jour. of Research, v. 2, no. 3, p. 263-270.

FOURNIER, R. O., WHITE, D. E., AND TRUESDELL, A. H., 1974, Geochemical indicators of subsurface temperature--part 1, basic assumptions: U.S. Geol. Survey Jour. Research, v. 2, p. 259-262.

GOODE, H. D., 1978, Thermal waters of Utah: Utah Geol. and Mineral Survey Report of Investigation No. 129, 183 p.

HACH CHEMICAL COMPANY, 1975, Hach Water and Wastewater Analysis Procedures, 2nd Ed., Ames, Iowa, 186 p.

HEM, J. D., 1970, Study and interpretation of the chemical characteristics of natural waters (2nd Ed.): U.S. Geol. Survey Water-Supply Paper 1473, 363 p.

ISRAELSON, O. W., 1952, Drainage in the Lewiston area, Utah: Utah State Agricultural College Experiment Station Spec. Report No. 9, 25 p.

KLAUK, R. H., DARLING, R., DAVIS, D. A., GWYNN, J. W., AND MURPHY, P. J., 1981, Progress report on the geothermal assessment of the Jordan Valley, Salt Lake County, Utah: Utah Geol. and Mineral Survey Progress Report, 22 p.

KOLESAR, P. T., AND DEGRAFF, J. D., 1978, A comparison of the silica and Na-K-Ca geothermometers for thermal springs in Utah: Geothermics, v. 6, p. 221-226.

KRAUSKOPF, K. B., 1979, Introduction to Geochemistry (2nd Ed.): New York, McGraw-Hill, 617 p.

KRONEMAN, R. L., 1981, Guide to water sampling: Earth Science Laboratory, University of Utah Research Institute, Salt Lake City, Utah, 10 p.

LACHENBRUCH, A. H., AND SASS, J. H., 1978, Models of an extending Lithosphere and heat flow in the Basin and Range province: Geol. Soc. of America Mem. 152, p. 209-250.

McGREEVY, L. J. AND BJORKLUND, L. J., 1970, Selected hydrologic data, Cache Valley, Utah and Idaho: Utah Basic-Data Release No. 21, 51 p.

MILLIGAN, J. H., MARSELL, R. E., AND BAGLEY, J. M., 1966, Mineralized springs in Utah and their effect on manageable water supplies: Utah State Univ. Water Research Lab Report WG23-6, 50 p.

MULLENS, T. E., AND IZETT, G. A., 1963, Geology of the Paradise Quadrangle, Utah: U.S. Geol. Survey Map GQ-185.

MUNDORFF, J. C., 1970, Major thermal springs of Utah: Utah Geol. and Mineral Survey Water-Resources Bull. no. 13, 60 p.

MURPHY, P. J. AND GWYNN, J. W., 1979, Geothermal investigations at selected thermal systems of the northern Wasatch front, Weber and Box Elder Counties, Utah: Utah Geol. and Mineral Survey Report of Investigation No. 141, 50 p.

PERKIN-ELMER CORP., 1973, Analytical Methods for Atomic Absorption Spectrophotometry. Norwalk, Connecticut.

PETERSON, D. L., AND ORIEL, S. S., 1970, Gravity anomalies in Cache Valley, Cache and Box Elder Counties, Utah, and Bannock and Franklin Counties, Idaho: U.S. Geol. Survey Prof. Paper 700-C, p. C114-C118.

PETERSON, W., 1946, Ground water supply in Cache Valley, Utah available for domestic use and irrigation: Utah State Agricultural College Extension Service, N.S. 133, 101 p.

RAINWATER, F. H., AND THATCHER, L. L., 1960, Methods for collection and analysis of water samples: U.S. Geol. Survey Water-Supply Paper 1454, 301 p.

RINEHART, J. S., 1980, Geysers and Geothermal Energy: Springer-Verlag: New York, 223 p.

ROMESBURG, H. C. AND MARSHALL, K., 1980, CLUSTAR and CLUSTID-programs for hierarchial cluster analysis: Am. Statistician, v. 34, no. 3, p. 186.

SASS, J. H., LACHENBRUCH, A. H., MONROE, R. J., GREENE, G. W., AND MOSES, T. H., Jr., 1971, Heat flow in the western United States: Jour. Geophys. Res., v. 76, p. 6376-6413.

SONDEREGGER, J. L., AND DONOVAN, J. J., 1981, Problems of trace element ratios and geothermometry in a gravel geothermal-aquifer system, in Ruscetta, C. A., and Foley, D., eds., Glenwood Technical Conference Proceedings, Vol. 1, State-coupled Geothermal Resource Assessment Program: Earth Science Laboratory, University of Utah Research Institute, Salt Lake City, Utah, p. 50-62.

STANLEY, W. D., 1971, An integrated geophysical study related to groundwater conditions in Cache Valley, Utah and Idaho (unpublished Ph.D. dissertation): Salt Lake City, University of Utah, 142 p.

TODD, D. K., 1980, Groundwater Hydrology (2nd Ed.): New York, John Wiley and Sons, 535 p.

TRUESDELL, A. H., AND FOURNIER, F. O., 1977, Procedure for estimating the temperature of a hot-water component in a mixed water by using a plot of dissolved silica versus enthalpy: U.S. Geol. Survey Jour. of Research, v. 5, no. 1, p. 49-52.

UTAH DEPT. OF TRANSPORTATION, 1975, General highway map, Cache County, Utah, no. 3.

UTAH GEOLOGICAL AND MINERAL SURVEY, 1980, Report on the measurements and initial assessment of ground-water temperatures with regard to geothermal potential, Cache Valley and lower Bear River drainage basin, Utah: Utah Geol. and Mineral Survey, Open-file report, 17 p.

UTAH WATER RESEARCH LABORATORY, 1979, Groundwater heat pump: an efficient way to heat and cool your home: Logan, Utah, 12 p.

WHITE, D. E., 1965, Saline waters of sedimentary rocks, in Young, A., and Galkey, J. E., eds., Fluids in Subsurface Environments--A Symposium: Am. Assoc. Petroleum Geologists Mem. 4, p. 342-366.

WILLIAMS, J. S., 1958, Geologic atlas of Utah, Cache County: Utah Geol. and Mineral Survey Bull. 64, 104 p.

WILLIAMS, J. S., 1962, Lake Bonneville: Geology of southern Cache Valley, Utah: U.S. Geol. Survey Prof. Paper 257-C, p. 131-152.

APPENDICES

Appendix I

Well- and Spring-numbering System

Appendix I

Well- and Spring-numbering System

The well- and spring-numbering system used in this report is shown in Fig. 10 and is based on the U.S. Bureau of Land Management's system of land subdivision. The well or spring number corresponds to the location of the well or spring by quadrant, township, range, section, and position within the section. The State of Utah has been divided into four quadrants formed by the intersection of the Salt Lake Base Line and the Salt Lake Meridian. The capital letter at the beginning of the code indicates the quadrant in which the spring or well is located: A, the northeast quadrant; B, the northwest quadrant; C, the southwest quadrant; and D, the southeast quadrant. Numbers designating the township and range, respectively, follow the quadrant letter, and the three are enclosed in parentheses. The number after the parentheses designates the section, and the letters following the section number give the location within the section. The first letter denotes the quarter section (usually 160 acres), the second letter denotes the quarter-quarter section (40 acres), and the third letter denotes the quarter-quarter-quarter section (10 acres). The letters are assigned within the section in a counterclockwise direction beginning with "a" in the northeast quarter of the section and within each quarter section in the same manner. The numbers that follow the letters indicate the serial number of the well or spring within the 10-acre tract. Thus well

(A-12-1)28caa-1 in Cache Valley, Utah is in the NE¼NE¼SW¼ sec. 28, T. 12N., R. 1E., and it was the first well visited in that tract. Springs are numbered similarly except that they are designated by the letter "S" preceding the serial number (Bjorklund and McGreevy, 1971; Murphy and Gwynn, 1979).

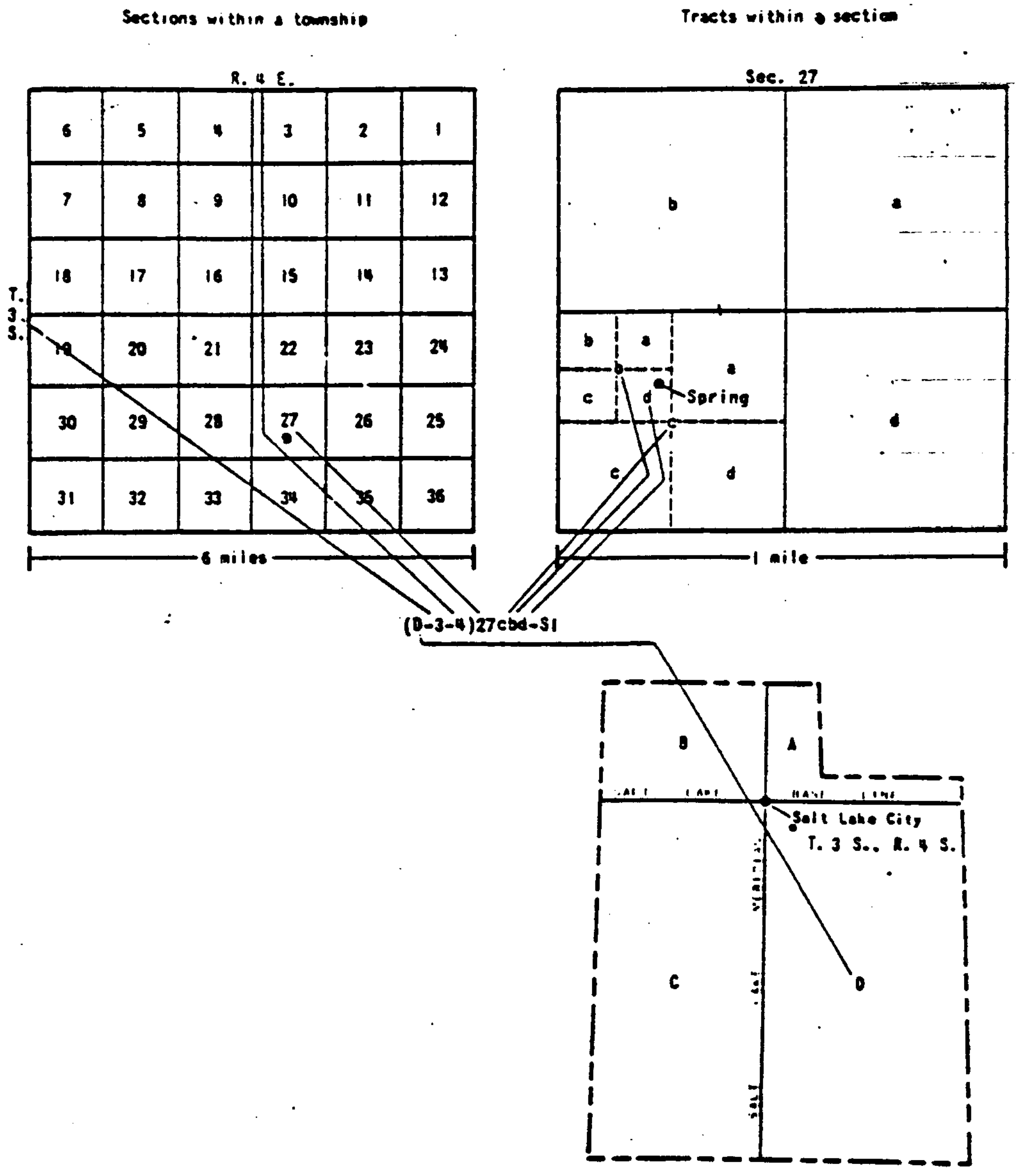


FIG. 10.--Well- and spring-numbering system (Murphy and Gwynn, 1979).

Appendix II

Thermal Gradient Data

Appendix II

Thermal Gradient Data

Included here are data summary sheets for all sites located in Plate 1.

"Dip Angle" refers to the dip of the well. This information is necessary for topographic corrections. "Completed By" refers to the date on or before which the drilling was completed. "Logged On" refers to the date when the temperature profile measurements were made. These dates are necessary to insure that the water temperatures have had enough time to stabilize between drilling and logging.

The gradient calculations were made over the depth range listed. Perforations in the casing are also listed by their depth range.

Oftentimes sediments begin to fill up the well. Therefore, in most of the wells logged for this study, the lithology taken from the driller's log covers a greater depth range than the depth range of temperatures measured by the author.

Area: Cache Valley, Utah
Locality: (A-10-1)26bbb
Well: Paradise CVG-1

Site Latitude: 41°34'56.5" N.
Site Longitude: 111°48'44" W.
Site Elevation: 1591.1 ± 5.8 m
Dip Angle: 90°
Completed By: 1-23-78
Logged On: 9-12-81

Depth Range (Grad. Calc.): #9-49 m
Gradient: isothermal
Depth To Water: 51 m
Perforations (Depth): 49.4 m to 58.5 m, 63.1 m to 76.2 m

Depth (m)	T (°C)
9	10.98
19	10.99
29	11.01
39	10.95
49	10.96
53	10.78

To Depth (m)	Lithology
9.1	brown clay
18.0	cemented sand
36.6	lightly cemented sand, gravel
42.7	brown clay
47.2	cemented gravel
49.4	brown clay
58.5	cemented gravel, water
63.1	brown clay, gravel
73.5	cemented gravel
75.0	lightly cemented gravel
76.2	brown clay
78.6	cemented gravel
80.2	unknown
82.3	lightly cemented gravel, water

Area: Cache Valley, Utah
Locality: (A-10-1)27dad
Well: Paradise CVG-2

Site Latitude: 41°34'25.5" N.
Site Longitude: 111°48'53" W.
Site Elevation: 1566.7 ± 5.8 m
Dip Angle: 90%
Completed By: 9-79
Logged On: 9-12-81

Depth Range (Grad. Calc.): 19-49 m
Gradient: isothermal
Depth To Water: 13 m
Perforations (Depth):

Depth (m)	T (°C)	To Depth (m)	Lithology
9	10.89		
19	10.65		
29	10.81		
39	10.92		
49	11.00		

Area: Cache Valley, Utah

Locality: (A-10-1) 16bbd

Well: Hyrum CVG-3

Site Latitude: 41°36'36" N.

Site Longitude: 111°50'48" W.

Site Elevation: 1466.1 ± 2.7 m

Dip Angle: 90°

Completed By: 10-2-79

Logged On: 9-14-81

Depth Range (Grad. Calc.): 19-79 m

Gradient: 15 ± 1 °C/km

Depth To Water: 44 m

Perforations (Depth): 73.8 m to 75.9 m, 81.4 m to 85.3 m

Depth (m)	T (°C)
9	11.61
19	11.87
29	12.03
39	12.30
49	12.31
59	12.50
69	12.65
79	12.83
85	12.85

To Depth (m)	Lithology
0.9	top soil
4.9	dry gravel
6.4	clay, sand, gravel
7.6	gravel, water
13.1	sand
18.3	sand and clay layers
33.5	clay, sand
39.6	blue clay
42.7	gravel
45.7	blue clay
46.6	gravel, iron water
54.3	clay, sand, gravel
68.0	gravel, iron water
73.8	clay, sand
75.9	gravel, water
81.4	clay, gravel
86.0	gravel, water

Area: Cache Valley, Utah
Locality: (A-10-1)23baa
Well: Millville CVG-4

Site Latitude: 41°41'07.5" N.
Site Longitude: 111°48'12" W.
Site Elevation: 1581.9 ± 2.7 m
Dip Angle: 90°
Completed By: 4-29-77
Logged On: 9-14-81

Depth Range (Grad. Calc.): 169-199m
Gradient: 40 ± 1 °C/km
Depth To Water: 199 m
Perforations (Depth): 154.2 m to 225.6 m

Depth (m)	T (°C)
9	12.83
19	12.13
29	12.00
39	12.00
49	12.05
59	12.18
69	12.30
79	12.43
89	12.57
99	12.82
109	13.03
119	13.24
129	13.43
139	13.65
149	13.96
159	14.44
169	14.63

To Depth (m)	Lithology
0.9	clay, cobbles
14.6	gravel, boulders
16.2	clay, gravel
18.6	dry gravel
19.8	clay, gravel
22.6	dry gravel
32.9	clay, gravel
45.1	clay, boulders
51.5	clay, gravel
72.5	dry sand, gravel
76.2	clay, sand
77.7	clay, gravel
88.4	hard conglomerate
93.9	clay, gravel
98.5	hard conglomerate
148.4	clay, gravel
156.4	conglomerate, water

Area: Cache Valley, Utah
Locality: (A-10-1)23baa
Well: Millville CVG-4 (Continued)

Site Latitude:
Site Longitude:
Site Elevation:
Dip Angle:
Completed By:
Logged On:

Depth Range (Grad. Calc.):
Gradient:
Depth To Water:
Perforations (Depth):

Depth (m)	T (°C)	To Depth (m)	Lithology
179	15.02	180.1	clay, gravel
189	15.43	181.7	conglomerate, water
199	15.83	184.1	clay, gravel, little water
		185.0	conglomerate, water
		185.9	sticky clay
		207.7	clay, gravel, little water
		224.9	conglomerate, water
		228.6	sticky clay

Area: Cache Valley, Utah
Locality: (B-10-1)13bca
Well: Mt. Sterling CVG-5

Site Latitude: 41°36'26" N.
Site Longitude: 111°54'24" W.
Site Elevation: 1466.1 ± 2.7 m
Dip Angle: 90°
Completed By: 2-75
Logged On: 9-14-81

Depth Range (Grad. Calc.): 19-39 m
Gradient: 29 ± 2 °C/km
Depth To Water: 5 m
Perforations (Depth): 29.0 m to 47.9 m

Depth (m)	T (°C)
9	10.27
19	10.58
29	10.86
34	11.03

To Depth (m)	Lithology
0.6	top soil, silt
10.7	brownish red silt
12.8	hard, white limestone
32.0	light brown clay, sand, gravel
43.9	hard, light brown clay, sand, gravel
47.9	brown silt

Area: Cache Valley, Utah

Locality: (A-9-1)10add

Well: Avon CVG-6

Site Latitude: 41°32'00" N

Site Longitude: 111°48'46" W.

Site Elevation: 1530.1 ± 5.8 m

Dip Angle: 90°

Completed By: 4-29-77

Logged On: 9-14-81

Depth Range (Grad. Calc.): 19-39 m

Gradient: 32 ± 4 °C/km

Depth To Water: 6 m

Perforations (Depth): 36.3 m to 39.9 m

Depth (m)	T (°C)
9	10.74
19	10.91
29	11.36
39	11.58
41	11.64

To Depth (m)	Lithology
1.5	top soil
3.7	dry gravel
7.3	clay, gravel
7.9	sand, gravel
9.8	clay, gravel
18.0	gray clay, sand
19.8	gravel, water
22.9	clay, gravel
36.3	blue clay
40.0	gravel, water
42.7	clay, gravel

Area: Cache Valley, Utah

Locality: (A-11-1)3acd

Well: River Heights CVG-7

Site Latitude: 41°43'24" N.

Site Longitude: 111°49'05" W.

Site Elevation: 1399.0 ± 5.8 m

Dip Angle: 90°

Completed By: 8-21-80

Logged On: 9-10-81

Depth Range (Grad. Calc.): 29-109 m

Gradient: isothermal

Depth To Water: 15 m

Perforations (Depth): 30.5 m to 37.2 m, 42.7 m to 54.3 m, 79.6 m to 83.2 m, 93.0 m to 98.5 m

Depth (m)	T (°C)
9	11.79
19	11.35
29	10.73
39	10.75
49	10.74
59	10.67
69	10.69
79	10.67
89	10.67
99	10.75
109	10.79
112	10.79

To Depth (m)	Lithology
0.9	top soil
3.0	sand, gravel
12.8	blue clay
15.2	sandy clay
17.4	blue clay
23.2	silty clay
24.7	sand
27.4	sandy clay
34.1	gravel, water
35.1	clay, gravel
37.2	gravel, water
38.7	clay, gravel
39.6	sand, gravel
54.3	gravel, water
55.2	sandy clay
57.9	gravel, water
58.8	sandy clay

Area: Cache Valley, Utah

Locality: (A-11-1)3acd

Well: River Hts. CVG-7 (Continued)

Site Latitude:	Depth Range (Grad. Calc.):
Site Longitude:	Gradient:
Site Elevation:	Depth To Water:
Dip Angle:	Perforations (Depth):
Completed By:	
Logged On:	

Depth (m)	T (°C)	To Depth (m)	Lithology
		66.4	silty sand
		79.6	sticky clay
		83.2	gravel, water
		85.6	silty clay
		89.0	clay, gravel
		90.8	hard conglomerate
		93.0	silty clay
		94.8	gravel, water
		96.0	brown clay
		98.5	gravel, water
		105.2	gravel, clay

Area: Cache Valley, Utah
Locality: (A-13-1)35cdc
Well: Smithfield CVG-8

Site Latitude: 41°49'02.5" N.
Site Longitude: 111°48'31" W.
Site Elevation: 1417.3 ± 5.8 m
Dip Angle: 90°
Completed By: 4-20-64
Logged On: 9-9-81

Depth Range (Grad. Calc.): 50-120 m
Gradient: 52 ± 1 °C/km
Depth To Water: 40 m
Perforations (Depth): 13.4 m to 164.6 m

Depth (m)	T (°C)	To Depth (m)	Lithology
10	14.16	0.6	top soil
20	12.87	0.9	gray clay
30	11.9	1.5	cemented gravel
40	12.06	7.3	clay, soft lime
50	12.25	7.9	gravel
60	12.72	13.7	brown clay
70	13.20	14.3	gravel, trace water
80	13.71	56.4	gray lime
90	14.26	56.7	gravel
100	14.82	87.5	gray lime
110	15.36	87.8	gravel
120	15.88	108.2	gray lime
127	16.03	108.5	sand
		167.6	gray lime, shale

Area: Cache Valley, Utah
Locality: (A-12-1)27aaa
Well: Logan CVG-9

Site Latitude:	41°45'23.5"	Depth Range (Grad. Calc.):	23.5-37.5 m
Site Longitude:	111°48'48"	Gradient:	297 ± 45 °C/km
Site Elevation:	1408.2 ± 5.8 m	Depth To Water:	37 m
Dip Angle:	90°	Perforations (Depth):	38.7 m to 41.8 m
Completed By:	6-9-55		
Logged On:	2-7-82		

Depth (m)	T (°C)
8.5	21.36
13.5	24.19
23.5	28.23
33.5	30.73
37.5	32.54

To Depth (m)	Lithology
34.7	clay
41.8	gravel

Area: Cache Valley, Utah
Locality: (A-13-1)3adb
Well: Richmond CVG-10

Site Latitude: 41°56'27.5" N.
Site Longitude: 111°51'21" W.
Site Elevation: 1385.3 ± 1.4 m
Dip Angle: 90°
Completed By: 8-13-79
Logged On: 9-11-81

Depth Range (Grad. Calc.): 29-125 m
Gradient: 36 ± 1 °C/km
Depth To Water: 1 m
Perforations (Depth): 11.0 m to 16.2 m

Depth (m)	T (°C)
9	10.03
19	10.13
29	10.33
39	10.63
49	10.93
59	11.25
69	11.61
79	11.98
89	12.36
99	12.77
109	13.20
119	13.53
125	13.70

To Depth (m)	Lithology
0.6	top soil
3.0	brown clay, gravel
7.3	light brown clay
11.0	gray clay
16.2	gravel, water
36.0	clay, gravel
52.1	gray clay, sand
102.4	hard, gray clay
104.5	sand
111.3	hard, gray clay
118.0	gray clay, sand
143.6	hard, gray clay

Area: Cache Valley, Utah
Locality: (B-15-2)32dda
Well: Clarkston CVG-11

Site Latitude: 41°59'32" N.
Site Longitude: 112°05'23" W.
Site Elevation: 1588.0 ± 5.8 m
Dip Angle: 90°
Completed By: 1980
Logged On: 9-11-81

Depth Range (Grad. Calc.): 49-149 m
Gradient: 31 ± 1 °C/km
Depth To Water: 29 m
Perforations (Depth):

Depth (m)	T (°C)
9	9.52
19	9.66
29	9.70
39	9.78
49	9.89
59	10.12
69	10.38
79	10.67
89	10.97
99	11.31
109	11.60
119	11.92
129	12.27
139	12.59
149	12.99
159	13.09
169	13.09
179	13.40

To Depth (m)	Lithology

Area: Cache Valley, Utah
Locality: (B-14-1)28cdb
Well: Trenton CVG-12

Site Latitude: 41°55'12.5" N.
Site Longitude: 111°57'56" W.
Site Elevation: 1392.9 ± 2.7 m
Dip Angle: 90°
Completed By: 12-6-79
Logged On: 9-9-81

Depth Range (Grad. Calc.): 19-39 m
Gradient: 36 ± 1 °C/km
Depth To Water: 10 m
Perforations (Depth): 30.5 m to 35.1 m

Depth (m)	T (°C)
9	12.52
19	14.78
29	15.15
39	15.50
49	15.71
54	15.71

To Depth (m)	Lithology
0.9	top soil
7.0	clay, gravel
9.4	brown sandstone
19.5	blue limestone
65.5	fractured limestone, water

Appendix III

Well and Spring Data

Appendix III

Well and Spring Data

This appendix includes the details about each well and spring. The location is described first by latitude and longitude, followed by the cadastral coordinates described in Appendix I. "Number" refers to the author's numbering system.

Under "Source," W = well and S = spring.

"Reference" indicates what agency did the chemical analysis. ESL stands for Earth Science Laboratory, Salt Lake City, Utah. All other analyses were performed by the author.

Alkalinity is expressed as mg/l HCO_3^-. This value has been adjusted for the pH at each location.

Cl^- and F^- were measured as activities, which is approximately equal to their concentrations.

Where blanks occur, the data were not collected or were not available.

LOCATION	NUMBER AND OWNER	SOURCE	TEMP °C	DEPTH meters	YIELD m³/min	DATE OF SAMPLE	REFERENCE	ANALYSIS EXPRESSED AS MILLIGRAMS PER LITER										DISSOLVED SOLIDS	COND mmhos	pH	Eh mv	REMARKS
								SiO_2	Fe	Ca^{+2}	Mg^{+2}	Na^+	K^+	HCO_3^-	SO_4^{-2}	Cl^-	F^-					
41°31' 57.5" N. 111°49'19" W. (A-9-1)10acc-1	CVV-69	W	11.0	45		8-27-81	ESL	12	0.0	67	23	6	2.1	184	17	10	0.3	308	330	6.9	+115	10885 S. Hwy 165, Avon
41°38'24.5" N. 111°49'05" W. (A-10-1)3aba-S1	CVV-63 Jan Blaugh	S	11.1			8-25-81		7	0.0	87	13	10	1.2	190	9	11	0.1	358	405	6.7		
41°37'38.5" N. 111°53'08" W. (A-10-1)7bab-1	CVV-60	W	15.1	34		8-25-81		19	0.0	63	20	13	2.1	223	10	12	0.2	278	355	6.9		
41°36'47" N. 111°50'31" W. (A-10-1)9dcc-1	CVV-74 Derwood Clawson	W	14.6	67		8-27-81		31	0.5	58	25	24	9	219	6	21	0.4	338	415	7.1	-67	464 E. 200 S., Hyrum
41°37'12.5" N. 111°49'48" W. (A-10-1)10bcc-1	CVV-75	W	14.5	99		8-27-81	ESL	18	0.0	64	26	19	1.8	184	8	23	0.3	352	410	6.9		
41°35'16" N. 111°50'18" W. (A-10-1)21dbd-1	CVV-73	W	12.5	32		8-27-81	ESL	22	1.6	70	27	19	3	219	3	29	0.5	370	410	7.2	-139	
41°34'40" N. 111°47'51" W. (A-10-1)26adb-1	CVV-71	W	11.9	62		8-27-81		6	0.0	63	25	7	0.9	165	34	9	0.1	264	330	7.1		
41°34'58" N. 111°51'00" W. (A-10-1)28bbb-1	CVV-72 Richard Nielson	W	17.2	128		8-27-81	ESL	54	0.1	7	10	250	17	484	2	91	2.9	874	1030	7.8		
41°33'59" N. 111°49'28" W. (A-10-1)34bac-1	CVV-70 Paradise City	W	17.8	221		8-27-81	ESL	6	0.0	57	18	3	0.5	172	9	6	0.3	244	330	7.3		
41°43'10.5" N. 111°50'02" W. (A-11-1)4bad-1	CVV-65 Griffin Garden Store	W	11.2	64		8-26-81		7	0.0	75	28	9	1.4	191	20	10	0.1	330	370	7.0		
41°43'23.5" N. 111°51'15" W. (A-11-1)5add-1	CVV-50 Susan Harris	W	16.5	54		7-29-81		9	0.2	70	28	8	1.9	289	19	8	0.1	314	425	6.9	+65	812 Three Point Ave., Logan
41°43'17.5" N. 111°52'29" W. (A-11-1)6dab-1	CVV-47	W	13.0	55		6-29-81		9	0.1	59	24	12	1.4	227	13	11	0.1	289	390	6.8		
41°41'36" N. 111°47'38" W. (A-11-1)14add-1	CVV-66 Reed Jorgenson	W	10.7	79		8-26-81		4	0.0	60	17	7	0.5	145	11	5	0.1	202	255	7.2		1590 E. Canyon Rd., Providence
41°41'25" N. 111°49'12" W. (A-11-1)15dbc-1	CVV-64 Matthew Ardell	W	13.8	107		8-26-81		7	0.0	70	24	12	1.5	198	23	11	0.1	350	390	6.9		
41°41'26" N. 111°52'03" W. (A-11-1)17cbd-1	CVV-57 Silven Olsen	W	10.3			8-24-81		8	0.0	67	24	8	1.0	237	32	7	0.2	266	310	7.0	+53	artesian
41°40'32" N. 111°52'46" W. (A-11-1)19dbc-1	CVV-56 T. L. Zilles	W	11.8			8-24-81		6	0.0	71	8	8	1.0	220	58	7	0.3	278	340	7.0		

LOCATION	NUMBER AND OWNER	SOURCE	TEMP °C	DEPTH meters	YIELD m^3/min	DATE OF SAMPLE	REFERENCE	ANALYSIS EXPRESSED AS MILLIGRAMS PER LITER											COND mmhos	pH	Eh mv	REMARKS
								SiO_2	Fe	Ca^{+2}	Mg^{+2}	Na^+	K^+	HCO_3^-	SO_4^{-2}	Cl^-	F^-	DISSOLVED SOLIDS				
41°40'55" N. 111°53'06" W. (A-11-1)20add-1	CVV-58	W	10.0			8-25-81		6	0.1	66	24	8	1.2	210	30	9	0.2	260	305	7.0		
41°40'52" N. 111°48'30" N. (A-11-1)23bcq-1	CVV-67 Owen Hancey	W	14.0			8-26-81	ESL	14	0.0	45	20	9	2.[illegible]	180	15	13	0.3	282	180	7.2		
41°39'31" N. 111°48'53" W. (A-11-1)27dda-1	CVV-68 Allen Jensen	W	11.3			8-26-81	ESL	12	0.0	67	39	8	4	217	23	6	0.4	376	217	6.9		651 E. 3800 S., Millville
41°53'30" N. 111°53'23" W. (A-11-1)31ccc-1	CVV-55 Evan Brown	W	13.4	38		8-24-81		30	2.8	77	15	24	10	366	6	27	0.4	374	435	7.0	-84	
41°38'39" N. 111°51'35" W. (A-11-1)32dcb-1	CVV-61 Miller Brothers Co	W	12.4	107		8-25-81		15	4.5	100	27	20	10	378	4	18	0.3	394	405	7.0		
41°39'16.5" N. 111°49'46" W. (A-11-1)34dbb-1	CVV-62 LeGrand-Johnson Construction Co.	W	10.8			8-25-81		4	0.0	76	10	9	1.1	184	48	7	0.2	310	315	7.2		
41°47'59.5" N. 111°51'23.5" W. (A-12-1)8aab-1	CVV-80	W	13.2			9- 1-81		15	0.6	30	21	63	1.6	296	2	44	0.3	304	370	7.4	-187	artesian
41°57'20" N. 111°50'02" W. (A-12-1)9ddd-1	CVV-7	W	16.4	64		6-16-81		21	0.1	42	18	40	6	291	10	14	0.3	298	420	7.4		
41°47'26" N. 111°48'12" W. (A-12-1)11bcd-1	CVV-6 Batty	W	14.3	63		6-16-81		14	0.2	52	38	4	0.9	260	3	6	0.1	292	415	6.9		1325 E. 3250 N., N. Logan
41°46'58" N. 111°50'00" W. (A-12-1)16ada-1	CVV-8 Ernest Olsen	W	16.6	62		6-16-81		22	0.1	51	21	26	7	303	6	10	0.3	298	415	7.5		2835 N. Main, N. Logan artesian
41°46'38.5" N. 111°50'32" W. (A-12-1)16dbc-1	CVV-4 Don Bodraro	W	19.9	49		6- 3-81		20	0.1	60	25	16	6	321	9	8	0.3	302	425	7.1	+43	2450 N. 400 W., artesian
41°45'44" N. 111°52'30" W. (A-12-1)19dac-1	CVV-9 Utah State Univ.	W	16.2	67		6-16-81		14	0.4	49	18	30	4	303	5	14	0.2	254	405	7.5		artesian
41°46'08.5" N. 111°50'02" W. (A-12-1)21ada-1	CVV-2 Greek Gardens	W	16.0	82		6- 3-81		14	0.1	61	34	12	4	321	9	9	0.2	338	490	7.1	+64	
41°45'25.5" N. 111°50'37" W. (A-12-1)20baa-1	CVV-3 K. Linquist	W	25.1	78		6- 3-81		18	0.1	51	20	22	6	247	21	20	0.3	290	485	7.2	+63	Logans Plunge
41°45'03.5" 111°50'37.5" W. (A-12-1)20caa-1	CVV-1 G. E. Pyle	W	21.1	50	.002	6- 3-81		13	0.2	48	22	13	3	244	18	10	0.2	252	400	7.1		395 N. 1000 W., Logan artesian
41°44'07" N. 111°52'33" W. (A-12-1)31dab-1	CVV-52 Cecil Nish	W	17.1	59		8-24- 1		9	0.0	56	14	12	2.0	217	11	9	0.2	222	290	6.9	+155	artesian
41°44'10.5" N. 111°52'08" W. (A-12-1)32cbb-1	CVV-48 State Fish Hatchery	W	14.7		.227	7-28-81		9	0.1	49	22	7	1.8	222	16	8	0.2	234	325	7.2	+73	artesian

LOCATION	NUMBER AND OWNER	SOURCE	TEMP. °C	DEPTH meters	YIELD m^3/min	DATE OF SAMPLE	REFERENCE	ANALYSIS EXPRESSED AS MILLIGRAMS PER LITER											COND mmhos	pH	Eh mv	REMARKS
								SiO_2	Fe	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{-2}	Cl^{-}	F^{-}	DISSOLVED SOLIDS				
41° 44'12.5" N. 111° 50'59" W. (A-12-1)33bcc-1	CVV-81 Elleson Packing Co.	W	11.3	30		7-29-81		6	0.1	55	23	4	0.8	236	17	6	0.2	242	300	7.1	+76	
41° 50'21.5" N. 111° 49'17" W. (A-13-1)27acd-1	CVV-89	W	10.9	76		9- 1-81		7	0.0	57	25	6	1.1	259	5	8	0.1	242	300	7.2		
41° 50'42.5" N. 111° 50'03.5" W. (A-13-1)28aaa-1	CVV-87 Logan North Irrigation Co.	W	11.7	145		8-31-81		7	0.0	53	22	6	0.7	236	5	6	0.1	220	310	7.2	+119	
41° 50'07.5" N. 111° 51'46" W. (A-13-1)29cbd-1	CVV-6 F. Watts	W	10.1			6-16-81		9	0.1	77	26	5	0.7	310	8	8	0.0	320	405	7.1		
41° 49'00" N. 111° 53'29" W. (A-13-1)31ccc-1	CVV-18 Arvel C. Reese	W	17.5	191		6-18-81		14	1.0	42	30	160	5	346	1	217	0.2	522	630	7.0	-153	
41° 49'41" N. 111° 49'51" W. (A-13-1)34bbd-1	CVV-88 Smithfield Irrigation Co.	W	11.9	191		9- 1-81		12	0.0	60	38	8	4	304	7	9	0.1	330	300	7.1	+112	
41° 58'34" N. 111° 48'43" W. (A-14-1)2cdc-1	CVV-82 Sherwin Larsen	W	11.5			8-31-81		19	2.5	87	19	180	8	341	2	141	0.4	584	660	7.3		Larsen's Conoco
41° 56'51" N. 111° 48'51" W. (A-14-1)14ccc-1	CVV-84 Richmond Irrigation Co.	W	12.0	91		8-31-81		8	0.1	59	24	4	0.7	244	3	7	0.1	242	330	7.2		
41° 56'58" N. 111° 50'14" W. (A-14-1)16dda-1	CVV-83 Sid Kerren	W	11.0			8-31-81		11	2.5	44	21	46	0.8	257	2	139	0.1	278	350	7.4		
41° 53'08" N. 111° 47'22" W. (A-14-1)25bdc-S1	CVV-35 Christensen	S	12.0		.019	6-24-81		15	0.1	17	57	10	0.6	210	5	13	0.2	248	315	7.0		
41° 55'08" N. 111° 49'25" W. (A-14-1)27dcc-1	CVV-85 Pet Milk Co.	W	12.9	46	.003	8-31-81		22	0.2	77	37	23	4	314	15	22	0.3	402	470	7.1	+117	artesian
41° 54'41.5" N. 111° 49'44" W. (A-14-1)34bdc-1	CVV-86 Thompson	W	10.6			8-31-81		12	0.1	88	26	10	1.2	332	10	11	0.1	368	400	7.0	+128	artesian
41° 37'02.5" N. 111° 56'24" W. (B-10-1)10cad-1	CVV-80 Louis Callister, Sr	W	13.3	59		8-28-81		7	0.0	61	21	22	1.4	154	11	148	0.2	294	360	7.1		1050 S. 200 W., Wellsville
41° 36'31.5" N. 111° 54'23" W. (B-10-1)13bbd-1	CVV-79 Leland Gunnell	W	13.0	64		8-28-81		33	0.1	95	12	44	5	172	24	141	0.3	434	475	6.9	+175	
41° 36'20" N. 111° 55'51" W. (B-10-1)15add-1	CVV-76 Tom Lindley Lindley Enterprises	W	13.7			8-28-81		12	0.0	71	26	59	4	142	10	135	0.2	432	610	7.0		
41° 34'16.5" N. 111° 54'21" W. (B-10-1)25cca-S1	CVV-78	S	17.0		.003	8-28-81		34	0.0	97	19	64	0.3	124	40	125	0.4	526	720	6.7		

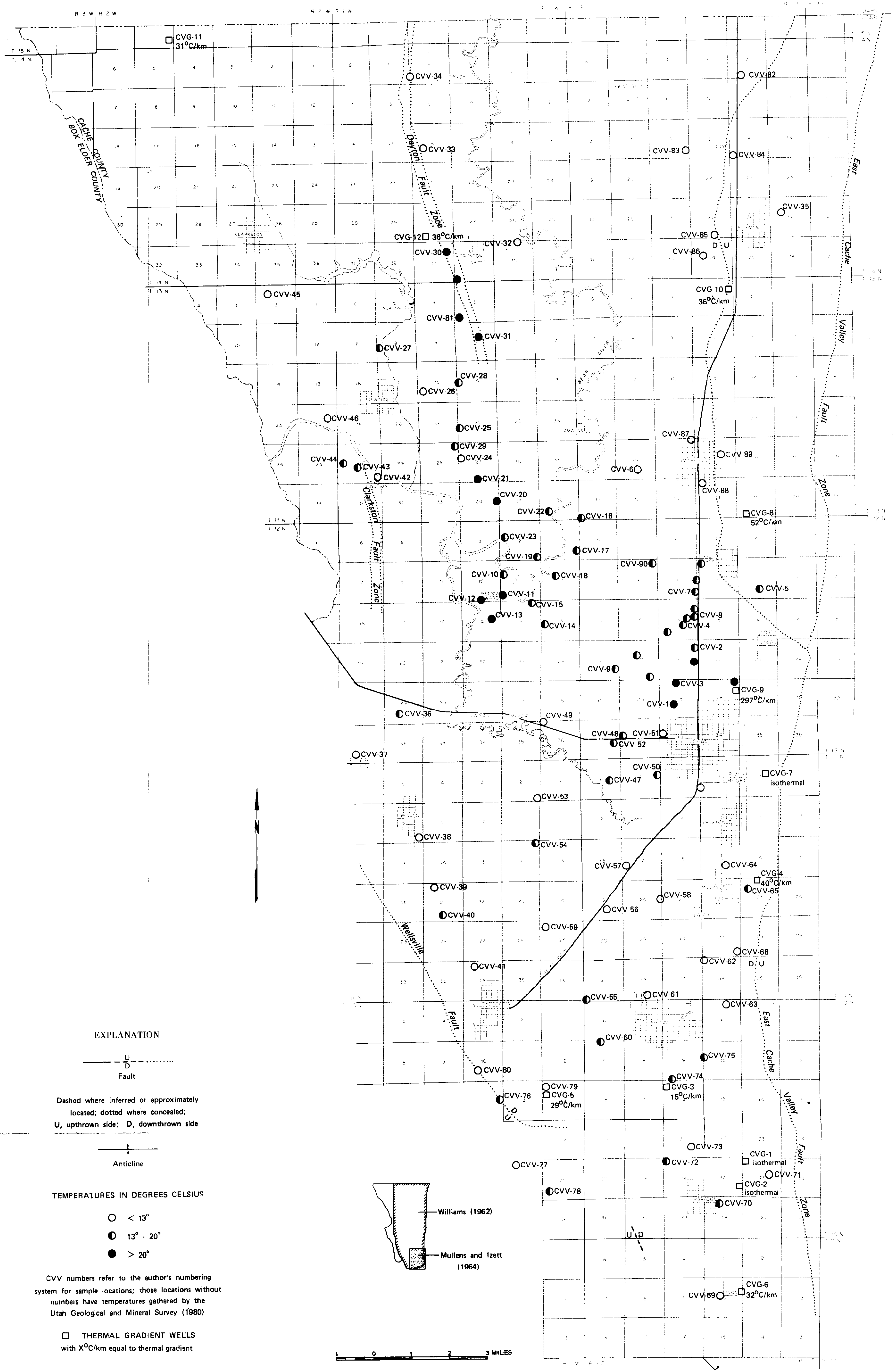
LOCATION	NUMBER AND OWNER	SOURCE	TEMP. °C	DEPTH meters	YIELD m³/min	DATE OF SAMPLE	REFERENCE	ANALYSIS EXPRESSED AS MILLIGRAMS PER LITER											COND mmhos	pH	Eh mv	REMARKS
								SiO_2	Fe	Ca^{+2}	Mg^{+2}	Na^+	K^+	HCO_3^-	SO_4^{-2}	Cl^-	F^-	DISSOLVED SOLIDS				
41° 34'38" N. 111° 54'17" W. (B-10-1)26bad-S1	CVV-77 Hall Spring	S	9.9			8-28-81	ESL	20	0.0	89	8	12	1.0	150	20	13	0.3	338	340	6.8	+134	
41° 42'58" N. 111° 54'40" W. (B-11-1)2ddd-1	CVV-53 Souter	W	11.1			8-24-81		14	0.5	63	22	53	1.3	310	6	30	0.2	304	365	7.3		
41° 42'06" N. 111° 56'07" W. (B-11-1)18dda-1	CVV-38 Elmer James	W	10.8	55		6-27-81		27	1.8	57	11	23	1.5	204	1	23	1.2	280	390	6.8	-171	1600 S. 560 W., Mendon
41° 41'58.5" N. 111° 54'15" W. (B-11-1)14daa-1	CVV-54 Clyde Sorensen	W	13.0	62		8-24-81		15	0.2	67	13	20	2.1	251	55	14	0.2	332	385	7.0		
41° 41'02.5" N. 111° 57'46" W. (B-11-1)21bad-1	CVV-39 Brent Hatch	W	11.1	48		6-27-81	ESL	16	0.0	78	7	14	1.0	210	12	14	0.4	300	385	6.9		
41° 40'23" N. 111° 57'29" W. (B-11-1)21dcd-1	CVV-40 Parkinson	W	13.8	87		6-27-81		11	0.2	77	10	11	1.5	204	7	13	0.2	284	430	6.8		
41° 40'08" N. 111° 54'58" W. (B-11-1)25bbc-1	CVV-59 Dwayne Hall	W	12.3	45		8-25-81		7	0.3	69	30	17	6	264	54	14	0.3	352	430	7.0	-42	
41° 39'15" N. 111° 56'33" W. (B-11-1)34bac-1	CVV-41 Richard Hamilton	W	10.2	61		6-27-81		7	0.2	65	14	16	1.3	191	8	31	0.1	276	600	7.0		
41° 48'19" N. 111° 53'32" W. (B-12-1)1dad-1	CVV-17	W	17.8	170		6-18-81		13	1.9	89	49	85	2.0	181	1	390	0.3	860	1160	7.1		
41° 48'33" N. 111° 55'41" W. (B-12-1)2bcd-1	CVV-23 Heber Cronquist	W	19.8	227		6-19-81		23	0.7	130	48	100	4	234	1	394	0.2	1012	1470	7.0	-170	artesian
41° 48'07.5" N. 111° 54'43" W. (B-12-1)2ddd-1	CVV-19 N. L. Ballard	W	18.1			6-18-81		11	0.8	120	59	92	5	160	7	410	0.3	958	1460	7.3	-126	
41° 47'33.5" N. 111° 56'08" W. (B-12-1)10ddd-1	CVV-12 Cecil Archibald	W	20.9	162		6-17-81		40	0.6	56	19	81	5	340	2	100	0.8	478	680	7.2	-130	artesian
41° 47'49" N. 111° 55'44" W. (B-12-1)11bcb-1	CVV-10 Norval Johnson	W	15.0	180		6-17-81		63	1.0	97	31	98	5	236	2	295	0.8	758	950	7.2		artesian
41° 47'18" N. 111° 55'46" W. (B-12-1)11ccc-1	CVV-11 Wayne Cardon	W	20.9	187		6-17-81		57	0.1	51	16	68	3	308	2	76	0.8	424	530	7.2	-138	artesian
41° 47'43" N. 111° 54'08" W. (B-12-1)12bdd-1	CVV-18 L. J. Argust	W	17.4	166		6-18-81		10	1.2	110	53	88	4	189	2	357	0.3	974	1300	7.2		2088 W. 3400 N., Benson artesian

LOCATION	NUMBER AND OWNER	SOURCE	TEMP. °C	DEPTH meters	YIELD m³/min	DATE OF SAMPLE	REFERENCE	ANALYSIS EXPRESSED AS MILLIGRAMS PER LITER											COND. micromhos	pH	Eh mv	REMARKS
								SiO_2	Fe	Ca^{+2}	Mg^{+2}	Na^+	K^+	HCO_3^-	SO_4^{-2}	Cl^-	F^-	DISSOLVED SOLIDS				
41°46'44.5" N. 111°54'36" W. (B-12-1)13cbb-1	CVV-14 Ronald Chambers	W	10.4	160		6-17-81		12	1.4	120	47	72	1.8	206	1	375	0.3	980	1200	7.1		artesian
41°47'08.5" N. 111°54'58" W. (B-12-1)14aab-1	CVV-15 D. R. Hubbs	W	19.0	106		6-17-81		19	0.9	150	54	93	2.0	216	0	530	0.2	1090	1660	7.1		artesian
41°46'47.5" N. 111°56'04" W. (B-12-1)15adc-1	CVV-13 Kendall Larsen	W	23.0	195		6-17-81		21	0.8	67	21	92	2.0	257	1	210	0.3	542	950	7.4	-153	artesian
41°44'46" N. 111°58'39" W. (B-12-1)29cda-1	CVV-36 Woodbrey	W	13.3	61		6-27-81		46	0.1	8	4	110	7	327	6	11	1.0	352	415	7.8	+31	
41°43'57" N. 111°59'55" W. (B-12-1)31cad-1	CVV-37 Crowshaw	W	10.1	61		6-27-81		40	0.1	87	24	24	1.8	307	20	24	0.8	416	580	6.9		
41°44'30.5" N. 111°54'37" W. (B-12-1)36bbc-1	CVV-49	W	11.4		.023	7-28-81		16	0.1	51	20	26	3.1	273	1	30	0.3	274	384	7.4	-65	artesian
41°51'27.5" N. 111°56'53" W. (B-13-1)3cca-S1	CVV-81 L. T. Cottle	S	22.0			8-20-81		28	0.0	85	36	920	87	277	76	1600	2.6	2926	3900	7.0	-193	
41°52'46.5" N. 111°59'19" W. (B-13-1)8cbb-1	CVV-27 Peterson Brothers Farm	W	13.3			6-19-81		48	1.2	91	34	56	16	383	3	84	0.4	556	710	6.9		
41°53'02" N. 111°56'22" W. (B-13-1)10acb-1	CVV-31 Linden Hauser	G	51.0	1587	.227	8-23-81		69	0.3	79	30	1300	70	588	2	2120	4.5	3784	8700	6.9	-165	artesian
41°51'59.5" N. 111°57'02" W. (B-13-1)15cbb-1	CVV-20 Wm. Kim Pitcher	W	14.8			6-19-81		20	0.3	24	10	100	4	280	21	43	0.6	367	500	7.6	-148	
41°51'48" N. 111°58'04" W. (B-13-1)16cbd-1	CVV-26 Joe Larsen	W	11.0	66		6-19-81		41	9.2	85	31	53	4	247	57	130	0.4	562	690	7.2		
41°50'59" N. 111°57'01" W. (B-13-1)22cbc-1	CVV-25 Annette Orton	W	14.8	134		6-19-81		58	1.6	110	51	150	18	842	4	108	0.5	904	1260	6.9	-108	gaseous
41°49'51" N. 111°56'28.5 W. (B-13-1)27cdd-1	CVV-21 Russell Seamons	W	23.1	203		6-18-81		33	0.8	69	29	110	4	236	1	298	0.2	766	1200	7.2	-123	
41°50'18" N. 111°57'00" W. (B-13-1)27bcc-1	CVV-24 James Anderson	W	11.4	49		6-18-81		46	2.1	75	29	150	16	329	2	248	0.4	738	1010	6.9	-154	
41°50'40.5" N. 111°57'08" W. (B-13-1)28aaa-1	CVV-29 Norris Anderson	W	15.1	68	.002	6-20-81		55	0.7	77	20	110	9	311	2	195	0.4	614	830	7.2	-160	artesian
41°45'09" N. 112°00'05" W. (B-13-1)30caa-1	CVV-43 Union Pacific Railroad	W	14.3	100		6-29-81		52	0.4	47	20	79	11	275	17	77	1.0	448	690	7.0	-104	artesian

LOCATION	NUMBER AND OWNER	[illegible]	TEMP. °C	DEPTH meters	YIELD m³/min.	DATE OF SAMPLE	REFERENCE	ANALYSIS EXPRESSED AS MILLIGRAMS PER LITER											COND. mmhos	pH	Eh mv	REMARKS
								SiO_2	Fe	Ca^{+2}	Mg^{+2}	Na^+	K^+	HCO_3^-	SO_4^{-2}	Cl^-	F^-	DISSOLVED SOLIDS				
41°48'14.8" N. 112°00'26" W. (B-13-1)30cbb-1	CVV-44 Ballard	W	13.6			6-29-81	ESL	32	0.0	46	18	64	4	203	33	66	0.7	400	520	7.0	+53	
41°50'04.5" N. 111°59'55" W. (B-13-1)30dbc-1	CVV-42 Grover Pace	W	12.5	55		6-29-81		49	0.6	67	25	35	8	263	10	42	0.5	412	500	7.0	-56	artesian
41°49'22" N. 111°55'53" W. (B-13-1)34daa-1	CVV-20 Mike Faisiev	W	20.0	216		6-18-81		24	0.3	130	56	110	5	233	2	440	0.2	1060	1650	7.2	-121	artesian
41°49'06.5" N. 111°54'25" W. (B-13-1)36cca-1	CVV-22 Thain Dairy Farm	W	17.5	220		6-18-81		11	2.2	120	66	99	4	187	3	475	0.3	1086	1550	7.5		
41°53'59" N. 112°02'32" W. (B-13-2)2bac-1	CVV-45	W	10.8			6-29-81		30	0.2	85	17	19	5	268	19	29	0.6	402	440	7.1	+125	artesian
41°46'16" N. 112°00'45" W. (B-13-2)24adb-1	CVV-46 Phyllis Hunter	W	11.2			6-29-81		37	0.1	130	108	160	18	449	172	319	0.9	1374	1520	7.3		
41°58'42" N. 111°58'21" W. (B-14-1)4ccb-1	CVV-34 Filmore	W	12.5			6-23-81		28	0.1	140	79	180	21	434	202	272	1.1	1298	1580	6.9		
41°54'52" N. 111°57'18" W. (B-14-1)33aac-S1	CVV-30 David Gancheff	S	30.1		.227	6-20-81		20	0.2	130	41	1500	130	501	58	2400	2.3	4466	9500	7.3	+ 44	tufa deposits
41°55'02" N. 111°55'27" W. (B-14-1)35abb-S1	CVV-32 Ervin Merrill	S	10.1			6-23-81		19	0.1	130	90	130	18	522	176	210	0.5	1122	1170	7.0		
41°57'00" N. 111°57'57" W. (B-14-1)35cdb-1	CVV-33 Ralph Pitcher	W	11.6			6-23-81		26	0.1	110	74	150	17	440	141	184	0.8	1024	1260	6.8		

Appendix IV.
Plates 1 and 2

PLATE I



EXPLANATION

U / D — Fault

Dashed where inferred or approximately located; dotted where concealed; U, upthrown side; D, downthrown side

Anticline

TEMPERATURES IN DEGREES CELSIUS

○ < 13°

◐ 13° - 20°

● > 20°

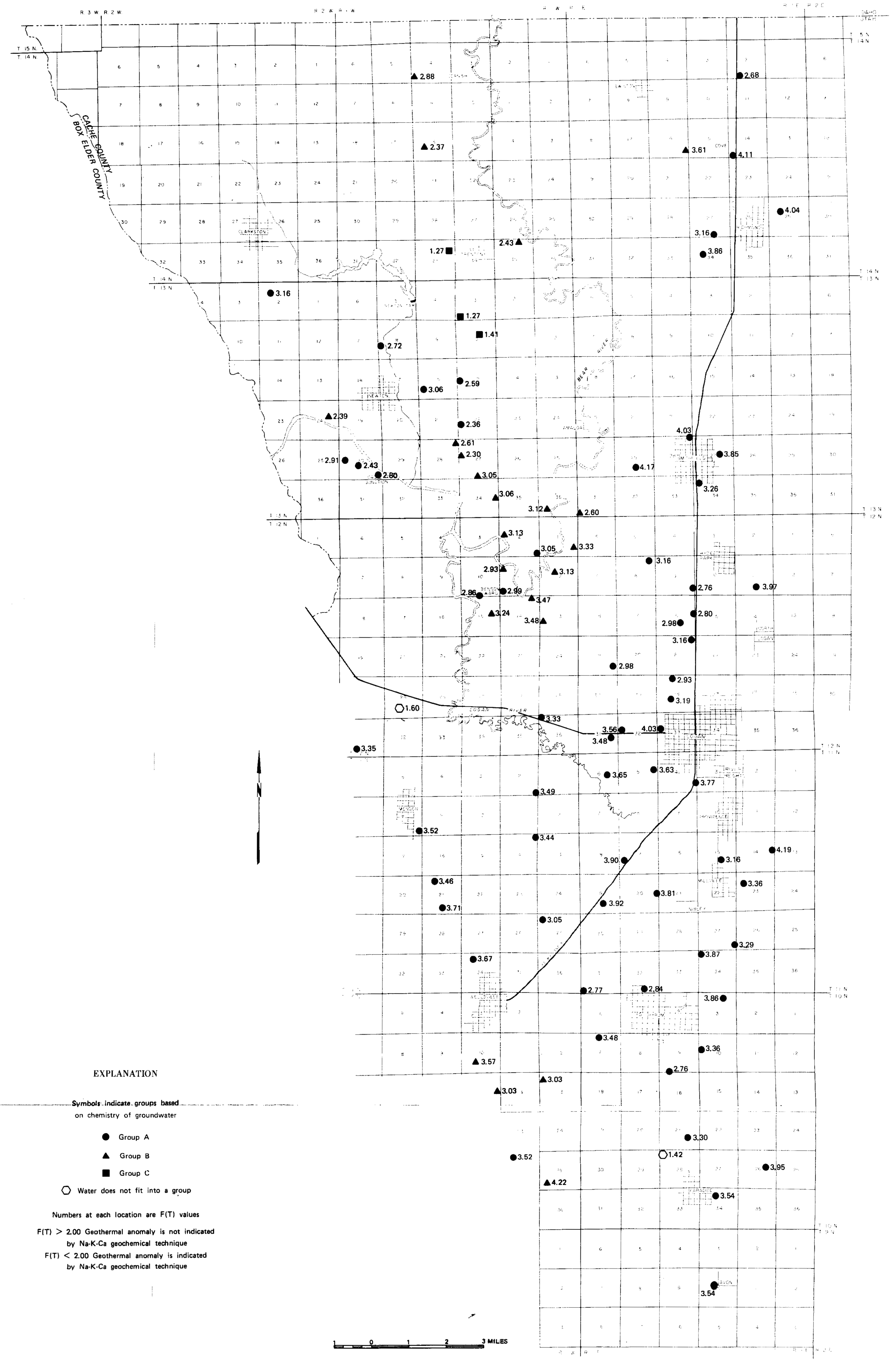
CVV numbers refer to the author's numbering system for sample locations; those locations without numbers have temperatures gathered by the Utah Geological and Mineral Survey (1980)

☐ THERMAL GRADIENT WELLS with X°C/km equal to thermal gradient

Base map from Williams (1962); Utah Dept. of Transportation (1975)

Map of Sample Locations, Groundwater Temperatures, Thermal Gradients, and Major Faults, Cache Valley, Utah

PLATE 2



EXPLANATION

Symbols indicate groups based on chemistry of groundwater

● Group A

▲ Group B

■ Group C

⬡ Water does not fit into a group

Numbers at each location are F(T) values

F(T) > 2.00 Geothermal anomaly is not indicated by Na-K-Ca geochemical technique

F(T) < 2.00 Geothermal anomaly is indicated by Na-K-Ca geochemical technique

Base map from Williams (1962); Utah Dept. of Transportation (1975)

Map of Groundwater Chemistry Groups and F(T) Values, Cache Valley, Utah