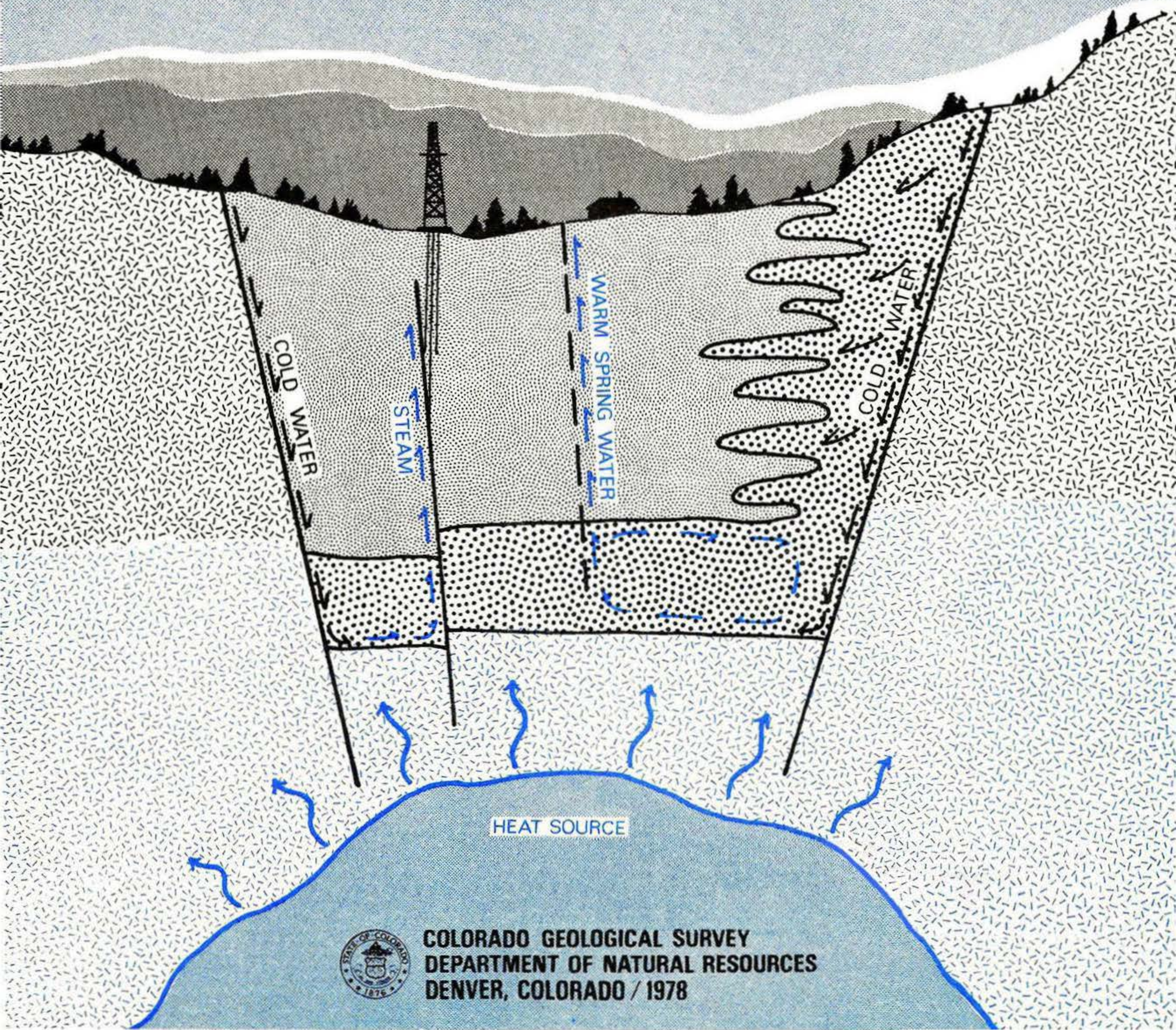
BULLETIN 39

An Appraisal of Colorado's Geothermal Resources

by

James K. Barrett and Richard Howard Pearl



COLORADO GEOLOGICAL SURVEY
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AN APPRAISAL OF COLORADO'S GEOTHERMAL RESOURCES

by
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ABSTRACT

The Colorado Geological Survey in conjunction with the U.S. Geological Survey in 1975 initiated a two-year evaluation of the geothermal resource potential of Colorado as determined by the usage of hydrogeological and geochemical data and geothermometer models. The geothermal resource potential of Colorado is expressed in numerous thermal springs and wells found throughout the western one-half of the state. In most instances the thermal waters of Colorado are unused, with minor amounts of thermal waters being used for recreation, space heating, domestic, and miscellaneous agricultural purposes. Although many energy companies have expressed interest in the geothermal resources of Colorado and have acquired leases to federal, state, and private lands, no large scale development has yet occurred.

During the investigation, 127 thermal springs and wells (temperatures in excess of 20°C or 68°F) were located, and field measurements of such physical parameters as discharge, pH, conductivity, and temperature were made. Water samples were collected for wet chemical and atomic absorption analysis and sent to the U.S. Geological Survey, Water Resources Division Central Laboratory in Salt Lake City, Utah, or to Atlanta, Georgia. Spectrographic analyses were performed at the Denver Analytical Laboratory of the U.S.G.S. Samples were also collected and sent to the U.S. Environmental Protection Agency Radiological Laboratory in Las Vegas, Nevada, for determination of radioactive elements.

Evaluation of the field data shows that there are 49 distinct thermal areas within the state consisting of one or more groups of springs or wells. The temperature of the springs varied from a low of 20°C at a number of springs to a high of 83°C at Hortense Hot Spring, southwest of Buena Vista. The discharge of the waters varied from a low of less than one gallon per minute (gpm) to a high of 2,263 gpm at the Big Spring in Glenwood Springs. The total dissolved solids of the waters varied from a low of 91 mg/l at Spring B at Eldorado Springs, southwest of Boulder to a high of 21,500 mg/l at Graves Spring in Glenwood Springs.

To determine what, if any, chemical and discharge changes might occur at a spring throughout a year's time, one spring in each thermal area was selected for sampling on a quarterly basis. This investigation showed that no consistent changes occurred throughout the year's time. The number of springs showing any change in the amount of total dissolved solids, temperature or discharge were very small, and the changes that did occur were not consistent from one spring to another. For example, one spring might show a change in the total amount of dissolved solids, while another spring might show a change in temperature or discharge. Temperature changes were usually only of a few degrees.

A major effort of this investigation was an appraisal of the reservoir temperatures through the use of four geothermometer models: silica, mixing model, sodium-potassium, and sodium-potassium-calcium. Research has shown that a relationship exists between the concentration levels of certain ions in thermal waters and reservoir temperatures. This relationship has led to the development of the above named geothermometer models, which are used to estimate the reservoir temperature of the thermal areas.

The range of subsurface temperatures estimates as calculated by the silica geothermometer ranged from a low of less than 20°C at a number of springs to a high of 157°C at Waunita Hot Spring. The estimated subsurface temperatures as determined through the use of the Mixing Model geothermometer ranged from a low of 15°C at McIntyre Warm Spring to a high of 291°C at Waunita Hot Spring. The Na-K-Ca geothermometer estimated temperatures ranged from a low of 4°C at Conundrum Hot Spring to a high of 220°C at Cebolla Hot Springs.

Other ions, such as chloride, found in the thermal waters, or deposits such as travertine around the springs may be used to make a preliminary appraisal of the reservoir conditions. An generalized appraisal of the thermal systems based on the chloride ionic concentrations may be used to evaluate whether the thermal system is a hot water system or a vapor-dominated system. Such an appraisal was made for the systems in Colorado.

INTRODUCTION

In May, 1975, the Colorado Geological Survey, as part of its ongoing evaluation of the geothermal resources of Colorado in conjunction with the U.S. Geological Survey initiated a two-year evaluation of the geothermal resource potential of Colorado as determined by the usage of hydrogeological and geochemical data and geothemometer models. This investigation, sponsored by the U.S. Geological Survey as part of its Geothermal Research Program, was funded in part by Grant No. 14-08-0001-G-221. This publication presents the findings and evaluations of that study. In 1976, Barrett and Pearl published data collected during the field investigation phase of the project. That publication included spring location, discharge, temperature, pH and chemical analyses.

Colorado's geothermal resource potential is expressed in the numerous thermal springs and wells found throughout the western one-half of the state. These springs and wells, numbering over 120, have been described by numerous authors. The first and most comprehensive inventory of the thermal springs and wells was published in 1920 by R. D. George and others. Since then summaries have been published by Lewis (1966), Mallory and Barnett (1973), Pearl (1972), and Waring (1965). A recent paper by Renner and others (1975) made a tentative appraisal of the total geothemal resource potential of Colorado.

In most instances the thermal waters of Colorado are unused. Minor amounts of thermal waters are being used for recreation, space heating, domestic, and miscellaneous agricultural purposes. Although many energy companies have expressed interest in the geothermal resources of the state and have acquired leases to federal, state, and private lands, no large scale development has occurred.

For a complete description of geothermal energy and its worldwide occurrences, the reader is referred to papers noted in the references at the end of the report. Papers by Grose (1971 and 1972), Kruger and Otte (1973), Lawrence Berkeley Lab. (1976) and Pearl (1972 and 1974), will give the reader an introduction to the subject.

The main thrust of this investigation, in addition to locating all sources of thermal waters in Colorado, is to appraise their hydrogeological conditions, recharge areas, and reservoir temperatures. Because it is not possible to evaluate in detail the hydrogeological conditions of all the thermal springs in Colorado, only those springs and wells in the Mount Princeton area are treated in detail. The hydrogeological conditions of the remainder of the springs and wells are evaluated from a reconnaissance standpoint only. A geothermometer determination of the estimated reservoir temperatures was made for all the thermal waters in the State. Four major geothermometer models were used during the course of this evaluation: 1) Silica, 2) Mixing Models I and II, 3) Sodium-Potassium, and 4) Sodium-Potassium-Calcium. In order to clarify the use of these models, a detailed explanation of each is presented. Hewlett Packard HP 25 and Texas Instruments SR 52 programmable calculators were used to aid in the solution of these models. Programs that were written for these calculators are presented in Appendix B.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation and thanks to the members of the staff of the Colorado District Water Resources Division, U.S. Geological Survey for their assistance during the course of this investigation. We especially wish to thank Dr. Robert Moran of the Colorado District for his advice and assistance during all phases of the investigation. The authors would like to thank the following persons for their help in drafting the illustrations: Ms. Cheryl Brchan, Ms. Paula Fedec; Mr. Tom Noll, Mr. Steve Enders; and Mr. Ben Foster. The manuscript was typed by Ms. Judith Primon, Ms. Doris Sweetman, and Mrs. Louise Slade. We would like to express our thanks to Mr. Jay D. Dick for his help in drafting and assembling the report and to Ms. Rebecca Goodman who researched historical hot spring data of Colorado. The manuscript was typed on a Wang Laboratories WCS 20-4 System. The software program was developed by Carl Schlaphoff of Schlaphoff and Associates.

USE OF THE REPORT

The report is organized so that the reader, depending upon his familiarity with geothermal resources and geothermometer models, can use any section of the report separately. The first section deals with data acquisition techniques and sampling procedures. The second section pertains to the precision of the laboratory analyses of the water samples. The third section is a detailed discussion of geothermometer model theory and examples. The fourth section discusses the effects of analytical precision on the geothermometer temperature estimates. The final section is a detailed discussion of each spring or well site. In this section the location of the thermal waters is presented along with a geological map of the area surrounding the site, and a brief discussion of the geology and hydrology of the site. In addition, a discussion of the geothermometer model analysis of the thermal area is presented. An evaluation of the geological conditions affecting the accuracy of the various reservoir temperature estimates is made for most sites.

FIELD-DATA ACQUISITION TECHNIQUES AND PROCEDURES

During the course of the investigation 127 thermal springs and wells having a temperature above 20°C (68°F) were located, and field measurements of such physical parameters as discharge, pH, conductivity, and temperatures were made. Water samples were collected and sent to the U.S. Geological Survey, Water Resources Division Central Laboratory in Salt Lake City, Utah, or to Atlanta, Georgia, for analysis and to the U.S. Geological Survey's Denver Analytical Laboratory for spectographic analysis. The field measurements and laboratory determinations were reported by Barrett and Pearl (1976). Isotope analysis of the water was done by Geochron Laboratories, Inc., L. D. White, and F. J. Pearson of the U.S. Geological Survey.

The location of the spring or well was determined to the nearest degree, minute and second of latitude and longitude by the use of either 7.5-minute or 15-minute U.S. Geological Survey topographic quadrangle maps. The land grid location was also determined if the township, range, and section had been determined and printed on the topographic map. To avoid confusion by the use of varying ambient air temperatures throughout western Colorado, an ambient air temperature of 60°F (15.6°C) was assumed. A base thermal temperature of 20°C (68°F) was then used. Field pH values to the nearest 1/2 unit were determined by using a Leeds and Northrup 7417 Specific Ion Mv pH meter supplied by the Colorado District, Water Resources Division, U.S. Geological Survey. Conductivity measurements were made using a Lab-line Lectro Mho-Meter Model Mc-1, Mark IV. Where possible the discharge of the spring or well was determined either by the use of a 3" Parshall Measuring Flume or by determining the time to fill a 2 gallon bucket. Where it was not possible to measure the discharge by either of these two methods, an estimate of the discharge was made. The water samples for analysis were collected, filtered, and acidized in accordance with standard U.S. Geological Survey, Water Resources Division field procedures.

All temperatures were measured in degrees Celcius (°C). To convert these temperatures to degrees Fahrenheit (°F) multiply the degrees Celcius by 1.8 and add 32. Conductance of the waters is a measure of the ability of the water to conduct an electrical current and as such is an indirect measurement of the amount of dissolved mineral matter in the water. Conductance is measured in Micromhos per centimeter at a temperature of 25°C.

Evaluation of the field data shows 49 distinct thermal areas within the state, consisting of one or more groups of springs or wells (Barrett and others, 1976). Although 127 thermal springs and wells were located and field information collected, only 103 of these springs and wells were sampled for chemical and spectrographic analysis of dissolved constituents. If the spring site consisted of only one spring or well, it was sampled and field data collected. If, however, the site consisted of multiple springs or wells, only the spring having the greatest discharge and highest temperature was sampled.

Table 1 (Appendix A) presents a statistical summary of the analytical results and field-determined values of discharge and temperature pertaining to all the thermal waters in Colorado. This table represents a composite of the statewide conditions and as such may not portray local conditions.

Water samples were collected from thermal and nonthermal waters for isotopic analysis in the Mount Princeton geothermal area. These samples were analyzed by Geochron Laboratories, Inc., or L. D. White, and F. J. Pearson of the U.S. Geological Survey.

To determine what, if any, changes might be occurring to a spring throughout the course of a year's time, one spring in each thermal area was sampled on a quarterly basis. The aim of this study was to measure all of these springs quarterly during the first year of the project. However, some of the springs could be sampled only two or three times. Results of these analyses are presented in Barrett and Pearl (1976). This investigation showed that no consistent changes occurred throughout the year's time. Very few springs showed any change in the amount of total dissolved mineral matter, temperature, or discharge. Any changes in temperature or discharge that did occur were usually only a few degrees and were not significant.

Figure 1 shows the location of the thermal springs and wells in Colorado. The numbers in the figure correspond to the order in which the springs and wells are discussed in the text.

Table 2 (Appendix A) is an alphabetical listing of all the thermal springs and wells in Colorado located as a result of this investigation.

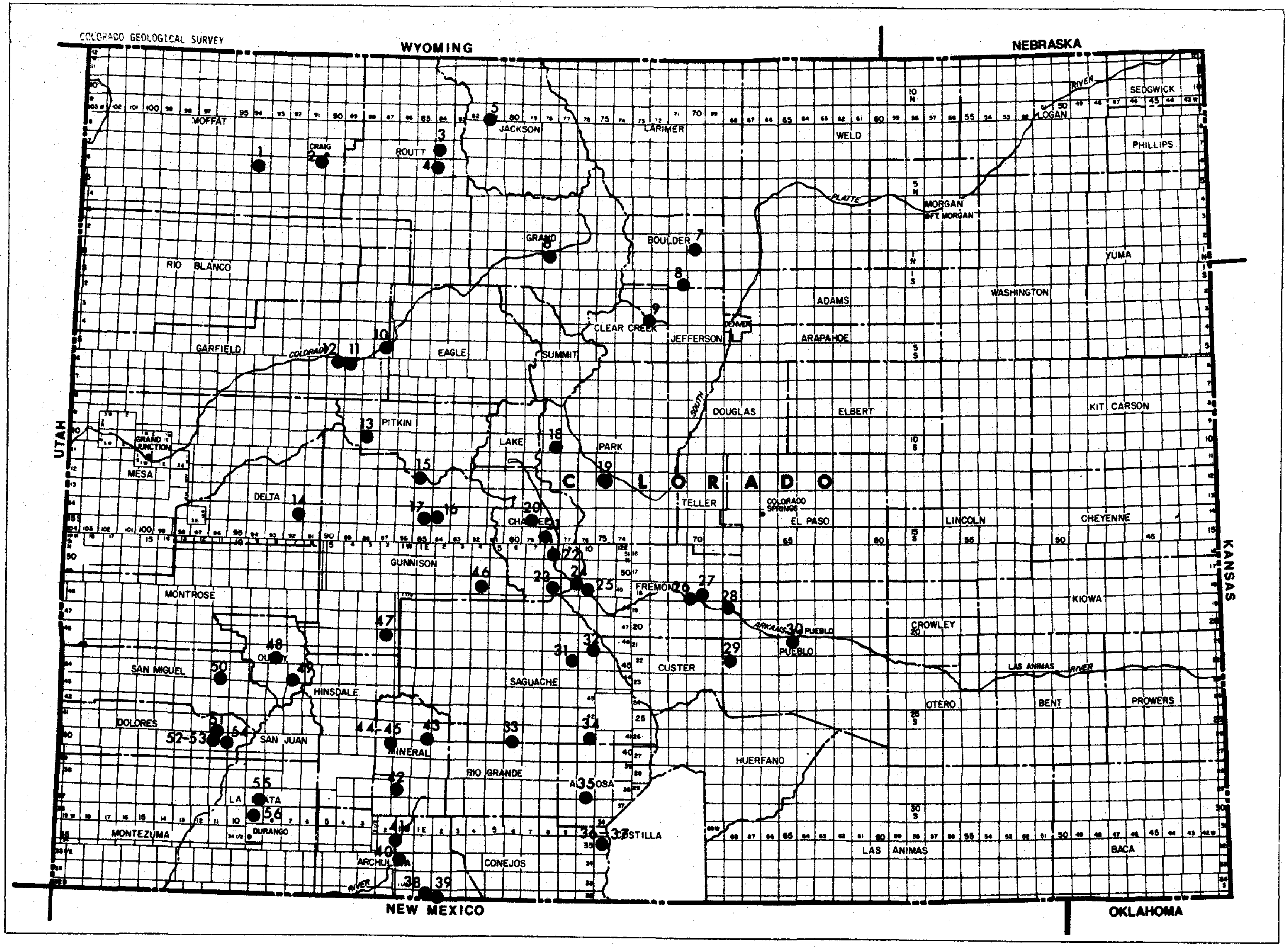


Figure 1.--Location of thermal springs and wells in Colorado. Numbers identify thermal areas. Thermal areas are discussed in numerical sequence beginning on page 35.

PRECISION AND ACCURACY OF LABORATORY ANALYSES

Table 3 (Appendix A) presents the expected precision and accuracy of laboratory analyses done by the USGS Central Laboratory (Salt Lake City, Utah) for twelve constituents commonly found in water. Confidence limits for the various concentration levels of each constituent are given to two standard deviations. For example, there is a 95% probability that the true concentration of any constituent listed in Table 3 is within the two standard deviation range. Given a bicarbonate (HCO) concentration of 53 mg/l, from Table 3, there is a 95% probability that the actual concentration is between 49 mg/l and 57 mg/l (53.0 ± 4.0 mg/l) or a 12% relative deviation.

GEOTHERMOMETER MODELS--THEORY AND EXAMPLES

Research by Fournier (1973, and 1977), Fournier and Rowe (1966), Fournier and Truesdell (1972, 1973, and 1974), Fournier and others (1974), and White (1972) on the relationship between the concentration of ions in thermal waters and reservoir temperatures has led to the development of a number of geothermometer models that can be used to estimate the subsurface reservoir temperature. These models have proved very useful in evaluating the geothermal resource potential of a region. Therefore, a large part of this investigation was directed toward an accurate geothermometer evaluation of the individual thermal sites within Colorado. The most frequently used geothermometers are related to the silica, sodium, potassium, and calcium content of thermal waters. However, new methods now being developed employ naturally occurring stable isotopes of oxygen, hydrogen, and sulfur.

The following assumptions are inherent in all geothermometer models (Fournier and others, 1974). Violation of any of these assumptions may cause erroneous subsurface temperature estimates:

1) Temperature-dependent reactions occur at depth.

2) All constituents involved in a temperature-dependent reaction are sufficiently abundant (i.e., supply is not a limiting factor).

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

4) Little or no re-equilibration or change in composition occurs at lower temperatures as the water flows from the reservoir to the surface.

5) The hot water coming from deep in the system does not mix with cooler shallow ground water.

For those readers not familiar with the theory and application of geothermometer models, the following pages describe each model and include examples of their use. To aid in the application of these geothermometer models, programs for their mathematical solution were written using Hewlett Packard and Texas Instruments programmable calculators. These programs are presented in Appendix B.

The estimated reservoir temperatures for all thermal wells and springs in Colorado are listed in Table 4 (Appendix A).

SILICA GEOTHERMOMETER MODELS

The silica geothermometer is derived from the experimentally determined relationship between silica solubility, temperature and pressure (Fournier, 1973). Dissolved silica found in thermal waters may be supplied by temperature-dependent reactions between the thermal water and either quartz, chalcedony, amorphous silica or cristobalite.

ASSUMPTIONS

Application of the various silica geothermometer models is restricted by four assumptions:

1) No Mixing Occurs Between Ascending Thermal Waters and Shallow Ground Waters.

If the ascending thermal water mixes with relatively dilute ground water, the estimated subsurface temperature will be too low. If, however, the silica content of the shallow ground-water is higher than that of the thermal water, the resultant subsurface temperature estimate will be too high. In either case the silica geothermometer analysis of the hot water at the surface may reflect the shallow subsurface conditions of last silica equilibration rather than the conditions of the geothermal reservoir at depth.

2) Silica Does Not Precipitate From the Solution

If silica precipitates from solution, the silica concentration of the water is lowered, causing reduced geothermometer temperature estimates. Laboratory research (Fournier, 1973) demonstrates that at temperatures above 150°C, quartz is the predominant source of dissolved silica. Geothermal waters originally at temperatures above 225°C are likely to precipitate silica while cooling during ascent as a result of rapid re-equilibration rates and intense supersaturation. Below 180°C precipitation rates decrease rapidly, possibly explaining why most silica geothermometer estimates are below 200°C.

3) Steam Does Not Separate From the Thermal Water During Ascent to the Surface.

If the temperature and pressure at depth are sufficient, water will remain in the liquid state above the normal atmospheric boiling point (100°C at sea level). Consequently, rapid discharge of this water to the surface will cause steam formation as a result of the sudden pressure drop (adiabatic cooling). Loss of steam during ascent increases the silica concentration of the hot water. Steam fractionation and the resultant silica enrichment yields an excessively high subsurface temperature estimate.

4) The Chemical Activity of the Thermal Water Is Not Greatly Diminished.

Chemical activity is defined as the "tendency to react spontaneously and energetically with other substances...." (AGI, 1962). In the case of geothermometer analysis, chemical activity can be considered as the ability of a thermal solution to undergo solubility reactions with solid mineral phases. If the chemical activity is not greatly diminished, the silica concentration in hot water is independent of the local mineral suite, gas partial pressure, and other dissolved constituents.

At constant temperatures quartz solubility decreases as the activity of the water decreases (Fournier, 1973), resulting in low geothermometer estimates. At low activities, local mineral suites may interfere with the silica solubility; dissolved-silica concentrations may decrease in silica-deficient Ca- and Mg-rich rocks due to the formation of calcium and/or magnesium silicates; dissolved silica concentrations may increase in alkali-rich, silica-deficient rocks due to high pH and increased solubilities resulting in the solution of sodium silicate complexes (Fournier, 1978 oral communication).

QUARTZ-SILICA GEOTHERMOMETER

The quartz-silica geothermometer is based on temperature-dependent equilibration between quartz and the thermal fluid. The model can be solved by either graphical or mathematical methods. The graphical solution is accomplished by use of Figure 2, which was developed by Fournier and Rowe (1966). At silica concentrations above approximately 60 mg/l, the silica vs. temperature curve splits into two branches: "A", the conductive cooling case (no steam loss), and "B", the adiabatic cooling case (maximum steam loss). Branch "B" is designed to correct for the increased silica concentration due to steam separation from the ascending thermal fluid (assumption 3). Branch "A" represents the equilibrium relationship between quartz and temperature assuming no steam loss. Similarly, the mathematical solution is accomplished by the use of Equations 1 and 2, for conductive or adiabatic cooling, respectively.

Eq. 1: Conductive Cooling Case:

$$T_{°C} = \frac{1309}{5.19 - \log(SiO_2)} - 273$$

Eq. 2: Adiabetic Cooling Case:

$$T_{°C} = \frac{1522}{5.75 - \log(SiO_2)} - 273$$

Where:
$T_{°C}$ = subsurface temperature estimate in °C
SiO_2 = silica content of hot spring in milligrams/liter

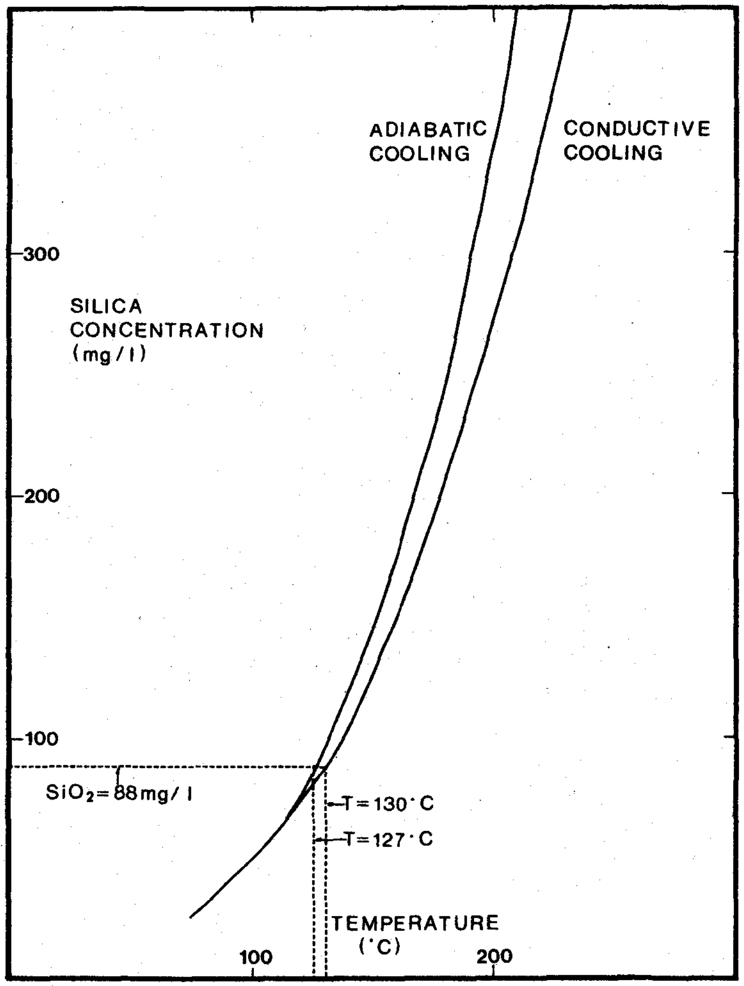


Figure 2.--Silica geothermometer (Fournier and Rowe, 1966).

As previously stated, quartz is the predominant source of silica above 150°C. If the deep-seated geothermal waters were originally at temperatures above 225°C, silica precipitation would likely occur during ascent to the surface. However, the rate of silica precipitation decreases rapidly below 180°C. The quartz silica geothermometer is most reliable as a subsurface temperature indicator in moderately discharging (greater than 50 gpm) or high temperature (greater than 50°C) hot springs with a silica content greater than 100 mg/l and subsurface temperatures between 150°C to 225°C (Fournier and Truesdell, 1972 and 1974).

For either method the silica geothermometer will yield a maximum subsurface temperature for the conductive cooling case and a minimum temperature estimate for the adiabatic cooling case.

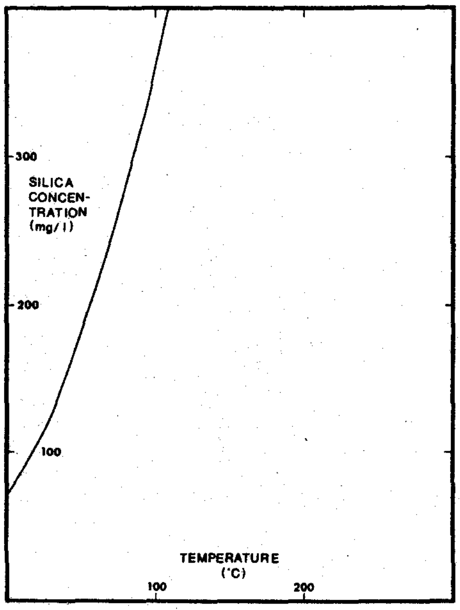


Figure 3.--Amorphous silica geothermometer (Reed, 1975).

APPLICATION OF MODEL

To demonstrate the use of this model, Hortense Hot Spring (#21) will be used. Hortense Hot Spring has a temperature of 83°C and a silica concentration of 88 mg/l.

GRAPHICAL SOLUTION

The estimated subsurface temperature of this spring is determined in Figure 2 by projecting the silica concentration horizontally from the vertical axis to where it intersects the curves and then downward to the horizontal axis, giving the estimated temperature. As shown in Figure 2, a silica concentration of 88 mg/l yields a subsurface temperature estimate of 130°C for the conductive cooling case and 127°C for the adiabatic cooling case.

MATHEMATICAL SOLUTION

To arrive at a mathematical solution, enter the silica content (88 mg/l) into Equations 1 and 2:

(Eq 1):

$$T_{^\circ C} = \frac{1309}{5.19 - \log(88)} - 273 = 130^\circ C$$

(Eq. 2):

$$T_{^\circ C} = \frac{1522}{5.75 - \log(88)} - 273 = 127^\circ C$$

AMORPHOUS SILICA, CHALCEDONY, AND CRISTOBALITE SILICA GEOTHERMOMETERS

At water temperatures below 150°C, amorphous silica, chalcedony, or cristobalite rather than quartz may control the dissolved silica content of the thermal water (Fourner, 1973). The approximate solubility of amorphous silica, chalcedony and cristobalite can be calculated from Equations 3, 4, and 5, respectively.

Eq 3: Amorphous Silica Solubility:

$$SiO_2 = 10^{[4.52 - 731/(t + 273)]}$$

Eq 4: Chalcedony Solubility:

$$SiO_2 = \frac{10^{[-1032/(t + 273)]} - .09}{1.665 \times 10^{-5}}$$

Eq 5: Alpha Cristobalite Solubility:

$$SiO_2 = \frac{10^{[-1000/(t + 273)]}}{1.665 \times 10^{-5}}$$

Where:
t = surface temperature of the thermal spring or well in °C
SiO = silica solubility in mg/l

The graphical solutions of Equations 3-5 are illustrated in Figures 3, 4, and 5. The mathematical solution is presented in Equations 6, 7, and 8 respectively (Reed, 1975).

Eq 6: Amorphous Silica Geothermometer:

$$T_{°C} = \frac{731}{4.52 - \log(SiO_2)} - 273$$

Eq 7: Chalcedony Silica Geothermometer:

$$T_{°C} = \frac{-\ 1032}{.09 + \log(SiO_2)(1.665 \times 10^{-5})} - 273$$

Eq 8: Alpha Cristobalite Silica Geothermometer:

$$T_{°C} = \frac{-1000}{\log(SiO_2)(1.665 \times 10^{-5})} - 273$$

Where:
$T_{°C}$ = subsurface reservoir temperature estimate in °C
SiO_2 = silica content of thermal spring or well in mg/l

APPLICATION OF MODEL

To demonstrate the use of these geothermometer models, Penny Hot Spring (#13) will be used. The waters of this spring have a temperature of 45°C, contain 150 mg/l of silica and have a discharge of 10 gpm.

Entering the silica concentration in the quartz silica geothermometer (Figure 2 or equations 1 and 2) yields subsurface temperature estimates of 161°C and 153°C for the conductive and adiabatic cooling cases, respectively. However, the surface temperature and discharge of Penny Hot Springs are well below the minimum conditions specified for the quartz silica geothermometer (see introduction to Quartz-Silica Geothermometer). Therefore, silica phases other than quartz may supply the silica, and Equations 3-5 must be used to compute the solubility of amorphous silica, chalcedony, and cristobalite at the surface temperature of the hot spring.

Entering the surface temperature of 45°C in Equations 3-5 yields the following results:

(Eq 3): $SiO_{2\ \mathrm{amorphous}} = 10^{[4.52 - (731/45 + 273)]} = 166$ mg/l

(Eq 4): $SiO_{2\ \mathrm{chalcedony}} = \dfrac{10^{[-1032/(45 + 273)]} - .09}{} = 28$ mg/l

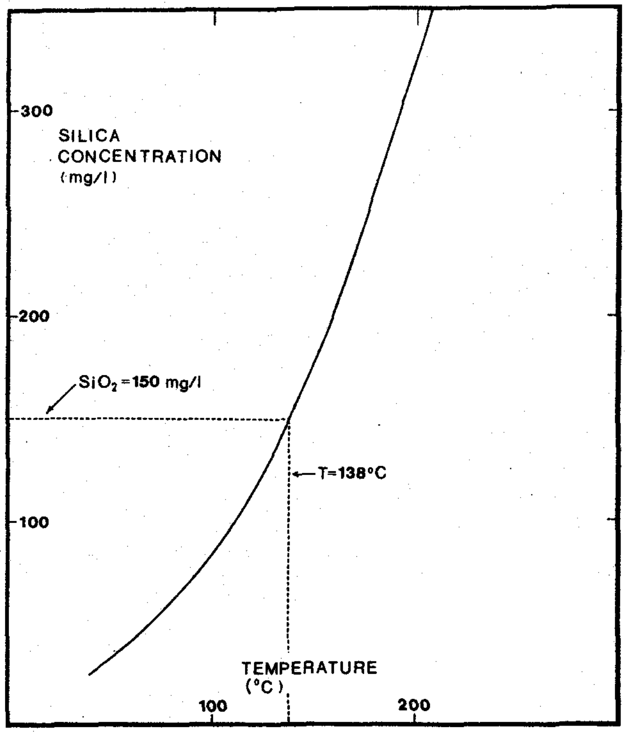


Figure 4.--Chalcedony silica geothermometer (Reed, 1975).

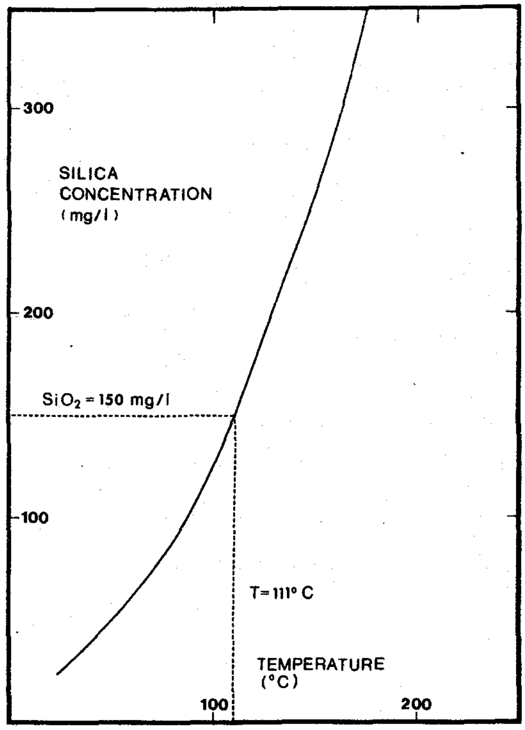


Figure 5.--Cristobalite geothermometer (Reed, 1975).

(Eq 5): $$\text{SiO}_2 \text{ cristobalite} = \frac{10[-1000/(45 + 273)]}{1.665 \times 10^{-5}} = 43 \text{ mg/l}$$

Note that the solubility of amorphous silica is very near the silica content of the hot spring. Therefore, amorphous silica may control the silica content of the thermal water, and the quartz silica geothermometer estimate may be too high. The subsurface temperature is then recalculated using the amorphous silica geothermometer. For demonstration purposes both the graphical and mathematical methods will be presented.

Graphical Method

Entering the silica content of the spring (150 mg/l) into Figure 6 (amorphous silica) yields a temperature of 39°C.

Mathematical Solution

To solve this problem mathematically, enter the silica content of the hot spring (150 mg/l) into Equation 6 (amorphous silica geothermometer) and solve.

(Eq 6): $$T = \frac{731}{4.52 - \log(150)} - 150 = 39°\text{C}$$

The subsurface temperature predicted by the amorphous silica geothermometer is below the surface temperature of the hot spring and, therefore, incorrect.

Conclusion

The amorphous silica, chalcedony and cristobalite silica geothermometers should be used as a check on the quartz geothermometer. When the solubility of amorphous silica, chalcedony or cristobalite at the spring's surface temperature approaches the silica content of the spring, the quartz silica geothermometer does not apply. In such cases, other silica geothermometers should be used to calculate the subsurface temperature.

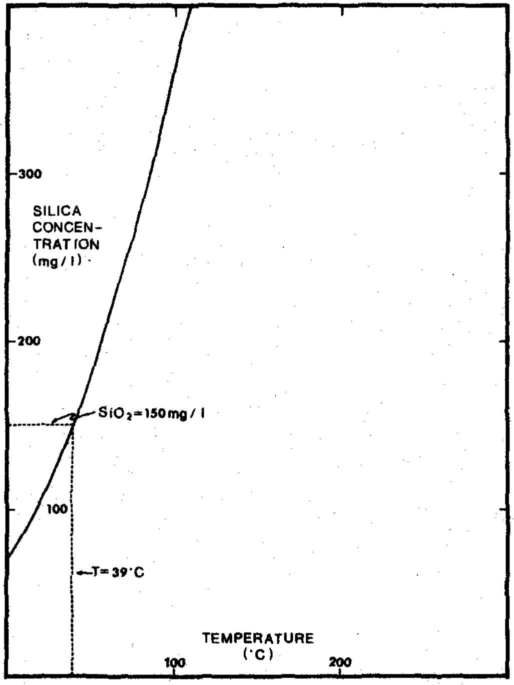


Figure 6.--Amorphous silica geothermometer solution (Reed, 1975).

MIXING MODELS

Assumption No. 1 of the silica geothermometer model states that the ascending thermal waters do not mix with the shallow ground waters. However, in many, if not most, geothermal systems mixing does occur between the thermal waters and ground water. To deal with this problem Fournier and Truesdell (1974) developed two models, Mixing Model I and Mixing Model II, to estimate the subsurface temperature and compute the fraction of cold ground water in the hot spring.

These models are based upon the relationship between the enthalpy (heat content) and the silica content of the ascending thermal water, the cold ground water, and the resultant mixed thermal spring water. These relationships are quantified by two versions of the mass balance equation (Equations 7 and 8). Equation 7 equates the amount of heat supplied by the fractions of thermal water and ground water to the total heat content of the mixed warm spring at the surface. Equation 8 equates the mass of silica supplied by the fractions of thermal water and ground water to the total masses of silica supplied by the fractions of thermal water and ground water to the total mass of silica contained in the mixed warm spring at the surface. Depending upon the relative amounts and the initial enthalpies of the hot and cold water, the mixed surface spring temperatures may range from cool to boiling (Fournier and Truesdell, 1974).

Eq 7: $(H_c)(X) + (H_h)(1-X) = S_{spg}$

Eq 8: $(Si_c)(X) + (Si_h)(1-X) = Si_{spg}$

Where:

H_c = Enthalpy of cold ground water (calories/gram)
H_h = Enthalpy of unmixed thermal waters (calories/gram)
H_{spg} = Enthalpy of mixed warm spring at the surface (calories/gram)
Si_c = Silica content of cold ground water (mg/l)
Si_h = Silica content of unmixed thermal water (mg/l)
Si_{spg} = Silica content of mixed warm spring at the surface (mg/l)

MIXING MODEL ASSUMPTIONS

The use of mixing models involves four additional assumptions to those discussed for the silica geothermometers.

1) Initial silica content is controlled by temperature-dependent reactions between the deep thermal water and quartz.

Solution of solid silicate phases (chalcedony, cristobalite, amorphous silica and others) other than quartz will allow higher concentrations of silica to be dissolved in the hot water because of their greater solubility. This will yield excessive estimates of both the subsurface temperature and the cold-water fraction of the warm spring.

2) Additional silica is not dissolved or deposited after mixing.

Additional solution of silica after mixing will cause the subsurface temperature and cold water fraction estimates to be too high. Deposition of silica after mixing with colder ground-waters will cause the subsurface temperature and cold-water fraction estimates to be too low.

3) Enthalpy is not lost by conductive cooling or steam loss before mixing.

The enthalpy of the thermal fluid will be reduced by conductive cooling due to heat transfer with the country rocks encountered along the flow path from the geothermal reservoir to the surface. However, conductive cooling will be minimal if the transition from depth to the surface is sufficiently rapid or if the temperature difference between the hot water and the country rocks is small. Enthalpy may also be reduced by steam formation (adiabatic cooling) if the steam separates from the ascending hot water prior to mixing. The reduction in enthalpy is proportional to the amount of steam that separates from the hot water prior to mixing. Both conductive cooling and steam loss prior to mixing will cause the subsurface temperature and cold water fraction estimates to be too low.

4) The temperature and silica content of cold springs are similar to the temperature and silica content of the ground-water that mixes with the ascending hot water.

Cold spring data is required to aproximate the temperature and silica content of the shallow, cold ground-water that mixes with the rising thermal water. An assumed cold water temperature in excess of the actual conditions will cause the subsurface temperature and cold water fractions estimates to be too high. If the assumed silica content of the cold ground-water is in excess of the actual concentration, then the subsurface temperature and cold water-fraction estimates will be too low.

Analysis of subsurface temperatures using the Mixing Model requires knowledge of the surface temperatures and silica contents of the thermal and nonthermal waters in the area. As many cold springs or wells as possible should be sampled in the vicinity of the hot spring to insure an adequate representation of the regional ground-water conditions. If no cold springs or wells exist in the area, the following assumptions can be made: The cold water can be assumed to have a silica content of 25 mg/l, and the temperature of the cold water may be assumed to equal the mean annual air temperature of the region.

MIXING MODEL NO. 1

Subsurface reservoir temperatures may be estimated by Mixing Model I either by graphical techniques or by use of a computer program (Truesdell and others, 1973).

An appraisal of analysis of subsurface tempertures using the Mixing Model requires the knowledge of the surface temperatures and silica contents of the thermal and nonthermal waters in the area. Time and money permitting as many cold springs or wells as possible should be sampled in the vicinity of the hot spring to insure an adequate representation of the regional ground-water conditions. If not cold springs or wells exist in the area, the above assumptions have to be made.

As stated earlier, programs were written (Appendix B) for Texas Instruments and Hewlett Packard programmable calculators to aid in the geothermometer calculations; the estimated temperatures listed in Table 4 were obtained by this method. While one may solve these models by mathematical methods, only the graphical method will be presented here. The following equations are used (Fournier and Truesdell, 1974) in the graphical method.

$$\text{Eq 9:}\quad X_t = \frac{E_h - T_{ws}}{E_h - T_{cs}}$$

$$\text{Eq. 10:}\quad X_{si} = \frac{Si_h - Si_{ws}}{Si_h - Si_{cs}}$$

Where:

E_h = enthalpy of hot water (from Table 6) Appendix A
Si_h = silica content of hot water (from Table 6) Appendix A
T_{ws} = surface temperature of warm spring (°C)
T_{cs} = surface temperature of cold spring (°C)
Si_{ws} = silica content of warm spring (mg/l)
Si_{cs} = silica content of hot spring (mg/l)

Along with the appropriate field data, the enthalpy and silica values for each temperature shown in Table 5 are entered into Equations 9 and 10, respectively. Values of X_t(Eq. 9) and X_{si}(Eq. 10) are then determined for each temperature on Table 5. These values of $X_t$and X_{si} are then plotted versus temperature. The intersection of the two curves provides the estimated subsurface temperature and the fraction of cold water present in the thermal spring.

TABLE 5

ENTHALPIES OF LIQUID WATER AND QUARTZ SOLUBILITIES AT SELECTED TEMPERATURES AND PRESSURES (FOURNIER AND TRUESDELL, 1974)

Temperature (°C)	Enthalpy (cal/g)	Silica (mg/l)
50	50.0	13.5
75	75.0	26.6
100	100.1	48.0
125	125.4	80.0
150	151.0	125.0
175	177.0	185.0
200	203.6	265.0
225	230.9	365.0
250	259.2	486.0
275	289.0	614.0
300	321.0	692.0

APPLICATION OF MODEL

To demonstrate the use of this model, Hortense Hot Spring will again be used. This spring has a temperature of 83°C and contains 88 mg/l of silica. Cold waters in the Mount Princeton area have a temperature of 11°C and contain 8 mg/l of silica (Table 6, Appendix A).

As the temperature and silica content of Hortense Hot Spring are greater than the enthalpies and silica solubilities listed for the lower temperatures in Table 5, the calculation of X_t and X_{si} was started at a temperature of 150°C and continued for all remaining temperatures.

From Table 5, it is noted that for a temperature of 150°C, the enthalpy = 151 cal/g and the silica = 125 mg/l.

Insert these values in Equations 9 and 10;

$$\text{(Eq 9):} \quad X_t = \frac{151 - 83}{151 - 11} = 0.846$$

$$\text{(Eq 10):} \quad X_{si} = \frac{125 - 88}{125 - 8} = 0.316$$

For a T of 175°C: Enthalpy = 177 cal/g, Silica = 185 mg/l

$$X_t = \frac{177 - 83}{177 - 11} = 0.566; \qquad X_{si} = \frac{185 - 88}{185 - 8} = 0.548$$

The calculated values of X_t and X_{si} for each temperature listed in table 5 are presented in Table 7.

TABLE 7

CALCULATED VALUES OF X_t AND X_{si} FOR MIXING MODEL I (HORTENSE HOT SPRING)

HOT WATER TEMP (°C)	X_t	X_{si}
150	0.486	0.316
175	0.566	0.548
200	0.626	0.689
225	0.673	0.776
250	0.710	0.833
275	0.741	0.868
300	0.768	0.883

The plot of the values of X_t and X_{si} vs. temperature listed in Table 7 are shown on Figure 7.

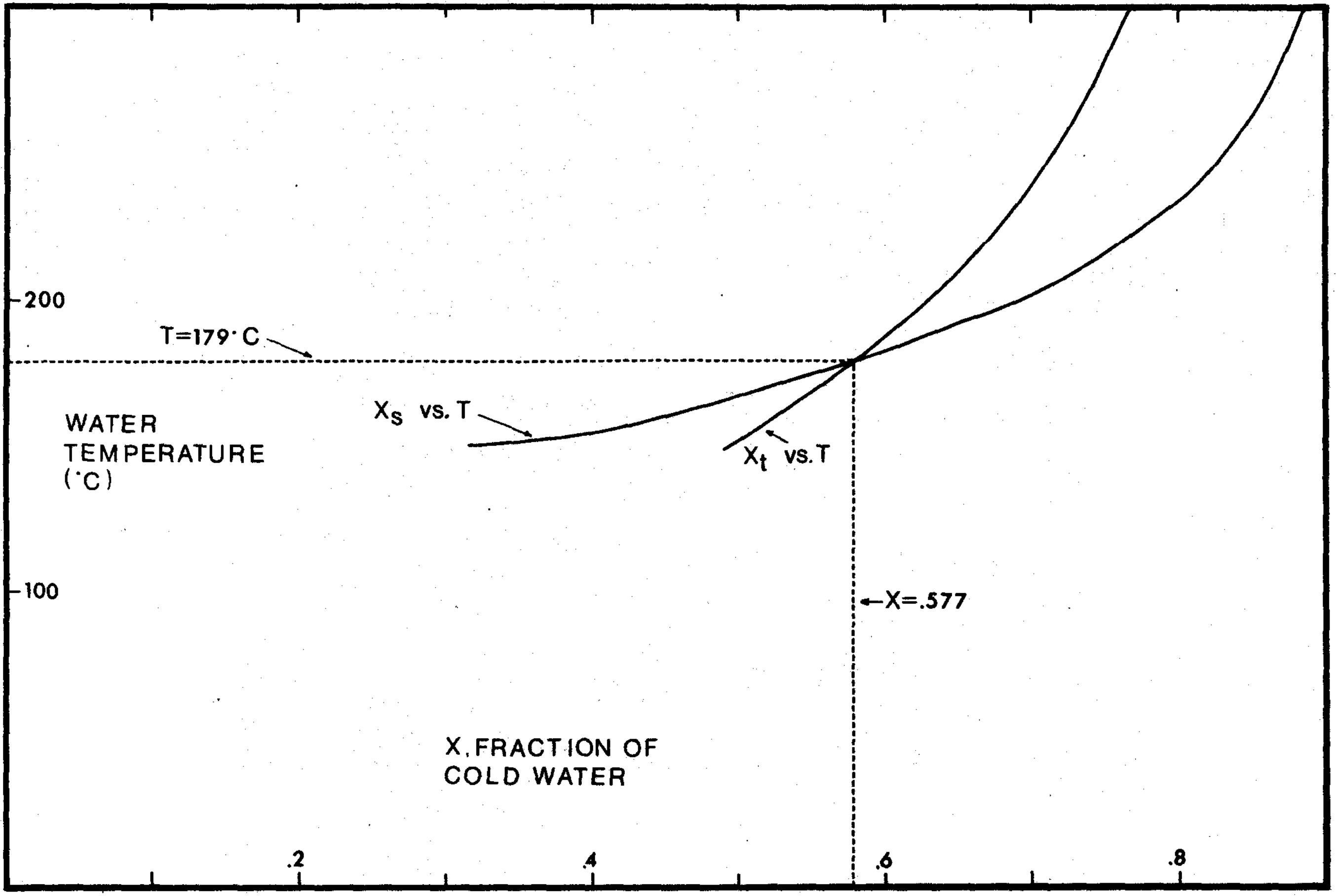


Figure 7.--Solution of Mixing Model I geothermometer.

The intersection of the two curves: X_t vs. T and X_{si} vs. T yields the estimated reservoir temperature and fraction of cold water present. From Figure 7 the estimated subsurface reservoir temperature is 179°C and the fraction of cold water in the hot spring is approximately 58 percent.

MIXING MODEL NO. II

For some thermal systems the two curves shown in Figure 7 either will not intersect or the intersection will occur at unrealistically high temperatures. This may be caused by either loss of steam from the ascending hot water prior to mixing or by the solution of amoprhous silica.

Mixing Model Number II (Fournier and Truesdell, 1974) should be used for those thermal systems where steam vents or fumaroles are present at the surface and the solution of amorphous silica is not significant. To test for the solution of amorphous silica in the thermal system, Equation 3 should be used. If amorphous silica is supplying silica ions to the thermal water, then Mixing Model #I provides excessive subsurface temperature estimates. If amorphous silica is not supplying any silica to the system, then steam separation is likely.

Mixing Model Number II should only be used when mixing model assumption 3 is violated, i.e., when steam is lost from the ascending hot water before mixing. In this case the enthalpy and silica content of the hot water at depth are greater than the enthalpy and silica content of the hot water after steam separation. The amount of steam fractionation and the resultant silica enrichment are estimated by assuming steam loss at atmospheric pressure for the hot springs elevation (Fournier and Truesdell, 1974). The hot water fraction (X) remaining after steam separation is determined by the following equation:

Eq 11: $H_c(X) + H_H(1-X) = H_{spg}$

Where:

X = hot-water fraction remaining after steam separation

H_H = enthalpy of steam (cal/g) at the atmospheric pressure (boiling point) for the warm spring elevation

H_c = enthalpy of cold spring (cal/g)

H_{spg} = enthalpy of mixed warm spring (cal/g)

The value of X determined in Equation 11 is then inserted into Equation 12 to find the original silica content Si_H(the original hot-water silica content before steam separation). This value is then inserted into Equation 13 to find the estimated subsurface temperature:

Eq 12: $Si_c(X) + Si_H(1-X) = Si_{spg}$

Where:

Si_c = silica content of cold spring (mg/l)

Si_H = silica content of thermal water (mg/l) before steam separation

Si_{spg} = silica content of mixed warm spring (mg/l)

X = hot water fraction remaining after steam separation

Eq 13: $$T_{°C} = \frac{1522}{5.72 - \log Si_H} - 273$$

Where:

$T_{°C}$ = subsurface temperature in °C

Si_H = silica content of thermal water before steam separation (from Eq. 12)

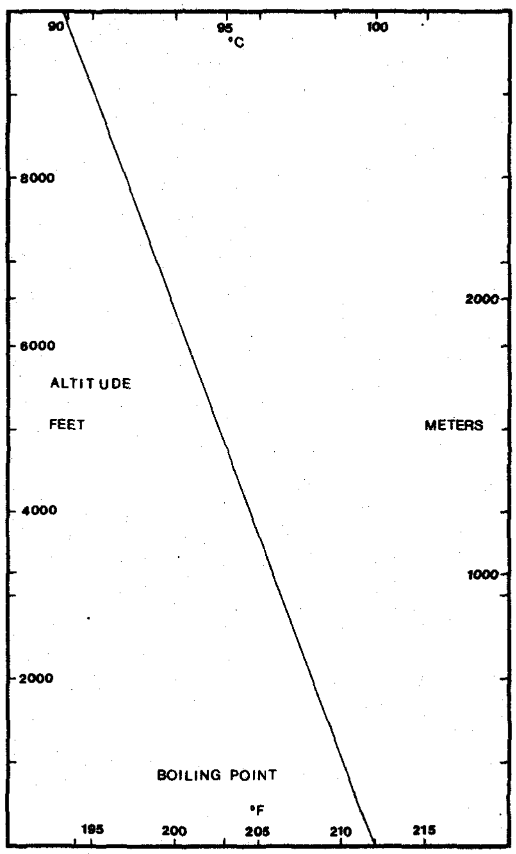


Figure 8.--Boiling point of water as a function of altitude (adapted from Wehlage, 1976).

APPLICATION OF MODEL

Steam fumaroles exist in the vicinity of Hortense Hot Spring (Jay Dick, 1976, personal communication). Therefore, the estimated subsurface temperature of the spring will be calculated using Mixing Model II.

Hortense Hot Spring has a temperature of 83°C, a silica concentration of 88 mg/l. The elevation of the spring is 8275 ft. The cold waters in the region have a temperature of 11°C and contain 8 mg/l of silica.

First, determine the boiling point at the hot spring elevation. From Figure 8 note that the boiling point at an elevation of 8,275 ft. is 91.4°C (196°F).

It was determined from steam tables (Keenan and others, 1969) that the enthalpies of the Hortense Hot Spring waters, the cold water sample and the boiling point are:

TABLE 8

HORTENSE HOT SPRING THERMAL WATER ENTHALPIES

	T°C	Enthalpy (cal/g)
Hortense Hot Spring	83	83.03
Cold water sample	11	11.06
Boiling point at 8275'	91.4	90.1

Insert the enthalpy values into Equation 11 and solve for X;

(Eq 11): $11.06(X) + 90.1(1-X) = 83.03; \quad X = 0.089$

Insert the value of X and the silica contents of the cold water sample (Si_c) and Hortense Hot Spring (Si_{spg}) into Equation 12 and solved for Si_H:

(Eq 12): $8(0.089) + Si_H(1 - 0.080) = 88; \quad Si_H = 96$ mg/l

Insert the value of Si_H into equation 13 and solve for $T_{°C}$:

(Eq 13): $$T_{°C} = \frac{1522}{5.75 - \log(96)} - 273 = 131°C$$

Mixing Model Number II yields an estimated subsurface temperature of 131°C for Hortense Hot Spring.

OTHER MIXING MODELS

At temperatures below 150°C amorphous silica, chalcedony, or cristobalite rather than quartz may control the dissolved silica content of the hot spring (Fournier, 1973). Temperature-dependent equilibration between the thermal water and solid silica phases other than quartz will cause the mixing model estimates of subsurface temperature and cold water fraction to be too high (Assumption No. 1). If the silica concentration of the thermal water approaches the theoretical solubility of amorphous silica, chalcedony or cristobalite at the spring's surface temperature (Equations 3, 4, and 5), then mixing models based on amorphous silica, chalcedony, or cristobalite should be used.

These models are identical to Mixing Model I in all respects except for the assumption that amorphous silica, chalcedony, or cristobalite rather than quartz is the source of silica in the thermal water. Tables 9-10 (Appendix A) should be used when using either the amorphous silica, chalcedony, or the cristobalite mixing models.

APPLICATION OF MODELS

To demonstrate the use of the model, data from Brands Ranch Artesian Well will be used. This 800-ft.-deep well has a surface temperature of 42°C, contains 26 mg/l of dissolved silica, and has a discharge of 80 gpm. Cold waters in the region have a temperature of 3°C and contain 15 mg/l of dissolved silica (Table 6).

Based on quartz silica solubility, Mixing Model I yields an estimated subsurface temperature of 94°C with a cold water fraction of 59 percent for this well. These estimates are probably not reliable since there is very little opportunity for such a large percentage of shallow ground water to percolate into a cased well. Therefore, the solubilities of amorphous silica, chalcedony, and cristobalite at the surface temperature of the artesian well should be computed using Equations 3, 4, and 5.

(Eq 3): $$SiO_{2\ \text{amorphous}} = 10^{[4.52 - 731/(t+273)]} = 169 \text{ mg/l}$$

(Eq 4): $$SiO_{2\ \text{chalcedony}} = \frac{10^{[-1032/(t + 273)]} - 0.09}{1.665 \times 10^{-5}} = 26 \text{ mg/l}$$

(Eq 5): $$SiO_{2\ \text{cristobalite}} = \frac{10^{[-1000/(t + 273)]}}{1.665 \times 10^{-5}} = 40 \text{ mg/l}$$

The calculations show that the chalcedony solubility is identical to the dissolved silica content of the artesian well. Therefore, the Mixing Model I analysis should be recalculated using chalcedony instead of silica.

From Table 10 (Appendix A) for a temperature of 40°C the enthalpy is 40 cal/g, and the solubility of chalcedony is 25 mg/l. Inserting these values in Equations 9 and 10, the following results are obtained:

(Eq 9): $X_t = \dfrac{40 - 42}{40 - 3} = -.05$

(Eq 10): $X_{si} = \dfrac{25 - 26}{25 - 10} = -0.10$

Calculated values of X_t and X_{si} for each temperature listed in Table 10 are listed below in Table 12:

TABLE 12

CALCULATED VALUES OF X_t AND X_{si} FOR MIXING MODEL I

BRANDS RANCH ARTESIAN WELL

Temperature (°C)	Enthalpy X_t	Silica X_{si}
25	-0.77	-4.5
30	-0.44	-1.75
35	-0.22	-0.57
40	-0.05	-0.10
50	0.17	0.31
75	0.46	0.71
100	0.60	0.84

A plot of these values is shown in Figure 9. As explained earlier, the point of intersection of the two curves yields the estimated subsurface temperature and the estimated amount of shallow ground water that mixed with the thermal water. From Figure 9 the subsurface temperature estimate is 42°C with almost no shallow ground water in the artesian well. These estimates are reasonable because if the well is properly constructed, shallow ground waters will not likely percolate into an 800-ft.-deep artesian well. If the silica content of the thermal well had been near the theoretical solubility of amorphous silica or cristobalite, then either of those mixing models would be applicable.

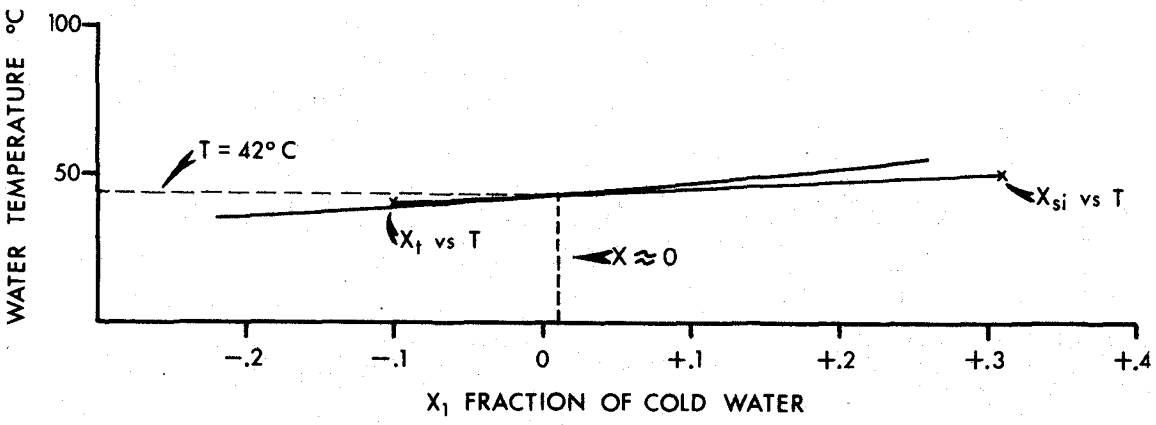


Figure 9.--Chalcedony Mixing Model I, Brands Ranch Artesian Well.

SUMMARY

Mixing Models I and II yield maximum and minimum subsurface temperature estimates, respectively (Fournier and Truesdell, 1974). They are best suited for the analysis of moderately discharging (greater than 50 gpm) hot springs with silica concentrations above 75 to 100 mg/l. These models should provide similar subsurface temperature estimates for multiple hot spring systems where each spring contains different proportions of cold water or for spring areas where mixing fluctuates seasonally. Even if the mixing model results should vary widely, the data obtained can be useful for evaluating the accuracy of the assumptions involved in geothermometer analysis.

ENTHALPY-CHLORIDE GEOTHERMOMETER

Mixing Models I and II are useful for the prediction of subsurface temperature from mixed hot springs. However, neither geothermometer model commonly predicts temperatures in excess of 200°C even in thermal systems where higher temperatures have been substantiated by deep drilling (Truesdell and Fournier, 1975).

To solve this problem, Truesdell and Fournier (1975) developed a mixing model in which chloride rather than silica ions are used in the calculation. This model, called enthalpy-chloride mixing model, was designed to calculate subsurface temperatures and hot water fractions for groups of mixed springs that issue at the boiling point. The derivation of this model is based upon the relationship between the enthalpies and chloride contents of the ascending hot water, the cold ground waters, and the resultant mixed warm spring waters. These relationships are quantified by 6 versions of the mass-balance equation representing three different subsurface conditions. The equations as presented by Truesdell and Fournier (1975) are:

Condition 1 - Ascending hot water mixes with colder ground water without any steam loss:

Eq 14: $Xh_h + (1 - X)h_c = h_{spg}$

Eq 15: $XCl_h + (1 - X)Cl_c = Cl_{spg}$

Condition 2 - Mixing between the ascending hot water and ground water with steam loss:

Eq 16: $Yh_m + (1 - Y)_m = h_{spg}$

Eq 17: $YCl_m + (1 - Y)Cl_m = Cl_{spg}$

Condition 3 - No mixing between the hot and cold water, with steam loss at surface:

Eq 18: $Zh_h + (1 - Z)h_h = h_{spg}$

Eq 19: $ZCl_h + (1 - Z)Cl_h = Cl_{spg}$

where:

X = fraction of hot water
Y = fraction of steam formed from mixed water
Z = fraction of steam formed from unmixed water
h = enthalpy (cal/g)
Cl = chloride content (mg/l)

Subscripts "m", "h", "c" refer to mixed water, hot (unmixed) water and cold water, respectively. Subscript "spg" refers to mixed warm spring at the surface. Superscripts "s", "w" refer to the surface temperature of steam and water, respectively.

Equations 14 through 19 can be combined and reduced to Equations 20 and 21, which are the analytical forms of the enthalpy-chloride geothermometer (Truesdell and Fournier, 1975):

Eq 20:

$$X = \frac{Cl_m h_h (h_m - h_m) + Cl_h h_m (h_m - h_c) - Cl_c h_m h_h}{Cl_h h_h (h_h - h_c) - Cl_c h_m h_h}$$

Eq 21: $$h_h = \frac{h_m - h_c}{X} + h_c$$

where:

Cl_h, Cl_m, Cl_c = surface chloride contents of the unmixed, mixed and cold water, respectively (mg/l)

X = hot water fraction

h_c = surface enthalpy of cold water (cal/g)

h_h = enthalpy of water in the geothermal reservoir (cal/g)

h_m = enthalpy of mixed water before steam loss (from SiO_2 geothermometer) (cal/g)

h_h^e = surface enthalpy of evaporation, unmixed water (cal/g)

h_h^s = surface enthalpy of steam, unmixed water (cal/g)

h_m^e = surface enthalpy of evaporation, mixed water (cal/g)

h_m^s = surface enthalpy of steam, mixed water (cal/g)

ASSUMPTIONS

The enthalpy-chloride geothermometer model is based on the following four assumptions (Truesdell and Fournier 1975):

1) An unmixed hot water sample is available

Unmixed thermal waters, or the least mixed possible, are needed to estimate the amount of steam loss and enrichment of the ascending thermal waters. Often these waters can be found in the center of a hot spring group. Using a mixed rather than a nonmixed thermal water sample reduces the subsurface temperature estimate.

2) Silica is not precipitated during ascent of the mixed water

Precipitation of silica after mixing will lower the enthalpy of the ascending thermal solution. This reduction of the enthalpy will cause the estimated subsurface temperatures to be too low.

3) No change in enthalpy occurs before or after mixing

The enthalpy of a thermal fluid is usually reduced due to adiabatic or conductive cooling during ascent. Enthalpy loss during ascent reduces the estimated subsurface temperature.

4) Quartz re-equilibration occurs after mixing

Hot water mixing with cold water usually creates a solution that is supersaturated in silica when compared to the quartz solubility. If precipitation of silica, i.e., re-equilibration of the mixed water does not occur, then the enthalpy of the solution will be too high. This results in an excessive subsurface temperature estimate.

APPLICATION OF MODEL

To demonstrate the application of this model, the thermal springs in the Chalk Creek Valley on the south flank of Mount Princeton will be used. Both the graphical and mathematical solution methods are presented.

Table 13 lists the analysis of five thermal springs and wells in the valley and one cold water analysis. Using published steam tables (Keenan and others, 1969) enthalpy values are calculated for all waters.

TABLE 13

DATA FOR THE CHALK CREEK THERMAL SPRING AREA

	Name	Surface Temp (°C)	Enthalpy cal/gm	Chloride (mg/l)	SiO_2 (mg/l)
1	Hortense H.S.	83	83.03	11.0	88
2	Hortense H.W.	82	82.02	8.3	72
3	Wright Well E	67	66.98	4.9	53
4	Wright Well W	72	71.99	6.4	68
5	Mt. Princeton H.S."A"	56	55.98	5.2	59
6	Cold Water	11	11.06	0.4	8

As Hortense Hot Spring and Hortense Hot Water Well are the only thermal waters in Colorado whose surface temperatures are near the boiling point, they will be used to demonstrate this model. However, this calculation is presented for descriptive purposes only, for the use of this model with these waters may yield an erroneous estimated subsurface temperature.

Mathematical Solution Method

Hortense Hot Spring has the highest surface temperature. Mixing model analysis reveals that it is the least mixed hot spring of those listed in Table 13. Therefore, this spring will be used to determine the values of **** *** and Cl_h in Equation 22. The Hortense Hot Water Well data is used to determine the values of ****, ****, and Cl_m in Equation 20.

The following procedure should be followed:

1) Determine h_m, the enthalpy of the mixed hot water before steam loss. Using Equation 2, compute the quartz silica geothermometer estimated subsurface temperature for Hortense Hot Spring (adiabatic cooling case).

$$\text{(Eq 2): } T_{^\circ C} = \frac{1522}{5.75 - \log(88)} - 273 = 127^\circ C$$

From steam tables (Keenan and others, 1969) it is determined that for a temperature of 127°C, $h_m = 127.5$ cal/g

2) Determine h_h^e and h_h^s using the surface temperature of Hortense Hot Spring (83°C)

h_h^e(surface enthalpy of evaporation, unmixed water) = 553.4 cal/g

h_h^s(surface enthalpy of steam, unmixed water) = 632.9 cal/g

3) Determine h_m^e and h_m^s using the surface temperature of Hortense Hot Water Well (82°C) and steam tables:

h_m^e(surface enthalpy of evaporation, mixed water) = 552.5 cal/g

h_m^s(surface enthalpy of steam, mixed water) = 632.7 cal/g

h_c(enthalpy of cold spring water) = 11.06 cal/g (Table 8)

From Table 13 it is noted that:

Cl_c = 0.4 mg/l (cold water analysis)
Cl_h = 11 mg/l (Hortense Hot Spring)
Cl_m = 8.3 mg/l (Hortense Hot Well)

4) Insert the above values into Equation 20 and solve for X, the hot water fraction of Hortense Hot Well.

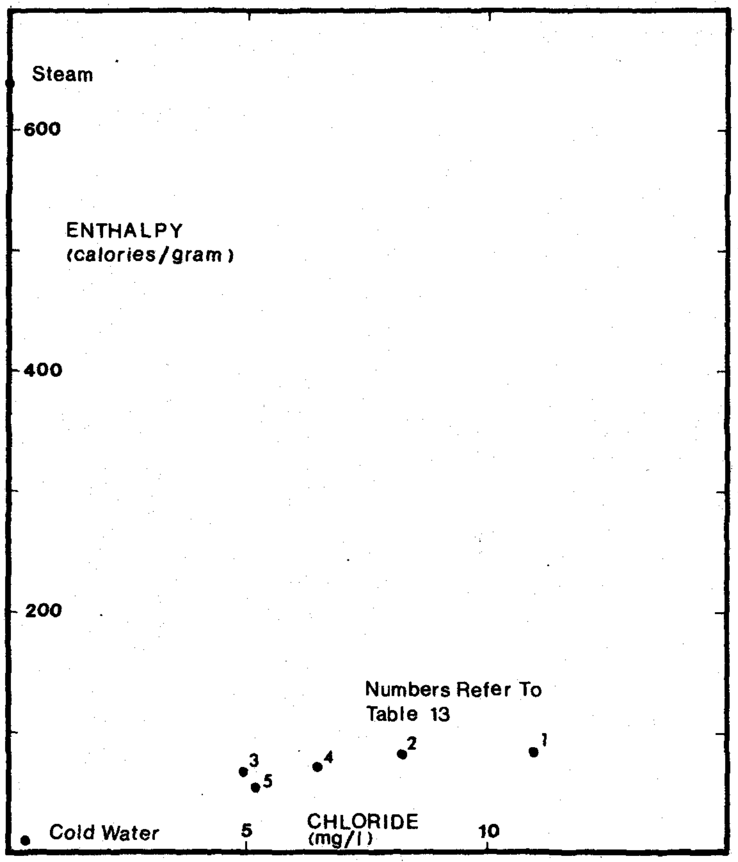


Figure 10.--Enthalpy-chloride geothermometer: Plot of chloride concentration in thermal waters of Chalk Creek Area vs. enthalpy.

(Eq 20):

$$X = \frac{(8.3)(55.3.4)(632.7 - 127.5) + (11)(552.5)(127.5 - 11.06) - (0.4)(552.5)}{(11)(553.4)(632.9 - 11.06) - (.4)(552.5)(553.4)}\ \underline{(553.4)}$$

$$X = 0.793$$

5) Enter the values of X, h_m and h_c into Equation 21 and solve for h_h, the enthalpy of the hot water in the geothermal reservoir:

$$\text{(Eq 21): } h_h = \frac{127.5 - 11.06}{0.793} + 11.06 = 157.8 \text{ cal/g}$$

6) Steam tables show that a water temperature corresponding to an enthalpy of 157.8 cal/g is 157°C.

The estimated subsurface temperature of Hortense Hot Water Well using the mathematical solution is 157°C, and the well contains 79 percent hot water at the surface (Equation 20).

Graphical Solution Method

1) Plot the values of enthalpy and chloride content for each spring listed in Table 13 (fig. 10). For steam, assume an enthlpy of 639 cal/g and a chloride content of zero.

2) Draw radial lines (steam loss lines) between the steam plot and each hot spring plot (fig. 11).

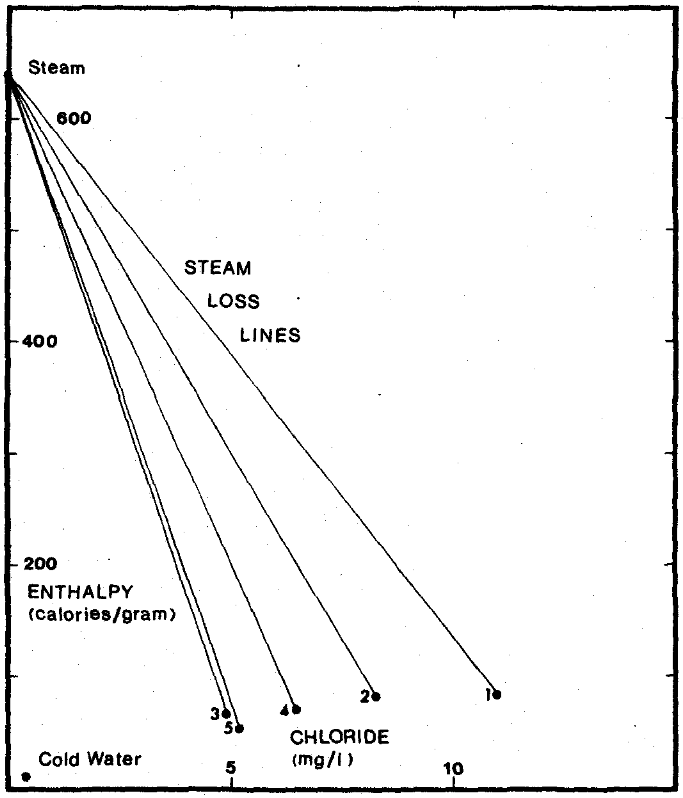


Figure 11.--Enthalpy-chloride geothermometer: Steam loss lines, thermal waters of Chalk Creek Area.

3) Use Equation 2 (adiabatic cooling) and compute the estimated subsurface reservoir temperatures for all the hot springs listed in Table 13. Use steam tables to determine the the enthalpy for each of these estimated temperatures shown below. The results of the two calculations are shown in Table 14.

TABLE 14

QUARTZ-SILICA GEOTHERMOMETER ESTIMATED RESERVOIR TEMPERATURE
AND ENTHALPY DATA FOR THERMAL SPRINGS IN THE CHALK CREEK VALLEY

Name	SiO_2 mg/l	SiO_2 G.T. Temp(°C)	Enthalpy (cal/g)	
1 Hortense Hot Spring	88	127	127.5	1'
2 Hortense Hot Well	72	118	118.4	2'
3 Wright Well East	53	105	105.2	3'
4 Wright Well West	68	116	116.4	4'
5 Mt Princeton H.S."A"	59	109	109.3	5'

4) Plot the enthalpy values of each hot spring listed Table 14 on its correspondence steam-loss line as shown in Figure 12.

5) Draw a line (the "dilution line") from the cold spring plot through the best fit of the enthalpy plots as shown in Figure 13.

The intersection of the dilution line with the steam loss line of the highest chloride water gives the chloride content and enthalpy of the hot water within the geothermal reservoir at depth. From Figure 13 it is seen that the enthalpy of the deep thermal water (h_b) is 161 cal/g. From steam tables, the water temperature corresponding to an enthalpy of 161 cal/g is 160°C. Therefore, the subsurface temperature estimate for this area is 160°C.

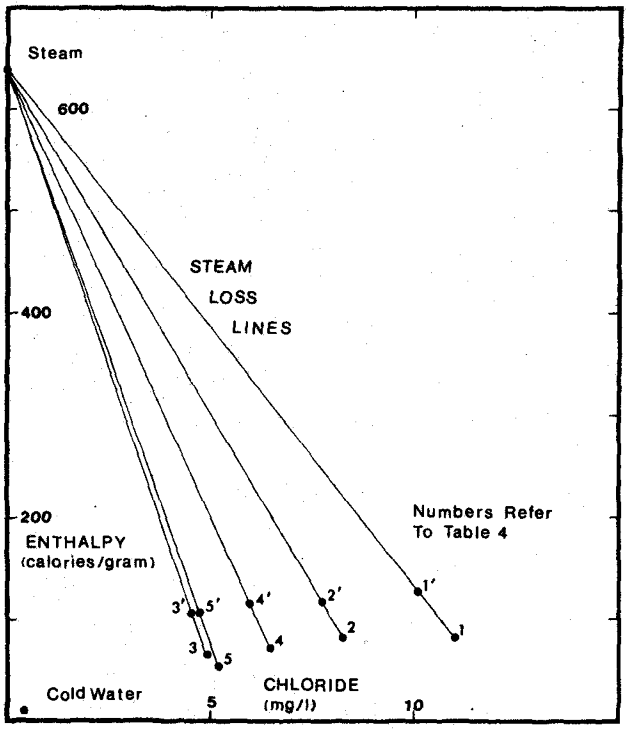


Figure 12.--Enthalpy-chloride geothermometer: Plot of enthalpy of hot waters plotted on steam-loss lines.

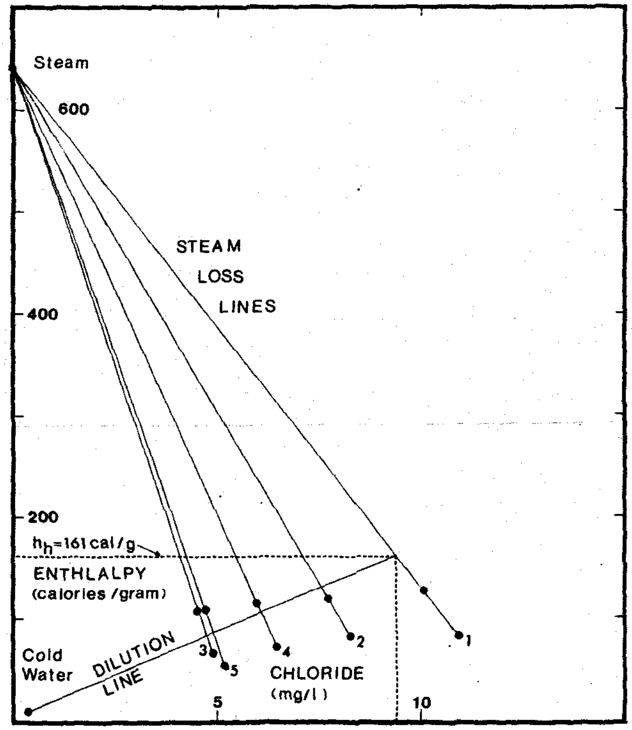


Figure 13.--Enthalpy-chloride geothermometer: Construction of "dilution line."

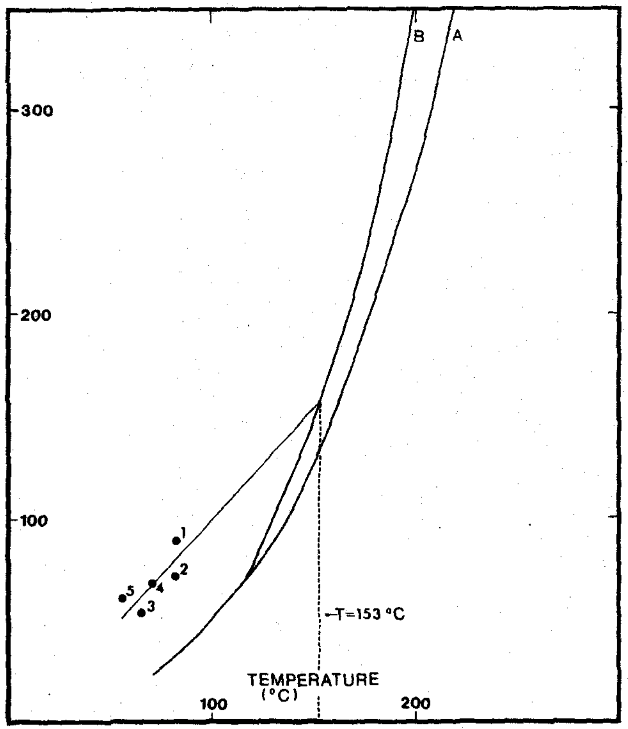


Figure 14.--Enthalpy-chloride geothermometer: Comparison of estimated chloride-enthalpy temperatures with estimated silica geothermometer temperatures.

This reservoir temperature estimate may be substantiated by plotting the field data (temperature and silica content) listed in Table 14 versus temperature on the quartz-silica geothermometer graph. A line is drawn through the plotted values and extended until it intersects Branch B of the silica geothermometer. As shown in Figure 14, this yields a subsurface temperature estimate of 153°C. Since this estimate is within 30°C of the enthalpy-chloride model estimate it is likely that 160°C represents the actual subsurface temperature (J. Pearson, 1976, personal communication).

SODIUM-POTASSIUM-CALCIUM GEOTHERMOMETER MODEL

The Na-K-Ca geothermometer model developed by Fournier and Truesdell (1973) is based on an empirical relationship between the molar concentrations of sodium, potassium and calcium ions and water temperature. This relationship is interpreted by Fournier and Truesdell (1973) as representing the temperature-dependent chemical equilibration between sodium, potassium, and calcium-bearing minerals and water. Fournier and Truesdell (1973) present a detailed account of the geochemical theory involved in the development of the Na-K-Ca geothermometer.

ASSUMPTIONS

Use of the Na-K-Ca geothermometer requires three assumptions:

1) No mixing occurs between the ascending thermal water and shallow ground water

Mixing between the hot thermal water and shallow, dilute, ground water will have little effect on the sodium-potassium ratio but may affect the calcium-sodium ratio due to the square root of calcium term used in Equation 22. If the original calcium content of the undiluted thermal water is low, mixing will have little effect on the geothermometer results. If the calcium content of the undiluted thermal water is high (greater than 50 to 100 mg/l), then mixing with dilute ground water will cause the subsurface temperature estimate to be too low.

2) Sodium potassium and calcium concentrations in the thermal water are controlled by temperature dependent equilibrium with albite, potassium feldspar and calcium-bearing carbonate minerals.

The sodium, potassium and calcium ratios are strongly affected by the bedrock mineral suite. Depending upon which mineral suite controls the water composition, a wide range in temperature estimates is possible. At similar water temperatures, the sodium-potassium-calcium ratios are widely variable in solutions equilibrated with potassium feldspar and albite, muscovite and abite, alkali-bearing carbonates, or other mineral suites.

For example, waters equilibrated with mineral suites containing potassium feldspar but no albite (sodium-deficient mineral suites) will provide excessive subsurface temperature estimates. On the other hand, waters equilibrated with mineral suites containing albite but no potassium feldspar (potassium-deficient mineral suites) yield temperature estimates that are too low. Waters in equilibrium with alkali-bearing carbonates (evaporite sequences) generally yield excessive temperature estimates. However, equilibration with zeolites may yield minimal temperature estimates.

3) Little or no re-equilibration occurs during ascent

Changes in the sodium-potassium-calcium ratios in thermal waters may be great or negligible depending upon the rate of ascent and the relative reactivity of the rocks and minerals along the flow path. Low calcium-content thermal waters generally yield low subsurface temperature estimates due to continued water-wall rock reactions during ascent (increased aqueous calcium ion concentration). High calcium-content waters, however, may yield excessive geothermometer temperature estimates because of calcium carbonate deposition (decreased aqueous calcium ion concentration) during ascent.

Equation 22, the mathematical form of the Na-K-Ca geothermometer (Fournier and Truesdell, 1973) is emperically derived and represents the equation of best fit of data plotted on graphs of the Na/K and Ca/Na ratios vs. temperature.

$$\text{Eq. 22:}\quad \log \frac{Na}{K} + B \log \frac{\sqrt{Ca}}{Na} = \frac{1647}{273 - T_{°C}} - 2.24$$

Equation 22 can be rewritten algebraically as:

Eq 23: $$T_{^\circ C} = \frac{1647}{\log \frac{Na}{K} + B \log \frac{\sqrt{Ca}}{Na} + 2.24} - 273$$

where:

Na, K, Ca = ionic concentration in moles/liter of the sodium, potassium and calcium ions in the hot water.

$T_{^\circ C}$ = estimated subsurface temperature in °C

B = 1/3 or 4/3 depending upon the stoichiometry of the reaction

Application of Model

To demonstrate the application of this geothermometer model, Hortense Hot Spring in the Chalk Creek Valley will be used.

The reported Na, K, and Ca ionic concentrations are:

Na = 94 mg/l; K = 3.2 mg/l; and Ca = 4.7 mg/l

1) Convert these values to moles per liter:

Na - (94 mg/l) x (0.0000435 moles/mg) = 0.004089 moles/liter
K - (3.2 mg/l) x (0.00002557 moles/mg) = 0.00008182 moles/liter
Ca - (4.7 mg/l) x(0.00002495 moles/mg) = 0.0001173 moles/liter

2) The value of B must be determined before the calculation can begin. To do this, determine the value of $\log \sqrt{Ca}/Na$. If the value negative, use B = 1/3 in Equation 23. If the value is positive, use B = 4/3 in Equation 23.

Inserting the above calcium and sodium concentrations (moles per liter) into the term $\log \sqrt{Ca}/Na$ gives the following results:

$$\log \frac{Ca}{Na} = \log \frac{\sqrt{0.0001173}}{0.004089} = \log 2.649 = 0.42$$

This value is positive, B = 4/3 is used in Equation 23:

Insert the respective moles/liter values of sodium, potassium, and calcium concentrations and B = 4/3 into Equation 23 and calculate:

(Eq 23): $$T_{^\circ C} = \frac{1647}{\log\left(\frac{0.004089}{0.00008182}\right) + 4/3 \log\left(\frac{\sqrt{0.0001173}}{0.004089}\right) + 2.24} - 273$$

$T_{^\circ C} = 93^\circ C$

Because this estimated temperature is less than 100°C, the use of B = 4/3 in the calculation is correct. If the estimated temperature is above 100°C then Equation 23 should be recalculated, with B = 1/3.

SODIUM-POTASSIUM GEOTHERMOMETER MODEL

The sodium-potassium geothermometer model is based on the same assumptions as the sodium-potassium-calcium geothermometer. In this case however, the value of B is zero, and Equation 22 is reduced to:

$$\text{Eq 24:} \quad \log \frac{Na}{K} = \frac{1647}{273 + T_{^\circ C}} - 2.24$$

Solving for $T_{^\circ C}$, Equation 24 can be rewritten:

$$\text{Eq 25:} \quad T_{^\circ C} = \frac{1647}{\log \frac{Na}{K} + 2.24} - 273$$

Where:

Na, K = concentration (moles/liter) of sodium and potassium ions, respectively, in the solution
$T_{^\circ C}$ = estimated subsurface temperature in °C

Application of Model

To demonstrate this model, Hortense Hot Spring will be used. Hortense Hot Spring contains 94 mg/l of Na, and 3.2 mg/l of K.

1) Convert from milligrams per liter to moles per liter:
   Na: (94 mg/l) (0.0000435 moles/mg) = 0.004089 moles/liter
   K: (3.2 mg/l) (0.00002557 moles/mg) = 0.00008182 moles/liter

2) Insert the molar values of sodium and potassium into Equation 25:

$$\text{(Eq 25):} \quad T_{^\circ C} = \frac{1647}{\log \frac{0.004089}{0.00008182} + 2.24} - 273$$

$$T_{^\circ C} = 145^\circ C$$

3) The Na-K geothermometer yields an estimated subsurface temperature of 145°C.

Summary

The Na-K-Ca and Na-K geothermometer models should only be used for spring waters in which other evidence of high subsurface temperatures are present (i.e. springs with high surface temperature and high silica content). Subsurface temperature estimates greater than 100°C should be treated skeptically for moderately discharging springs (15 gpm) unless the results are substantiated by other geothermometers. Both geothermometers are intended for the analysis of low magnesium (below 5 mg/l) and of near-neutral and alkaline waters that do not deposit travertine. Travertine- and calcium carbonate-depositing springs yield excessive Na-K and Na-K-Ca geothermometer subsurface temperature estimates. On the other hand, excessive solution of calcium carbonate will lower the Na-K-Ca geothermometer estimate (Fournier and Truesdell, 1973). In addition, these models should not be used in situations where the value of the term $\log \sqrt{Ca}/Na$ is greater than 0.5. If this term exceeds 0.5, then the Na-K geothermometer yields excessive temperature estimates.

PRECISION AND ACCURACY OF GEOTHERMOMETER MODELS

In some cases the precision and accuracy of the laboratory analysis (Table 3 Appendix A) can cause significant variations in the geothermometer estimated subsurface temperature. The magnitude of these variations will depend upon the sensitivity of the particular model to the change of the various ion concentrations used in the geothermometer model. In general the sensivitity of any geothermometer model is inversely proportional to the total dissolved solids content of the thermal spring. The following example illustrates the possible variation in subsurface temperature estimates resulting from normal laboratory analytical error. Data from the Big Spring at Pagosa Springs is used in the following example. A partial analysis of this spring is:

Temperature:	54°C
Discharge:	260 gpm
SiO_2:	59 mg/l
Na:	730 mg/l
K:	85 mg/l
Ca:	230 mg/l

From Table 3 the 95% confidence limits, (relative deviations) for the SiO_2, Na, K, and Ca analyses are:

SiO_2	59 mg/l	± 8%	or	54.3 - 63.7 mg/l
Na	730 mg/l	± 4%	or	700.8 - 759.2 mg/l
K	85 mg/l	± 16%	or	71.4 - 98.6 mg/l
Ca	230 mg/l	± 5%	or	218.5 - 241.5 mg/1

Applying these ranges of values to the cristobalite-silica, cristobalite mixing model and the Na-K-Ca geothermometer models, the following is obtained:

Cristobalite-Silica Geothermometer

SiO_2 Concentration	Estimated Subsurface Temperature
59.0 mg/l (reported concentration)	59°C
54.3 mg/l (-8% relative deviation)	56°C
63.7 mg/l (+8% relative deviation)	63°C

Cristobalite Mixing Model (cold spring data: T=7°C, SiO_2 = 12 mg/l)

SiO_2 concentration	Estimated Subsurface Temperature
59.0 mg/l (reported concentration)	79°C, 37% cold water
54.3 mg/l (-8% relative deviation)	63°C, 17% cold water
63.7 mg/l (+8% relative deviation)	93°C, 47% cold water

Na-K-Ca Geothermometer Estimated Subsurface Temperatures

Constituent	Based on Reported Concentration	-X% Relative Deviation	+X% Relative Deviation
Na	193°C	195°C	192°C
K	193°C	184°C	202°C
Ca	193°C	194°C	193°C

As noted the Na-K-Ca subsurface temperature estimate varies from 192°C to 195°C for a ± 4% deviation of the Na ion concentration, 184°C to 202°C for a ± 16% deviation of the K ion concentration, and 193°C to 194°C for a ± 5% deviation of the Ca ion concentration.

For Pagosa Springs the cristobalite mixing model subsurface temperature estimate fluctuates by a greater amount than the other geothermometer model estimates. This is not always the case. Determination of the relative accuracy and precision of the geothermometer models must be done on a case by case basis for each thermal system.

OTHER INDICATORS OF SUBSURFACE RESERVOIR TEMPERATURES

White (1965 and 1972) has shown that some of the mineral deposits around a thermal spring or the concentration level of some of the dissolved elements in the thermal waters may be used to make a generalized appraisal of the spring's reservoir temperature to type. White (1972) states that deposits such as siliceous sinter or natural geyser action implies high reservoir temperatures. On the other hand low reservoir temperatures are implied by deposits of travertine. The chloride content of the thermal waters may be used to make a generalized estimate whether the system is hot-water dominated or vapor dominated (White, 1972). White (1972) stated that hot water systems may have dissolved chloride contents in excess of 50 mg/l, while vapor-dominated systems have chloride contents below 20 mg/l. R. Fournier (1978, personnel communication) has stated that some reservations are held regarding this concept, and that it should only be used in context with other indicators. Using the above criteria, a generalized appraisal of the thermal waters of Colorado based on the chloride content was made (Table 15).

TABLE 15

GEOTHERMAL SYSTEMS IN COLORADO BASED ON CHOLRIDE CONTENT OF THE WATERS

High Chloride Thermal Systems
(Chloride content above 50 mg/l)

- Canon City
- Cebolla
- Colonel Chinn
- Don K Ranch
- Dotsero
- Florence
- Glenwood Springs
  - All Thermal Waters
- Hartsel
  - Springs A and B
- Hot Sulphur
  - Springs A, B, C, and D
- Idaho Springs
  - Springs A and B
  - Hot Water Well
- Juniper
- Lemon
- Orvis
- Ouray Wiesbaden B
- Pagosa
  - Big Spring
  - Courthouse
  - Spa Well
- Paradise
- Penny, Granges
- Pinkerton A, B, Mound
- Poncha A, C
- Routt A, B
- South Canyon A, B
- Steamboat
  - Heart
  - Sulphur Cave
  - Steamboat
- Trimble
- Tripp
- Wagon Wheel
  - 4UR Spring
  - CFI Spring
- Wellsville

Low Chloride Thermal Systems
(Chloride content below 20 mg/l)

- Antelope
- Cement Creek
- Conundrum
- Craig Warm Water Well
- Dunton
- Eldorado A, B
- Fullinwider
- Geyser
- Mt. Princeton
  - Hortense Hot Spring
  - Hortense Hot Well
  - Mt. Princeton Springs A and F
  - Woolmington Well
  - Wright Well, East, West
  - Young Life
- Rainbow
- Ranger
- Rhodes
- Rico
  - Diamond
  - Big Geyser
  - Geyser
  - Little Geyser
- Sand Dunes
- Shaws
- Splashland
- Stinking
- Valley View
  - Springs A, B, and D
- Waunita
  - Springs C and D
- Lower Waunita
  - Springs B and D

DESCRIPTION OF INDIVIDUAL THERMAL AREAS

Following is a description of the individual thermal areas in Colorado. For the purposes of the report a thermal area is defined as an area consisting of one or more springs or groups of springs. For example, Orvis Hot Spring, consisting of only one spring, is considered a thermal area, while the Chalk Creek area on the south flank of Mount Princeton, which contain numerous hot springs and well, is also considered a thermal area.

Each thermal area is numbered on the index map (Fig. 1). For example, Area #1, in the northwest corner of the map, is Juniper Hot Springs. In the following discussion the thermal areas will be described in numerical, rather than alphabetical order so that all the thermal areas in the same region can be discussed together.

Each spring or group of springs is discussed in the following manner:

1. The location of the spring or springs is presented in several ways:
    a) latitude and longitude.
    b) township, range, and section (For those not familiar with the U.S. Bureau of Land Management Land Classification System they are referred to Fig. 15).
    c) county
    d) the topographic quadrangle map in which the area is located.

2. Directions are given to the area from the nearest town or other prominent geographic feature. Also presented are any other pertinent facts about the area.

3. The hydrology and geological conditions of the area are discussed. Reported are such measured hydrological parameters as: temperature, pH, concentration of elemental ions if determined, the measured conductance values, and water type. For most thermal areas a geological map was prepared. In many instances these maps were adopted from previously published geologic maps of the area by reconnaissance geologic mapping.

4. The subsurface temperature of each spring or spring area was determined utilizing the Silica, Mixing Model, Sodium-Potassium (Na-K), and Sodium-Potassium-Calcium (Na-K-Ca) geothermometer models. Before applying the silica and mixing model geothermometers, it was determined from silica solubility and temperature relationships which form of silica was controlling the silica found in the waters.

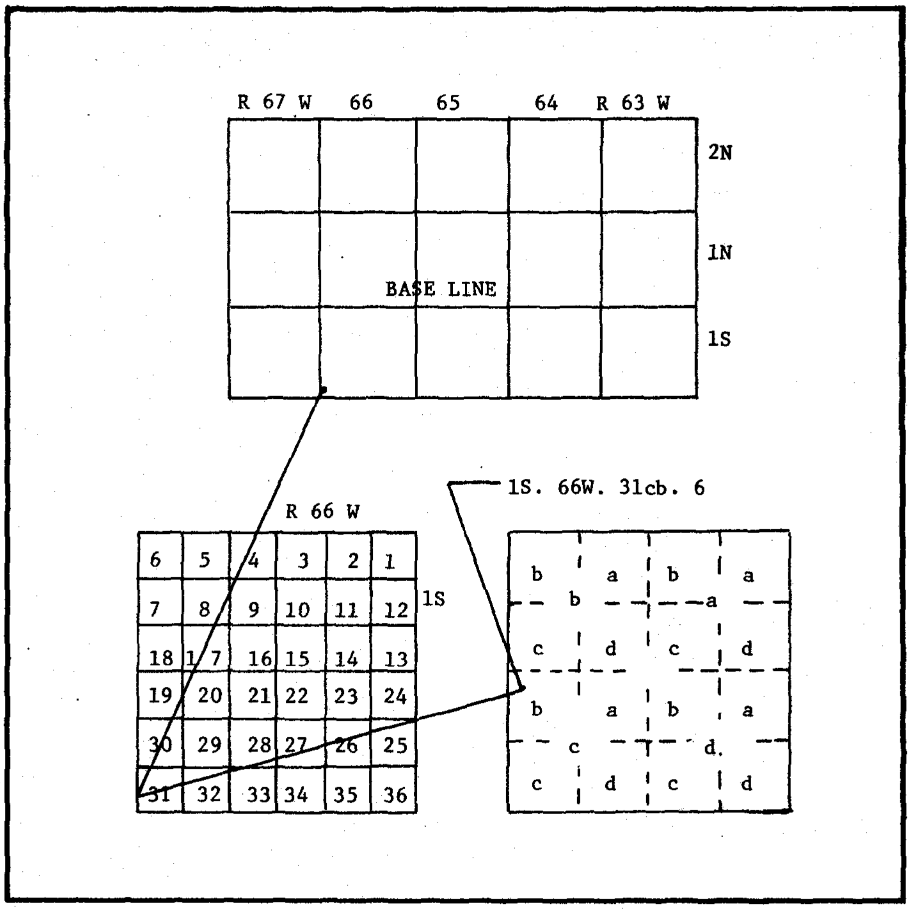


Figure 15.--Spring location numbering system used in Colorado.

The well numbering system used in this report is based on the U.S. Bureau of Land Management system of land subdivision, and shows the location of the spring or well by township, range, section, and position within the section. In this report all lands are referenced to the 6th Principal Meridian or the New Mexico Principal Meridian. The first two segments of the number designate the township and range, the third number designates the section. The letters following the section number locate the feature within the section. The first letter denotes the quarter section, the second the quarter-quarter section. These letters are assigned within the section in a counter-clockwise direction beginning with "a" in the northeast quarter. Letters are assigned within each quarter section and within each quarter-quarter section in the same manner. In the example above the spring is located in the NW 1/4, SW 1/4, Sec. 31, T. 1 S., R. 66 W., 6th Principal Meridian.

#1 JUNIPER HOT SPRINGS

LOCATION: Latitude: 40°28'01"N.; Longitude: 107°57'10"W.; T. 6 N., R. 94 W., Sec. 16 cd, 6th P.M.; Moffat County; *Juniper Hot Springs 7 1/2-minute topographic quadrangle map.*

GENERAL: These springs are located on the south bank of the Yampa River in northwest Colorado. The springs are approximately 27 miles south and west of Craig, Colorado. The springs are reached by traveling west on U.S. Highway 40 from Craig for 19 miles to Lay, Colorado. On the west side of Lay turn south on a dirt road and go approximately 5 miles to the intersection with an east-west dirt road. Turn west on this road and go approximately 2.0 miles to the junction with a north-south dirt road that comes from the hot springs which are just across the river. Turn left on this road and cross the Yampa River and follow the road to the springs which are just a short distance to the west. The waters from the springs are used in the swimming pool and for hot baths at the Juniper Hot Springs Lodge (Fig. 16)

GEOLOGY AND HYDROLOGY: The springs emerge into the hot bath pools, therefore, it was not possible to obtain an accurate measurement of their temperature or discharge. Field measurements of these values throughout a year's time were: Temperature: 33°C to 38°C; Discharge: 13 to 18 gpm; and total dissolved solids: 1,150 mg/l. The waters are a sodium bicarbonate type.

Sears (1924) mapped the Juniper Hot Springs as occurring at a point of transition from the flanks of a southeasterly plunging syncline to the southeast flank of Juniper Mountain to the west. Sears has shown that the strike of the Cretaceous sedimentary formations change in the immediate vicinity of Juniper Springs from generally southeast to northeast. Tweto (1975) states that a small section of undifferentiated Mesozoic sedimentary rocks is overlain by Cretaceous Mancos Shale at the site of the springs (Fig. 17). If this is the case, then a fault must lie in the immediate vicinity of the springs. If present, this fault could be the conduit along which the waters move up from depth. It is believed that the waters come from the Dakota Formation and migrate up faults associated with Juniper Mountain to the west.

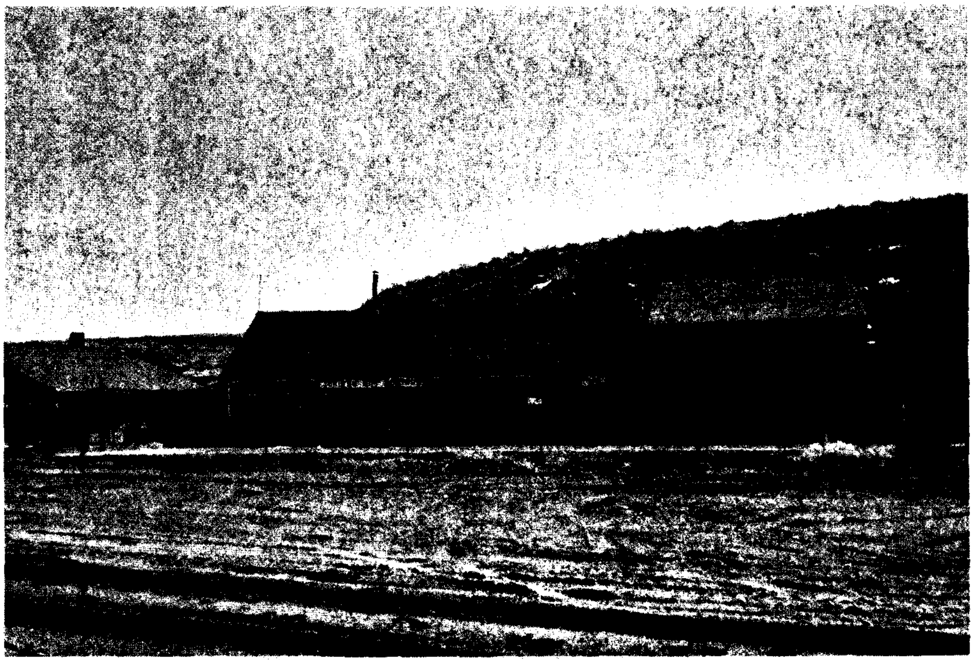
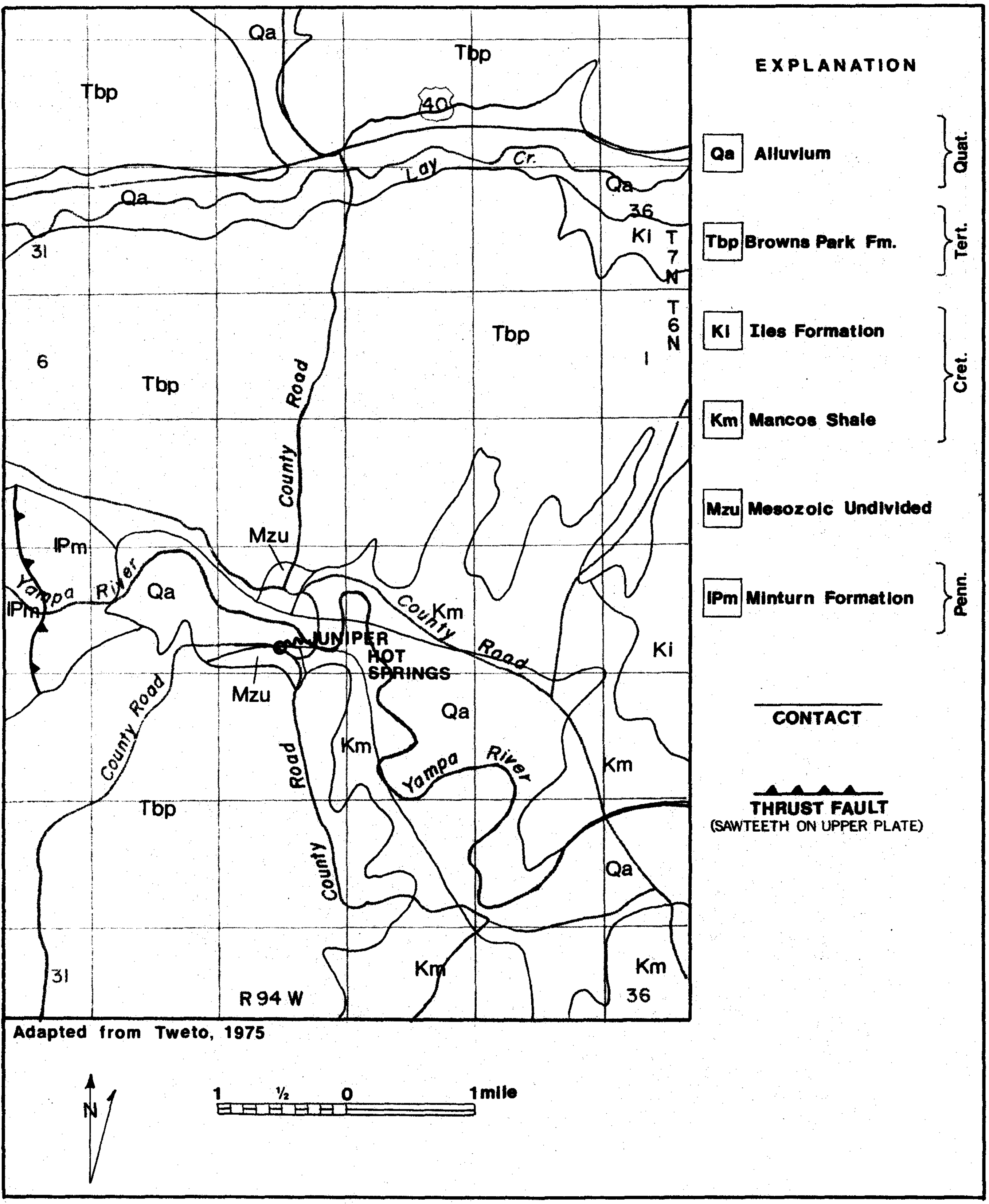


Figure 16.--Juniper Hot Spring.



Adapted from Tweto, 1975

Figure 17.--Geologic map of Juniper Hot Springs area.

GEOTHERMOMETER ANALYSES

Silica Geothermometer: Silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and chalcedony may control the silica content of the hot springs. Therefore, the chalcedony-silica geothermometer model was used. This model gave an estimated subsurface temperature ranging from 47°C to 53°C, based on varying silica content throughout the year's time. This estimate may be close to the actual temperature at depth because the theoretical chalcedony-induced silica solubility (26 mg/l) at the surface temperature of the spring (42°C) is near the silica content of the spring (29 to 33 mg/l).

Mixing Model: Since temperature-dependent equilibration between the thermal water and chalcedony apparently controls the silica content of the hot spring, the chalcedony mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 73°C to 81°C with a cold water fraction of 55 to 61 percent of the spring flow. These estimates are well within the range of values that could result from normal analytical error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-C geothermometers yield subsurface temperature estimates of 67°C to 75°C and 76°C to 80°C, respectively. The close agreement of these results with the other geothermometer estimates suggest they represent the actual temperature at depth.

Conclusion: Geothermometer models must be used with caution when applied to Juniper Hot Springs because most of the assumptions inherent in their use are violated. Moreover, samples of the thermal water were taken from large, quiescent pools. Such sampling situations may exaggerate the effects of the surface conditions on the thermal water, allowing evaporative concentration of the silica content and other re-equilibration reactions to occur.

In light of the agreement between the geothermometer estimates, the subsurface temperature in this area is probably between 50°C and 75°C (Table 4).

#2 CRAIG WARM WATER WELL

LOCATION: Latitude: 40°29'11"N.; Longitude: 107°36'03"W.; T. 6 N., R. 91 W., Sec. 9 dcb, 6th P.M.; Moffat County; Craig 7 1/2-minute topographic quadrangle map.

GENERAL: The well, an oil test well, is reported to be 1,400 ft.deep. The well is located 0.75 mile south of Craig near Colorado highways 13/789. From these roads, one turns east on a dirt road, about 0.25 mile north of the bridge over the Yampa River. The well is along the dirt road approximately 300 ft north of the farmhouse.

GEOLOGY AND HYDROLOGY: The surface temperature of this well is 39°C with a discharge of 24 gpm. The bedrock of the area is the Lewis Shale of Late Cretaceous age. As shown on the geologic map (Fig. 18) no major structural features lie in the immediate vicinity of the well.

Since the exact depth of this well is not known, it is not possible to state with any degree of certainty what formations the waters come from or their recharge area. It appears that the area from Steamboat Springs to Craig is an area of above normal geothermal gradient. Elevated bottom-hole temperatures have been reported (Al Miller, 1976, oral communication) in numerous oil wells drilled along the Yampa River. The heat source of this well may be related to these elevated temperatures in the other oil wells.

GEOTHERMOMETER ANALYSES:

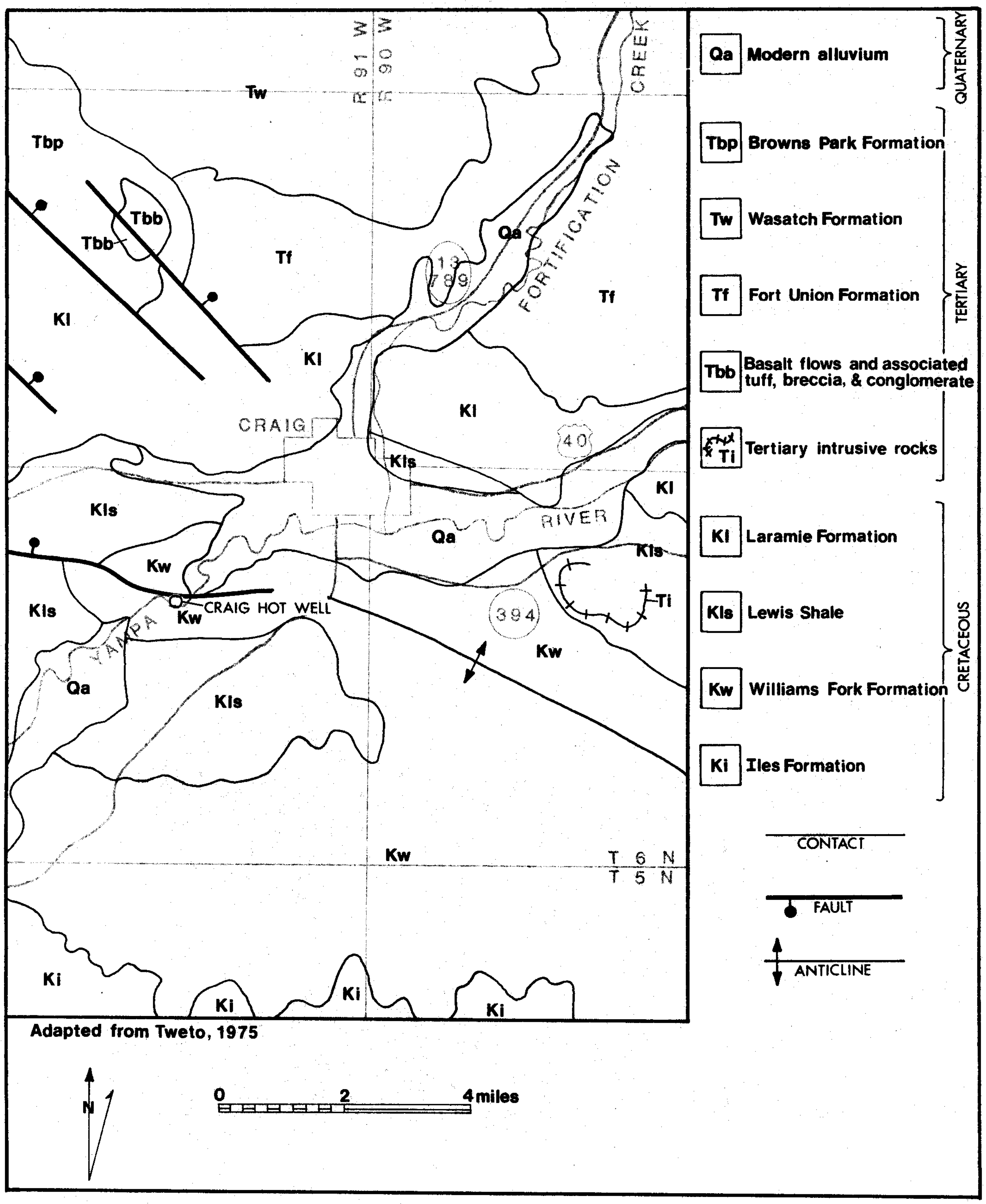
Silica Geothermometer: Analysis shows that chalcedony or quartz may control the silica content of the artesian well. The quartz-silica geothermometer yields a subsurface temperature estimate of 58°C (Table 4). The chalcedony-silica geothermometer subsurface temperature estimate is 30°C (Table 4), which is below the surface temperature of the thermal water (39°C).

Mixing Model: Since temperature-dependent equilibration between the thermal water and quartz or chalcedony may control the silica content of the well, both mixing models are applicable. The quartz mixing model yields a subsurface temperature estimate of 70°C with a cold water fraction of 50 percent. These estimates are probably excessive because the silica content and the flow rate of the artesian well are are below the minimum conditions specified for the reliable application of this geothermometer.

The chalcedony mixing model yields a subsurface temperature estimate of 35°C with a cold water fraction of 20 percent of the total flow. Although the subsurface temperature estimate is below the surface temperature of the well (39°C), it is within the expected margin of error

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 100°C and 104°C, respectively (Table 4). Both of these estimates are too high because calcium carbonate is being deposited at the surface of the artesian well.

Conclusion: The subsurface temperature in this area is best represented by the chalcedony and quartz mixing models. Therefore, the temperature at depth is probably between 40°C and 60°C (Table 4).



Adapted from Tweto, 1975

Figure 18.--Geology surrounding Craig Warm Water Well.

#3 ROUTT HOT SPRINGS

LOCATION: Latitude: 40°33'34"N.; Longitude: 106°51'00"W.; T. 7 N., R. 84 W., Sec. 18 dc, 6th P.M.; Routt County; Rocky Peak 7 1/2-minute topographic quadrangle map.

GENERAL: This group of 5 unused springs is located approximately 8 miles north of Steamboat Springs on Hot Spring Creek. Access is north on 7th Street in Steamboat Springs past the hospital to Park Road, then north on this road to the springs.

GEOLOGY AND HYDROLOGY: The following springs were measured during the course of this investigation.

Spring A: Located approximately 100 ft up the hillside on the south side of the creek (Fig. 19); Temperature: 64°C; Discharge: 25 to 50 gpm; Total Dissolved Solids: 518-552 mg/l; Water Type: sodium chloride-bicarbonate.

Spring B: Biggest spring on north bank of creek, approximately 5 ft above creek; Temperature: 62°C; Discharge: 30 gpm; Total Dissolved Solids: 539 mg/l; Water Type: sodium chloride-bicarbonate.

Spring C: Not sampled; Located 50 ft east of Spring A; Temperature: 54°C; Discharge: Est. 2 gpm; Conductance: 830 micromhos.

Spring D: Not sampled; Located approximately 40 ft southeast of Spring C; Temperature: 51°C; Discharge: Est. 2 gpm; Conductance: 830 micromhos.

No detailed geologic reports or maps have been prepared or published on this area. As shown by Tweto (1975) the springs issue from northwest-trending fracture zones within faulted Precambrian metamorphic rocks (Fig. 20).

Recharge of these springs may occur along the western edge of the Park Range to the east with deep circulation of the waters along fault zones in an area of above-normal heat flow.

Figure 19.--Routt Hot Springs, Spring A (looking across creek and uphill).

GEOTHERMOMETER ANALYSIS:

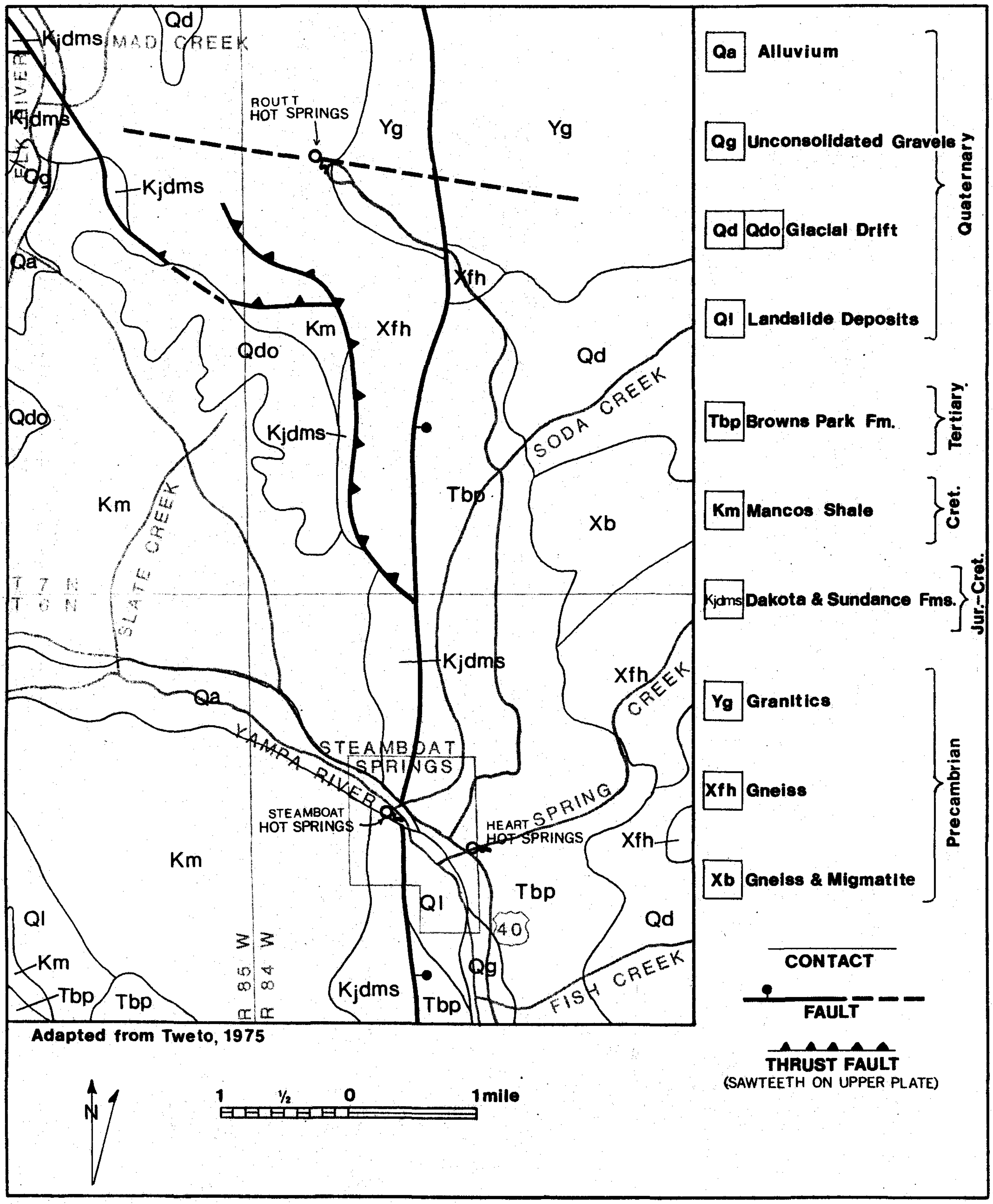
Silica Geothermometer: Silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and quartz may control the silica content of the hot springs. Therefore, the quartz-silica geothermometer yields an estimat of 125°C to 136°C (Table 4).

Mixing Model: Since temperature-dependent equilibration between the thermal water and quartz apparently controls the silica content of the hot springs, the cristobalite mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 192°C to 231°C with a cold water fraction of 71 to 76 percent of the spring flow.

The seasonal fluctuation of the subsurface temperature estimates suggests that the assumed cold-water analysis and percent of mixing estimates do not adequately represent the hydrogeological conditions at depth. However, no certain conclusions can be made from these estimates because they are within the range of values that could result from normal analytical error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 165°C to 170°C and 154°C to 159°C, respectively (Table 4). The high surface temperature (64°C), rapid flow (100 gpm) and close agreement with the mixing model results suggest that these are reasonable estimates.

Conclusion: The fluctuation of the various geothermometer estimates is within the range of values that could result from normal analytical error. The close agreement between the mixing model and the Na-K-Ca model estimates suggests that these geothermometers adequately reflect the temperature at depth. Therefore, these results and the precision of the geothermometers suggest temperatures at depth between 125°C and 175°C (Table 4).



Adapted from Tweto, 1975

Figure 20.--Geology of Routt and Steamboat Springs.

#4 STEAMBOAT SPRINGS

These springs are located on the Yampa River in Northwestern Colorado in the town of Steamboat Springs. Three springs were located and sampled and are discussed below.

LOCATION:

(Heart Spring): Latitude: 40°28'58"N.; Longitude: 106°49'37"W.; T. 6 N., R. 84 W., Sec. 17 abd, 6th P.M.; Routt County; Steamboat Springs 7 1/2-minute topographic quadrangle map.

GENERAL: With the exception of the Heart Spring (Fig. 21) which is located at the southeast end of the town, all the springs are unused at the present time. Waters from the Heart Spring are used in the large community swimming pool. The spring is located just to the northwest of the pool.

At the northwest end of town are several springs spread over a large area. Most of these springs are cold, but the original Steamboat Spring is warm. This spring is located on the west bank of the Yampa River along the railroad tracks, (Fig. 22) just to the west of the little City Park.

The other thermal spring, Sulphur Cave Spring, is located 1,100 ft. northwest of the rodeo grounds and approximately 80 ft above the level of the river.

GEOLOGY AND HYDROLOGY: The Heart Spring has a temperature of 39°C with a discharge of 140 gpm. The total dissolved mineral matter in the waters is 903 mg/l, and the waters are a sodium-chloride type with a strong concentration of sulfate.

Steamboat Spring has a temperature of 26°C with a discharge of 20 gpm. The waters are a sodium-bicarbonate type and contained 6,170 mg/l of dissolved mineral matter.

The waters of the Sulphur Cave Spring had a temperature of 20°C with a discharge of 10 gpm. The waters are a sodium chloride type and contain 4,530 mg/l of dissolved mineral matter.

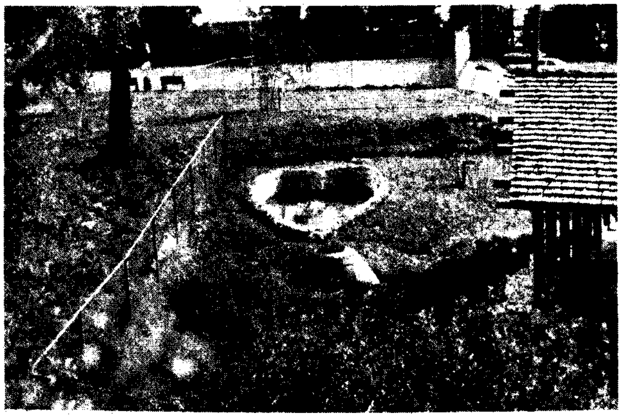


Figure 21.--Photo of Steamboat Springs, Heart Spring.

As shown on Figure 20 these springs are situated on or just off of a major north-south trending fault paralleling the western front of the Park Range. This fault has brought sandstones of the Cretaceous Dakota Formation into contact with the Tertiary Browns Park Formation. The Dakota Formation, primarily a sandstone unit, contains large amounts of sulfur-rich black shales. The Browns Park Formation is a consolidated to semiconsolidated, coarse-grained sandstone that contains some shale and clay beds.

While no values of heat flow have been determined for this part of Colorado, it is believed to be above normal. As reported earlier, Al Miller (1976, oral communication), states that most of the oil test wells in the region from Steamboat Springs to Craig have elevated bottom-hole temperatures.

The occurrence of these thermal waters may be due to deep circulation of ground waters along some of the many faults found in the region.

GEOTHERMOMETER ANALYSES:

The low surface temperature and flow of Steamboat and Sulphur Cave spring renders geothermometer analysis unreliable; therefore, only Heart Hot Spring will be discussed in this section.

Silica Geothermometer: The quartz-silica geothermometer model yields a maximum subsurface temperature estimate of 101°C (Table 4).

Mixing Model: Since temperature-dependent equilibation between the thermal water and quartz-silica apparently controls the silica content of the spring, the quartz-silica mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 179°C with a cold-water fraction of 81 percent of the spring flow. The low silica content of this spring casts doubts upon the reliability of these estimates.

Figure 22.--Photo of Steamboat Springs,
Steamboat Springs.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometer estimates of subsurface temperature are 148°C and 141°C, respectively (Table 4). Although precipitation of calcium carbonate does not occur at the present time at this site, extensive travertine deposits exist in the western half of section 17, T. 6 N., R.84 W. If these deposits represent current conditions at depth for Heart Hot Spring, then the Na-K and Na-K-Ca geothermometer estimates are too high.

Conclusion: Except for the two-week interval from 4/15/76 to 4/30/76, the Heart Hot Spring waters were regularly chlorinated for use in a nearby swimming pool. The spring was sampled on 4/19/76; it is not known whether or not this allowed sufficient time for removal of the chlorine compounds. However, the sodium-to-chloride ratio of Heart Hot Spring was similar to that of the Routt Hot Spring group, implying that most, if not all, of the chemical additives had been removed from the spring pool when sampled.

It is difficult to make a precise prediction of subsurface temperature for this area because of the wide range of geothermometer results and the unknown effects of the chemical additives on the water chemistry of the hot spring. However, the Na-K and Na-K-Ca geothermometer estimates are substantiated by the analysis of the Routt Hot Spring group 5 miles northwest of this spring (see preceding section on Routt Hot Springs). The best estimate of subsurface temperature for this area is between 125°C and 130°C (Table 4).

#5 BRAND'S RANCH ARTESIAN WELL

LOCATION: Latitude: 40°42'17" N.; Longitude: 106°32'05" W.; T. 9 N., R. 81 W., Sec. 31 dcd, 6th. P.M.: Jackson County; Pitchpine Mountain 7 1/2-minute topographic quadrangle map.

GENERAL: The unused well is located west of Walden, Colorado, and may be reached by going 7.7 miles west of Walden on a paved county road to the North Platte River. Cross the river and go 2.6 miles to an intersection. Turn right at the intersection and proceed 0.6 mile to an intersection near South Delaney Lake. Turn left on the dirt road and go west 3.8 miles to Brand's Ranch, a group of abandoned buildings. Go 0.2 miles west of the ranch and cross twin irrigation ditches. Turn right immediately west of the ditches. Go 0.7 mile north on the dirt road along the west side of the ditches. Park at the locked gate and walk 0.3 mile east of the gate to a small foot bridge. The well is about 300 ft. south of the foot bridge in a swampy area in a pasture.

GEOLOGY AND HYDROLOGY: This artesian well, an old oil test well 800 ft deep, has an estimated discharge of 80 gpm at a temperature of 42°C. The conductance of the water is 405 micromhos with a pH of 6.0.

This well is located on the west side of North Park, a large intermontane basin in northwest Colorado. The geology of the area has been discussed in detail by Hail (1965). As shown on the geologic map (fig. 23) the well is located on the outcrop of the Niobrara Formation, and no major faults have been mapped in the immediate vicinity of the well. It is postulated that the waters come from the Dakota, Sundance, or Chugwater Formations.

Recharge to the well probably occurs along the east flank of the Park Range to the west.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Analysis of silica solubility and temperature relationships suggest that the chalcedony silica geothermometer should be used. The chalcedony-silica geothermometer subsurface temperature estimate is 42°C (Table 4), which is the same as the surface temperature of the hot well.

Mixing Model: Since temperature-dependent equilibration between the thermal water and chalcedony apparently controls the silica content of the thermal water, the chalcedony mixing model is applicable. The mixing model yields a subsurface temperature estimate of 43°C with a cold-water fraction of 1 percent of the total flow.

The negligible cold-water content predicted by the mixing model is reasonable because there is almost no opportunity for shallow ground water to percolate into an 800 ft.-deep cased well. In addition the rapid flow (80 gpm) of the well implies that the mixing model estimates are accurate.

Na-K and N-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 199°C and 171°C, respectively.

Although no calcium carbonate deposits were noticed near the artesian well, large travertine deposits (800 ft x 2000 ft x 25 ft thick) occur in section 27, T. 9 N., R. 81 W. approximately 2.5 miles northeast of the artesian well (Fig. 23). Hail (1965) states that the spring waters responsible for this deposit ascend along a large reverse fault from unknown depth and surface at the junction of the fault and an an anticlinal axis. Field data for one of these springs follows (Barrett, unpublished field data):

Temperature	18°C
Conductance	3500 micromhos
pH	7.0
Discharge	less than 2 gpm

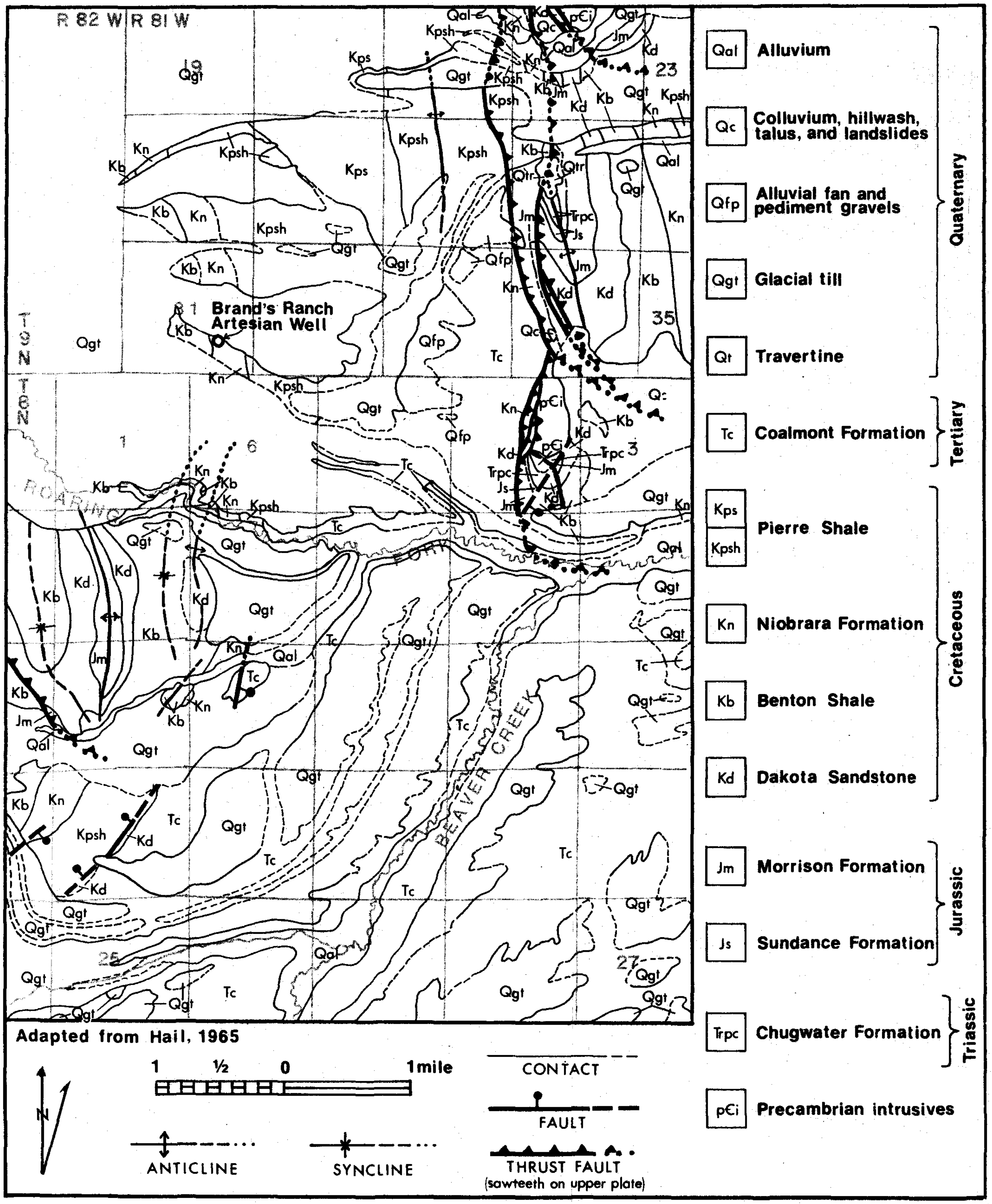


Figure 23.--Geology map of Brands Ranch Artesian Well.

If the spring and thermal artesian well waters are of similar origin, then the travertine deposits around the springs may indicate similar conditions occurring at depth within the artesian well. If calcium carbonate is deposited within the artesian well, then the Na-K and Na-K-Ca geothermometer estimates are too high. In any case the value of the term $\log \sqrt{Ca}/Na$ is greater than 0.5 for the artesian well water, so the Na-K geothermometer estimate is too high.

Conclusion: The rapid flow of the well, the excellent agreement between the silica and mixing models with the temperature and silica content of the thermal water imply that the subsurface temperature is near the surface temperature of the artesian well. The temperature at depth in this area, therefore, is probably 42°C to 55°C (Table 4).

#6 HOT SULPHUR SPRINGS

LOCATION: Latitude: 40°04'33"N.; Longitude 106°06'43"W.; T. 1 N., R. 78 W., Sec. 3 dc, 6th P.M.; Grand County; Hot Sulphur Springs 15-minute topographic quadrangle map.

GENERAL: This group of springs, is located immediately to the northwest of Hot Sulphur Springs across the Colorado River. The springs are located on the west side of the office and around the swimming pool building (Fig. 24). Due to the modifications of the spring discharge points, it was not possible to accurately determine the true number of springs; however, 5 to 10 springs appear to be present. The largest springs, those along the boardwalk, are piped to the various buildings on the property where the waters are used for swimming, steam baths, and laundry purposes.

Figure 24.--Photo of Hot Sulphur Springs. Springs are to the right rear and around the building with word "Pool" written on it. Colorado River in foreground.

GEOLOGY AND HYDROLOGY: The waters are a sodium bicarbonate type with a large concentration of sulfate. The total dissolved solids of the water is 1,200 mg/l, and the temperature ranges from 40°C to 44°C. While the discharge of the various springs ranges from 1 to 23 gpm, the total discharge of all the springs is approximately 50 gpm. A large travertine deposit surrounds the spring. The waters come from the Dakota Sandstone, the underlying bedrock formation.

The geology of the surrounding area has been discussed in detail by Izett (1968). Izett and Barclay (1964) and Izett and Hoover (1963) have published detailed geologic maps of the Hot Sulphur Springs area. The accompanying geologic map (Fig. 25), taken from Izett and Hoover (1963) and Izett and Barclay (1964), shows that Precambrian igneus and metamorphic rocks are exposed less than one mile southwest of Hot Sulphur Springs in Byers Canyon. Uncomformably overlying these rocks and dipping to the northeast is a sequence of sedimentary sandstones, siltstones, shales, and limestones, belonging in ascending order to the Morrrison, Dakota, Benton, Niobrara Formations and Pierre Shale. Overlying these formations is the Tertiary Middle Park Formation consisting of lava flows and associated rocks, siltstones and sandstones.

The Mount Brass Fault, a major northwest-trending thrust fault occurs less than one half mile to the northeast of the springs. This fault may not control the occurrence of the springs since they are located on a small north trending normal fault. The thermal waters may be ascending along this fault zone.

The occurrence of the thermal waters may be due to deep circulation of ground water along fault zones in an area having above normal geothermal gradients. Reiter (1975) has shown this area to have a heat flow of approximately 2.3 heat flow units.

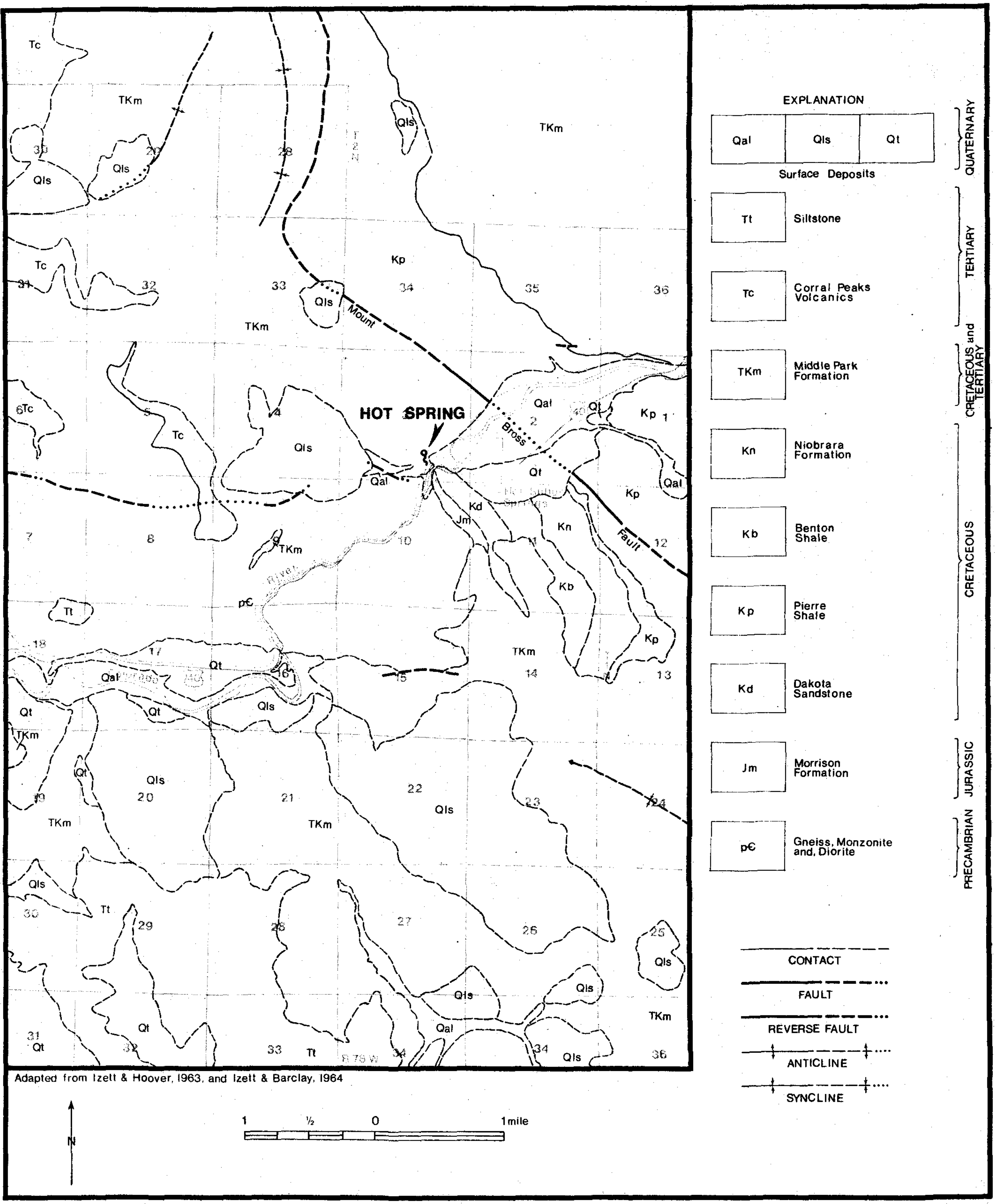
GEOTHERMOMETER ANALYSES

Silica Geothermometer: The quartz-silica geothermometer model yields a subsurface temperature estimate of 80°C to 86°C. G. E. Walton's (1883) description of these hot springs states, "Near the springs are many patches of agate, where moss agate, chalcedony, and amethyst may be found". Apparently these deposits have been entirely collected because none of these minerals were noticed during recent visits to the area. However, if deposition still continues at depth, the silica geothermometer and mixing model estimates of subsurface temperature are too low.

Mixing Model: Quartz mixing model analysis yields a subsurface temperature estimate of 97°C to 115°C with a cold-water fraction of 59 to 69 percent of the spring flow.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 165°C to 170°C, and 164°C to 171°C, respectively (Table 4). These estimates should be treated skeptically because there is no substantiation of such high subsurface temperatures by the other geothermometers. In addition both the temperature and flow rate of these springs are well below the minimum conditions specified for reliable geothermometer results.

Conclusion: Most geothermometer techniques yield unreliable estimates when applied to Hot Sulphur Springs because many of the assumptions inherent in their use are violated. The best geothermometer subsurface temperature estimate for this spring group is between 75° and 150°C.



Adapted from Izett & Hoover, 1963, and Izett & Barclay, 1964

Figure 25.--Map showing geologic conditions surrounding Hot Sulphur Springs.

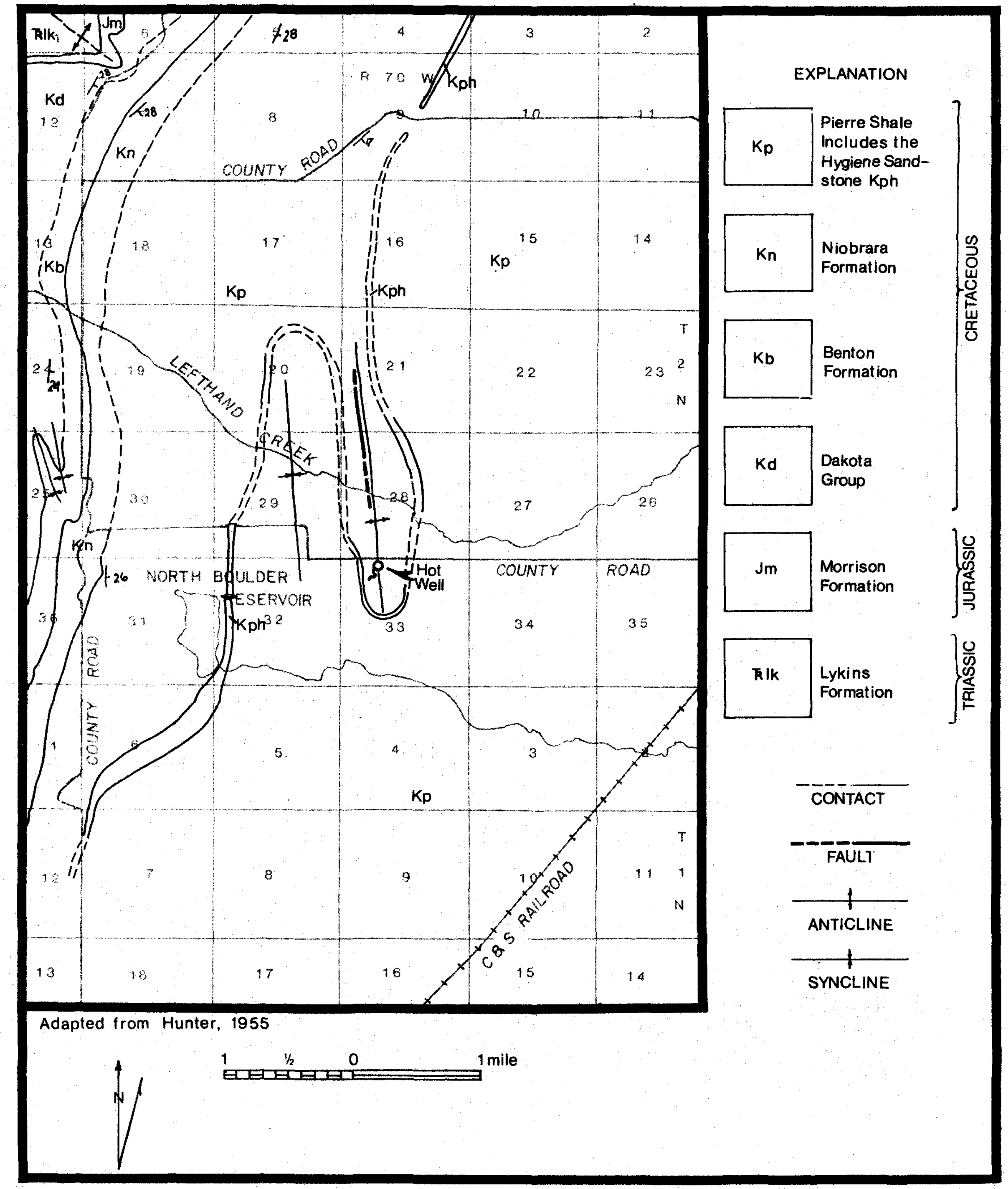


Figure 26.--Geology of Haystack Butte area.

#7 HAYSTACK BUTTE WARM WATER WELL

LOCATION: Latitude: 40°05'48"N; Longitude: 105°14'16"W.; T. 2 N., R. 70 W., Sec. 33 ba, 6th P.M.; Boulder County; Niwot 71/2-minute topographic quadrangle map.

GENERAL: This unused oil test hole is located approximately halfway between Boulder and Longmont. Access is northeast from Boulder on State Highway 119 to N 63d Street, north for 1.9 miles, west for 1.75 miles on Niwot Road. The well is 650 ft south and 1,550 ft east of the northwest corner of sec. 33.

Another unused well was located in 1977. This well is located 1,100 ft south and 1,850 ft east of the northwest corner of sec. 33. The well has a temperature of 32°C with a discharge of approximately 5 gpm.

The Haystack Butte Warm Water well has had a long and varied history according to an unpublished report (Bruce Florquist, 1975, personal comm.). It was drilled in 1920 to a total depth of 2,932 ft. The well was abandoned due to the large amount of water encountered. An attempt made to plug the well was unsuccessful. In a few years time, due to removal of the casing and the plug, the well started leaking. The seeping water was used for a wading pool in the 1920's and 1930's and was later used as a baptismal font by a religious group. At the present time the waters are used in a swimming pool and for watering game birds.

GEOLOGY AND HYDROLOGY: The discharge of this well, which is just seeping around all the material that has been thrown in the well in attempt to plug it, is approximately 4 gpm. The waters have a temperature of 28°C, with 1,200 mg/l of dissolved solids. The waters are a sodium-bicarbonate type.

As shown on Figure 26 the well is located on the south end of a faulted anticline. While the fault does not extend as far south as the well, the well is on strike with the fault. The bedrock of the area is the Pierre Shale and with the reported depth of the well, 2,932 ft, it is believed that the waters come from the Dakota Formation, which outcrops a few miles to the west. Recharge probably occurs along the front of the mountains to the west. The source of the heat is unknown; however, a number of Tertiary igneous features dot the mountain front north from Golden (Ralson Butte, Valmont Dike, etc.). These rocks may be too old to supply the needed heat.

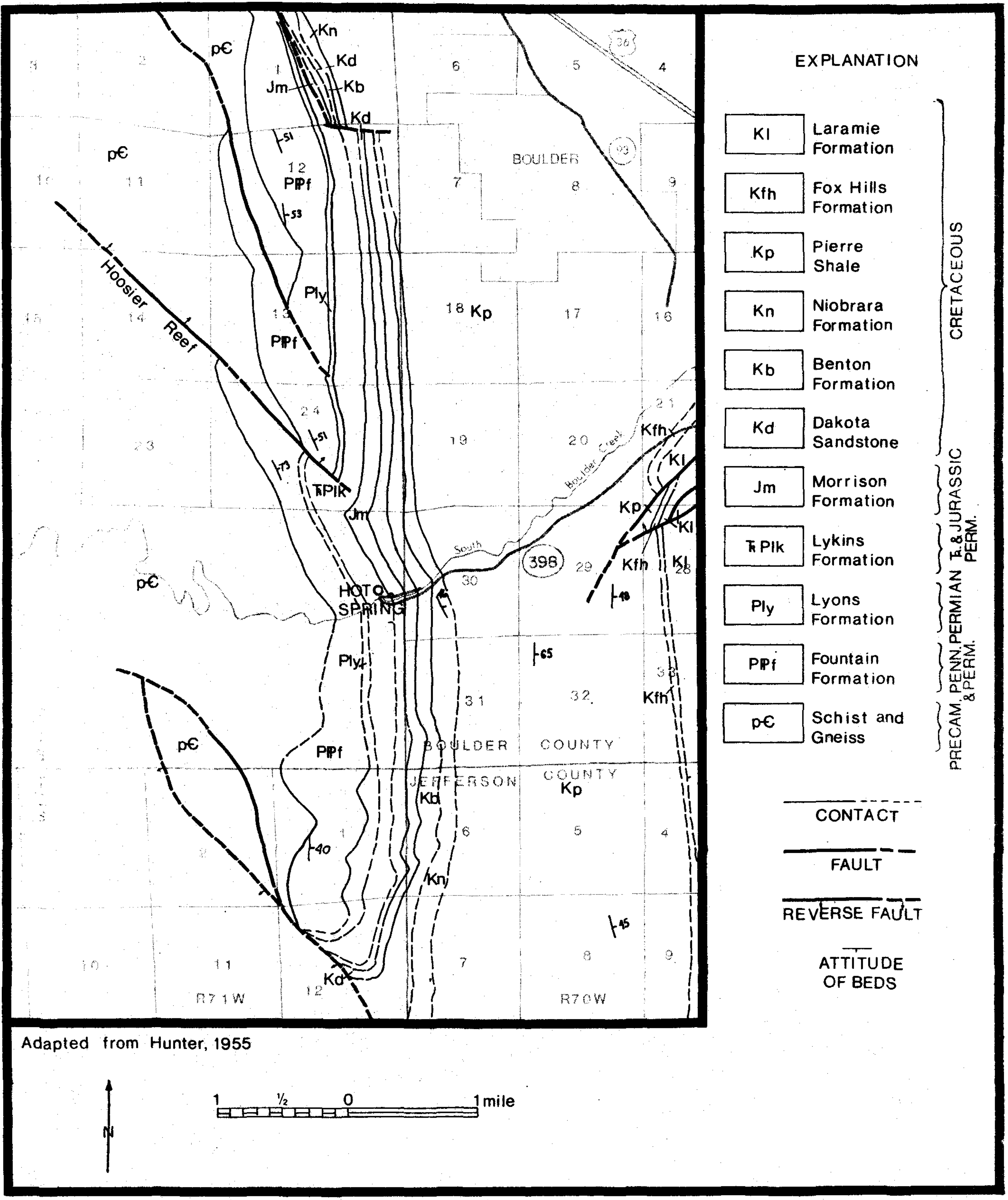
GEOTHERMOMETER ANALYSES

Silica Geothermometer: The chalcedeony-silica geothermometer predicts an estimated subsurface temperature of 47°C with a cold water fraction of 53 percent of the total flow.

Mixing Model: Mixing model analysis yields a subsurface temperature estimate of 57°C with a cold water fraction of 53 percent of the total flow.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 52°C and 62°C, respectively (Table 4). These estimates may be unrealistic because the low temperature (28°C) and low flow (4 gpm) of this well are below the minimum conditions specified for the reliable application of these geothermometers.

Conclusion: Most geothermometers are unreliable when applied to the Haystack Butte Warm Water Well because most of the assumptions inherent in their use are violated. The best estimate of the temperature at depth in this area is probably near 50°C.



Adapted from Hunter, 1955

Figure 27.--Geologic map of Eldorado Springs area.

#8 ELDORADO WARM SPRINGS

LOCATION: Latitude: 39°55'52" N.; Longitude: 105°16'46" W.; T. 1 S., R. 71 W., Sec 25 da, 6th P.M.; Boulder County; Eldorado Springs 7 1/2-minute topographic quadrangle map.

GENERAL: These springs are located approximately 10 miles south of Boulder at the eastern edge of the Front Range. The springs are reached by State Highway 93 from Boulder, then west on State Highway 398.

The springs, which are actually three wells and one spring, are located on both sides of South Boulder Creek. The spring is located in the basement of the large rock and cement building on the north side of the creek west of the swimming pool. The waters from these wells and spring are used in the swimming pool and are bottled and sold commercially.

GEOLOGY AND HYDROLOGY: Throughout the year's time, the temperature of the water ranged from 24°C to 26°C, and the total dissolved solids ranged from 84 to 101 mg/l. Due to the physical layout of the water collection system, it was not possible to measure the discharge of these wells and spring. The waters are a calcium sulfate type.

The waters emerge from South Boulder Creek alluvium, which overlies steeply easterly dipping sandstones of the Fountain and Lyons Formations (Fig. 27). While there are no major faults mapped in the region it is believed that the waters originated by deep circulation through fault and fracture zones in the underlying basement rocks of the mountains a few miles to the west.

GEOTHERMOMETER ANALYSES:

Chalcedony Silica Geothermometer: Silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and chalcedony controls the silica content of the warm spring.

The chalcedony-silica geothermometer estimate of subsurface temperature is 21°C to 23°C (Table 4). Although this result is slightly below the surface temperature of the warm springs, it is within the margin of error inherent in this geothermometer technique.

Mixing Model: Since temperature-dependent equilibration between the thermal water and chalcedony apparently controls the silica content of the warm springs, the chalcedony mixing model is applicable. Chalcedony mixing model analysis yields a subsurface temperature estimate of 26°C to 27°C with a cold-water fraction of 1 to 19 percent of the spring flow.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 254°C to 320°C and 43°C to 57°C, respectively. The Na-K geothermometer estimate is definitely too high because the value of the term $\log \sqrt{Ca}/Na$ exceeds 0.5. As explained earlier, if the value $\log Ca/Na$ exceeds 0.5, excessive temperature estimates occur. Both geothermometer results are unreliable since the flow and temperature of these warm springs are well below the minimum conditions

Conclusion: The mixing model and silica geothermometer provide a minimum subsurface temperature estimate while the Na-K-Ca geothermometer estimate is probably a maximum value of subsurface temperature. Therefore, the subsurface temperature in this area is probably between 26°C and 40°C (Table 4).

#9 IDAHO HOT SPRINGS

LOCATION: Latitude: 39°44'20"N.; Longitude: 105°30'43"W.; T. 4 S., R. 73 W., Sec I ba, 6th P.M.; Clear Creek County; Idaho Springs 7 1/2-minute topograpnhic quadrangle map.

GENERAL: This group of three thermal springs and one well are located along Soda Creek at the Indian Springs Lodge south of Idaho Springs (Fig. 28). The exact location of all the wells and the distribution of the waters are not entirely known. As best as could be determined, one spring is located 50 ft east of the southeast corner of the lodge, one 75 ft south of the lodge, and one 100 ft south of the lodge and the well located at the south end of the swimming pool on the north side of the lodge.

The waters from the springs and well are used for baths and swimming purposes.

GEOLOGY AND HYDROLOGY: The temperatures of the waters ranges from a low of 20°C to a high of 46°C. The discharge varies from 1 gpm to 30 gpm.

The following springs and well were the only thermal water source found at this site:

Spring A: located in a tunnel 75 ft south of the lodge, and east of the creek. During the year the temperature of the water ranged from 40°C to 45°C. The spring had a discharge of 21 gpm and total dissolved solids in the water varied from 1,940 to 2,110 mg/l. Waters are a a sodium-bicarbonate type.

Spring B: This spring is located 50 ft east of the southeast corner of the lodge in a tunnel in the cliff face. The spring has a temperature of 24°C, a discharge of less than one gpm and the total dissolved solids in the water is 1,070 mg/l of a sodium-bicarbonate type.

Spring C: This spring is located in a tunnel 100 ft south of the lodge. When measured, the spring had a temperature of 20°C, a discharge of one gpm, total dissolved mineral matter of 1,070 mg/l in waters of a sodium-bicarbonate type.

Lodge Hot Water Well: This spring, located at the south end of the swimming pool, has a temperature of 46°C and a discharge of 30 gpm. The water contains 2,070 mg/l of total dissolved solids and is a sodium-bicarbonate type.

The following brief description of the geological history of the Idaho Springs region is taken from Harrison and Wells (1959), Lovering and Goddard (1950), and Moench and Drake (1966).

The Idaho Hot Springs are located within the Colorado Mineral Belt. The Mineral Belt is a northeast-trending zone of intrusive rocks and hydrothermal veins of early Tertiary age. The bedrock of the area is composed largely of layered Precambrian gneissic rocks, the Idaho Springs Formation, and small bodies of granite and pegmatite.

Unfortunately none of the various reports published on the Idaho Springs area describes in any detail the geological conditions surrounding the hot springs. As noted on Figure 29 the hot springs are located on the trace of a northwest-trending fault cutting Precambrian metamorphic rocks of the Idaho Springs Formation.

The origin of the hot springs is unclear, but they are believed to be due to deep circulation of ground waters through fracture and fault zones within the basement complex. Reiter (1975) has shown Idaho Springs to have a heat flow of 2.0 heat flow units.

GEOTHERMOMETER ANALYSES

Due to the extensive modification of the natural springs for bathing purposes, the following sections will be based on data from the Lodge Hot Water Well.

Silica Geothermometer: Silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and cristobalite may control the silica content of the hot springs. The cristobalite-silica geothermometer yields a subsurface temperature estimate of 59°C. This estimate may be unreliable because these springs have deposited silica in the past (Spurr and others, 1908). Unfortunately, the extensive modifications made to the springs and the surrounding area do not permit confirmation of these observations.

Mixing Model: Since temperature-dependent equilibration between the thermal water and cristobalite apparently controls the silica content of the springs, the cristobalite mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 81°C with a cold-water fraction of 48 percent of the total flow. These estimates are unreliable, however, because the low flow and silica content of the thermal waters are well below the minimum conditions specified for the reliable application of this geothermometer technique.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 231°C and 210°C, respectively. Spurr and others (1908) noted calcium carbonate deposits among the stream gravels in the area around the hot springs and Berthoud (1866) states that the springs were depositing travertine and that the nearby stream gravels were extensively cemented by calcium carbonate. The high magnesium concentration of the waters renders these geothermometers unreliable.

In any case both of these geothermometer results should be treated skeptically because the temperature and discharge of the springs are well below the minimum conditions specified for the reliable application of this technique.

Conclusion: Geothermometer models should be used with caution when applied to the Idaho Hot Springs because most of the assumptions inherent in their use are violated. The estimation of subsurface temperature for this area is unreliable due to the ambiguous geochemistry of the thermal waters.

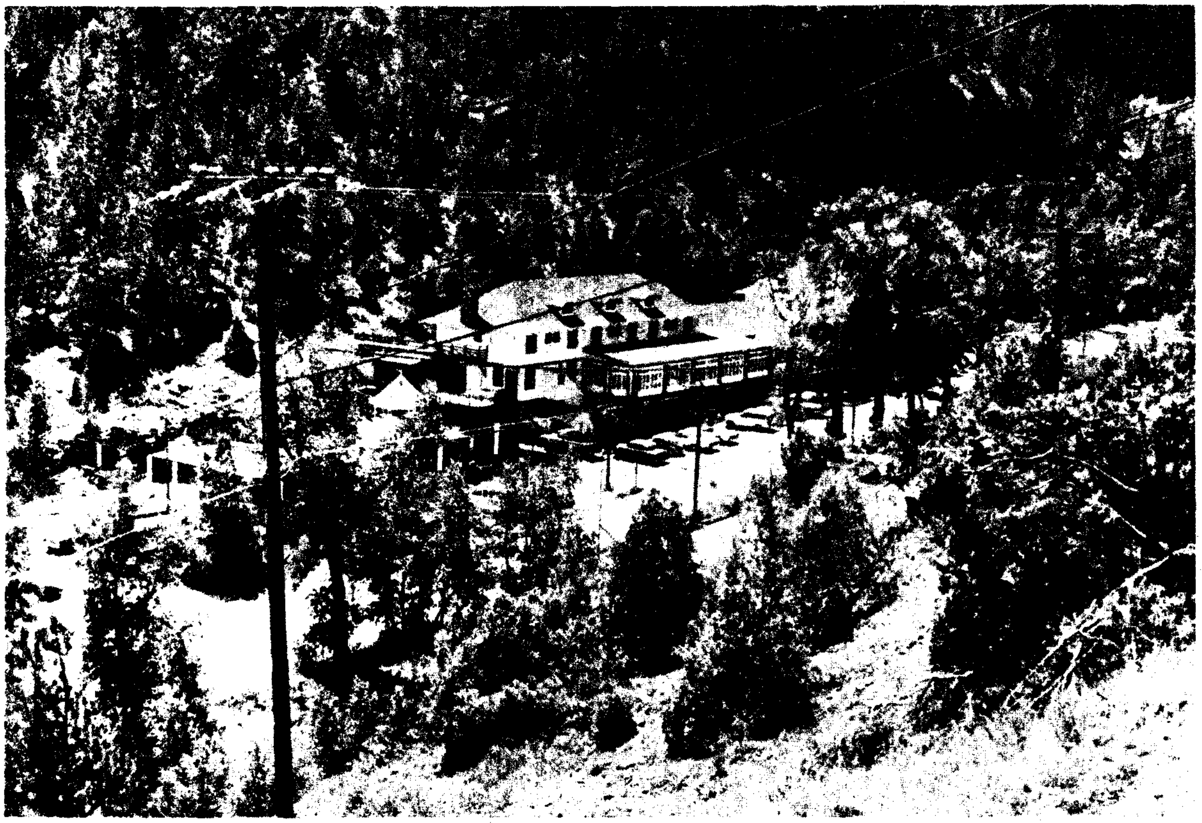
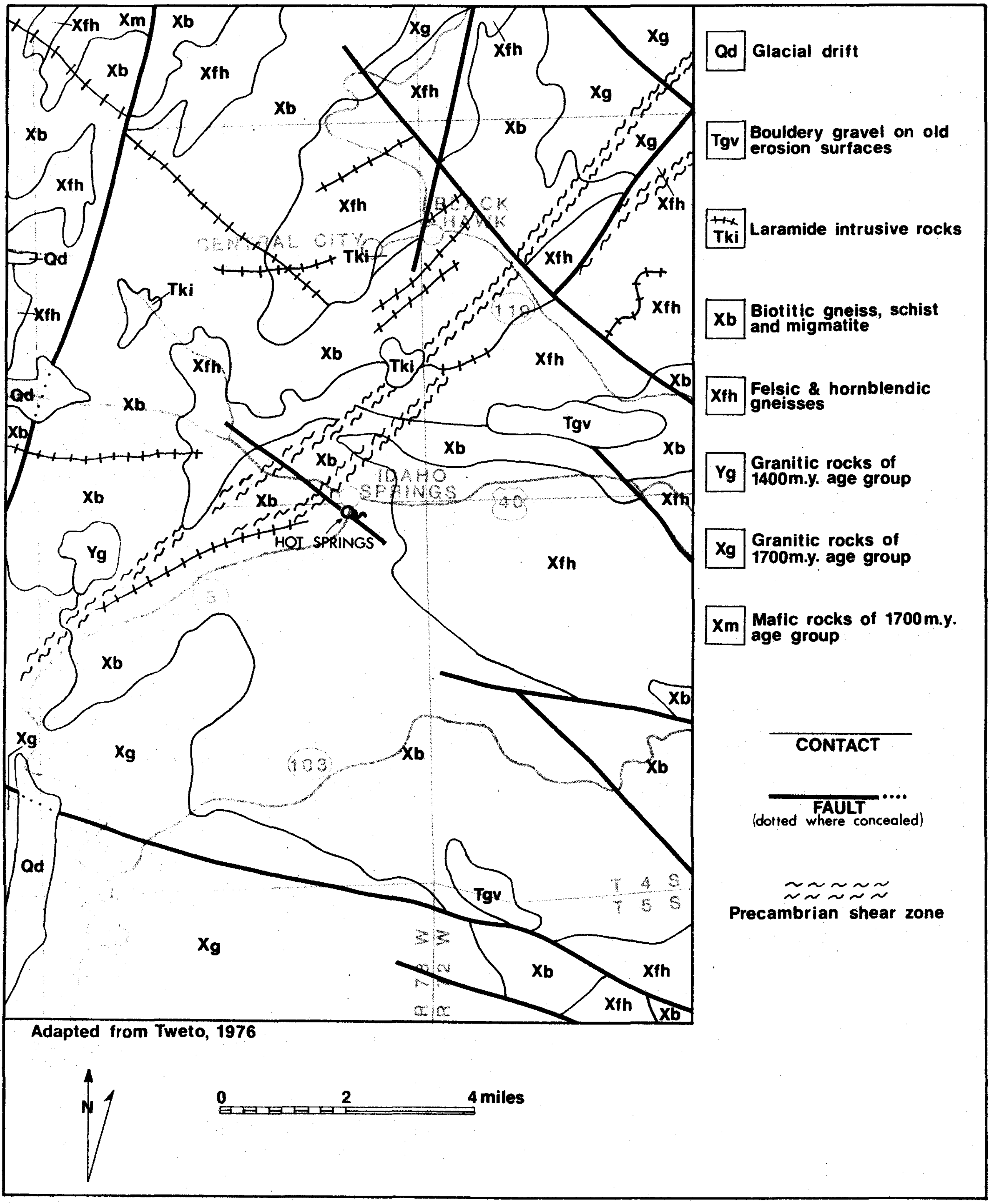


Figure 28.--Idaho Hot Springs. Springs are behind and to the right of the lodge, and to the left of the lodge.



Adapted from Tweto, 1976

Figure 29.--Geology surrounding Idaho Springs.

#10 DOTSERO WARM SPRINGS

LOCATION: Latitude: 39°37'39"N.; Longitude: 107°06'22"; T. 5 S., R. 87 W., Sec. 12 bd, 6th P.M.; Eagle County; Glenwood Springs 15-minute topographic quadrangle map.

GENERAL: This group of unused springs is located on both sides and in the Colorado River approximately 0.5 mile upstream from where the river bends before entering Glenwood Canyon and approximately 3 miles downstream from the confluence of the Colorado and Eagle Rivers. The springs on the west side of the river are located approximately 150 yd north of the house and flow out from under U.S. Highways 6 and 24 at the level of the Colorado River (Fig. 30). About 5 springs comprise the group.

Figure 30.--Dotsero Hot Springs, west side of the Colorado River.

The springs on the south side of the river are located at the bend of the river (Fig. 31). Access to these springs is either by a bridge a couple miles down the river or by a foot bridge several miles upriver.

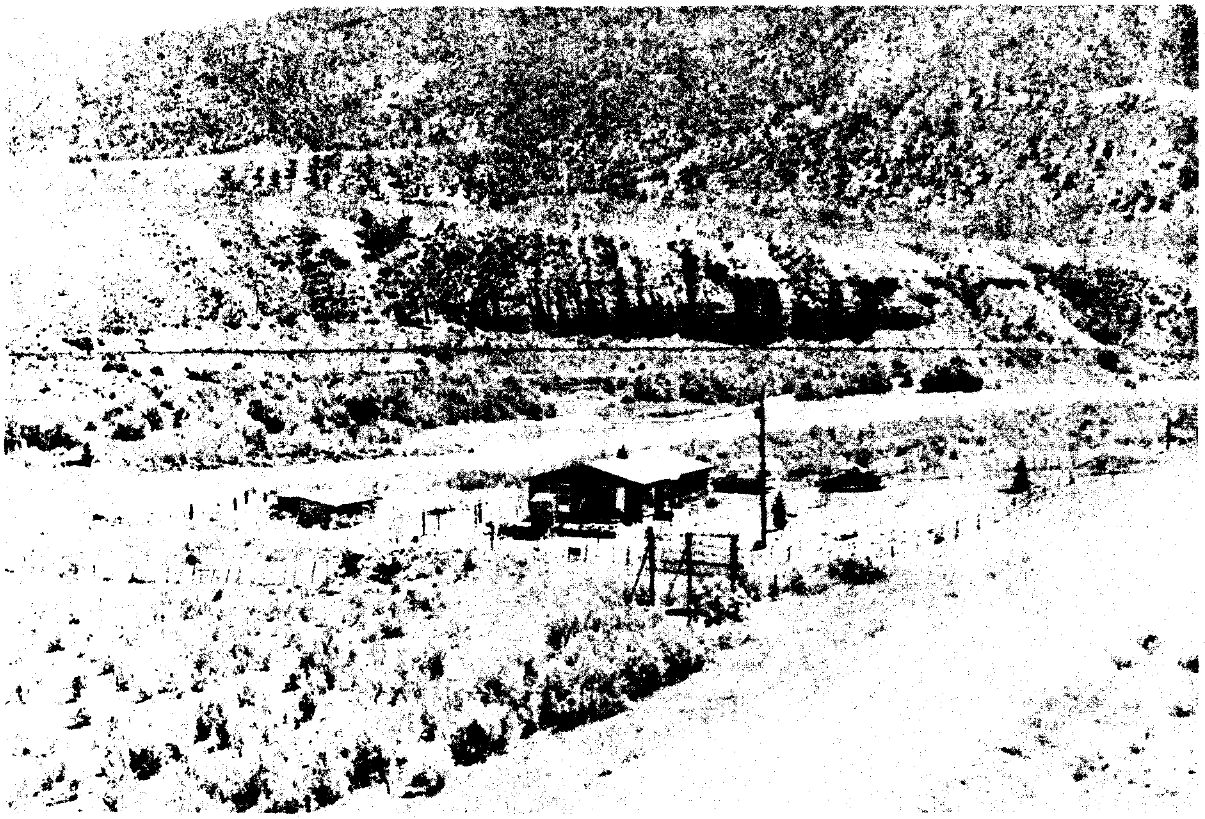


Figure 31.--Dotsero Hot Springs. Springs are located on far side (east side) of Colorado River directly above roof of house.

GEOLOGY AND HYDROLOGY: Due to the spring's high flow, and the near submergence of the springs by the river, one cannot accurately measure the discharge of either groups of springs. Depending upon the time of year, the discharge of the springs on the west side varied between 500 and 800 gpm. The discharge of the springs on the southeast side of the river was estimated to be 1,000 gpm. Waters from both groups contained approximately 10,000 mg/l of dissolved solids, and the waters are a sodium-chloride type. The temperature of both spring groups was 32°C.

While the springs emerge from the Colorado River alluvium, which overlies the Belden shale, it is believed that the waters actually come from the nearby Leadville Limestone (Figure 32).

Recharge probably occurs where the Leadville Limestone crops out to the north and west along the flanks of the White River Uplift. The source of heat is unknown but may be related to the volcanic rocks capping the White River Uplift. Thermal waters found around the White River Uplift at: Glenwood Springs, Dotsero, the reported hot-water well at Yampa (not sampled), and Steamboat Springs and the elevated bottom-hole temperatures in oil wells between Steamboat Springs and Craig lead one to postulate that a residual heat source remains in association with the White River Uplift. Volcanic rocks that were erupted approximately 4,000 years ago are found approximately one mile east of the confluence of the Colorado River and the Eagle River (Grose, 1974). Another possible source of the heat could be elevated geothermal gradients in the area.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Analysis of the silica solubility and temperature relationships suggest that quartz or chalcedony may control the silica content of the warm springs.

The chalcedony-silica geothermometer yields a subsurface temperature estimate of 16°C, which is obviously incorrect because it is below the surface temperature of the warm springs (31°C to 32°C) (Table 4). The quartz-silica geothermometer estimate of subsurface temperature is 45°C to 47°C, which may be too high.

Mixing Model: The chalcedony mixing model yields a subsurface temperature estimate of 27°C-29°C with a cold-water fraction of 26 to 36 percent of the spring flow. Although this temperature estimate is a few degrees below the surface temperature of the warm springs, the result is well within the margin of error that can be expected.

The quartz mixing model yields a subsurface temperature estimate of 74°C to 76°C with a cold-water fraction of 65 to 67 percent of the spring flow. These estimates are probably too high because quartz may not be controlling the silica content of the warm springs.

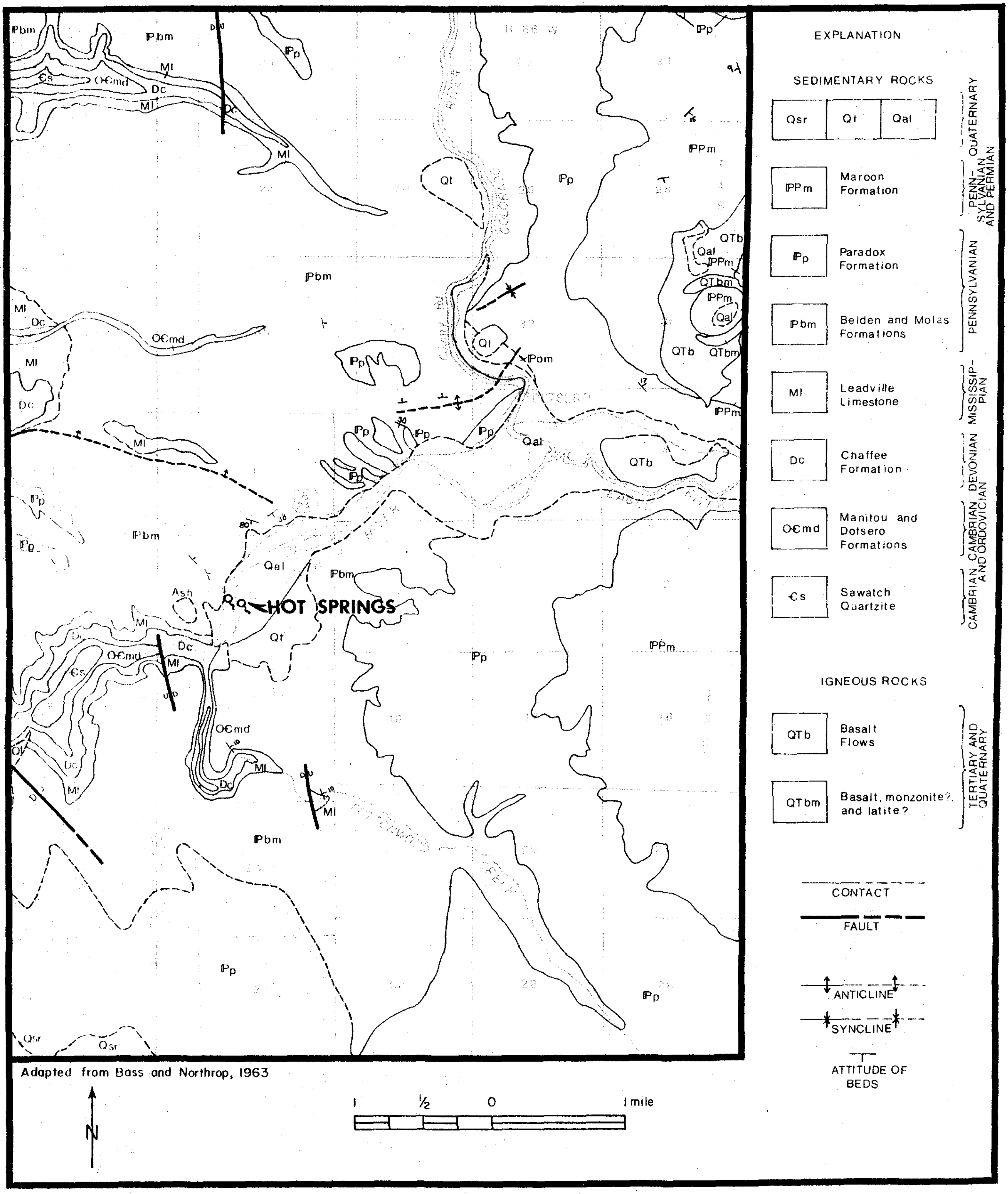
The reliability of both the quartz and chalcedony mixing models is questionable because the silica contents of the warm springs are well below the minimum conditions specified for the application of this geothermometer. (See silica geothermometer model assumption.)

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 102°C to 135°C and 109°C to 144°C, respectively.

The high dissolved sodium, chloride, calcium and magnesium contents of these warm springs suggests that the ascending thermal water may encounter evaporite deposits at depth. The Eagle Valley Evaporite, which outcrops nearby, contains several hundred feet of salt, gypsum and other evaporite deposits. Although this formation as mapped by Bass and Northrop (1963) occurs approximately 700 ft above the warm springs elevation, it is possible that minor sections may also occur lower in the geologic section due to unmapped faults.

Conclusion: The insignificant yearly variation in flow, surface temperature, mineral content and geothermometer estimates imply that these warm springs are not materially affected by seasonal metereological conditions. Moreover, the fluctuation of the various geothermometer estimates is well within the range of values that could result from normal analytical error.

The extremely high flow (greater than 1,500 gpm) of this group suggests very little difference between the surface temperature of these springs and the temperature at depth. Therefore, the likely subsurface temperature in this area is between 32°C and 45°C (Table 4).



Adapted from Bass and Northrop, 1963

Figure 32.--Geologic map of Dotsero Hot Springs.

#11 GLENWOOD HOT SPRINGS

LOCATION: Latitude: 39°32'59"N; Longitude: 107°19'18"W.; T. 6 S., R. 89 W., Sec. 9 ad, 6th P.M.; Garfield County; Glenwood Springs 7 1/2- minute topographic quadrangle map.

GENERAL: The 12 to 15 springs collectively known as Glenwood Springs are located in and adjacent to the community of Glenwood Springs along the Colorado River on Interstate Highway 70 in western Colorado. These springs are located along both banks of and in the Colorado River from a point approximately 0.5 to 0.75 mile east of the canyon mouth to the west edge of Glenwood Springs. The springs on the south side of the river are not developed, but the springs on the north side are developed. The largest spring in this group, which also happens to be the largest spring in Colorado but not the hottest, feeds the big swimming pool on the north side of the river (Fig. 33). These springs are also the greatest point source of salinity to the Colorado River of any spring in the state. The waters from the springs are used for swimming and medicinal purposes.

The following springs were located and either sampled or field measurements taken:

South Side of River from East to West

Railroad Spring: Located approximately 0.75 mile west of the westernmost tunnel on the railroad, approximately 0.5 to 0.75 mile east of the canyon mouth. The spring, which is located just at the water line of the river has a discharge of 75 gpm, a temperature of 51°C, and contains 18,400 mg/l of total dissolved solids.

Spring D: Located approximately 250 ft east of the siphon pipes crossing the river below the cliffs. This spring has a discharge of 74 gpm, a temperature of 50°C, and contains 18,000 mg/l of total dissolved solids.

Spring C: Located 170 ft east of the siphon pipe (Fig. 34). This spring has a discharge of 2 to 3 gpm, a temperature of 46°C. The spring was not sampled for dissolved mineral matter.

Spring B: Located 27 ft west of the siphon (Fig. 34 & 35), this spring has a discharge ranging from 75 to 110 gpm with a temperature of 49°C and contains 17,700 to 18,400 mg/l of total dissolved solids.

Spring A: This spring is located 480 ft west of siphon (Fig. 34) and has a discharge of 2 to 3 gpm with a temperature of 44°C and contains 17,600 mg/l of total dissolved solids.

River Springs: Located about 50 ft out into the Colorado River, directly north of Spring A, are two large boulders of Leadville Limestone. Hot Springs issue from these boulders with discharges of about 10 gpm and 50 gpm. The temperature of the springs nearest to the shore were 50°C. These springs were not sampled for dissolved mineral matter.

North Side of River, from East to West

The Vapor Caves are located at the canyon mouth in the Vapor Caves building. The discharge of the spring in the men's side was estimated at 5 gpm, the temperature was 50°C, and the total dissolved solids were 18,000 mg/l. A strong sulfur dioxide gas content in the spring is apparent for it takes your breath away when you enter the tunnel.

Big Spring (also called Yampa Spring) is located approximately 75 yd to the east of the swimming pool (Fig. 33). The waters from this spring are used in the swimming pool. The spring has a discharge of 2,263 gpm with a temperature of 50°C and contains 20,200 mg/l of total dissolved solids.

Drinking Spring: located approximately 100 ft east of the swimming pool (Fig. 33). The spring has a discharge of 140 to 161 gpm with a temperature of 50°C to 51°C, and contains 18,800 to 20,500 mg/l of total dissolved solids.

Graves Spring is located at 0281 164 Road in T. 6 S., R. 89 W., Sec. 9 bb, 6th P.M. south and west of the State Highway buildings. This spring is located under the front porch of Dr. Charles Graves' chiropractic office. The discharge of this spring is 5 gpm with a temperature of 46°C and contains 21,500 mg/l of total dissolved solids. A number of other hot springs in this immediate vicinity were not sampled.

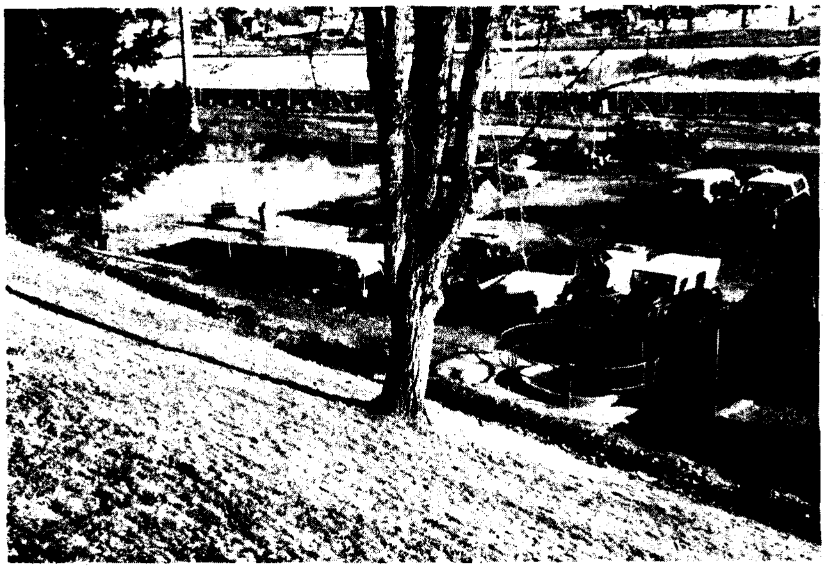


Figure 33.--Big Spring and Drinking Spring - Glenwood Springs. Big Spring at left center, Drinking Spring right center.

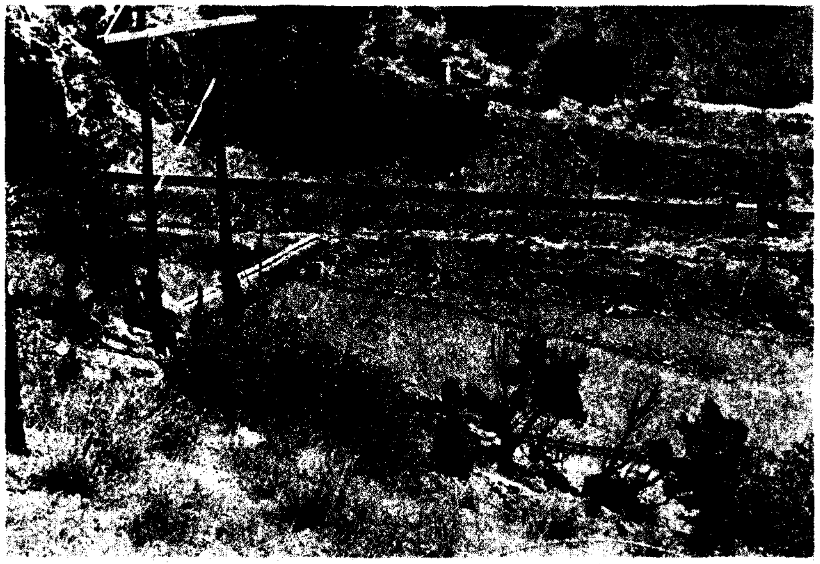


Figure 34.--Spring B at Glenwood Springs.

Figure 35.--Springs on south side of Colorado River at Glenwood.

All of the above springs are a sodium-chloride type with a high concentration of sulfate.

While all the springs issue from alluvial deposits along the Colorado River, it is believed that the waters migrate up from depth through the underlying Leadville Limestone. The Leadville Limestone is very porous and permeable as evidenced by the large solution caves present at the canyon mouth on the south side. (Fig. 34).

Glenwood Springs are located at the west end of Glenwood Canyon and on the south flank of the White River Uplift. Rocks from Precambrian to Mississippian in age are exposed in the canyon just a few miles to the east. As shown on Fig. 36, the area to the north and east of the springs is cut by many faults.

One of the major faults, that probably controls the occurrence of the hot springs is the northwest-trending Storm King Fault. Although it has not been proven that this fault actually extends as far east as the hot springs, Bass and Northrop (1963) have projected it to the spring area.

One of the unexplained circumstances regarding this group of springs is the origin of the sulfate ions found in the water. The Leadville Limestone and underlying formations consist of limestones, sandstones, and some thin shale units. If the thermal waters moved only through these formations, no sulfate minerals would be dissolved since these units do not contain any large amounts of sulfate-bearing minerals. Overlying the Leadville Formation are the red beds of the Maroon Formation and its lateral equivalents, the Eagle Valley Evaporite. These units do contain large amounts of sulfate-bearing minerals. Therefore, from the mineralogy of the thermal waters, it appears that at some point they contact the Maroon Formation. The hydrology of this system appears to be quite complex and must be studied.

The recharge area is probably to the north along the flanks of the White River Uplift with the waters migrating downward and upward along fault zones into the Leadville Limestone.

GEOTHERMOMETER ANALYSES

Silica Geothermometer: Silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and chalcedony may control the silica content of the hot springs. Therefore, the chalcedony-silica geothermometer yields the most reliable subsurface temperature estimate.

The chalcedony-silica geothermometer estimate of subsurface temperature is 44°C to 51°C, which is very close to the surface temperature of the hot springs in this area (46°C to 51°C). The extremely high flow rate of this spring group (3000 gpm), the excellent agreement between the theoretical chalcedony-induced silica solubility (27 to 32 mg/l), and the actual silica content of the springs (29 to 32 mg/l) suggest that these geothermometer estimates may closely approximate the actual temperature at depth.

Mixing Model: Since temperature-dependent equilibration between the thermal water and chalcedony apparently controls the silica content of the hot springs, the chalcedony mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 49°C to 77°C with a cold-water fraction of 0 to 46 percent of the spring flow.

Graves Hot Spring and Hot Spring "A" yield the highest subsurface temperature estimates of the group (77°C and 73°C, respectively), but they are the least suitable springs for mixing model analysis. Samples of these springs had to be taken from low-flowing (less than 5 gpm), quiescent pools. Such sampling conditions may exaggerate the effects of the surface conditions on the thermal water, allowing evaporative concentration of the silica content and other re-equilibration reactions to occur.

If the results for Graves Hot Spring and Hot Spring "A" are omitted, the subsurface temperature for this area ranges from 47°C to 59°C with a cold-water fraction of 0 to 18 percent. These estimates are well within the range of values that could result from normal analytical error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 129°C to 168°C and 143°C to 186°C, respectively (Table 4).

The presence of extensive travertine deposits in the vicinity (T. 6 S., R. 89 W., Sections 3, 4, 5, 9, 10) and travertine-depositing springs (Springs B and D, Railroad Hot Springs and others) suggest that the Na-K and Na-K-Ca geothermometer estimates are too high. In addition the extremely high sodium, chloride, calcium, magnesium, and sulfate contents of the hot springs suggest that the ascending thermal water encounters the Eagle Valley Evaporite at depth (Bass and Northrop, 1963), further raising the geothermometer estimates.

Conclusion: The insignificant variation in flow, mineral content, surface temperature and geothermometer estimates of these hot springs suggest that they are not materially affected by seasonal meterological conditions. Moreover, the fluctuation of the various geothermometer estimates is well within the range of values that could result from normal analytical error.

The extremely high flow (3000 gpm), and excellent agreement between the chalcedony-silica and the mixing models with the silica content and surface temperature of the hot springs suggest that the temperature at depth is probably not much higher than the surface temperature of the hot springs. However, the geochemistry of these thermal waters is too complex for accurate prediction of subsurface temperature.

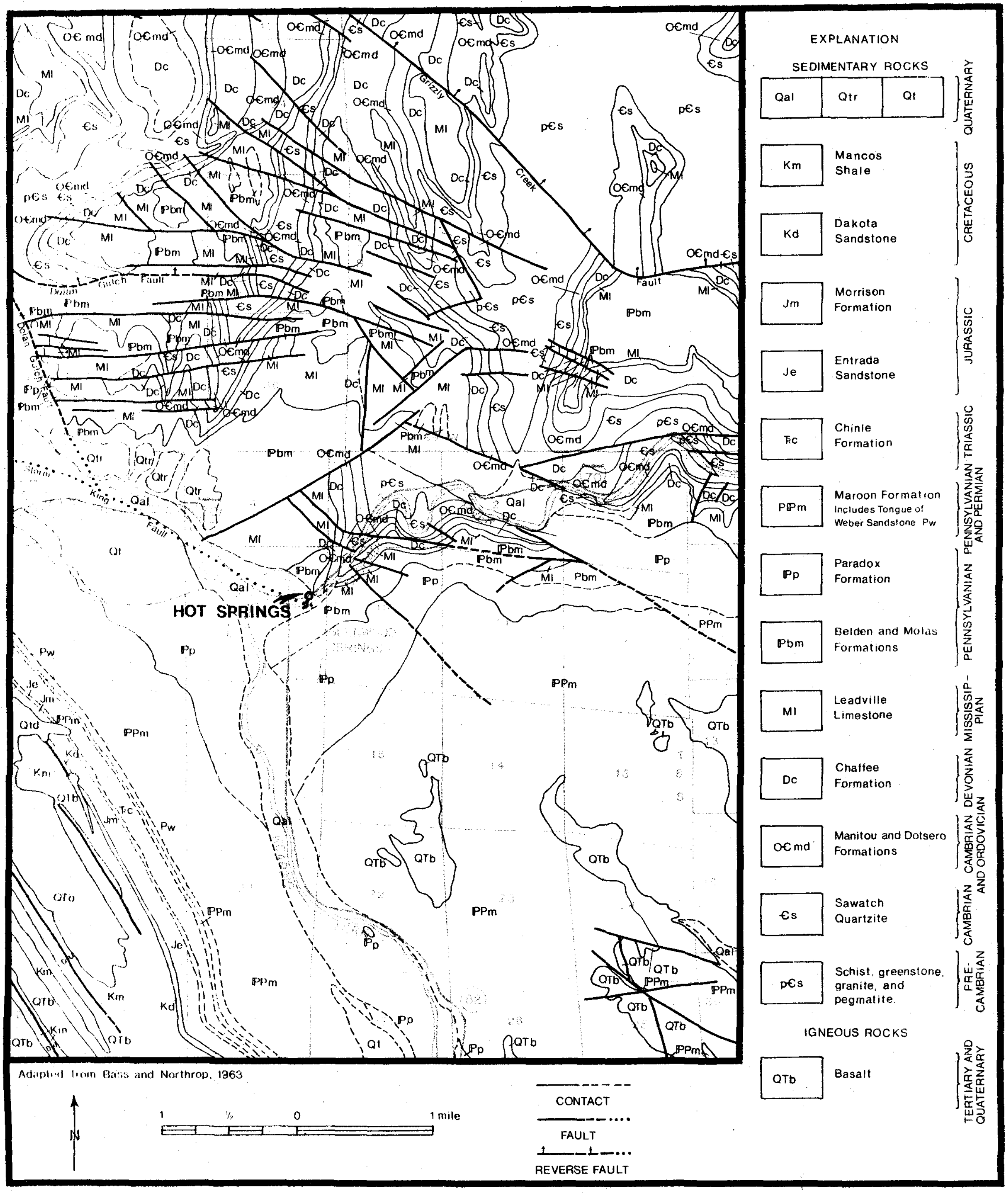


Figure 36.--Geologic map of Glenwood Springs and surrounding region.

#12 SOUTH CANYON HOT SPRINGS

LOCATION: Latitude: 39°33'16"N.; Longitude: 107°23'53"W.; T. 6 S., R. 90 W., Sec. 2 cd, 6th P.M.; Garfield County; Storm King Mountain 7 1/2-minute topographic quadrangle map.

GENERAL: This small group of unused springs is located 0.5 mile south of Interstate Highway 70 in South Canyon west of Glenwood Springs. The springs may be reached by driving approximately 5 miles west on I-70 to the South Canyon interchange, then south 0.5 mile on the dirt road. The springs cannot be seen from the road, but can be reached by a trail leading from a small parking area on the west side of the road with a trail leading off to the springs, which are on the other side of the creek.

There are three distinct springs or seeps in this group. Spring A, which is the largest, is actually the discharge of three small springs that flow together. Spring B lies approximately 75 ft east of A, and Spring C is located 5 feet upstream from the footbridge crossing the creek. Waters from A and B are piped to the pool for bathing purposes. Waters from Spring C are unused.

GEOLOGY AND HYDROLOGY:

Spring A: Temperature: 48°C; Discharge 7 to 17 gpm; Total dissolved solids: 772-800 mgl; Water type: sodium-bicarbonate.

Spring B: Temperature: 48°C; Discharge est.: 1 gpm; Total dissolved solids: 757 mg/l; Water type: sodium-bicarbonate.

Spring C: Temperature: 49°C; Discharge: 6 gpm.

These waters come from the Dakota Formation along the Grand Hogback. As shown on the geologic map (Fig. 37), The occurrence of these thermal springs is peculiar because there are near by faults or folds. The springs probably represent deep circulation through the Dakota Formation in an area of high geothermal gradient.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: The chalcedony geothermometer yields a subsurface temperature estimate of 60°C to 67°C.

Mixing Model: Mixing model analysis yields a subsurface temperature estimate of 103°C to 127°C with a cold-water fraction of 60 to 68 percent of the spring flow (Table 4). These results are well within the range of values that could result from normal analytical error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 137°C to 140°C and 135°C to 137°C, respectively (Table 4). Although no travertine deposits occur in the vicinity, extensive deposits occur at Glenwood Springs 3 miles east (T. 6 S., R. 89 W., Sections 3, 4, 5, 9, 10).

If the thermal waters at South Canyon and Glenwood Springs are of similar origin, then travertine or calcium carbonate deposition may be occurring at depth in the South Canyon area. If so, then the Na-K and Na-K-Ca geothermometer estimates are too high.

Conclusion: The insignificant fluctuation in flow, surface temperature, mineral content, and geothermometer temperature estimates suggest that these hot springs are not substantially affected by seasonal meteorological conditions. The fluctuation of the temperature estimates is well within the range of values that could result from analytical error.

Consideration of the data listed in Table 4 and the precision of the geothermometer model suggest temperatures at depth in this area between 100°C and 130.

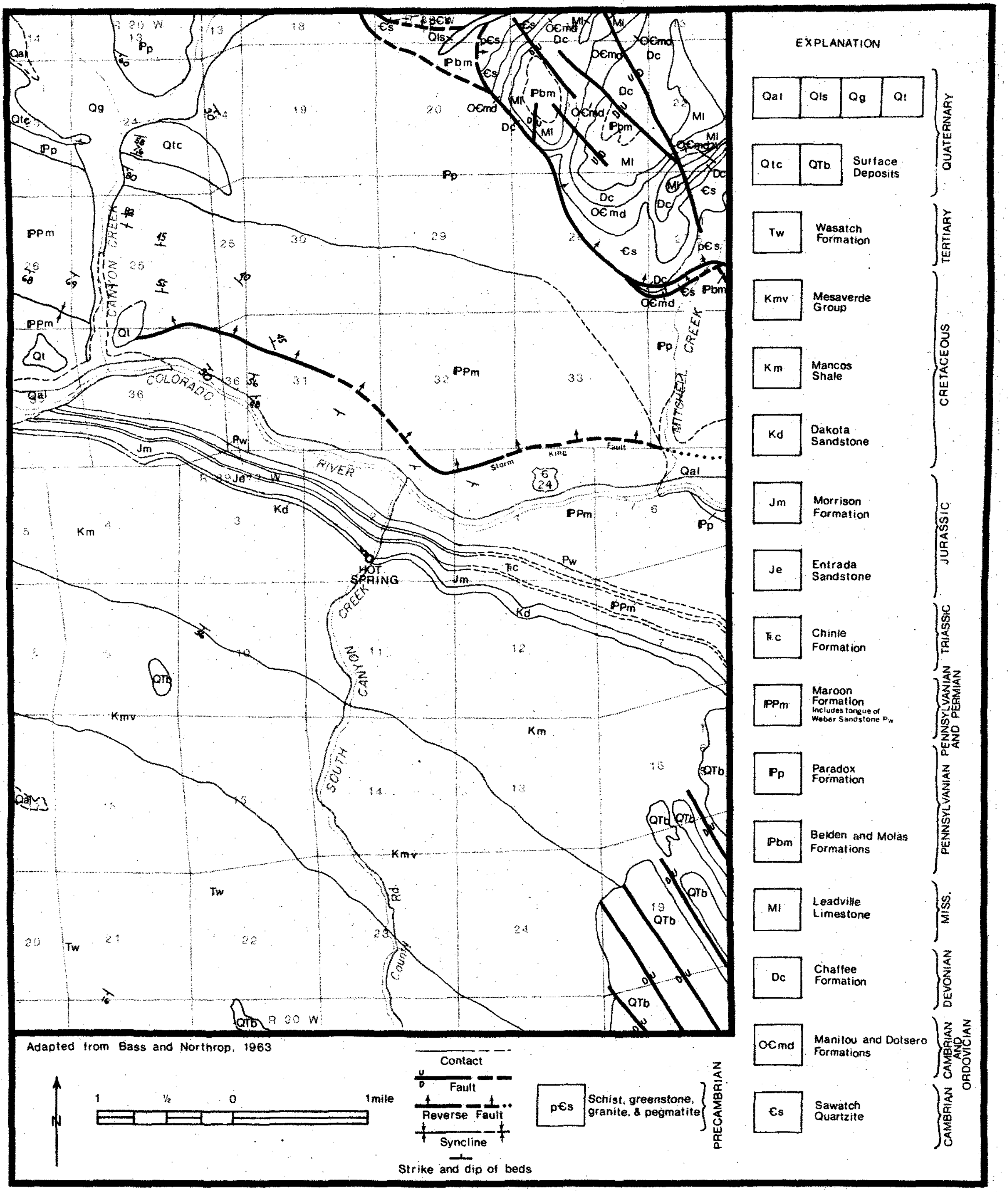


Figure 37.--Geologic map of South Canyon Hot Springs and surrounding region.

#13 PENNY HOT SPRINGS (AVALANCHE HOT SPRINGS)

LOCATION: Latitude: 39°13'33"N.; Longitude: 107°13'28"W.; T. 10 S., R. 88 W., Sec. 4 ba, 6th P.M.; Pitkin County; Redstone 7 1/2-minute topographic quadrangle map.

GENERAL: This large group of hot springs extends for over 0.5 mile along both banks of the Crystal River approximately 3 miles north of Redstone and 13.5 miles south of Carbondale on State Highway 133 (Fig. 38). With the exception of one small spring, which is used in a small greenhouse, the thermal waters are unused.

The spring, whose location was given above and here named Penny Hot Spring, is the largest in a group of springs that issue in a marshy area on the east side of the Crystal River (Fig. 30). Approximately 100 yd downriver and on the same side of the river as the Penny Spring and across from the house is a group of springs that are only visible when the river is at low stage.

Of the several springs on the west side of the river, one lies below the house and is used in a small greenhouse. The largest spring, Granges Spring, is located approximately 100 yds north of the house and is only visible at low river stage. Two other springs (issuing out from under the highway fill) are located several hundred yards downstream from Granges Spring and upstream from the U.S. Geological Survey gaging station.

GEOLOGY AND HYDROLOGY: Only two springs, the Penny and the Granges Springs, were sampled and measured. The Penny Hot Springs temperature throughout a year's time varied from 40°C to 46°C, while its discharge remained constant at 10 gpm. The waters contained 2,750 to 2,820 mg/l of dissolved solids and are a mixed calcium-sodium sulfate type.

The Granges Spring discharges 12 gpm with a temperature of 56°C, total dissolved solids of 2,960 mg/l, and the waters are a calcium-sodium sulfate type. This spring was sampled during a period of low river flow, and the samples were collected from the edge of the spring pool. The Penny Spring sampling point is 50 ft south of a wooden fence-like structure in the field (Fig. 39).

The geologic map (Fig. 40) of the Penny Hot Springs area shows that the waters ascend through Crystal River alluvium overlying the Pennsylvanian Maroon Formation. While the upper springs are associated with the Maroon Formation, the lower springs may be associated with the large Tertiary intrusive there. It is believed that waters from all springs are associated with the intrusive body. While no faults are shown on the geologic map, the intrusive body is cut by numerous faults and fractures. These features do not continue into the overlying sedimentary formations. It is believed that the waters ascend from depth along these faults and fractures. Recharge probably occurs in the high area to the northwest with the waters moving downdip in the sedimentary formations and then up the fractures in the intrusive.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Silica solubility and temperature relationships suggest that amorphous silica controls the silica content of the hot springs. The amorphous silica geothermometer estimate of subsurface temperature is 3°C to 39°C (Table 4). This low estimate may be caused by dilution of the ascending thermal water by shallow ground water.

Mixing Model: Amorphous silica mixing model analysis yields a subsurface temperature estimate of 35°C to 45°C with a cold water fraction of 2 to 50 percent of the spring flow (Table 4). Although the subsurface temperature estimate is below the surface temperature of the hot springs (45°C to 56°C), it is within the expected margin of error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 197°C to 202°C and 89°C to 93°C, respectively. The Na-K geothermometer estimates are too high because the value of the term log $\sqrt{Ca}/Na$ exceeds 0.5.

Extensive travertine deposits surround the hot springs and occur along the east bank of the Crystal River approximately 0.75 mile to the north in NW 1/4 section 33, T. 9 S., R. 88 W. Although Penny and Granges Hot Springs are not currently depositing calcium carbonate or travertine, three such hot springs occur 0.5 mile northwest of Penny Hot Springs in SW 1/4 section 33, T. 9 S., R. 88 W. (on the western river bank opposite a USGS gaging station). Field data for these springs are as follows (Barrett, unpublished data):

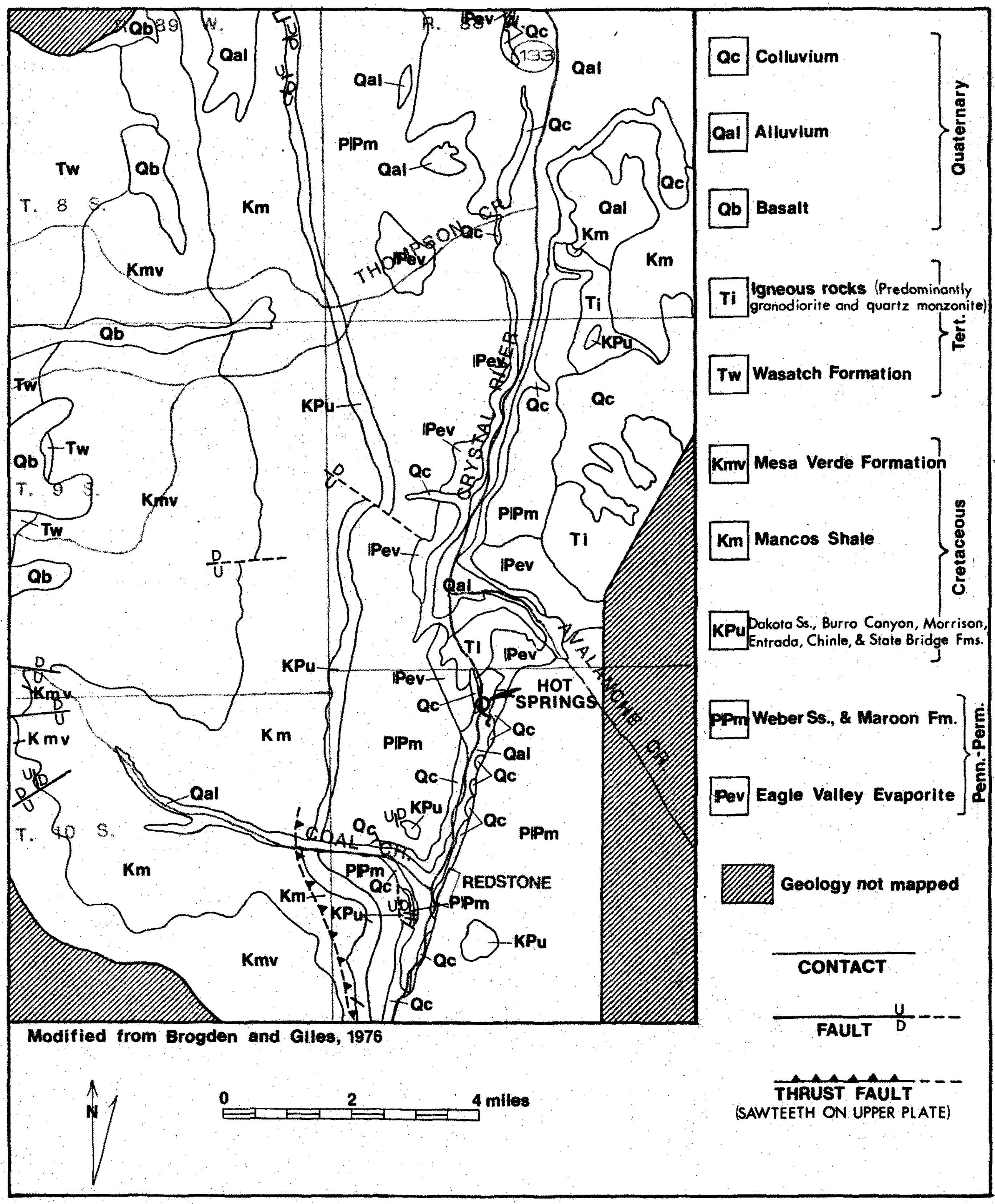
Temperature	54°C to 62°C
Conductance	3100 to 3150 micromhos
pH	6.7 (pH papers)
Flow	1 to 5 gpm

If these springs and Penny Hot Springs are of the same origin, then calcium carbonate deposition may occur at depth in the Penny Hot Springs group. In any case, these estimates are unreliable because of the high magnesium content of the thermal waters.

Conclusion: When applied to Penny Hot Springs most of the assumptions inherent in the use of the geothermometer models are violated. Therefore, they must be used with caution. The Na-K-Ca geothermometer and the amorphous silica mixing model provide maximum and minimum estimated subsurface temperatures, respectively. The reservoir temperature in this area is probably between 60°C and 90°C (Table 4).

Figure 38.--Penny Hot Springs. Looking up river toward Penny Hot Springs from lower group of springs. Granges Spring is located on right bank of Crystal River at far bend.

Figure 39.--Penny Hot Springs from downriver. Spring is located at poles sticking up in swampy area across Crystal River.



Modified from Brogden and Giles, 1976

Figure 40.--Geology of Penny Hot Springs.

#14 COLONEL CHINN HOT WATER WELL

LOCATION: Latitude: 38°52'23"N.; Longitude: 107°38'04"W.; T. 14 S., R. 92 W., Sec. 14 add, 6th P.M.; Delta County; Paonia 7 1/2-minute topographic quadrangle map.

GENERAL: This well is located southwest of Paonia, Colorado, on Stewart's Mesa. Access is southwest from Paonia on a paved county road paralleling the Denver and Rio Grande Western railroad. The well is approximately 2.25 miles from Paonia and 0.25 mile south of the curve in the road where the road tops the mesa and heads due south. Farmhouses lie a few hundred feet north of the T intersection by the well.

GEOLOGY AND HYDROLOGY: The well is reported to be 4,499 ft deep, and the waters have a surface temperature of 42°C. While the total dissolved solids were not determined, the conductance was 3,560 micromhos.

As noted on Figure 41 the geological conditions of the area appear very simple. Stewart's Mesa is an erosional geomorphic feature capped with alluvial sand and gravel deposits. The bedrock of the area is the black shale of the Mancos Formation. The thermal waters may come from the Dakota Formation which underlies the Mancos shale. Hail (1972) mapped the Dakota Sandstone as having uniform north dip from the outcrop area approximately 9 miles south of the well. It is believed that the waters found in this well are being recharged at the outcrop area along the Smith Fork and then migrate downdip to the north. Their elevated temperatures probably arise from high geothermal gradients in the area due to a Tertiary intrusive located 5 miles to the Southeast.

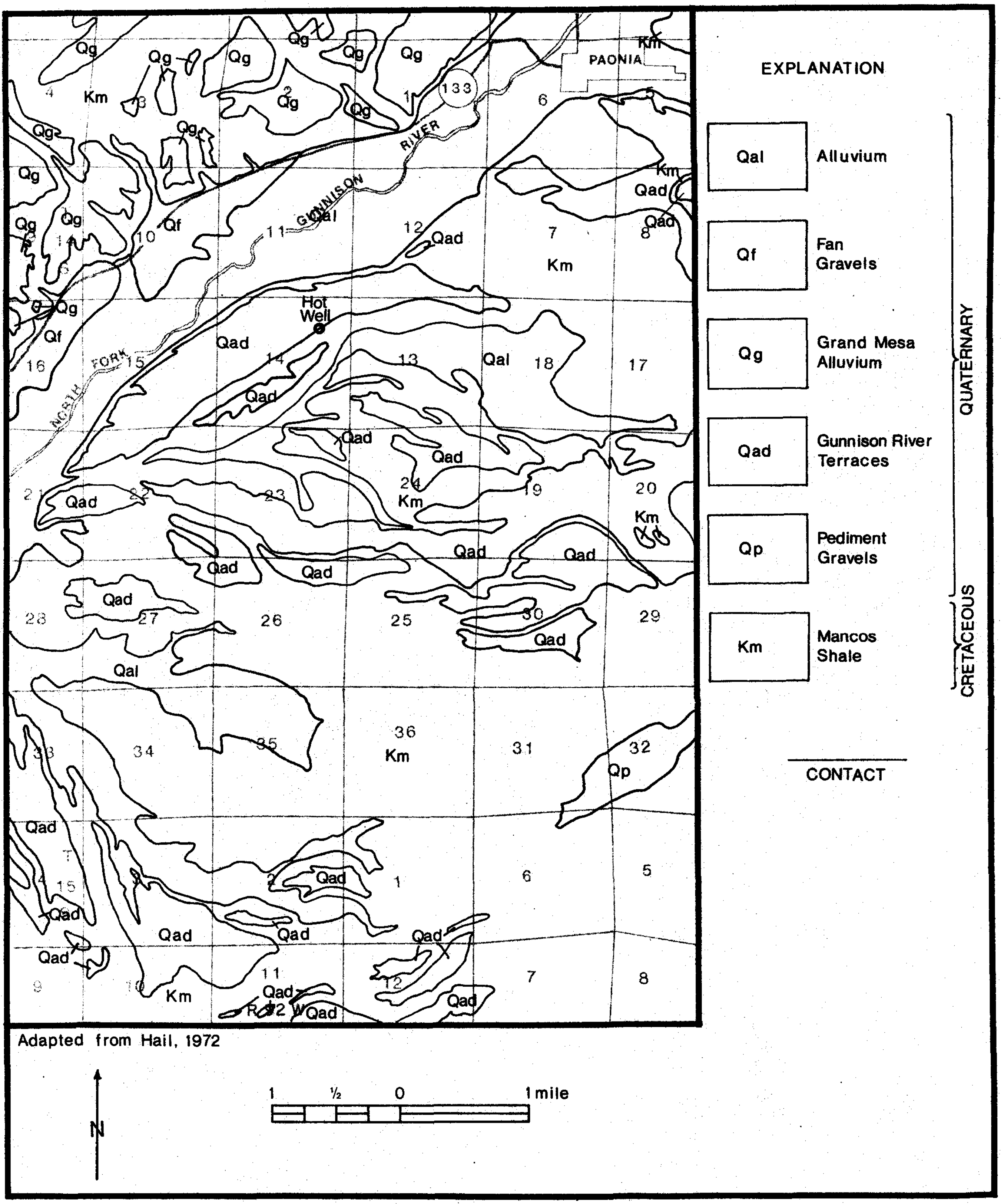
GEOTHERMOMETER ANALYSES:

Silica Geothermometer: From calculation of the silica solubility and temperature relationships, it was determined that chalcedony controls the silica content of the thermal waters. Therefore, the chalcedony-silica geothermometer is applicable. This model yields a subsurface temperature estimate of 41°C. This result is probably close to the actual temperature at depth due to the excellent agreement between the theoretical chalcedony-induced silica solubility (26 mg/l) at the surface temperature (42°C) and the silica content of the artesian well (25 mg/l).

Mixing Model: Since temperature-dependent equilibration between the thermal water and chalcedony apparently controls the silica content of the artesian well, the chalcedony mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 43°C with a cold water fraction of 1 percent of the total flow (Table 4).

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 183°C and 170°C, respectively. These results are unreliable due to the low discharge (5 gpm) and low temperature (42°C) of the artesian well. Moreover, the high magnesium content of the thermal waters further reduces the reliability of these models.

Conclusion: The mixing model and the silica geothermometers imply that the temperature at depth is near the surface temperature of the artesian well. However, the ambiguous natjure of the geochemistry of these waters is such that no reliable subsurface temperature estimates are possible.



Adapted from Hail, 1972

Figure 41.--Map showing geologic conditions surrounding Colonel Chinn Water Well.

#15 CONUNDRUM HOT SPRINGS

LOCATION: Latitude: 39°00'44"N; Longitude: 106°53'26"W.; T. 12 S., R. 85 W., Sec. 16, 6th P.M.; Pitkin County; Maroon Bells 7 1/2-minute topographic quadrangle map.

GENERAL: This group of two unused springs is located at an elevation of 11,200 ft in the Maroon Bells-Snowmass Wilderness area. Access is from Aspen, up Castle Creek along the county road for 6.0 miles to Conundrum Creek, along the jeep trail up Conundrum Creek until it ends, and then along the hiking trail to the springs. The springs are approximately 15.5 miles south of Aspen.

GEOLOGY AND HYDROLOGY: The upper spring (approximately 100 ft south of the lower spring) has a discharge of approximately 10 gpm, with a temperature of 32°C. The lower spring has an estimated discharge of 50 gpm with a temperature of 38°C. The calcium sulfate waters of the spring contain 1,910 mg/l of dissolved solids.

The springs issue from the Pennsylvanian Maroon Formation (Fig. 42). The origin and occurrence of this spring is very anomalous. The springs are near the top of the drainage divide between the Roaring Fork and Gunnison Rivers in a sedimentary sequence that dips to the northeast. While no faults are mapped in the immediate vicinity, several normal faults located approximately 0.25 mile to the west. As shown on the geologic map (Fig. 42) the sedimentary formations of the area have been intruded by Tertiary granodiorite. The authors believe that the waters enter the Maroon Formation on the outcrop area to the south of the divide. As they are migrate downdip, they become heated by residual heat from the granodiorite body.

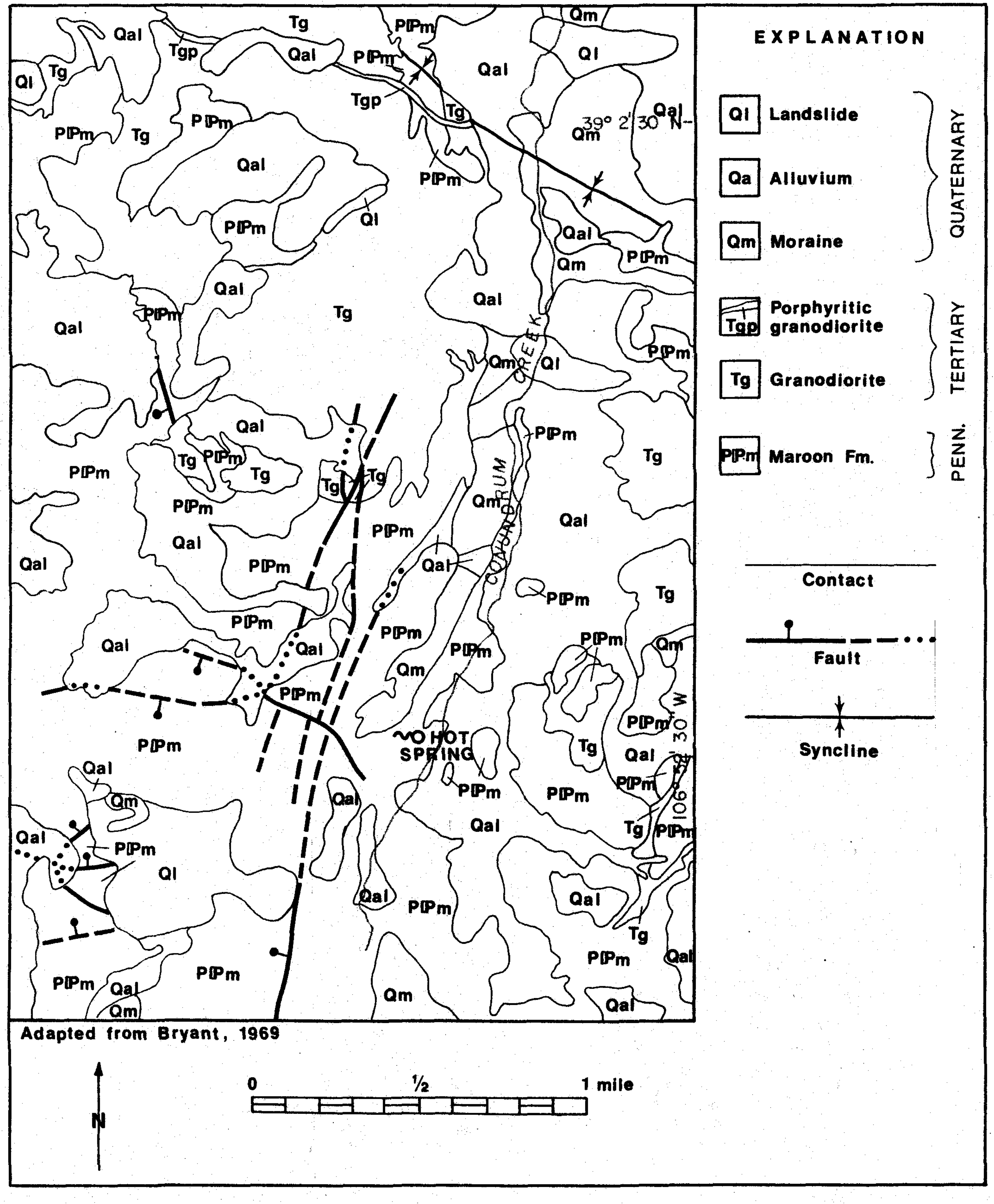
GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Analysis of silica solubility and temperature relationships has shown that cristobalite appears to control the silica content of the hot springs. Therefore, the cristobalite-silica geothermometer was used to estimate the subsurface temperature. This model yields an estimated subsurface temperature of 40°C (Table 4), which is slightly above the surface temperature of the hot springs (38°C).

Mixing Model: The cristobalite mixing model analysis yields a subsurface temperature estimate of 41°C with a cold water fraction of 6 percent of the spring flow.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 187°C and 4°C, respectively. The Na-K geothermometer estimate is too high because the value of the term log $\sqrt{Ca}/Na$ is greater than 0.5. The Na-K-Ca geothermometer estimate is obviously incorrect since it is below the surface temperature of the hot springs. This result is probably due to the excessive solution of calcium carbonate by the thermal water during ascent through the calcareous sandstones, conglomerates and limestones of the Maroon formation.

Conclusion: The moderate flow rate (50 gpm) and the excellent agreement between the theoretical cristobalite-induced silica solubility and the silica content of the springs suggest the subsurface temperature is not much greater than the surface temperature of the hot springs. Therefore, the temperature at depth in this area is probably between 40°C and 50°C.



Adapted from Bryant, 1969

Figure 42.--Geology of Conundrum Hot Springs region.

#16 CEMENT CREEK WARM SPRING

LOCATION: Latitude: 38°50'06"N.; Longitude: 106°49'34"W.; T. 14 S.; R. 84 W.; Sec. 18 cac., 6th P.M.; Gunnison County; Cement Mtn. 7 1/2-minute topographic quadrangle map.

GENERAL: This small spring is located approximately 11.5 miles southeast of Crested Butte, Colorado. Access is via State Highway 135 south from Crested Butte for 7 miles, then left on the dirt road running along Cement Creek for 4.5 miles. The spring is on the property of the Cement Creek Ranch. It is used for swimming and as a domestic water supply.

GEOLOGY AND HYDROLOGY: The spring, which emerges from colluvium at the base of the hill, is located across the road from the ranch buildings (Fig. 43). The waters are piped across the road and used in the swimming pool. In the past the waters emerged farther to the east, for the ranch buildings east of the road are located on a large travertine mound approximately 15 to 20 ft high and several hundred feet in diameter.

The spring has a discharge that varied throughout the year's time from 60 to 80 gpm with a temperature of 25°C. The waters are a calcium-carbonate type with total dissolved solids of approximately 390 mg/l.

The geology of the Cement Creek Valley and surrounding area has been described in detail by McFarlan (1961). As shown on the accompanying geologic map (Fig. 44) the thermal waters come from undifferentiated Precambrian granitic rocks. While no fault zones are shown on the map, the waters come from fracture zones whithin these rocks.

Figure 43.--Photo of Cement Creek Warm Spring.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Chalcedony appears to control the silica content of the warm spring. Therefore, the chalcedony-silica geothermometer model yields the most reliable estimate of the subsurface temperature. Calculations of this model yielded a temperature of 25°C to 30°C.

Mixing Model: Since temperature-dependent equilibration between the thermal water and chalcedony controls the silica content of the warm spring, the chalcedony mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 27°C to 53°C with a cold-water fraction of 0 to 61 percent of the spring flow. While this range is great, these estimates are within the range of values that could result from normal analytical error (see Precision and accuracy of geothermometer models).

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 225°C to 238°C and 45°C to 49°C, respectively. The Na-K geothermometer estimate is too high because the value of the term log $\sqrt{Ca}/Na$ exceeds 0.5. Large travertine deposits surround the springs. If calcium carbonate deposition still occurs, then both the Na-K and Na-K-Ca geothermometer estimates are too high.

Conclusion: The good agreement bewteen the mixing model and the silica and Na-K-Ca geothermometers suggests a subsurface temperature between 30°C and 60°C (Table 4).

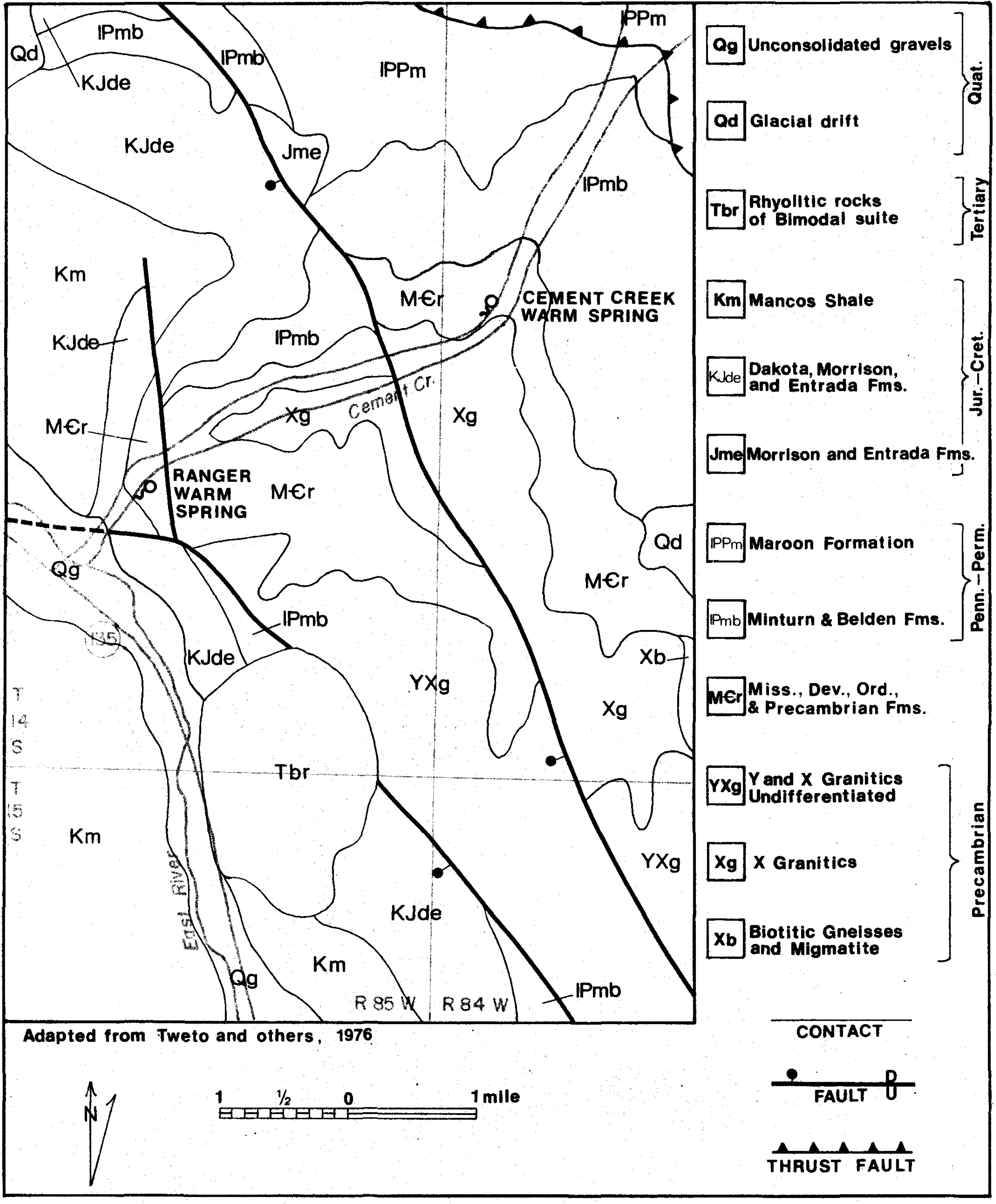


Figure 44.--Geologic map of Cement Creek and Ranger Warm Springs.

#17 RANGER WARM SPRING

LOCATION: Latitude: 38°48'57"N.; Longitude: 106°52'28"W.; T. 14 S., R. 85 W., Sec. 22 dc., 6th P.M.; Gunnison county; Cement Mtn. 7 1/2-minute topographic quadrangle map.

GENERAL: Access is via State Highway 135 south from Crested Butte for approximately 7 miles, then east on the Cement Creek dirt road for one mile to a private dirt road leading south into some ranch buildings. The spring is on the south side of Cement Creek. Waters from the spring are unused. The mouth of the spring has been altered so that the spring flows out from under a limestone ledge into a pool up to 3 ft deep and approximately 30 ft wide (Fig. 45). The pool overflows through the rock embankment and makes accurate discharge measurements impossible.

GEOLOGY AND HYDROLOGY: The temperature of the spring remained fairly constant throughout the year's time at 26 to 27°C. The discharge varied from 132 to an estimated 250 gpm. The waters contain approximately 465 mg/l of dissolved solids and are a sodium-bicarbonate type.

As noted on Figure 44 the springs emerge from undifferentiated sedimentary rocks of Cambrian-Mississippian age. These formations are an alternating sequence of sandstones and limestones with some thin shale units. Due to the scale of the geologic map it was not possible to show all the fault zones. McFarlan (1961) has projected an east-west fault passing very near or through this spring along the valley floor. Tweto and others (1976) show one major north-south trending fault in the vicinity. It appears, therefore, that the thermal waters move up along fault zones.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Review of the silica solubility and temperature relationships suggests that chalcedony controls the silica content in the therml waters. Therefore, the chalcedony-silica geothermometer model is the most applicable to estimate the subsurface temperature. This model yields an estimate of 28°C to 32°C (Table 4).

Mixing Model: The chalcedony mixing model yields an estimated reservoir temperature ranging from 29°C to 67°C with a cold-water fraction of 1 to 71 percent of the spring flow (Table 4).

Na-K and Na-K-Ca Geothermometers: These models yield estimated reservoir temperatures ranging from 56°C to 218°C (Table 4), depending upon the time of year the sample was taken. The Na-K geothermometer estimate is too high because the value of the term log $\sqrt{Ca}/Na$ exceeds 0.5. Travertine deposits surrounds the spring and if calcium carbonate deposition still occurs, both the Na-K and Na-K-Ca geothermometer estimates will be too high.

Conclusion: The good agreement between the mixing model and the silica and Na-K-Ca geothermometers suggests subsurface temperatures between 30°C and 60°C (Table 4).

Figure 45.--Ranger Warm Spring.

#18 RHODES WARM SPRING

LOCATION: Latitude: 30°09'49"N.; Longitude: 106°03'53"W.; T. 10 S., R. 78 W., Sec. 24 cd, 6th P.M.; Park County; Fairplay West 7 1/2-minute topographic quadrangle map.

GENERAL: The spring is reached by going south on U.S. 285 from Fairplay for approximately 4.0 miles, or 0.3 mile south of the bridge over Fourmile Creek and then west on a dirt trail for approximately 3.75 miles. As shown on Figure 46, the waters are unused and flow from a rubble zone on the side of a hill.

GEOLOGY AND HYDROLOGY: The spring has a temperature of 24°C and a discharge of 200 gpm. The waters contain approximately 190 mg/l of dissolved solids and are a calcium bicarbonate type.

Rhodes Warm Spring is located on the west side of South Park, a large intermontain basin. Very little has been written on the geology of this part of South Park. DeVoto (1971) described in general the Cenozoic history of South Park. Knepper and Grose (1976) have described South Park as a complexly faulted Laramide structural basin that was excavated in late Cenozoic time. Chronic (1964) has described the stratigraphy along the west side of the basin.

As shown on Figure 47 the area around the warm springs is cut by numerous faults. While the waters are shown as issuing from Quaternary gravels and colluvial deposits overlying the Pennsylvanian Maroon Formation, it is believed that they are fault controlled. Recharge probably occurs along the Tenmile Range to the west. Reiter (1975) indicates that this area has a heat flow of 2.5 heat flow units.

Figure 46.--Rhodes Warm Spring.

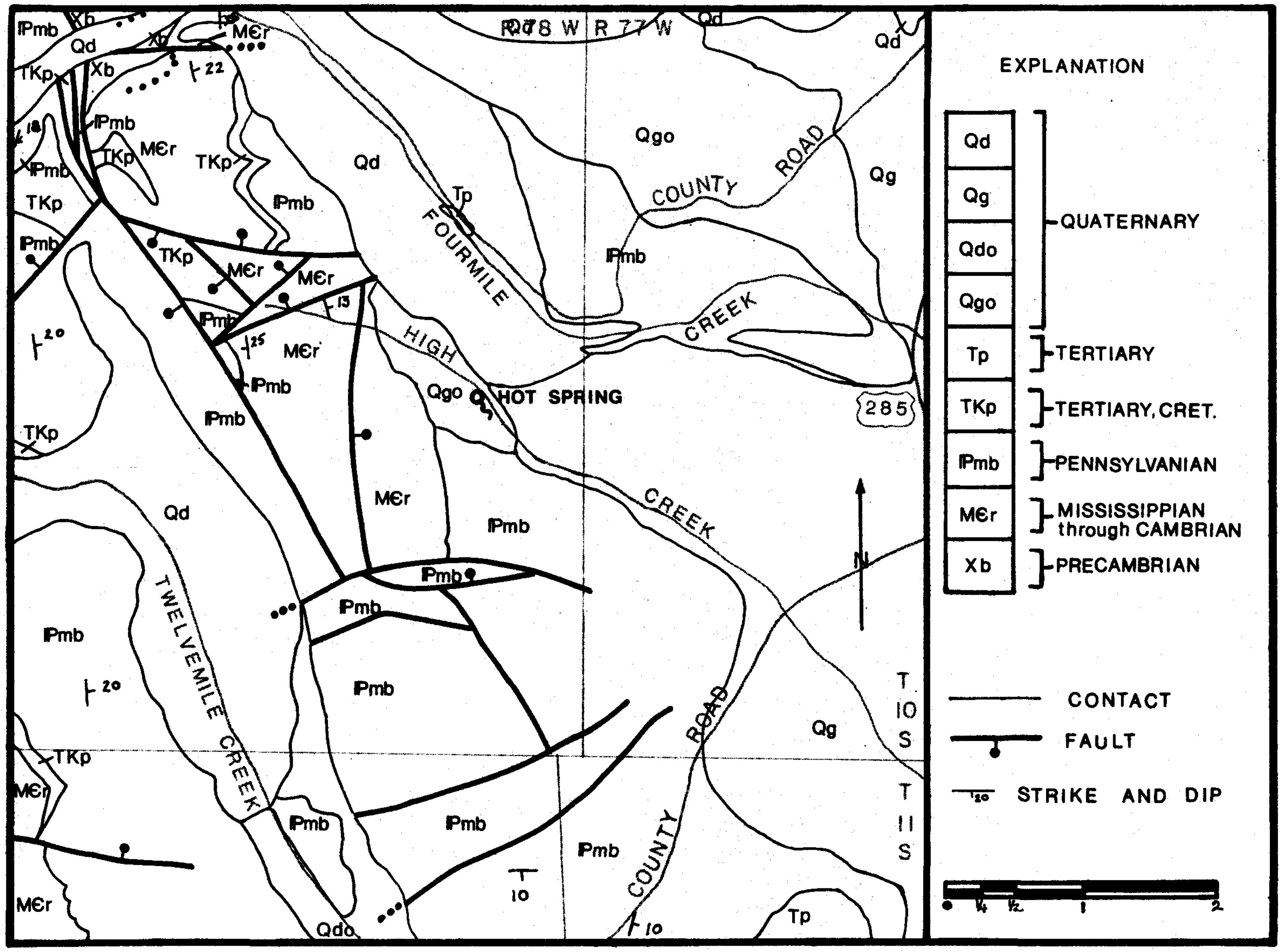
GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Review of silica solubility and temperature relationships suggests that chalcedony controls the silica content of the warm spring. Therefore, the chalcedony-silica geothermometer is applicable. This model yields a subsurface temperature esitmate of 10°C to 13°C (Table 4), which is below the surface temperature of the warm spring (25°C). This low estimate may be caused by mixing of the ascending thermal water and relatively dilute ground water.

Mixing Model: Since temperature-dependent equilibration between the thermal water and chalcedony apparently controls the silica content of the warm spring, the chalcedony mixing model is applicable. Chalcedony mixing model analysis yields a subsurface temperature estimate of 21°C to 23°C with a cold water fraction of 41 to 65 percent of the spring flow (Table 4). Although the subsurface temperature estimate is below the surface temperature of the warm spring (25°C), it is well within the expected margin of error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 222°C to 240°C and 2°C to 10°C, respectively (Table 4). The Na-K geothermometer estimate is definitely too high because the value of the term log $\sqrt{}$Ca/Na exceeds 0.5. The Na-K-Ca geothermometer estimate is obviously incorrect because it is below the surface temperature of the warm spring (25°C). This low estimate may be caused by excessive solution of calcium carbonate by the thermal water during ascent through the limestone formations.

Conclusion: Geothermometer models should be used with caution when applied to Rhodes Warm Spring because many of the assumptions inherent in their use do not apply. The high flow rate (approximately 200 gpm) and low surface temperature of this spring (25°C) suggest that the subsurface temperature is not much greater than the surface temperature of the warm water. Therefore, the subsurface temperature in this area is probably between 25°C and 35°C (Table 4).



Adapted from Tweto and others, 1976

Figure 47.--Geologic map of area around Rhodes Warm Spring.

19 HARTSEL HOT SPRING

LOCATION: Latitude: 39°01'05"N; Longitude: 105°47'40"W.; T. 12 S., R. 75 W., Sec. 8 da, 6th P.M.; Park County; Hartsel 7 1/2-minute topographic quadrangle map.

GENERAL: The Hartsel Hot Springs are located in South Park on U. S. Highway 24 just south of the town of Hartsel. The westernmost of the two springs is located in a small wooden shed at the southeast edge of the swampy area. The eastern spring flows out under the eastern side of an unused building (Fig. 48). Both springs are presently unused.

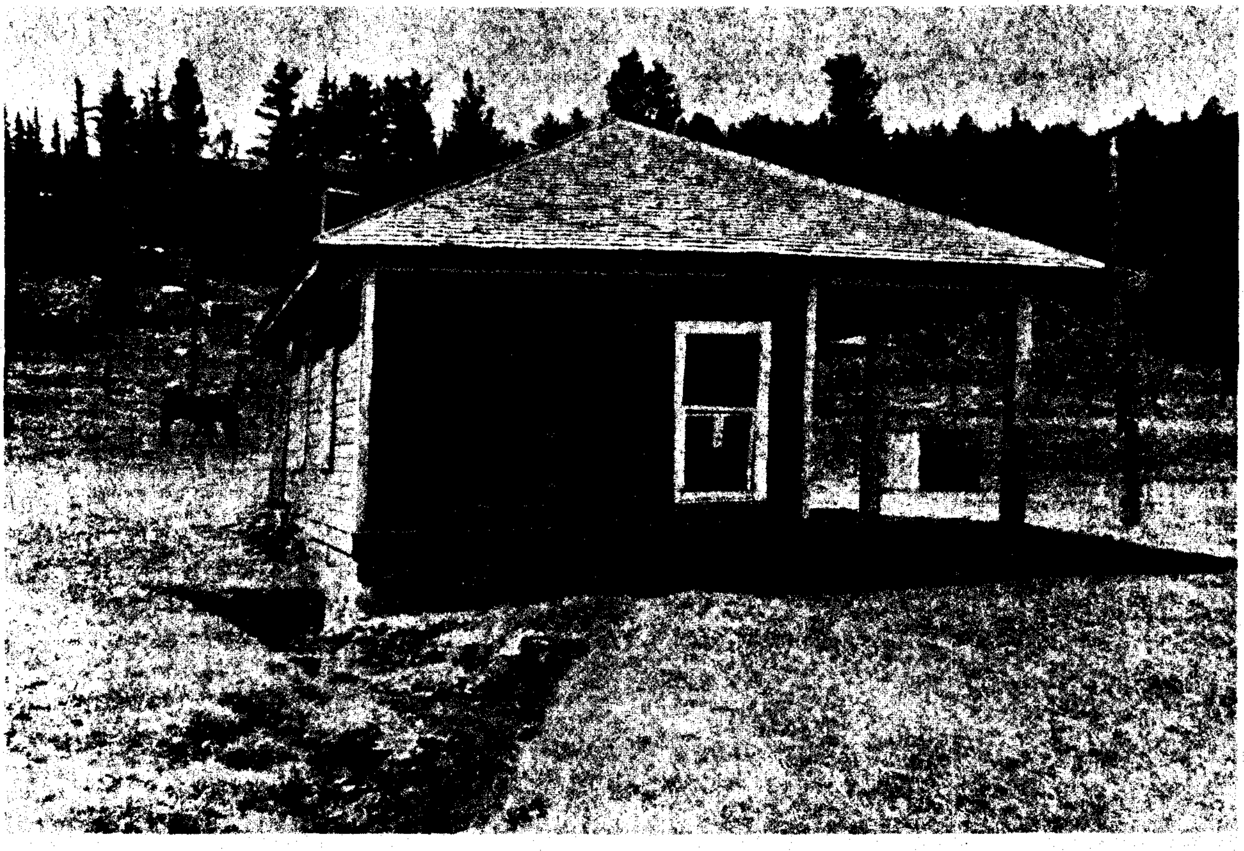


Figure 48.--Hartsel Hot Springs. Spring flowing out from under building.

GEOLOGY AND HYDROLOGY: These springs have a combined discharge of 107 gpm. The western spring has a discharge of approximately 57 gpm and the eastern spring has a discharge of 50 gpm. Water of both springs are a sodium-chloride type. Throughout a year's time the temperature of the springs ranged from 45°C to 52°C, with the total dissolved solids content varying from 2,140 mg/l to 2,330 mg/l.

These springs are located in the south-central part of South Park, a large intermontane basin bounded by the Mosquito Mountains on the west, the Continental Divide on the north, and the Front Range on the east. Several large north-south faults traverse the basin. One of these, the South Park Fault, is within 0.5 mile of the Hot Springs (Fig. 49). The springs emerge from the Morrison Formation, which overlies a large outcrop of Precambrian granitic rocks. Not shown on the geologic map (Fig. 49) are, to the south and east, the extensive outcrops of Tertiary volcanic rocks. The distribution, age, and mode of occurrence of these volcanic rocks have been discussed in detail by Epis and Chapin (1968).

The origin of these hot springs has not been determined, but they may be related to the South Park Fault and the volcanic rocks to the south and east. Reiter (1975) states that this area has a heat flow of 2.4 heat flow units.

GEOTHERMOMETER ANALYSES

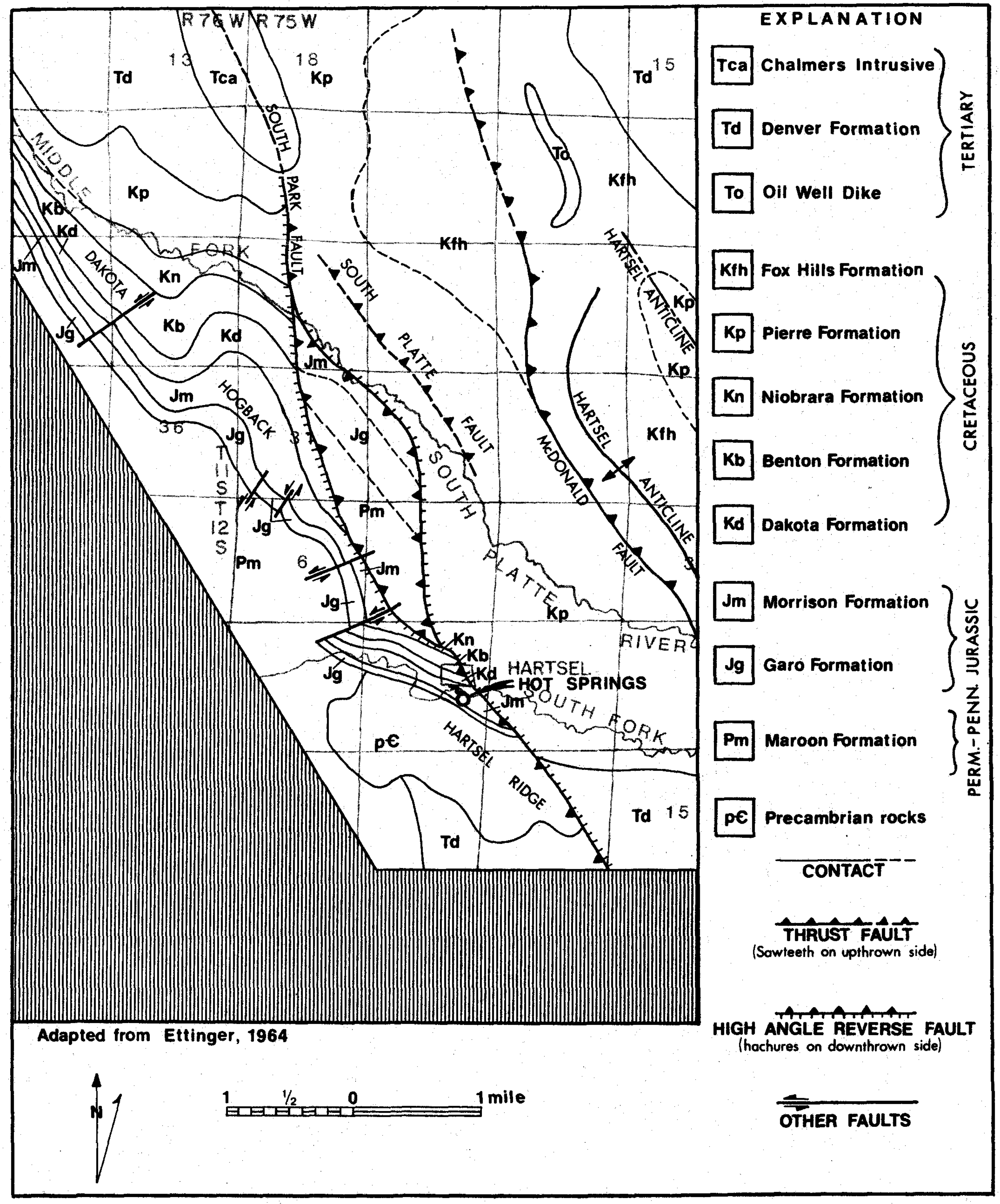
Silica Geothermometer: Review of silica solubility and temperature relationships suggests that chalcedony controls the silica content of the hot springs. Therefore the chalcedony-silica geothermometer is the most applicable. This model yields a subsurface temperature estimate of 55°C to 63°C (Table 4).

Mixing Model: Since temperature-dependent equilibration between the thermal water and chalcedony apparently controls the silica content of the hot springs, the chalcedony mixing model is applicable. Mixing model analysis yields a subsurface estimate of 73°C to 87°C with a cold water fraction of 33 to 53 percent of the spring flow.

The seasonal fluctuation of the subsurface temperature estimates suggests that the assumed cold-water analysis and percent-mixing estimates do not adequately represent the hydrological conditions at depth. However, no certain conclusions can be made from these estimates since they are within the range of values that could result from normal analytical error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield maximum subsurface temperature estimates of 163°C and 153°C respectively. The high sodium, chloride and sulfate contents of the hot springs suggest that the ascending thermal water encounters the evaporite deposits of the Belden and Maroon Formations at depth. Interaction between the hot water and evaporite deposits probably causes the Na-K and Na-K-Ca geothermometer estimates to be too high.

Conclusion: The insignificant variation in flow, mineral content, surface temperature and geothermometer temperature estimates of these hot springs suggests that they are not materially affected by seasonal metereological conditions. Moreover, the fluctuation of the various geothermometer temperature estimates is well within the range of values that could result from normal analytical error. The geochemistry opf these waters is such that no reliable subsurface temperature estimate is possible.



Adapted from Ettinger, 1964

Figure 49.--Geologic map of Hartsel Hot Springs.

#20 COTTONWOOD CREEK

COTTONWOOD AND JUMP-STEADY HOT SPRINGS

LOCATION: Latitude: 38°48'48"N.; Longitude: 106°13'21"W.; T. 14 S., R. 79 W., Sec. 21 dca and ddb, 6th P.M.; Chaffee County; Buena Vista 15-minute topographic quadrangle map.

GENERAL: The Cottonwood Hot springs are located approximately 5.6 miles west of Buena Vista along Colorado Highway 306 along the banks of Cottonwood Creek on the north side of Mt. Princeton. Modifications of the topography by the highway and the users of the springs make it impossible to accurately determine the number of springs in this group. According to Mrs. Merrifield, who lives approximately 0.5 mile south of Cottonwood Hot Spring, a number of years ago a tunnel was driven back into the hillside at the point where the springs emerged at the surface. This tunnel has since collapsed and all that remains today is a cinder block building constructed over where the waters flow out from the hillside (Fig. 50). Water from this spring is piped across Cottonwood Creek and up hill to the Merrifield house. Excess thermal waters are wasted to the creek. The Jump-Steady resort, 0.5 mile east of the springs, uses the waters from another spring a short distance east of the Cottonwood Hot Spring. It was possible to locate the pipeline coming from this spring, but due to modifications of the land, the spring itself could not be located. Waters from the Jump-Steady Hot Springs are piped to the resort where they are used for space heating and domestic purposes.

Mr. and Mrs. Merrifield, who live approximately 0.75 mile south of Cottonwood Creek, have a 115-ft-deep-hot-water well. The waters from this well are used in their greenhouse and swimming pool, and for space heating.

GEOLOGY AND HYDROLOGY: The temperatures of these springs and one well range from a low of 46°C to a high of 58°C. The waters are a sodium-bicarbonate type and contain between 300 and 370 mg/l of dissolved solids.

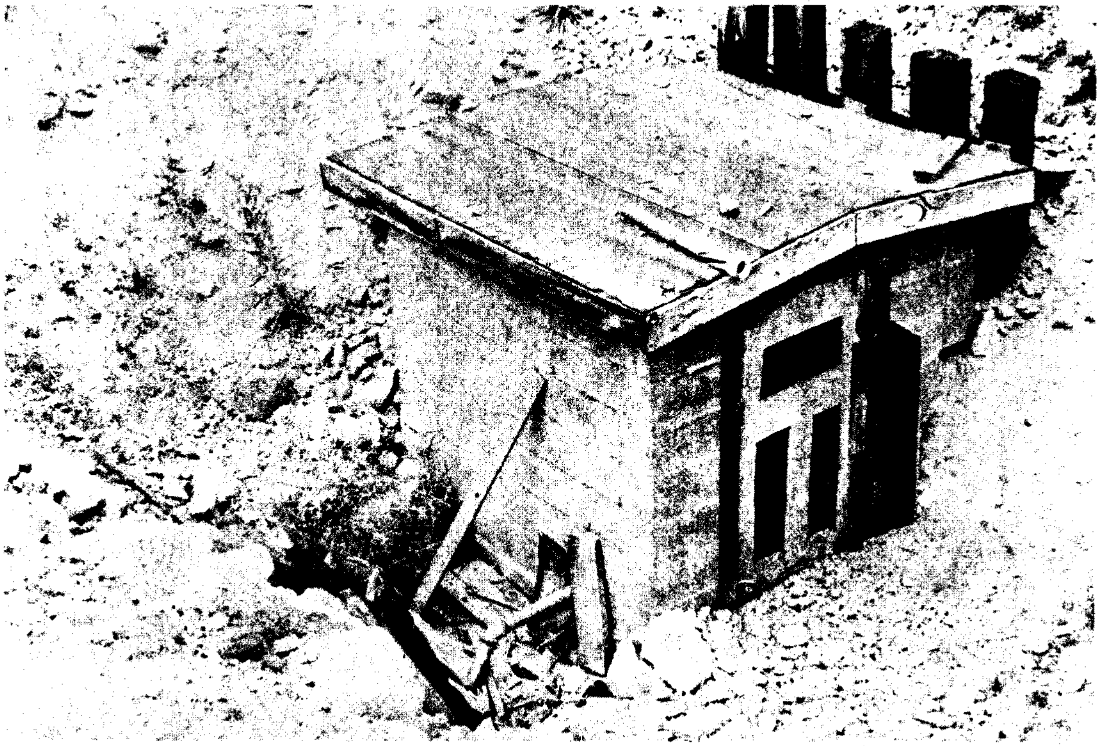
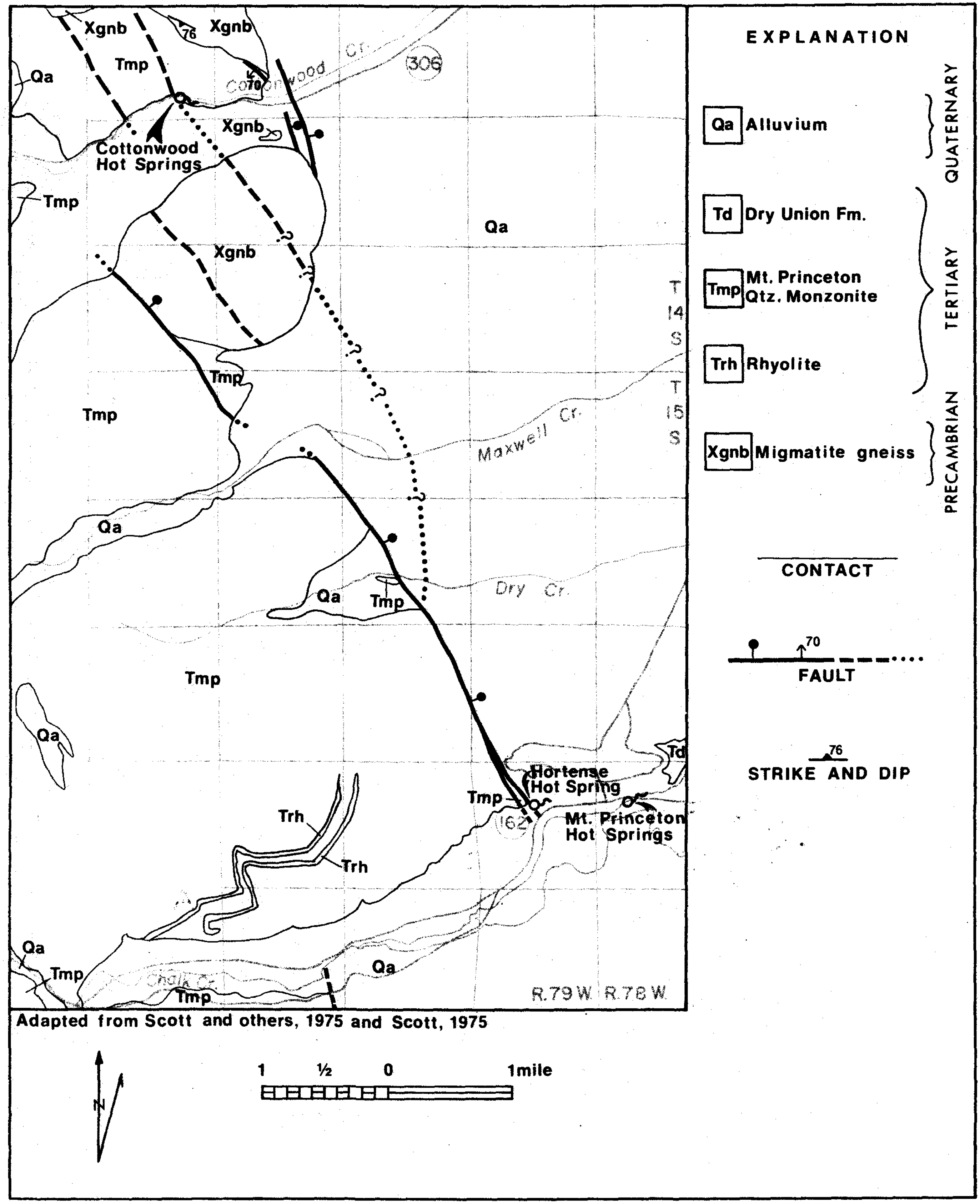


Figure 50.--Cottonwood Hot Springs.



Adapted from Scott and others, 1975 and Scott, 1975

Figure 51.--Geologic map of region surrounding Cottonwood Creek and Chalk Creek valleys.

Although the waters issue from alluvium and coluvium covering the Mount Princeton quartz monzonite, they are related to the faulting and fracturing of that rock body. The accompanying geologic map (Fig. 51) shows that the Cottonwood Hot Springs are located on a major northwest-trending fault bordering the east side of Mount Princeton. In addition to this fault, other factors may control the occurrence of these springs because the rock types change from Precambrian migmatitic gneiss on the south side of Cottonwood Creek to the Mt. Princeton Quartz Monzonite on the north side of Cottonwood Creek. Scott (1975) did not map any faults in this area; however, some workers have postulated that a fault does follow Cottonwood Creek (Robert Kirkham, 1977, oral communication).

One possible recharge area for these springs is the Arkansas River to the east, where the waters enter the thick valley-fill sequence (Zohdy and others, 1971), move to the west, and then up the fault zones. The other possible source is the high country along the Continental Divide just to the west where the waters enter and migrate downward along fault zones, and then up the faults to the Cottonwood Hot Springs.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and cristobalite may control the silica content of the thermal springs and wells in this area. However, this locality lies within the boundaries of the Mt. Princeton quartz monzonite batholith (Scott, 1975); thus quartz, not cristobalite, is probably the most abundant solid silica phase. Therefore, the quartz-silica geothermometer and the quartz mixing model are applicable. The quartz silica geothermometer estimate of subsurface temperature is 105°C to 110°C (Table 4).

Mixing Model: Mixing model analysis of Cottonwood and Jump-Steady Hot yields a subsurface temperature estimate of 174°C to 182°C with a cold waterfraction of 70 to 74 percent of the spring flow.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers estimates of subsurface temperature are 131°C to 135°C and 79°C to 85°C, respectively. The Na-K geothermometer estimates appear reasonable for both springs, and they are substantiated by the silica geothermometer and mixing model results, but the Na-K-Ca geothermometer estimates are too low. This may be caused by temperature-dependent equilibration between the thermal water and the relatively potassium-deficient quartz monzonite.

Conclusion: The insignificant variation in flow, mineral content, and surface temperature of these hot springs suggests they are not affected by seasonal meteorological conditions. The fluctuation of the calculated geothermometer temperature estimates is within the range of values that could result from normal analytical error.

The most realistic geothermometer estimates of subsurface temperature range from 105°C to 182°C (Table 4).

#21 CHALK CREEK AREA

The following thermal springs and wells are located in the Chalk Creek Valley on the south flank of Mount Princeton: Mount Princeton Hot Springs, Hortense Hot Spring and Well, Woolmington Hot Water Well, Wright Hot Water Wells, and Young Life Hot Water Well (Fig. 52).

These springs are located on the south side of Mount Princeton southwest of Buena Vista in the Chalk Creek Valley within 1 or 2 miles of each other along Colorado Rt. 162 approximately 4.5 miles west of U.S. Highway 285.

#21 MOUNT PRINCETON HOT SPRING

LOCATION: Latitude: 38°43'58"N.; Longitude: 106°09'40"W.; T. 15 S., R. 78 W., Sec. 19 bca, 6th P.M.; Chaffee County; Poncha Springs 15-minute topographic quadrangle.

GENERAL: The Mount Princeton Hot Springs are the largest group of springs in the Chalk Creek Valley. The springs are located in and along the north bank of Chalk Creek extending from just west of the big wooden building by the swimming pool to just east of the swimming pool. Due to the modification of the points of discharge, it was impossible to accurately determine the number of springs in this group. It appears, however, that at least 8 springs issue from the north bank of the creek and a number from the creek itself. Some of the waters are piped uphill and used to heat the swimming pool and cabins, north of Colorado 162.

GEOLOGY AND HYDROLOGY: All of the springs in this group have temperatures ranging between 44°C and 56°C. The waters contain approximately 250 mg/l of dissolved solids and are a mixed sodium sulfate-bicarbonate type. The combined flow of all the springs, as measured by a Parshall Flume, was 175 gpm. This value may be low due to any pumping of thermal waters that might have occurred.

Figure 52.--Chalk Creek Valley. A: Mount Princeton Hot Springs; B: Wright Hot Water Well, east; C: West Wright Hot Water Well; D: Hortense Hot Spring; F: Woolmington Hot Water Well; G: Young Life Hot Water Well.

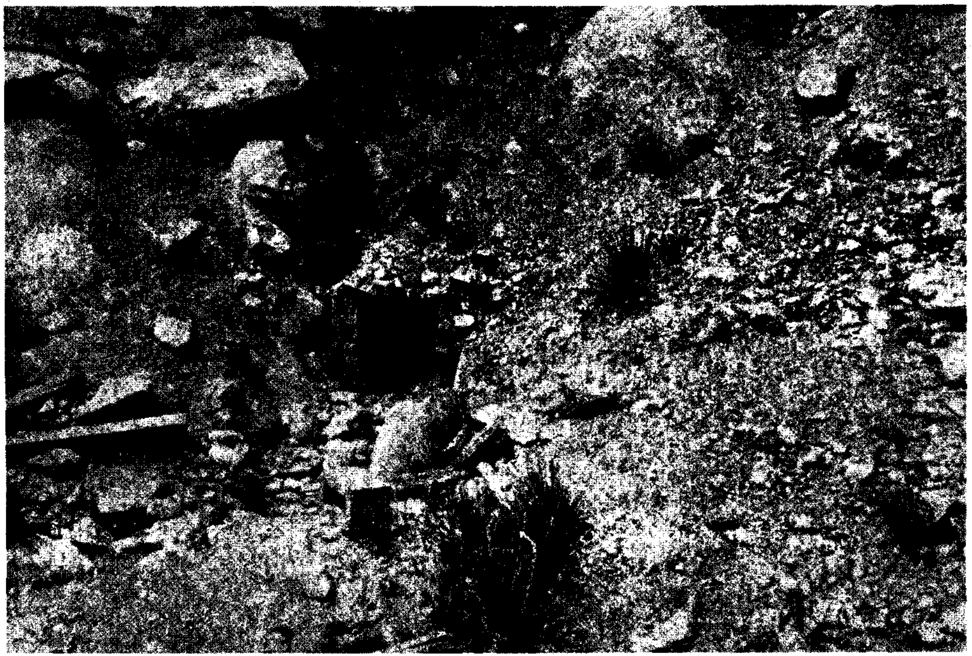


Figure 53.--Hortense Hot Spring.

#21 WRIGHT HOT WATER WELLS (EAST AND WEST)

LOCATION:

East Well: Latitude: 38°44'00"N.; Longitude: 106°10'00"W.; T. 15 S., R. 79 W.; Sec. 24 ca, 6th P.M.; Chaffee County; Poncha Springs 15-minute topographic quadrangle map.

GENERAL: West from the Mount Princeton Hot Springs are two thermal wells owned by William Wright (Fig. 52). Waters from these two wells are used to heat greenhouses. In addition the waters from the east well are used for heating two houses immediately to the south. The east well is located in the greenhouse situated on the south shoulder of Highway 162. The west well is located in the greenhouse located approximately 0.5 mile west and 0.25 mile north of the east greenhouse.

GEOLOGY AND HYDROLOGY: The east well is 40 ft deep, and the waters have a temperature of 67°C with 234 mg/l of dissolved solids. The waters are a mixed sodium sulfate-bicarbonate type. Waters from the west well have a temperature of 72°C with 313 mg/l of dissolved solids. Unlike the waters from the east well, these waters are a sodium-bicarbonate type.

#21 HORTENSE HOT SPRING AND WELL, AND YOUNG LIFE HOT WATER WELL

Just to the north and to the west of the West Wright Hot Water Well are two wells and one spring. The Hortense Hot Springs are located approximatey 100 to 200 yd north and just west of the Wright Well (Fig. 52). Waters from this spring, which are the hottest in the State (Fig. 53), are piped to the Young Life Camps and used for recreational purposes. The Hortense Hot Water Well is located to the west of the Wright Greenhouse (Fig. 52). Waters from this well, approximately 180 ft deep, are also used in the Young Life Camp for domestic purposes. The Young Life Hot Water Well is located approximately 200 yd to the west of the Hortense Hot Water Well (Fig. 52). Waters from this well are also piped to the Young Life Camp.

LOCATION:

Hortense Hot Spring: Latitude: 38°43'59"N.; Longitude: 106°10'26"W.; T. 15 S., R. 79 W.; Sec. 24 bd, 6th P.M.; Chaffee County; Poncha Springs 15-minute topographic quadrangle map.

Hortense Hot Water Well: Latitude: 38°43'58"N.; Longitude: 106°10'27"W.; T. 15 S., R. 79 W., Sec. 24 bd; Chaffee County; Poncha Springs 15-minute topographic quadrangle map.

Young Life Hot Water Well: Latitude: 38°43'57"N.; Longitude: 106°10'27" W.; T. 15 S., R. 79 W.; Sec. 4b; Chaffee County; Poncha Springs 15-minute topographic quadrangle map.

HYDROLOGY: Both the Hortense Hot Water Well and Spring have temperatures of 82°C. The discharge of the spring is 18 gpm. The total dissolved solids content of the spring is approximately 340 mg/l, and the well was 318 mg/l. The Young Life Well has a dissolved mineral content of 259 mg/l. Waters from all three are a mixed sodium sulfate-bicarbonate type.

#21 WOOLMINGTON HOT WATER WELL

LOCATION: Latitude: 38°43'24"N.; Longitude: 106°10'38"W.; T. 15 S., R. 79 W.; Sec. 24 db, 6th P.M.; Chaffee County; Poncha Springs 15-minute topographic quadrangle map.

GENERAL: This well, which is the westernmost thermal water found in the Chalk Creek valley, is located approximately 0.75 mile west of the Young Life Camp and 100 yd south of the highway (Fig. 52). At the time the well was visited (Fall, 1975), the waters were unused.

HYDROLOGY: The temperature of the waters is 39°C and the total dissolved solids content is 143 mg/l. The waters are a sodium-bicarbonate type. The waters come from the alluvial and colluvial deposits north of Chalk Creek.

GEOLOGY: The geological conditions surrounding the thermal springs and wells in the Chalk Creek Valley are nearly identical. The springs lie on the south side of Mount Princeton on the west side of the Upper Arkansas Valley graben. Southwest of Buena Vista the graben is asymetrical with the east side downdropped more than the west side. Geophysical work has revealed as much as 4,600 ft of valley-fill sediments near Buena Vista (Zohdy and others, 1971). All the thermal waters are associated with faults and fractures within the Mount Princeton Quartz Monzonite batholith. The accompanying geological map (Fig. 51) does not show the numerous faults and fractures in the Chalk Cliffs. The whole Upper Arkansas Valley is cut by numerous faults, however Scott and others (1975) show only one major northwest trending fault in the southern Mount Princeton area. This fault lies along the east face of Mount Princeton and terminates at the Hortense Hot Spring. Other workers have postulated that a major fault trends northeast along the Chalk Creek Valley (Robert Kirkham, 1977, oral communication).

The possible recharge areas are either the Arkansas River to the east or the high country to the west.

GEOTHERMOMETER ANALYSES OF CHALK CREEK AREA:

Silica Geothermometer: Analysis of silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and chalcedony controls the silica content of the hot springs and wells. However, chalcedony is not likely to be abundant because this thermal area is located well within the boundaries of the Mount Princeton Batholith (Scott and others, 1975). The most abundant solid silica phase in this area is probably quartz. Therefore, the quartz-silica geothermometer and the quartz mixing models are applicable.

The quartz-silica geothermometer estimate of subsurface temperature is 105°C to 127°C for Mount Princeton Hot Springs and 116°C to 129°C for Hortense Hot Spring. Sharp (1970) noted that boulders near Hortense Hot Spring are coated with a mixture of calcite, opal and phillipsite. If deposition of silica occurs at depth, then the silica geothermometer and mixing model estimates are too low.

Mixing Model: Mixing model analysis yields a subsurface temperature estimate of 186°C to 236°C with a cold-water fraction of 77 to 81 percent for Mount Princeton Hot Springs and a subsurface temperature estimate of 156°C to 186°C with a cold-water fraction of 54 to 61 percent for Hortense Hot Spring (Table 4). These estimates may be too high, however, because steam fumeroles occur near Hortense Hot Spring (Jay Dick, 1976, personal communication).

Since steam vents are associated with these waters, Mixing Model II may be applied. This model yields a subsurface temperature estimate of 131°C to 150°C with a hot water fraction of 43% to 52% for Mount Princeton Hot Springs and a subsurface temperature estimate of 120°C to 131°C with a hot-water fraction of 9 to 12 percent for Hortense Hot Spring. These estimates may be too low, with the actual subsurface temperature probably lying between the Mixing Model I and Mixing Model II estimates.

Enthalpy-Chloride Geothermometer: The enthalpy-chloride geothermometer can be applied to this thermal area because the surface temperature of Hortense Hot Spring (83°C) is near the boiling point for the elevation. This geothermometer yields a subsurface temperature estimate of 160°C. A plot of the field data (temperature and silica content) of the hot springs superimposed on the quartz silica geothermometer yields 153°C (Fig. 14).

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 148°C to 151°C and 51°C to 59°C, respectively, for Mount Princeton Hot Springs and 141°C to 146°C and 93°C to 97°C, respectively, for Hortense Hot Spring (Table 4). The Na-K geothermometer estimates for both springs groups appear reasonable, and they are substantiated by the silica geothermometer and mixing model results. On the other hand, the Na-K-Ca geothermometer estimates seem to be too low.

The low Na-K-Ca geothermometer estimates may be caused by temperature-dependent equilibration between the ascending thermal water and the relatively potassium-deficient quartz monzonite. In addition the hot spring waters are supersaturated with respect to albite, calcite, laumontite, and quartz (Limbach, 1975). Supersaturation of the thermal waters with respect to calcite would cause the Na-K-Ca geothermometer estimates to be too low.

Conclusion: It appears that these hot springs are not materially affected by seasonal meteorological conditions, for there is insignificant variation in flow, mineral content and surface temperature of these hot springs. The fluctuation of the various geothermometer temperature estimates noted is well within the range of values that could result from normal analytical error.

The most realistic geothermometer estimates of subsurface temperature range from 150°C to 200°C (Table 4). These results are in close agreement with the formation temperature of laumontite (hydrated leonhardite) 145°C to 220°C, reported by Combs (Sharp, 1970).

Hydrogen and Oxygen Isotope Analysis of the Mount Princeton Geothermal Area

As part of the investigation of the geothermal resources of the Mount Princeton area, a study was made to determime the age and origin of the thermal waters. This evaluation was made using the carbon, hydrogen and oxygen isotopic composition of the thermal and nonthermal waters of the region. The field work for this investigation was done during the summer of 1976 when personnel from the Colorado Geological Survey and U.S. Geological Survey sampled thermal and nonthermal springs and wells and surface water sites around the flanks of Mount Princeton for their isotopic composition.

A number of workers (Bedinger and others, 1974, Craig, 1961b, and White, 1968, and White and others, 1973 among others) have used the concentration of various isotopes of hydrogen and oxygen in thermal waters to determine the age and origin of those waters. Bedinger and others (1974) present a detailed explanation of the geochemistry and use of hydrogen and oxygen isotopes. A brief summary of their explanation follows.

Several isotopic forms of hydrogen and oxygen, which occcur naturally, are used in hydrological studies. These isotopes are: hydrogen (H^1), deuterium (H^2) and tritium (H^3) and oxygen-18 (O^{18}). The relative abundance of these isotopes in cold and thermal waters can provide qualitative information about the subsurface temperature and hydrology of the hydrothermal system.

The deuterium and oxygen-18 composition of water is usually analyzed and presented in delta notation (δ). This notation expresses the divergence of the deuterium and oxygen-18 content of the sample from Standard Mean Ocean Water (SMOW) (Craig, 1961a). Standard Mean Ocean Water has the following molecular isotopic composition:

H_20^{18} = 2,000 ppm

H_20^{17} = 420 ppm

HD_20^{16} = 316 ppm

H_20^{16} = 997,264 ppm

The diverengence of deuterium and oxygen-18 content of a sample from SMOW may be calculated by Equations 26 and 27.

$$\text{Eq. 26:}\quad \delta D = \frac{D/H_{\text{sample}} - D/H_{\text{standard}}}{D/H_{\text{standard}}} \times 1000$$

$$\text{Eq. 27:}\quad \delta O^{18} = \frac{O^{18}/O^{16}{}_{\text{sample}} - O^{18}/O^{16}{}_{\text{standard}}}{O^{18}/O^{16}{}_{\text{standard}}} \times 1000$$

Where

D = deuterium concentration

H = hydrogen concentration

O^{18} = oxygen-18 concentration

O^{16} = oxygen-16 concentration

δ = parts per thousand or per mil (o/oo)

Craig (1961a) determined that the values of δO^{18} of natural meteoric waters are related by eq 28.

$$\text{Eq. 28:}\quad \delta D = 8\delta O^{18} + 10$$

The plot of Equation 28 is illustrated in Figure 54 as the "Trend Line for Meteoric Waters". Figure 54 shows the plot of δD and δO^{18} data from various hydrothermal systems around the world. Data from some of the hydrothermal systems plotted in Figure 54 show significant enrichment (more positive values) of δO^{18} relative to the meteoric waters trend line. Such a shift may be caused by high subsurface temperatures and/or the presence of magmatic water in the hot springs. Magmatic water in thermal springs should also cause a similar enrichment of the δD values (Bedinger and others, 1974). The absence of a δD suggests that magmatic waters are not abundant in the hydrothermal system. Therefore, the δD shift is probably caused by high subsurface temperature.

Table 16 (Appendix A) lists the determined δD and δO^{18} values of hot and cold waters in the Mount Princeton area. These values are negative because natural fresh waters have a lower heavy isotope concentration than SMOW.

The water samples that were collected for hydrogen and oxygen isotope measurements were collected in thoroughly rinsed 4-oz glass bottles having caps lined with polyethylene-core inner seals. Two full bottles were collected per sampling site, and their tops and caps coated and sealed with hot paraffin. When sealed by this method, the isotopic composition remains stable almost idenfinitely (F. J. Pearson, 1976, personal communication). The waters were analyzed by Geochron Laboratories Inc. and L. D. White of the U.S. Geological Survey.

Analysis determined that the average δD in the cold waters is -130.4 mills and the average value of deuterium in the thermal waters is -125.9 mills (Table 16). The insignificant difference between the average values for the hot and cold waters suggests that (1) the thermal springs and wells contain little or no magmatic water, and (2) the geothermal system is recharged by local precipitation with no meteoric water contributed from outside the region.

The average δO^{18} in the cold waters is -17.9 mills and the average δO^{18} in the thermal waters is -17.3 mills (Table 16). The small difference between these values reinforces the evidence for little or no magmatic water in the hot springs. In addition the near coincidence of the average δO^{18} values of the thermal and cold waters suggests either a subsurface temperature below 150°C or a short residence time of the meteoric water in the geothermal reservoir (F.J. Pearson, 1976, personal communication).

Water samples for tritium analysis were collected in throughly rinsed 1-liter bottles having caps lines with polyethylene-core inner seals. Two full bottles were collected per sampling site and their tops and caps coated and sealed with hot paraffin. The samples were analyzed by F. J. Pearson, U.S. Geological Survey.

The tritium (H^3) is an isotope of hydrogen (H^1) and has a half-life of approximately 12.25 years. While this isotope is naturally formed in minute amounts by cosmic ray bombardment of the upper atmosphere, the predominant source is atmospheric testing of atomic weapons (Bedinger and others, 1974).

Tritium content of water is normally reported in tritium units (TU). One TU equals one tritium atom per 10^{18} hydrogen atoms. These values are expressed with a statistical-error term corresponding to one standard deviation (1d). There is a 67 percent probability that the true concentration of the isotope is within the 1d range. For example, the tritium analysis for Hortense Hot Spring is 32.1 ± 2.0 TU (Table 16); thus, within 67-percent probability, the true concentration is between 30.1 TU and 34.1 TU.

Knowledge of the tritium content of natural water provides qualitative data concerning the age of the water and the degree of mixing between the ascending thermal water and cold ground water. Waters containing more than 5 to 10 TU are probably less than ten years old; while waters containing less than 5 TU are probably greater than 30 years old (I. Friedman, 1976, personal communication). However, mixing between the thermal water and cold ground water can complicate this relationship.

Table 16 lists the tritium contents of the thermal and cold waters in the Mount Princeton Thermal area. The tritium contents of the thermal springs and wells range from 19.7 ± 1.7 TU to 105 ± 5 TU. This suggests that either the thermal water is very young (rapid recharge to and discharge from the geothermal reservoir) or the thermal springs and wells contain a significant cold-water fraction.

An attempt was made to also age date the thermal waters using C^{14} methods, but the results were inconclusive.

Conclusions from the Geothermometer and Isotope Geochemistry Analysis

Analysis of geothermometer and isotope geochemistry data from the Mount Princenton area supplies the following conclusions:

1) The thermal springs and well contain virtually no magmatic water.

2) The geothermal system is recharged with local precipitation, i.e., no meteoric water is contributed to the system from outside the region.

3) A significant amount of shallow ground water mixes with the ascending thermal water.

4) The subsurface temperature of the geothermal reservoir is between 150° and 200°C (Table 4).

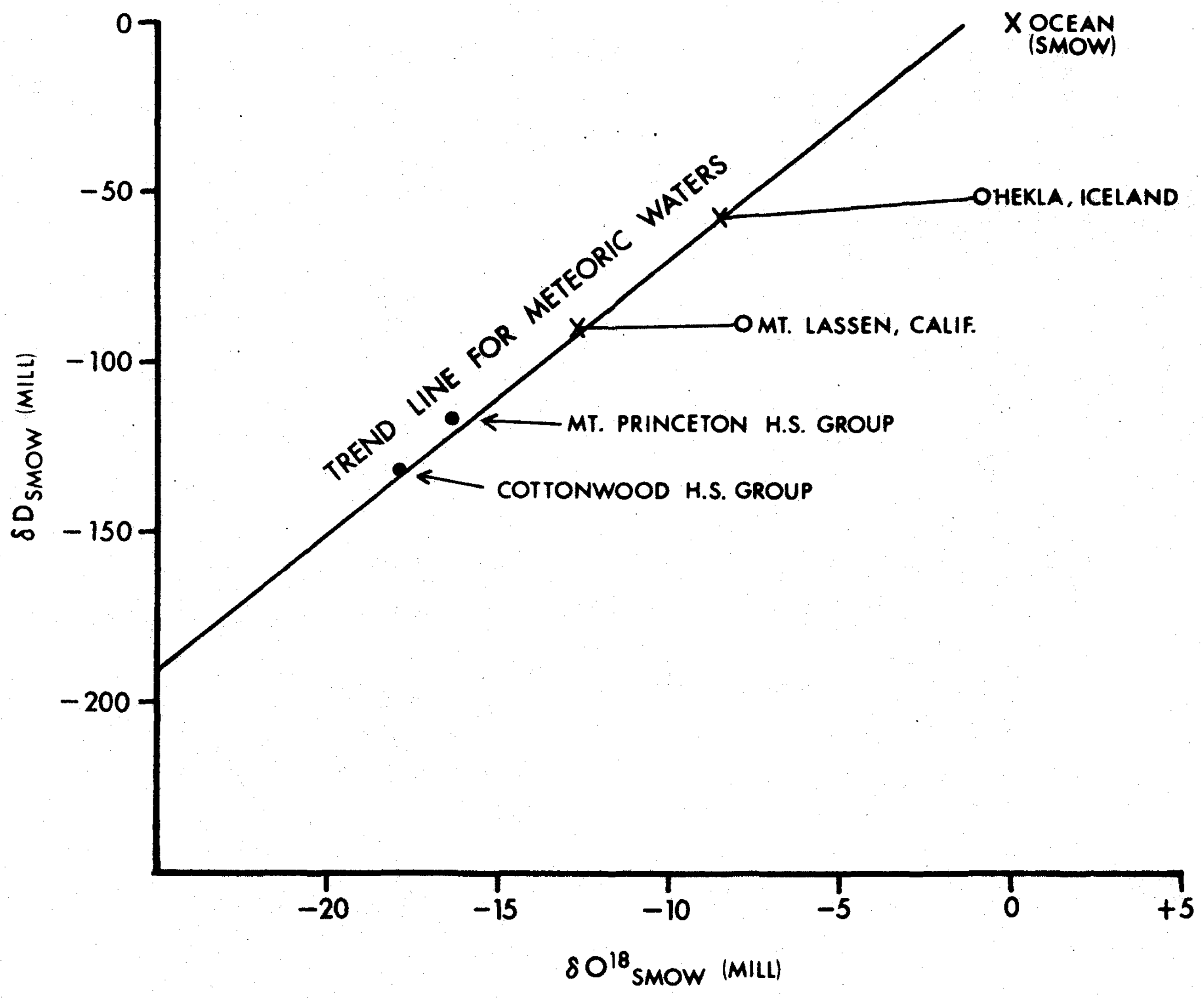


Figure 54.--Comparison of isotopic composition of hot springs, Mount Princeton area, and other thermal areas of the world.

#22 BROWNS CANYON THERMAL AREA

Located in Browns Canyon, approximately 12 miles north and west of Salida, Colorado, are two unused springs and one unused well.

BROWN'S CANYON WARM SPRING

LOCATION: Latitude: 38°39'13"N.; Longitude: 106°03'11"W.; T. 51 N., R. 8 E., Sec. 23 cdb, N.M.P.M.; Chaffee County; Poncha Springs 15 minute topographic quadrangle map.

GENERAL: This unused spring may be located by going northwest from Salida on State Highway 291 to U.S. 285. One half mile north of this intersection turn east on county road 194 and proceed northeast for approximately 2.4 miles to an old stone cabin. The spring is in an open area approximately 550 ft north of the cabin (Fig. 55).

HYDROLOGY: The spring has a discharge estimated at 1 gpm with a temperature of 25°C. The waters of the spring were not sampled for determination of dissolved mineral matter. Field measurement of specific conductance is 7,877 micromhos, and the pH is 8.0.

#22 BROWNS GROTTO WARM SPRING

LOCATION: Latitude: 38°38'13"N.; Longitude: 106°04'26"W.; T. 51 N., R. 8 E., Sec. 27 ccd, N.M.P.M.; Chaffee County; Poncha Springs 15 minute topographic quadrangle map.

GENERAL: This unused spring may be reached by turning off U.S. 285 on Chaffee County 194. After going 0.2 mile turn south and drive approximately 0.5 mile to the spring. The spring is on the east side of the small gulch (Fig. 56).

HYDROLOGY: This is the only spring sampled in Browns Canyon during the course of this investigation. This spring had an estiamated discharge of 5 gpm with a temperature of 23°C. The waters contain 494 mg/l of dissolved mineral matter and are a mixed sodium sulfate-bicarbonate type.

#22 CHIMNEY HILL WARM WATER WELL

LOCATION: Latitude: 38°38'40"N.; Longitude: 106°04'41"W.; T. 51 N., R. 9 E., Sec. 28 add, N.M.P.M.; Chaffee County; Poncha Springs 15-minute topographic map.

GENERAL: This well was located by J.D. Dick (1976) during the course of the field work for his M.S. degree in geology. This well is approximately 0.25 mile north from the junction of U.S. 285 and Chaffee County 194. The depth of the well is unknown, and the waters are unused. Dick believes that the well may be used for drainage purposes at the abandoned Chimney Hill Mine. The well is capped but may be sampled by opening a valve on top of the casing.

HYDROLOGY: According to Dick (1976) the waters have a temperature of 27°C. The discharge of the well was not measured. Dick (1976) determined that the waters contain 170 mg/l of sodium, 2.7 mg/l of potassium, 7 mg/l of calcium and 47 mg/l of silica.

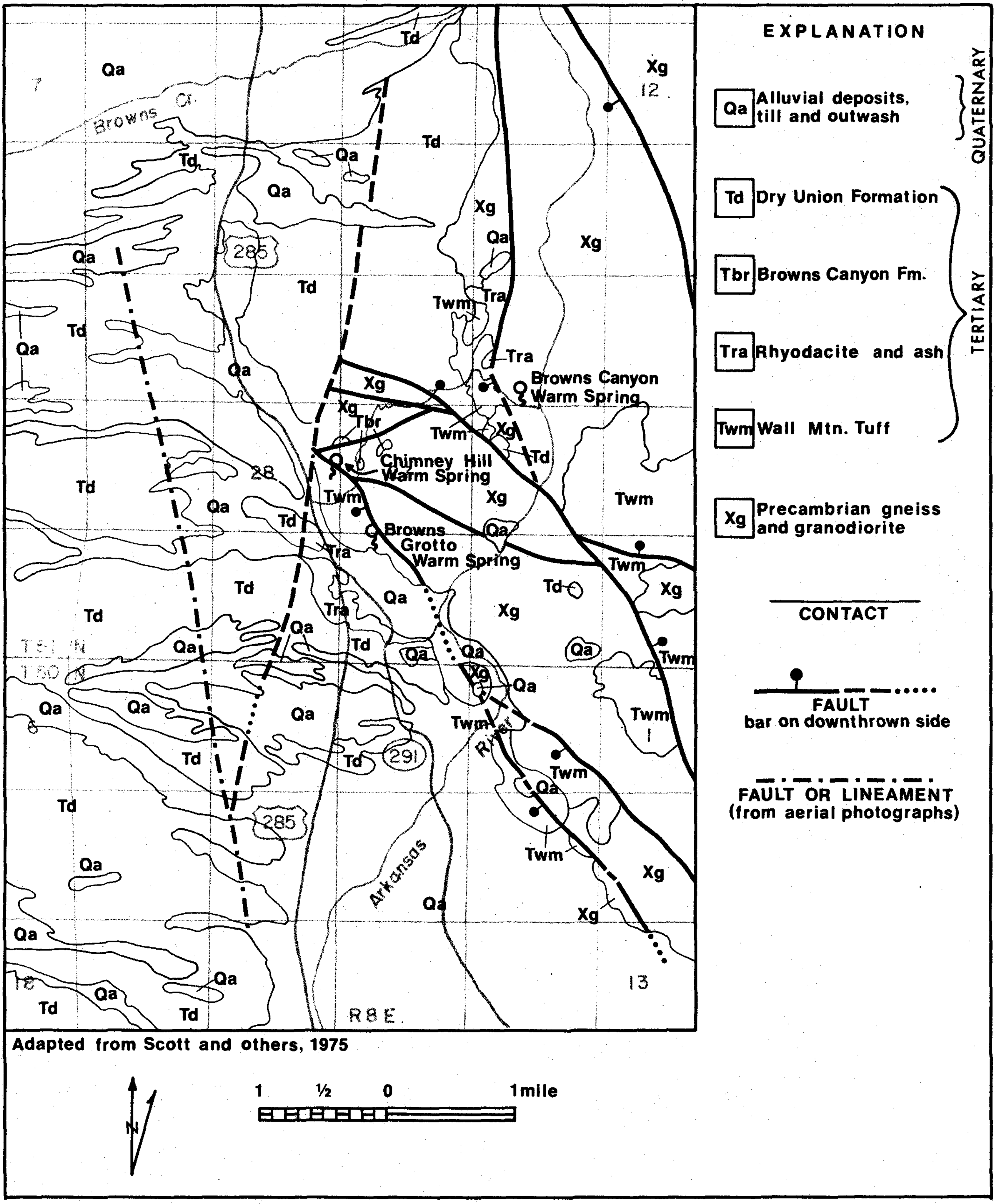
GEOLOGY OF BROWNS CANYON:

As shown on Figure 57, the springs and wells in Browns Canyon are situated in a geologically complex region. Browns Canyon is located on the east side of the Upper Arkansas Valley, a structural extension of the Rio Grande Rift zone. The bedrock of the area consists of Precambrian granitic and metamorphic rocks that make up the Arkansas Hills, on the east side of valley. In fault contact with these rocks is a middle Tertiary age complex assemblage of lava flows, ash beds, sandstones and shales of the Dry Union Formation, and alluvial deposits. This region has had a long and varied geological history. Rather than present it in detail here the reader is referred to papers by Van Alstine (1974), Van Alstine and Cox (1969), and Knepper (1976).

All the thermal waters in the region appear to be fault controlled, especially Browns Grotto Warm Spring and Chimney Hill Warm Water Well. Reiter (1975) has shown that this area has a heat flow in excess of 2.5 heat flow units. The thermal waters probably represent deep circulation of ground water through fault zones

Figure 55.--Browns Canyon Hot Spring.

Figure 56.--Browns Grotto Hot Spring.



Adapted from Scott and others, 1975

Figure 57.--Geologic map of Browns Canyon.

in an area of high heat flow.

GEOTHERMOMETER ANALYSES OF BROWNS CANYON:

Silica Geothermometer: Analysis has determined that temperature-dependent equilibration between the thermal water and cristobalite may be controlling the silica content of Brown Grotto warm springs. Therefore, the cristobalite-silica geothermometer will yield the most reliable temperature estimate. This model yields an estimated temperature of 49°C (Table 4). However, this estimate may be too high because the theoretical cristobalite-induced silica content (24 mg/l) at the springs surface temperature (22°C) is well below the silica content of the warm spring (47 mg/l).

Van Alstine and Cox (1969) present an analysis of the waters from a spring found on the 100-ft level of the Colorado-American Fluorspar Mine in November, 1945. A partial list of this analysis follows:

Temperature	18.5	°C
Discharge	2	gpm
SiO_2	38	mg/l
Na	151	mg/l
K	4.8	mg/l
Ca	7.9	mg/l

Silica solubility vs. temperature relationships suggest that the silica content of this spring may be controlled by cristobalite. The cristobalite-silica geothermometer yielded a subsurface temperature estimate of 40°C, which may be a maximum value.

Mixing Model: The cristobalite mixing model analysis yields a subsurface temperature estimate of 129°C with a cold water fraction of 87 percent for Brown's Grotto Warm Spring and an estimated temperature of 95°C with a cold-water fraction of 86 percent for the spring in fluorspar mine.

The occurrence of thick (up to 12 in.) deposits of microcrystalline silica, opal, and chalcedony associated with the warm springs and fluorspar deposits within the mine (Van Alstine and Cox (1969) greatly complicates the mixing-model analysis. If the microcrystalline silica is more soluble than cristobalite, then the mixing model results are too high; conversely, if silica precipitation occurs at depth then the mixing model results are too low. At any rate, these estimates should be treated skeptically because the flow rate and silica contents of these springs are well below the minimum conditions specified for reliable mixing model results.

Chimney Hill Warm Water Well has a calculated reservoir temperature of 287°C with a cold water fraction of 95 percent (Dick, 1976).

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 123°C and 89°C, respectively, for Brown's Grotto Warm Spring (Table 4), and 142°C and 131°C for the spring within the fluorspar mine. It should be noted that the Na-K geothermometer estimates for both of these springs are too high since the value of the term log $\sqrt{Ca}/Na$ is greater than 0.5. Dick (1976) calculated the Chimney Hill Warm Water Well subsurface temperature with this model to be 85°C.

Although no travertine deposits occur in the immediate vicinity of the springs, a calcium carbonate-depositing spring occurs approximately 1.25 mile to the northeast in sec. 23 cca, T. 51 N., R 81 E. Field data for this spring follows (Barrett, unpublished field data):

Temperature	18°C
conductance	775 micromhos
pH	8.0
Flow	1 gpm

If this spring represents conditions at depth in the Browns Canyon area, then both the Na-K and the Na-K-Ca geothermometer model estimated temperatures are too high.

Conclusion: Geothermometer models should be used with caution when applied to Brown's Grotto Warm Spring since most of the assumptions inherent in their use are violated.

The presence of opal deposits at depth within the fluorspar mine (Van Alstine and Cox, 1969) suggests temperatures at depth below 100°C. However, the extensive fluorspar deposits indicate subsurface temperatures between 119°C and 168°C. At any rate these considerations probably pertain to historical rather than present-day subsurface conditions. The best estimated temperature possible for this area range from 50°C to 100°C (Table 4).

#23 PONCHA HOT SPRINGS

Located several hundred feet above the Arkansas River at the southern end of the Upper Arkansas River Valley is a large group of hot springs known as Poncha Hot Springs.

LOCATIONS: The following five springs were located during the course of this investigation.

Spring A: Latitude: 38°29'49"N.; Longitude: 106°04'37"W.; T. 49 N., R. 8 E., Sec. 15 cb, N.M.P.M.; Chaffee County; Bonanza 15 minute topographic quadrangle map.

Spring B: Latitude: 38°29'49"N.; Longitude: 106°04'36"W.; T. 49 N., R. 8 E., Sec. 15 cb, N.M.P.M.; Chaffee County; Bonanza 15-minute topographic quadrangle map.

Spring C: Latitude: 38°29'50"N.; Longitude: 106°04'31"W.; T. 49 N., R. 8 E., Sec. 15 bc, N.M.P.M.; Chaffee County; Bonanza 15-minute topographic quadrangle map.

Spring D: Latitude: 38°29'50"N.; Longitude: 106°04'32"W.; T. 49 N., R. 8 E., Sec. 15 bc, N.M.P.M.; Chaffee County; Bonanza 15-minute topographic quadrangle map.

Spring E: Latitude: 38°29'50"N.; Longitude: 106°04'32"W.; T. 49 N., R. 8 E., Sec. 15 bc, N.M.P.M.; Chaffee County; Bonanza 15-minute topographic quadrangle map.

GENERAL: This large group of springs is located approximately one mile south of the town of Poncha Springs and just east of U.S. Highway 285. Access is via a dirt road from U.S. 285, 1,000 ft south of the bridge crossing the South Arkansas River.

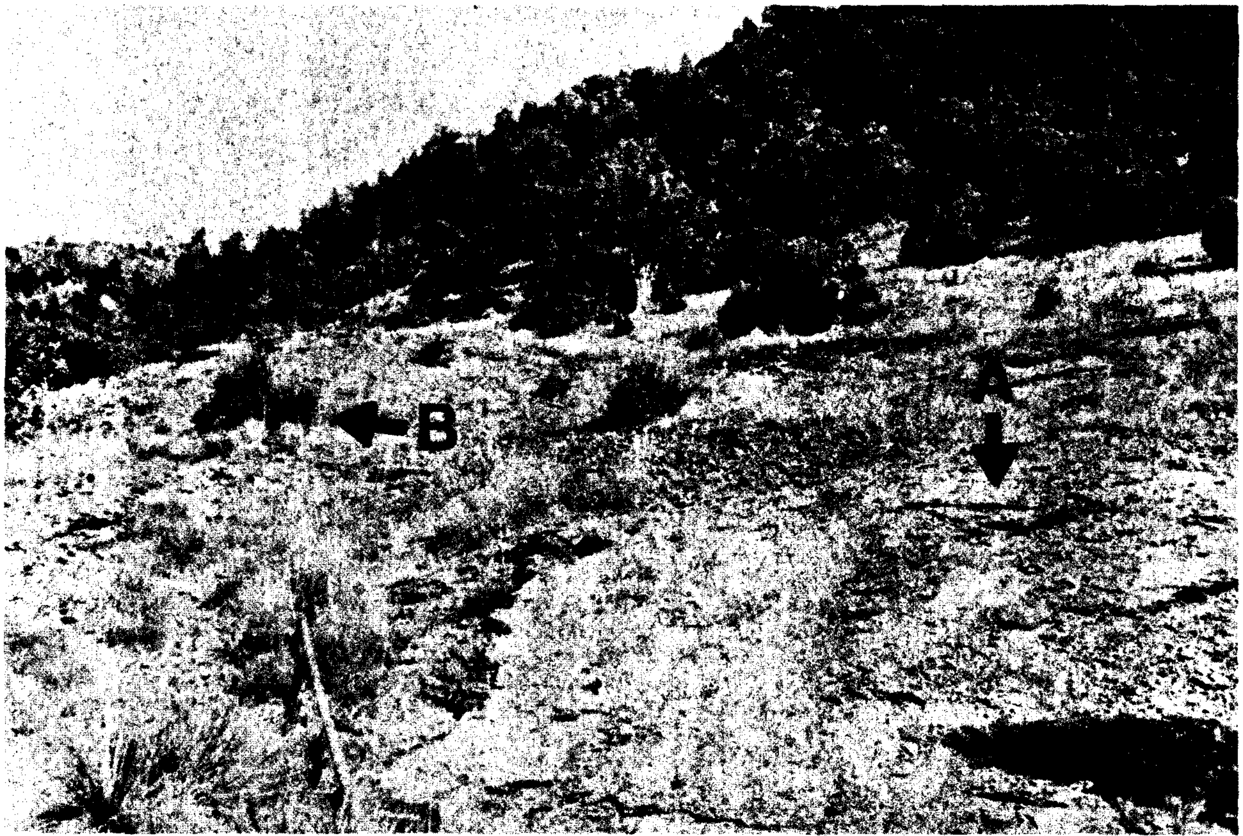


Figure 58.--Poncha Hot Springs. A: Spring A, B: Spring B.

The springs are contained in two distinct groups. The south group, Springs A & B, just uphill from the buildings, is the main spring area. Another group of three unused springs lies over the ridge line and down in a small valley north of the main spring area (Fig. 58). The main spring area is characterized by a large travertine apron extending over the entire hillside. At one time up to 40 springs issued on this hillside, but at the present time, no thermal waters flow to the surface because of collection by buried pipelines. Most of the waters are piped approximately 5 miles to Salida where they are used in the municipal swimming pool. During the summer some of the waters are used in a swimming pool at the hot springs area. Some of the waters are also used to heat the caretaker's house at the hot springs. In the main spring area only two spring were found that could be sampled, Springs A and B. Both of these "springs" flow from buried pipelines leading into concrete-lined junction boxes where the waters are collected and piped to Salida.

Springs C, D, and E are located in a separate area approximately 500 ft northeast of the main spring area. These three springs are small and unused.

GEOLOGY AND HYDROLOGY:

Spring A: Temperature: 50°C-71°C; Discharge: 200 gpm; Total Dissolved Solids: 654 to 697 mg/l; Water Type: sodium bicarbonate-sulfate. Spring A, which is a concrete-lined junction box, is located approximately half the way uphill and on the south side of the travertine apron (Fig. 58).

Spring B: Temperature: 66°C; Discharge: Estimated 30 gpm; Total Dissolved Solids: 655 mg/l; Water Type: sodium bicarbonate-sulfate. Spring B is located approximately 140 ft northeast of A and approximately 50 ft higher uphill (Fig. 58).

Spring C: Temperature: 62°C; Discharge: 2 to 4 gpm; Total Dissolved Solids: 655 to 685 mg/l; Water Type: sodium sulfate-bicarbonate type. Spring C is the easternmost spring.

Spring D: Temperature: 56°C; Discharge: 2 gpm est.: Conductance: 1,000 micromhos. Spring D is located approximately 40 ft northwest of C.

Spring E: Temperature: 60°C; Discharge: 2 gpm est.; Conductance: 950 micromhos. Spring E is located approximately 20 ft southwest of Spring D.

The Poncha Hot Springs, which issue from colluvial deposits overlying the Dry Union Formation, are located at the southern end of the Upper Arkansas River Valley and on the northwest side of the Sangre de Cristo Horst (Knepper, 1976). The geology of the region has been described in detail by a number of authors. Chapin (1971), Knepper (1976), and Van Alstine (1970 and 1974) have all presented excellent summaries of the geology in the immediate vicinity. Chapin (1971) presents a general discussion of the structural development of the Rio Grande Rift Zone. Knepper (1976) presents a detailed discussion of the structural development of the Upper San Luis Valley and the Upper Arkansas River Valley. Knepper (1976) states that the hot springs are located on the northwest end of the Sangre de Cristo Horst, a structurally high area between the two valleys. Van Alstine (1970) states that this part of the horst consists of, in part, blocks of allochthonous Paleozoic rocks that originated to the west in the Sawatch Range. Chapin (1971), Knepper (1976), and Van Alstine (1970) all state that the area around the hot springs is structually complex (Fig. 59). In describing the geologic history of the region, Van Alstine (1970) states that in Late Tertiary time the Upper Arkansas Valley was connected to the San Luis Valley by a trough along the west edge of the Sangre de Cristo Horst. Chapin (1971) and Knepper (1976) state that faulting began in the region sometime after the close of Oligocene time, for Oligocene rocks along the margins of the valleys have been offset at least 5,000 ft by faulting.

Due to the complexity of the structure in this region, it is difficult to ascertain the origin of the hot springs. The springs are probably fault controlled. Although the area of recharge is not known, the Arkansas River may be the source of the waters. Recharge may also be occurring along the Collegiate and Sawatch Ranges to the west. Reiter (1975) states that the heat flow near Poncha Hot Springs is +2.5 heat flow units.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: The quartz-silica geothermometer model yields an estimate of 119°C to 137°C

Mixing Model: The quartz mixing model yields a subsurface temperature estimate of 157°C to 209°C, with a cold water fraction of 60 to 73 percent of the spring flow (Table 4).

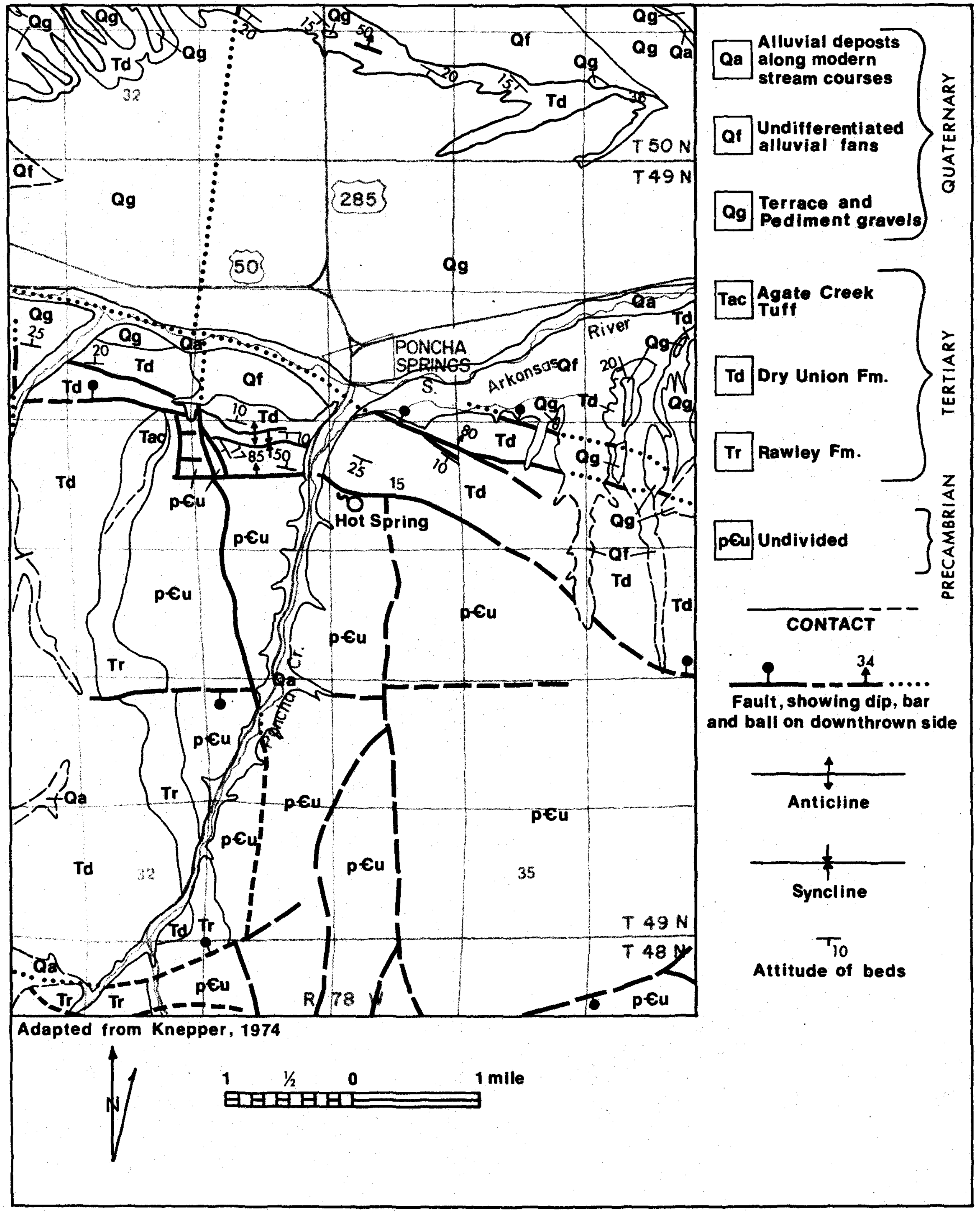
Due to the 3-month turn-around time between sampling the hot springs and receiving the analytical results, it was not known until after the October 1975 sampling date that silica was precipitating from solution in the sample containers. Eventually the turn-around time was reduced to 4 to 6 weeks, and later silica samples were diluted 10:1 with deionized water. The samples taken in January 1976, and April 1976, from springs A and C were diluted and show a marked increase in the silica content compared to the earlier analysis.

The mixing model results for the January 1976, and April 1976, samples yield temperature estimates of 195°C to 209°C with a cold-water fraction of 69 to 73 percent of the spring flow (Table 4). These estimates are well within the range of values that could result from normal analytical error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 154°C to 159°C and 96°C to 145°C, respectively (Table 4). Extensive travertine deposits occur in the vicinity of these hot springs, and Hot Springs A and B currently deposit calcium carbonate within the collection box. Therefore, the Na-K and Na-K-Ca geothermometer estimates are too high.

Conclusion: The insignificant variation in surface temperature, mineral content, and geothermometer estimates (January, 1976 and April, 1976) of these hot springs suggests that they are not affected by seasonal metereological condtions. The fluctuation of the geothermometer temperature estimates is well within the range of values that could result from analytical error.

The best approximation of subsurface temperature is provided by the cristobalite mixing model; the Na-K-Ca geothermometer yields a maximum estimate of temperature. Therefore, the temperature at depth in this area is probably within the range of 150°C to 200°C (Table 4).



Adapted from Knepper, 1974

Figure 59.--Map showing geologic conditions surrounding Poncha Hot Springs.

#24 WELLSVILLE WARM SPRING

LOCATION: Latitude: 38°29'07"N; Longitude: 105°54'36"W.; T. 49 N., R. 10 E., Sec. 18 -, N.M.P.M.; Chaffee County; Howard 15-minute topographic quadrangle map.

GENERAL: This large warm spring is located on the north bank of the Arkansas River approximately 6 miles east of Salida. This spring may be reached by traveling east on U.S. 50 from Salida for 5.2 miles to a bridge crossing the Arkansas River. After crossing the bridge, continue east on a dirt road to the small commmunity of Wellsville. Just before crossing the railroad tracks in Wellsville turn right on the private road leading to some homes. Waters from the spring are used in tropical fish-rearing ponds. Algae and tropical plants are also grown commercially in some of the ponds.

Figure 60 shows that the spring emerges from a large limestone ledge to the east of the fish ponds in a large marshy area. The marshy area prevented sampling the spring at its discharge point. Samples were collected from the edge of the pool closest to the spring.

GEOLOGY AND HYDROLOGY: The temperature of the waters ranged from 28°C to 33°C in a year's time. The discharge varied from 160 to 200 gpm. The total dissolved solids content range from 470 mg/l to 484 mg/l. The waters are a calcium bicarbonate type.

As shown on the accompanying geologic map (Fig. 61), the Wellsville Warm Spring is located on a small northeast-trending fault. While the bedrock has been mapped as undivided Mississippian, Devonian, and Ordovician sedimentary formations, the waters come from the Leadville Limestone. Due to the erosional history of the Arkansas River and faulting, only a small remnant of Leadville Limestone is present.

No attempt was made to decipher the hydrogeological conditions surrounding this spring, but the waters may be recharged from the high ground either to the north or to the south. The springs are located on the extreme edge of the Rio Grande rift zone. Reiter (1975), states that the area has a heat flow of just below 2.0 H.F.U. The origin of the heat is unknown.

Figure 60.--Wellsville Warm Spring.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and cristobalite controls the silica content of the warm spring. Therefore, the cristobalite-silica geothermometer yields the most reliable subsurface temperature estimate. This model yields a temperature of 30°C to 31°C (Table 4) which is the same as the surface temperature of the warm spring. The high flow rate of this warm spring (approximately 200 gpm), and the excellent agreement between the theoretical cristobalite-induced silica solubility (29 to 32 mg/l) and the actual silica content of the spring (30 to 32 mg/l) suggest that this geothermometer estimate is close to the actual temperature at depth.

Mixing Model: Since temperature-dependent equilibration between the thermal water and cristobalite apparently controls the silica content of the warm spring, the cristobalite mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 33°C with a cold water fraction of 2 to 15 percent of the spring flow. These estimates are well within the range of values that could result from normal analytical error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 213°C to 216°C and 48°C to 50°C, respectively (Table 4).

The Na-K geothermometer estimate is too high because the value of the term log $\sqrt{Ca}/Na$ is greater than 0.5. Although no calcium carbonate deposits occur near Wellsville Warm Spring, travertine deposits of Pleistocene age occur in sec. 18 T. 49 N., R. 10 E. In addition to these deposits, river gravels in sections 18 and 19, T. 49 N., R. 10 E. are thickly coated and firmly cemented by calcium carbonate. If calcium carbonate deposition occurs at depth, then the Na-K-Ca geothermometer estimate is also too high.

Conclusion: The insignificant variation in flow, mineral content, surface temperature and geothermometer estimates of this warm spring suggest that it is not affected by seasonal metereological conditions. The fluctuations of the geothermometer estimates are well within the range of values that could result from normal analytical error.

The high flow, and excellent agreement between the silica geothermometer and mixing models with the silica content and temperature of the warm spring suggest that the temperature at depth is near the surface temperature of the warm spring. Therefore, the subsurface temperature in near 35°C and certainly between 35°C to 50°C (Table 4).

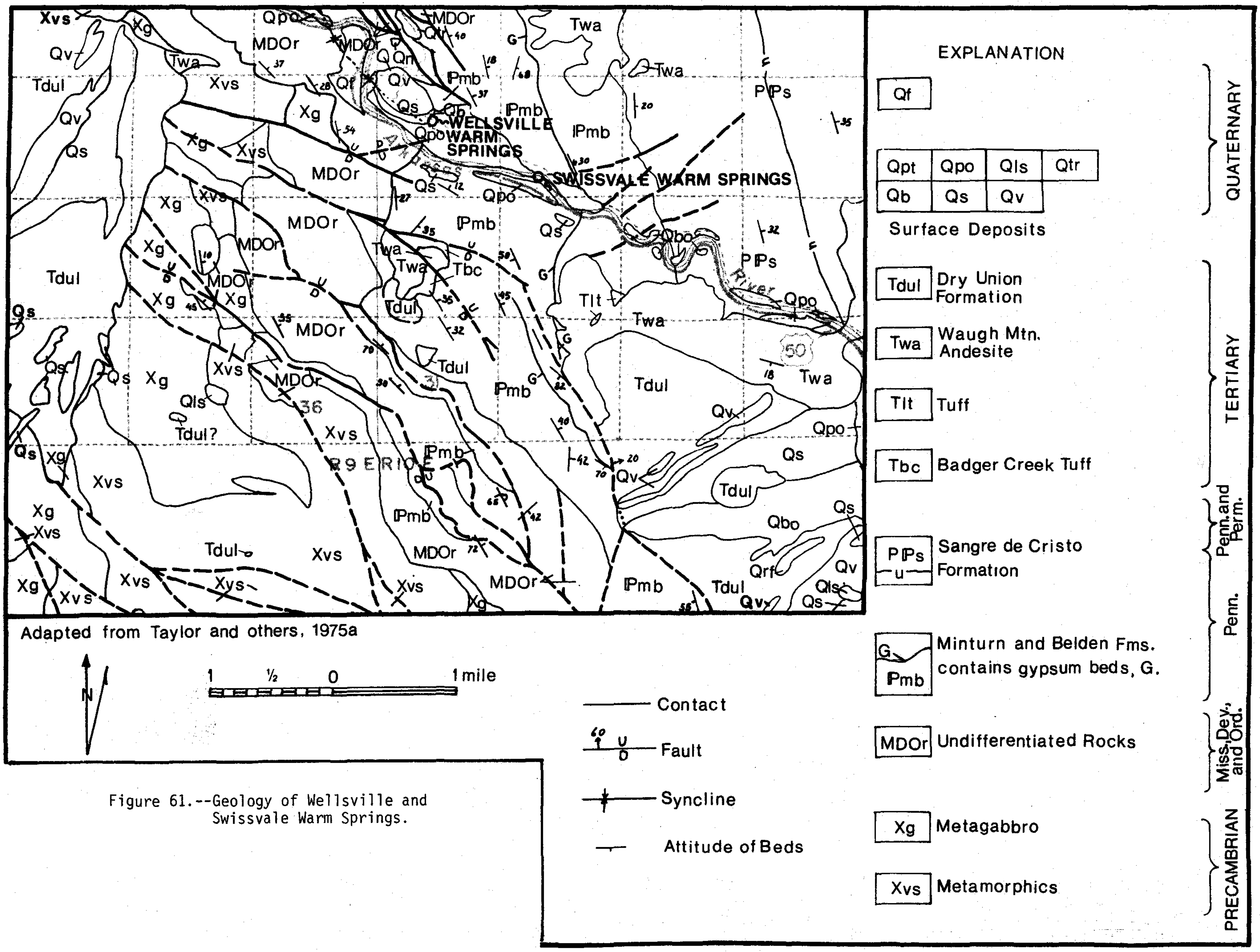


Figure 61.--Geology of Wellsville and Swissvale Warm Springs.

#25 SWISSVALE WARM SPRINGS

LOCATION: Latitude: 38°28'49"N.; Longitude: 105°53'25"W; T. 49 N., R. 10 E., Sec. 20 cda, N.M.P.M.; Fremont County; Howard 15-minute topographic quadrangle map.

GENERAL: This group of nine unused springs is located along the north bank of the Arkansas River approximately 6.5 miles east of Salida. Field measurements were made at the two largest springs in the group. Spring A (Fig. 62), the largest and easternmost spring, is located 30 ft south of a U.S. Bureau of Land Management cadastral survey marker. Spring F is located approximately 350 ft west of Spring A and about 20 ft above the river bank.

GEOLOGY AND HYDROLOGY: Spring A has a temperature of 28°C, a discharge of 125 gpm with a conductance of 880 micromhos. Spring F has a temperature of 20°C, a discharge estimated at 20 gallons per minute, and a specific conductance of 775 micromhos. Total discharge of all springs is approximately 200 gpm.

As shown on Figure 61 the waters come from the Pennsylvanian Maroon and Belden Formations. These formations dip to the northeast and are cut by a north-northeast trending fault less than 1 mile to the east. Taylor and others (1975) mapped numerous major southeast-trending faults to the south, southwest, and northwest of the spring. None were projected into the spring area; however, one north-trending fault was mapped less than 1 mile east of the springs. The thermal waters may migrate up one of these faults into the fracture zones within the Maroon Formation.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Review of silica solubility and temperature relationships suggests that cristobalite controls the silica content of the warm springs. Therefore, the cristobalite-silica geothermometer is applicable. This model yields a subsurface temperature estimate of 32°C, which is near the surface temperature of the warm springs (28°C). The high flow (175 gpm) and the excellent agreement between the theoretical cristobalite-induced silica solubility (29 mg/l) and the actual silica content of the spring (31 to 32 mg/l) suggest that this geothermometer estimate is close to the actual temperature at depth.

Mixing Model: Since temperature-dependent equilibration between the thermal water and cristobalite apparently controls the silica content of the warm springs, the cristobalite mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 35°C to 47°C with a cold-water fraction of 22 percent to 69 percent of the spring flow (Table 4).

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 214°C and 44°C to 48°C, respectively (Table 4).

The Na-K geothermometer estimate is too high because the value of the term log $\sqrt{Ca}/Na$ is greater than 0.5. Spring A deposits small amounts of calcium carbonate, and large travertine deposits occur approximately 750 ft to the west along the north bank of the Arkansas River. Calcium carbonate deposition causes both the Na-K and Na-K-Ca geothermometer estimates to be too high.

Conclusion: The high flow and the excellent agreement between the silica geothermometer and mixing model estimates suggest that the temperature at depth is near the surface temperature of the warm springs. Therefore, the subsurface temperature in this area is probably near 35°C and certainly between 35°C and 50°C (Table 4).

Figure 62.--Swissvale Warm Spring.

#26 CANON CITY HOT SPRINGS

LOCATION: Latitude: 38°25'57"N.; Longitude: 105°15'46"W.; T. 18S., R.70 W., Sec. 31 d, 6th P.M.; Fremont County; Royal Gorge 7 1/2-minute topographic quadrangle map.

GENERAL: The spring is located in the front yard of the house at 1400 Riverside Drive in Canon City. The spring may be reached by going south from the intersection of 1st Street and U.S. 50 across the Arkansas River, then turning west at the first intersection, Riverside Drive. Drive one mile to the house at the end of the road. The spring, located at the southeast corner of the abandoned swimming pool, is cased wih a 6-in. diameter pipe to a depth of 50 ft (Fig. 63).

GEOLOGY AND HYDROLOGYY: This unused spring has a discharge estimated to be 5 gpm with a temperature of 40°C. The total dissolved solids content of the water is 1,230 mg/l.

The spring is locted at the contact between the Leadville Limestone and the overlying Fountain Formtion (Fig. 64). No faults have been mapped in the vicinity of the spring, and none are apparent on the surface. Therefore, the waters must ascend through the Leadville Limestone. The recharge area for this spring is probably to the north and east along the northern flanks of the Canon City Embayment.

GEOTHERMOMETER ANALYSES:

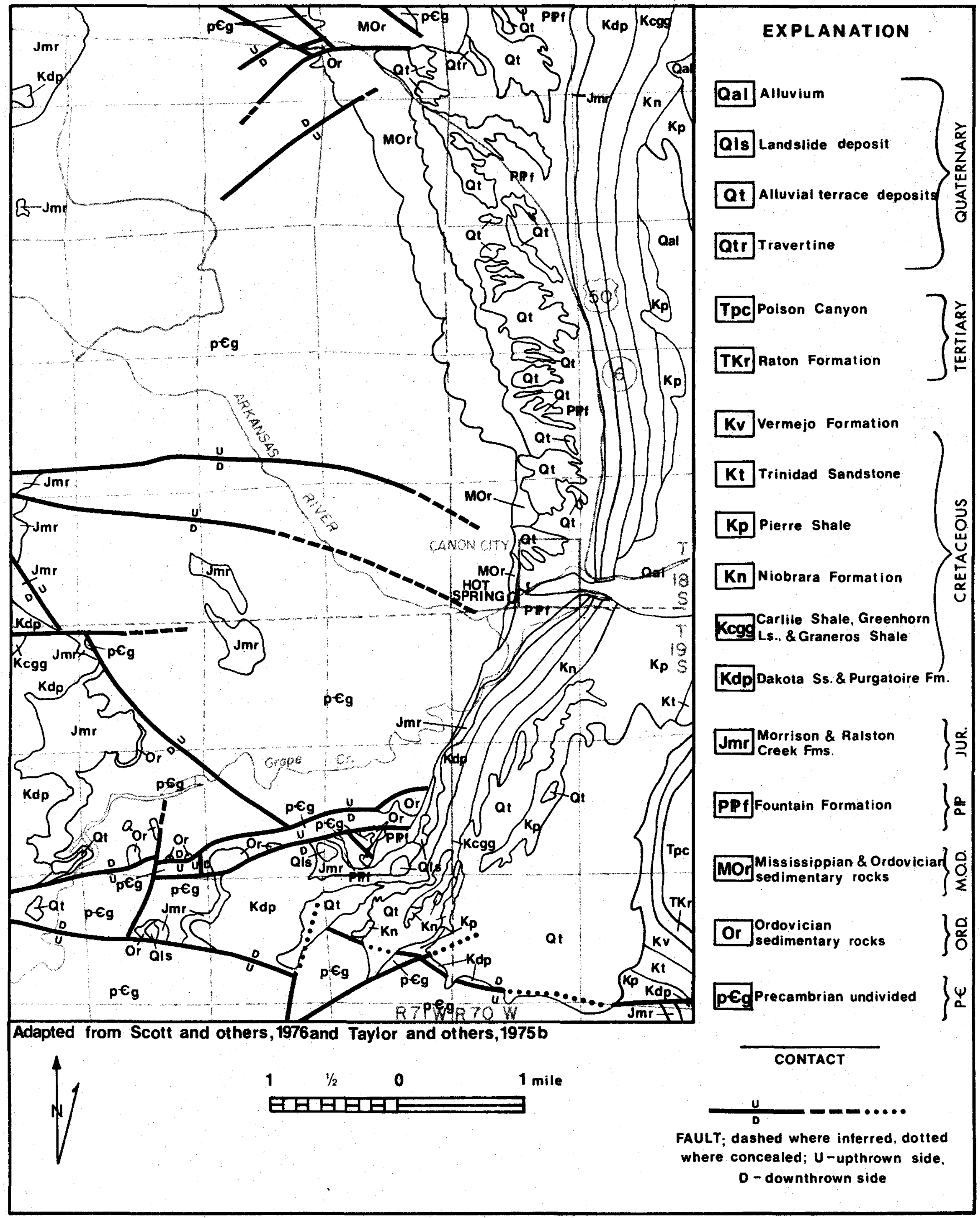
Silica Geothermometer: Analysis of the silica solubility and temperaure relationships suggests that chalcedony controls the silica silica content of the hot springs. Therefore, the chalcedony-silica geothermometer is applicable. This model yielded a subsurface temperature estimate of 34°C to 35°C, which is below the surface temperature of the thermal spring (40°C). This low temperature estimate may be caused by mixing of the ascending thermal water and dilute ground water.

Mixing Model: Since the chalcedony silica geothermometer was used above, the chalcedony mixing model is used here also. The chalcedony mixing model yields a subsurface temperature estimate of 38°C to 40°C with a cold-water fraction of 3 to 12 percent of the total flow. These estimates are well within the range of values that could result from normal analytical error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers estimates are 187°C and 68°C to 72°C, respectively. Both of these estimates are too high because calcium carbonate is deposited on the well casing.

Conclusion: The common geothermometer models are not reliable when applied to the Canon City Hot Springs because many of the assumptions inherent in their use are violated. From analysis of the data it appears that no reliable estimate of the subsurface temperature is possible.

Figure 63.--Canon City Hot Spring.



Adapted from Scott and others, 1976 and Taylor and others, 1975b

Figure 64.--Geology of Canon City region.

#27 FREMONT NATATORIUM

LOCATION: Latitude: 38°27'38"N.; Longitude: 105°11'46"W.; T. 18 S., R. 70 W., Sec. 26 bbb, 6th P.M.; Fremont County; Canon City 7 1/2-minute topographic quadrangle map.

GENERAL: This hot spring, which is actually an 1,800-ft-deep artesian well, is located at 3095 Central Avenue in northeast Canon City. Access to the well is by U.S. 50 east to Dozier Street, then north on Dozier Street for 0.9 miles to where the road bends sharply to the west. The well, which supplied waters to the pool at the natatorium, is just behind the unused swimming pool north of the bend in the road.

GEOLOGY AND HYDROLOGY: The temperature of the waters is 35°C with a discharge of 20 gpm. The total dissolved solids content varied from 1,300 mg/l to a high of 1,370 mg/l throughout the year's time.

This well is located on the west side of the Canon City Embayment, and the bedrock of the area is the Cretaceous Pierre Shale. As noted on the geologic map (Fig. 65) no faults or folds occur in the immediate vicinity of this well.

The depth of the well suggests that the waters come from the Dakota Formation, which is the principal aquifer in the Canon City Embayment. Recharge probably occurs to the north around the flanks of the embayment with the heating of the waters caused by decay of radioactive minerals. The Dakota Formation in western portions of the Canon City Embayment contains above-normal concentrations of radioactive minerals (Richard Gamewell, 1975, oral communication).

GEOTHERMOMETER ANALYSES

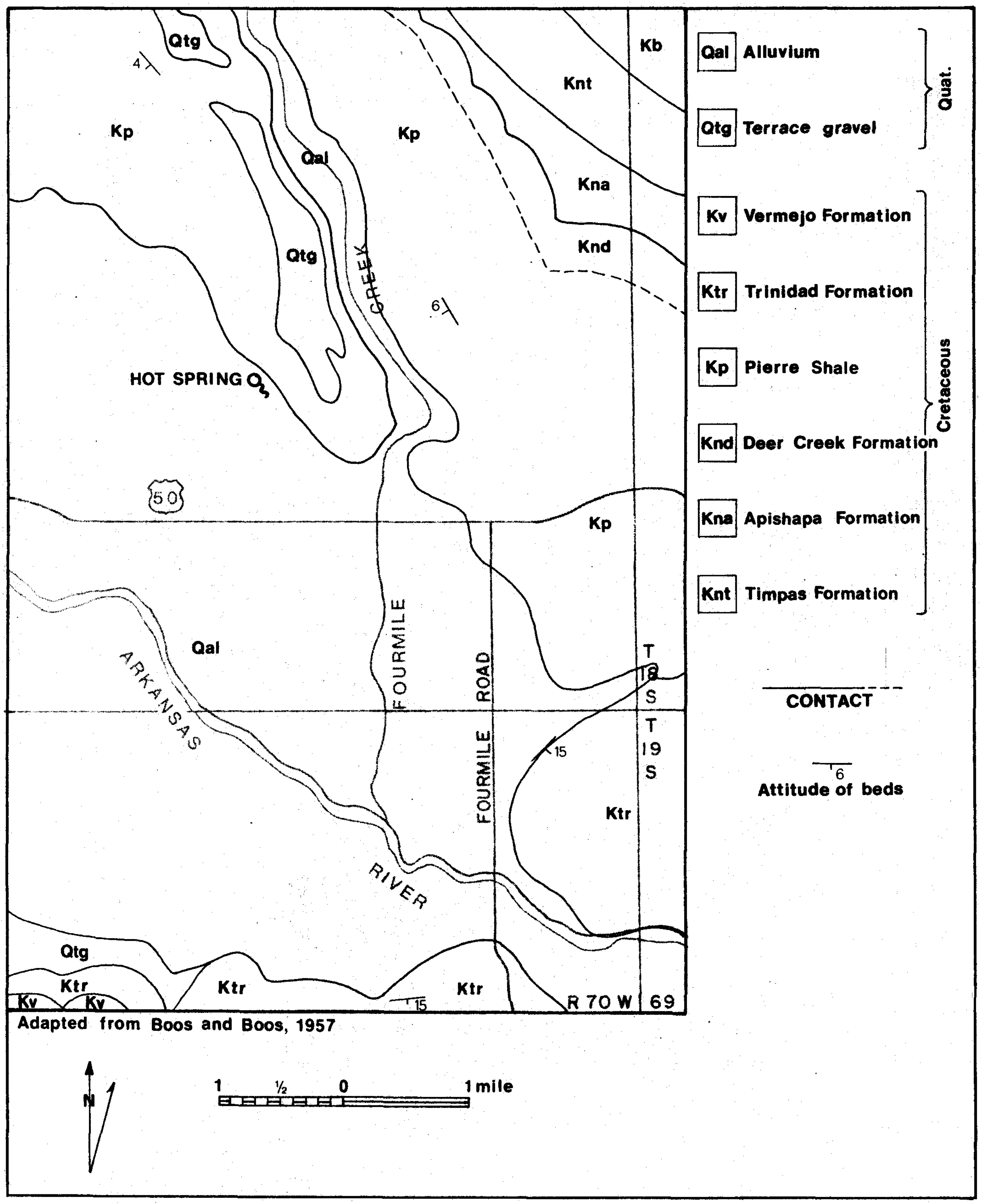
Silica Geothermometer: Silica solubility and temperature relationships suggest that chalcedony or quartz may control the silica content of the artesian well. The quartz-silica geothermometer yields a subsurface temperature estimate of 50°C and the maximum chalcedony-silica geothermometer subsurface temperature estimate is 23°C, which is below the surface temperature of the thermal water (35°C).

Mixing Model: Both the quartz and the chalcedony mixing models are appropriate for use here. The quartz mixing model yields a subsurface temperature estimate of 78°C to 88°C with a cold water fraction of 63 to 69 percent. These estimates are probably too high because both the silica content and the flow rate of the artesian well are below the minimum conditions specified for the reliable application of this geothermometer.

The chalcedony mixing model yields a subsurface temperature estimate of 32°C with a cold water fraction of 23 percent of the total flow. Although the subsurface temperature estimate is below the surface temperature of the well (35°C), it is within the expected margin of error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield maximum subsurface temperature estimates of 174°C and 73°C, respectively. Both of these estimates are too high because calcium carbonate is being deposited around the well.

Conclusion: The subsurface temperature is this area is probably between the surface temperature of the artesian well and the quartz silica geothermometer estimate, namely 35°C to 50°C (Table 4).



Adapted from Boos and Boos, 1957

Figure 65.--Geologic map of Fremont Natatorium region.

#28 FLORENCE ARTESIAN WELL

LOCATION: Latitude: 38°24'53"N.; Longitude: 105°02'43"W.; T. 19 S., R. 68 W., Sec. 7 bac; 6th P.M.; Fremont County; Florence 7 1/2-minute topographic quadrangle map.

GENERAL: This unused well (Fig. 66) of unknown depth, is located approximately 1,800 ft southwest of the junction of U.S. 50 and Colorado 115 south of Penrose. The well is located on the east side of Colorado 115 and southwest of an abandoned farm building.

GEOLOGY AND HYDROLOGY: The waters have a surface temperature of 28°C, with a discharge of 130 gpm. The waters contain 1,480 mg/l of dissolved solids, and the waters are a sodium-bicarbonate type.

This well is located in the Canyon City Embayment. The bedrock of the area is the Pierre Shale, and no major structural features are present in the area (Fig. 67). The depth of the well is unknown, but the waters probably come from the Dakota Formation, which is the main aquifer in the Canyon City Embayment. The origin of the heat is unknown but may be related to decay of radioactive minerals in the Dakota Formation (see Clark Artesian Well discussion).

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and chalcedony controls the silica content of the artesian well. The chalcedony-silica geothermometer model gave an estimated subsurface temperature of 34°C.

Mixing Model: Since temperature-dependent equilibration between the thermal water and chalcedony may control the silica content of the artesian well, the chalcedony mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 41°C with a cold water fraction of 40 percent of the total flow.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 212°C and 178°C, respectively. The Na-K geothermometer estimate is too high because the value of the term log $\sqrt{Ca}/Na$ exceeds 0.5. Moroever, the high magnesium content(78 mg/l) of the waters makes geothermometers unreliable.

Conclusion: Most geothermometers are not reliable when applied to Florence Artesian Well because many of the assumptions inherent in their use are violated. Therefore, the most likely subsurface temperature in this area is between 34°C and 50°C (Table 4).

Figure 66.--Florence Artesian Well.

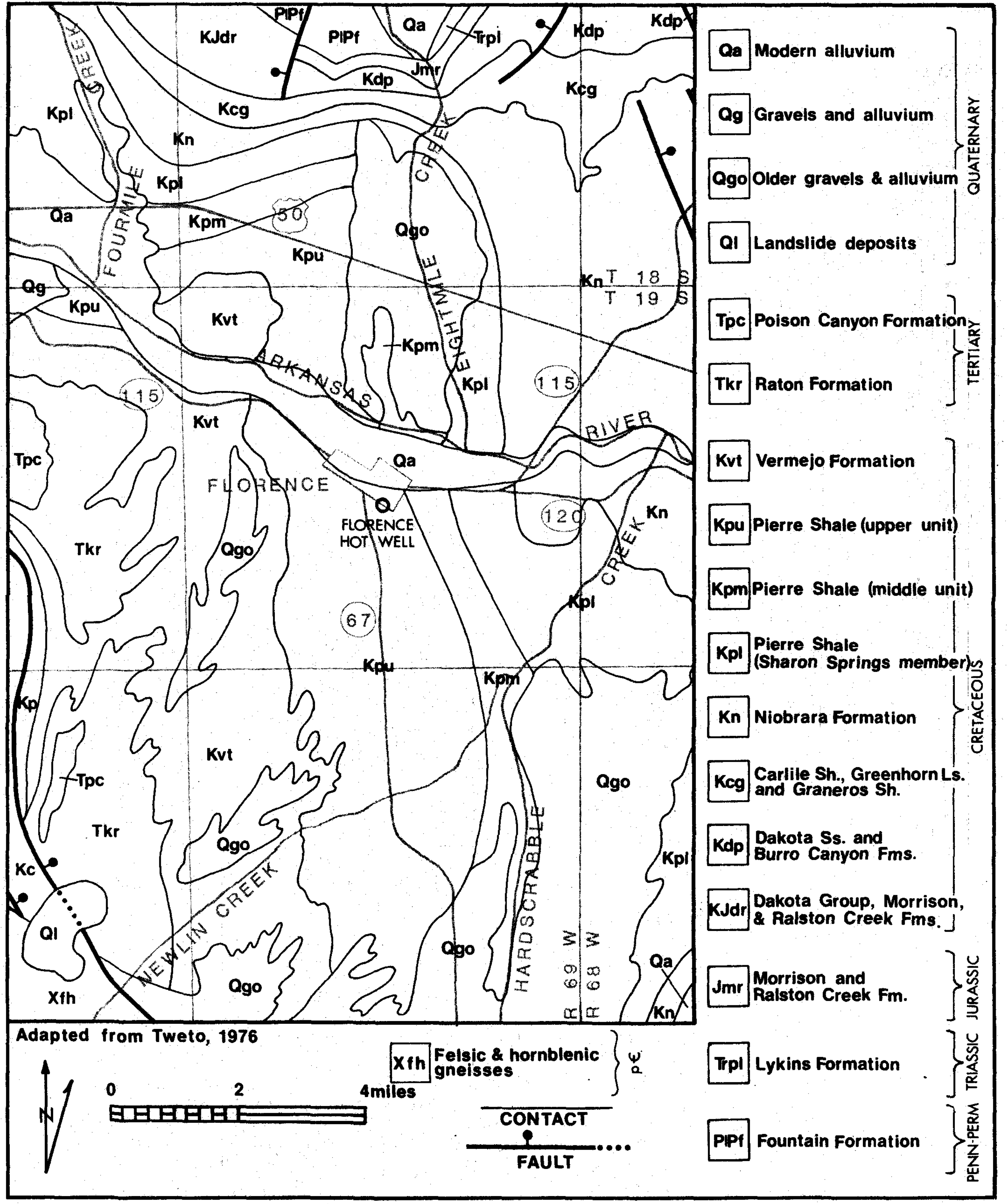


Figure 67.--Geology of the Florence area.

#29 DON K RANCH ARTESIAN WELL

LOCATION: Latitude: 38°10'20"N.; Longitude: 105°00'32"W.; T. 22 S., R. 68 W., Sec. 5 a, 6th P.M.; Fremont County; Wetmore 7 1/2-minute topographic quadrangle map.

GENERAL: This unused well, of unknown depth, may be reached by going west from Pueblo for approximately 19.5 miles on State Highway 96 to the community of Siloam. At Siloam turn left on a dirt road, called Siloam Road, and go approximately 4.75 miles to the turnoff to the Don K. Ranch. Follow this road for approximately one mile to the ranch house.

GEOLOGY AND HYDROLOGY: The waters of this well have a surface temperature of 28°C and a discharge of 25 gpm. The total dissolved solids of the waters are 1,710 mg/l, and the waters are a sodium bicarbonate type.

The well is located down on the northeast flank of the Red Anticline (Fig. 68). The bedrock of the area is the Pennsylvanian Fountain Formation. Taylor and Scott (1973) mapped no faults in the area. On the crest of the anticline, approximately one mile to the southwest, Precambrian biotite gneiss crops out. No attempt was made to determine the origin of the thermal waters or the heat source; however, a cursory appraisal suggests that heat lensing occurs within the Precambrian metamorphic rocks. Dr. Trobe Grose (1977, oral communication) states that "heat lensing" can occur when a granitic or metamorphic rock body is overlain by a sedimentary sequence. Because sedimentary rocks have lower specific heat content than the granitic or metamorphic rocks, the heat is drawn to and concentrated in the metamorphic and granitic rocks.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: The silica content of this artesian well does not approach the solubility of amorphous silica, chalcedony, cristobalite or quartz; therefore, application of any of these silica geothermometers yields questionable results. For an explanation, see earlier discussion of silica geothermometer assumptions.

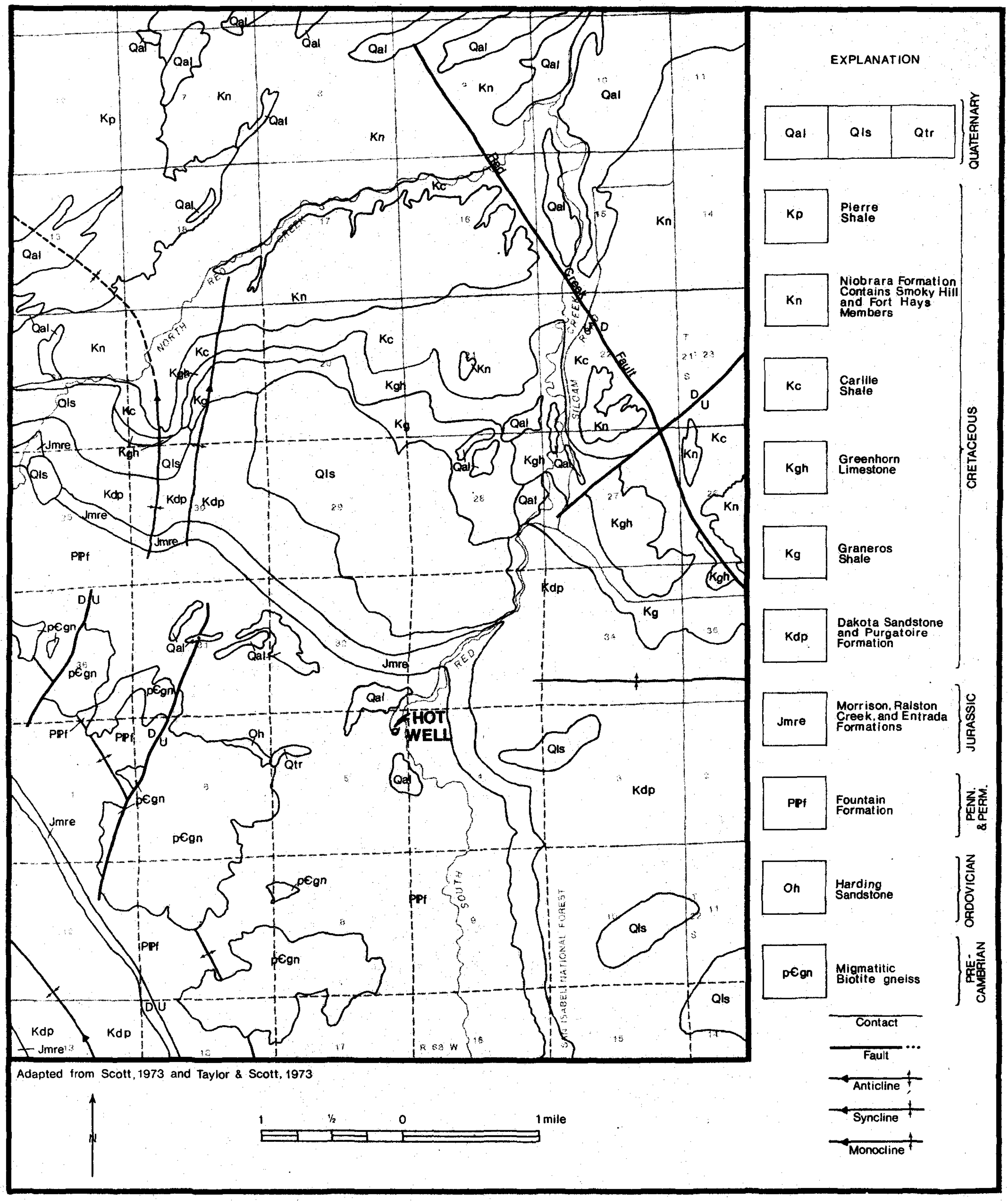
The cristobalite-silica geothermometer model yielded an estimated subsurface temperature of 42°C. However, this estimate is probably too high because the theoretical cristobalite solubility (29 mg/l) at the surface temperature of the well (28°C) is below the silica content of the thermal water (40 mg/l).

Mixing Model: Mixing model analysis is unreliable when applied to the thermal waters in this well because the temperature and flow of well are below the minimum conditions specified for the reliable use of this model. (See section on basic assumptions of this model for a fuller explanation).

The solubility of amorphous silica at the surface temperature of the artesian well (28°C) is 123 mg/l, which is above the actual silica content of the well (40 mg/l). This may be due to mixing or silica precipitation at depth. The amorphous silica mixing model yields a subsurface temperature estimate of 23°C with a cold-water fraction of 47 percent of the artesian flow. The cristobalite mixing model yields a subsurface temperature estimate of 63°C with a cold water content of 61 percent.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 219°C and 190°C, respectively. Both of these estimates are too high because calcium bicarbonate is deposited on the well casing.

Conclusion: Geothermometer analysis for this area is not reliable because most of the assumptions do not apply.



Adapted from Scott, 1973 and Taylor & Scott, 1973

Figure 68.--Geology of Don K Ranch area.

#30 CLARK ARTESIAN WELL (CLARK SPRING WARM WATER WELL)

LOCATION: Latitude: 38°15'29"N.; Longitude: 104°36'35"W.; T. 21 S., R. 65 W.; Sec. 1 aab, 6th P.M.; Pueblo County; NE Pueblo 7 1/2-minute topographic quadrangle map.

GENERAL: This well is located inside the Clark Spring Water Company building on the north corner of Clark and B Streets in Pueblo, Colorado (Fig. 69). The waters are bottled and sold commercially by the Clark Spring Water Company.

GEOLOGY AND HYDROLOGY: This well is 1,412 ft deep. The waters, which issue at the surface with a temperature of 25°C, contain 1,210 mg/l of dissolved elemental mineral matter and are a sodium sulfate type.

As shown on Figure 70, the well is located on the southeast flank of an unnamed syncline. The origin of the thermal waters is unknown but may be caused by decay of radioactive minerals in the Dakota Formation. Richard Gamewell (1977, oral communication), a radiological specialist for the Colorado Department of Health, has reported elevated levels of radioactivity in the Pueblo area associated with ground waters from the Dakota and other Cretaceous formations.

Recharge to the Dakota Formation occurs primarily along the flanks of the Canon City Embayment to the west of Pueblo.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: The quartz-silica geothermometer model yields a a subsurface temperature of 40°C.

Mixing Model: Use of the quartz mixing model yields a subsurface temperature estimate of 61°C with a cold water fraction of 65 percent of the total flow. Any estimates of subsurface temperatures with this model are unreliable because the silica content (11 mg/l) and the flow of this well are below the minimum conditions specified for the reliable application of this geothermometer.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 280°C and 159°C, respectively. The high magnesium content (45 mg/l), low surface temperature and flow of this well and the lack of substantiation of such high subsurface temperatures by the other geothermometers render these estimates unreliable.

Conclusion: Most geothermometer models are not reliable for estimating the Clark Artesian Well reservoir temperature because many of the assumptions inherent in their use are violated. From analysis of all data it appears that the most likely subsurface temperature in this area is between 25°C and 50°C (Table 4).

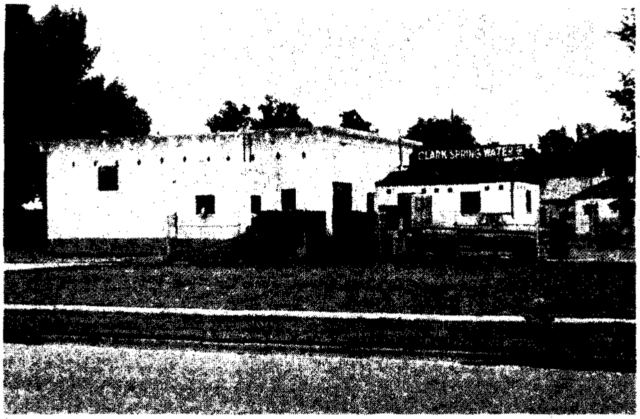
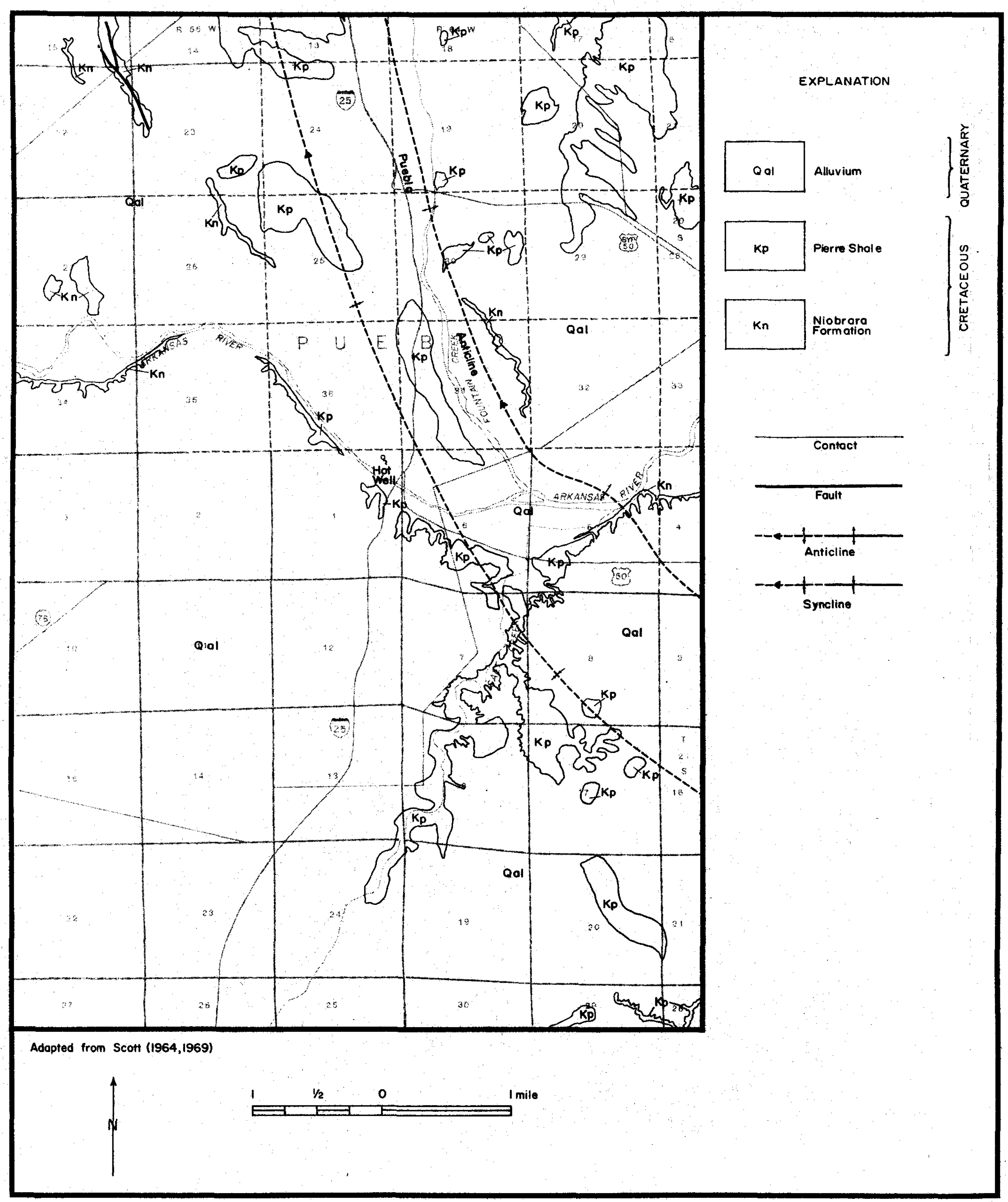


Figure 69.--Building in which Clark Artesian Water Well is located.



Adapted from Scott (1964,1969)

Figure 70.--Geologic map of Pueblo region.

#31 MINERAL HOT SPRINGS

LOCATION: Latitude: 38°10'08"N.; Longitude: 105°55'05"W.; T. 45 N., R. 9 E., Sec. 12 ad, N.M.P.M.; Saguache County; Villa Grove 7 1/2-minute topographic quadrangle map.

GENERAL: The Mineral Hot Springs consists of a number of unused springs scattered over approximately 80 acres just east of Colorado 17, 6.5 miles south of Villa Grove in the northern San Luis Valley.

The springs are located in three groups, an eastern group of two springs and one well, a central group of one spring and one seep in a western group. At the present time the spring waters are not used, and one cannot accurately determine how and where the spring waters were used originally. It appears that when the resort area was in operation, waters from the central group, located on a large travertine mound, were piped to the mineral baths and swimming pool area. Resulting development of the area has reduced the many springs around the travertine mound to just one seep and the main spring, which flows into a concrete-lined cistern.

GEOLOGY AND HYDROLOGY: The waters of all the springs are quite similar. The temperature of the springs is 60°C, and the total dissolved solids content is approximately 650 mg/l (varies slightly throughout the year's time). The waters are a sodium bicarbonate type.

Spring A, which is actually a well, (Fig. 71) has the largest discharge of all the springs. Its discharge ranges between 70 and 167 gpm throughout the year. Spring A comprises almost all of the discharge of the easternmost group of three springs. The other two are seeps having a discharge of 1 to 2 gpm. Spring D, (Fig. 72) which is the large spring flowing into the concrete-lined cistern in the center group, has an estimated discharge of 5 gpm.

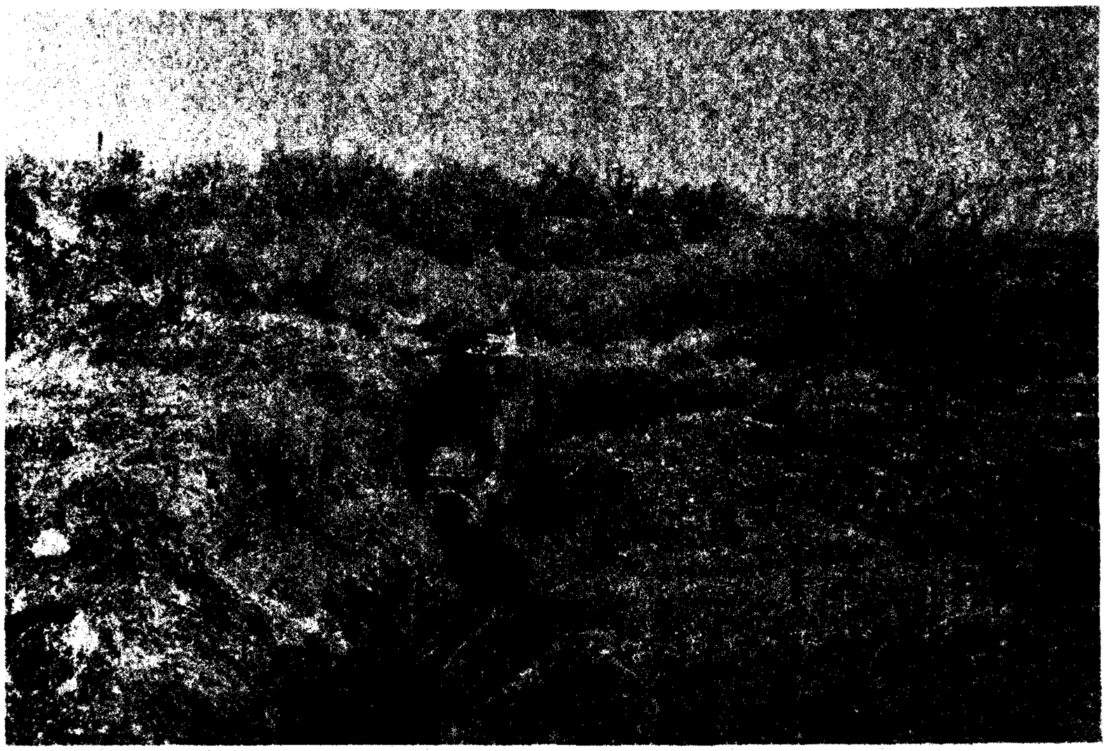


Figure 71.--Mineral Hot Springs, Spring A.

The Mineral Hot Springs are located in the northern end of the San Luis Valley, a part of the Rio Grande rift zone. There are no surface expressions of any fault systems crossing this area. However, several authors have projected one and possibly two faults in the vicinity of the springs (Fig. 73). It has been postulated that a northwest-trending fault extends from the Bonanza area as far east as the Mineral Hot Springs area. This theory was confirmed by students from the Department of Geophysical Engineering, Colorado School of Mines, who conducted a geophysical investigation in this area during the summer of 1977. Their work confirmed that the springs are located at the intersection of two fault zones (Dr. George Keller, 1977, oral communication). During the course of their investigation a small-diameter hole, located almost due west of Spring A and due north of Spring D, was drilled to a depth of 320 ft. This well encountered ground waters under artesian conditions. The flow of the well established at 2 to 5 gpm, and the waters had a temperature of 38°C. The thermal waters appear to be narrowly restricted for less than 1/2 mile to the east of the Spring A there is a cold ground-water well.

The area is underlain by thick valley-fill alluvium. Dr. George Keller (1977, oral communication) reported that the 1977 geophysical investigations showed up to 5,000 ft of alluvium just a few hundred feet north of the springs. At Spring D the bedrock is very close to the surface, thus implying a rapid southwest elevation of the bedrock surface or a large normal fault.

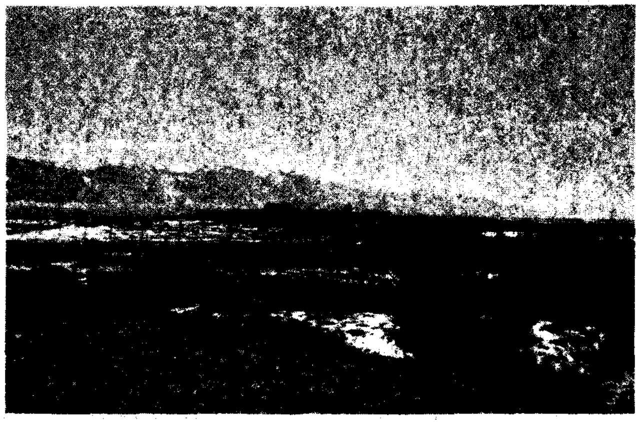
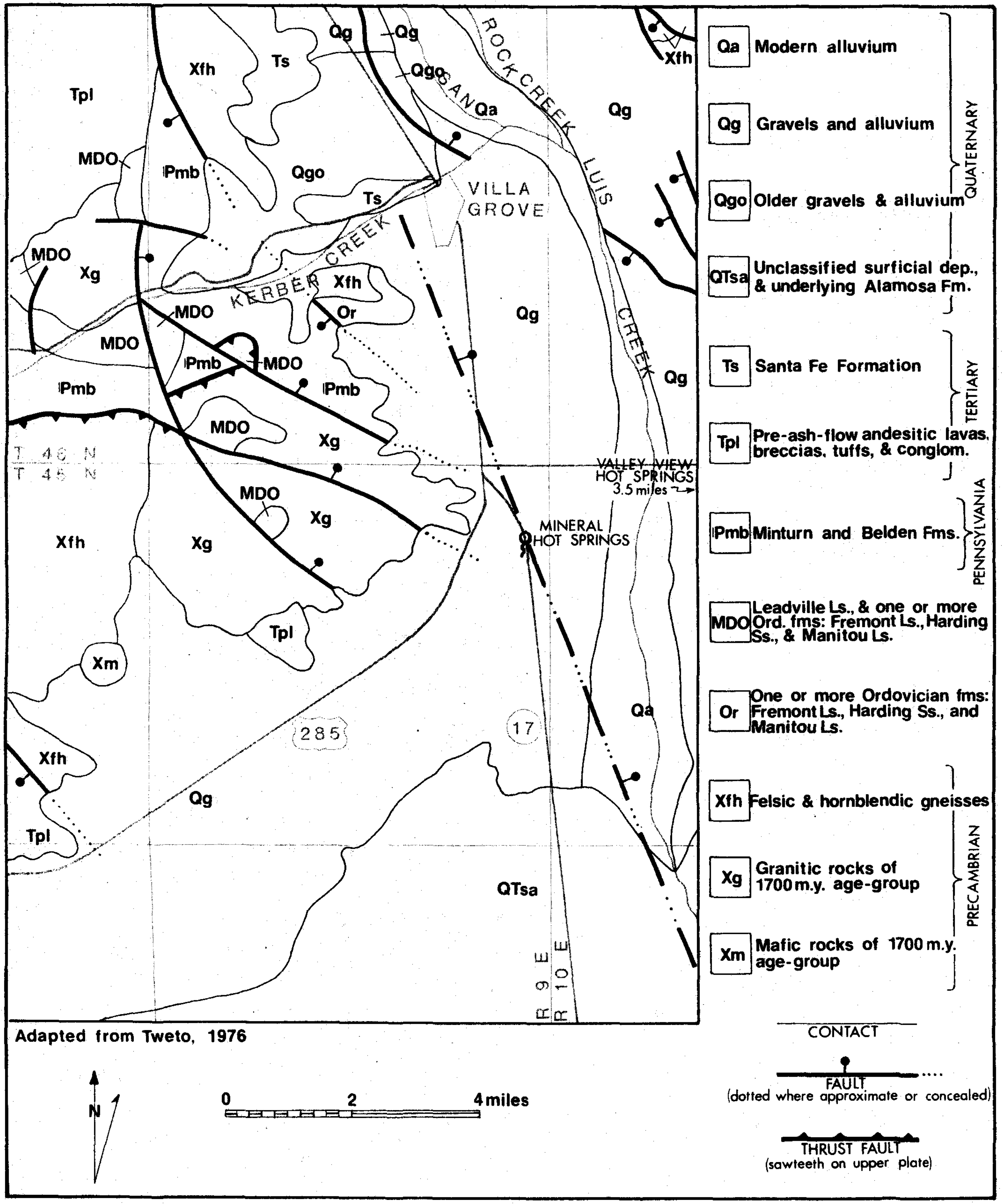


Figure 72.--Mineral Hot Springs, Spring D.



Adapted from Tweto, 1976

Figure 73.--Geologic map of Mineral Hot Springs area.

In addition to the geophysical investigations by the Colorado School of Mines in 1977, the Colorado Division of Water Resources did extensive geophysical and test drilling in the vicinity of Mineral and Valley View Hot Springs during the winter and summer of 1976. Their investigation showed that the valley floor is approximately 5,000 ft deep in the vicinity of Mineral and Valley View Hot Springs and is cut by numerous high angle normal faults (John Romero, 1976, oral communication).

The investigations of the Colorado Division of Water Resources were funded by a U.S. Geological Survey grant. The results of their investigations will be published later either in various journals or in a Division publication (John Romero, 1977, personnel communication).

It is believed that the Mineral Hot Springs represent deep circulation of ground waters through fault zones in a region of above-normal heat flow (Reiter, 1975). Another possible explanation for this thermal spring is the upward welling of ground waters along a fault zone that blocks the normal south-southeast flow in a region of above-normal heat flow.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Review of silica solubility and temperature relationships for the Mineral Hot Springs suggest that chalcedony may control the silica content of Spring A. Therefore, the chalcedony-silica geothermometer was used. This geothermometer yielded a temperature estimate of 67°C to 72°C.

Mixing Model: Since temperature-dependent equilibration between chalcedony apparently controls the silica content of the artesian well, the chalcedony mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 79°C to 93°C with a cold water fraction of 30 to 43 percent of the total flow.

The cold-water data used in this calculation (T: 11°C, SiO_2: 19 mg/l, Table 6) may not reflect the actual ground water conditions at depth. Klein (1976) states that ground water in the San Luis Valley area has an exceedingly high silica content. If this is true and the assumed silica ground water is below the actual concentration, then the subsurface temperature and cold-water-fraction estimates are too high.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 195°C to 206°C and 87°C to 92°C, respectively. The Na-K geothermometer estimate is too high because the value of the term log $\sqrt{Ca}/Na$ is greater than 0.5. Large travertine mounds and calcium carbonate-depositing springs suggest that both the Na-K and Na-K-Ca geothermometer estimates are too high.

Conclusion: The insignificant variation in flow, mineral content, temperature of the springs and artesian wells in this area suggests that they are not materially affected by seasonal metereological conditions. Moreover, the fluctuation of the various geothermometer estimates is well within the range of values that could result from normal analytical error.

The mixing model, and the silica and Na-K-Ca geothermometers predict that the temperature at depth in this area is between 70°C and 90°C (Table 4).

#32 VALLEY VIEW HOT SPRINGS (ORIENT HOT SPRINGS)

LOCATION: Latitude: 38°11'32"N.; Longitude: 105°48'49"W; T. 46 N., R. 10 E Sec. 36 db, N.M.P.M.; Saguache County; Valley View Hot Springs 7 1/2-minute topographic quadrangle map.

GENERAL: The Valley View Hot Springs, also known as the Orient Hot Springs, are located on the east side of the San Luis Valley east of Villa Grove. Access is via a dirt road east from U.S. Highway 285, 4.5 miles south of Villa Grove. The springs are approximately 7 miles east of U.S. Highway 285. The area around these thermal springs is relatively undeveloped, with the waters being used for bathing purposes by those camping in the area.

The springs are found in two groups a lower group consisting of three springs, and an upper group of one spring. Waters from the largest spring in the lower group were once piped to a large swimming pool. After this pool collapsed in 1974 or 1975, a crude dirt-embankment swimming pool was constructed over Spring A (Fig. 74). Spring B, in the lower group and located approximately 50 yd south of A, is a small rock-ringed pool. Spring C is located several yards south of B on a hillside.

Spring D, the upper spring (Fig. 75), is several hundred feet in elevation above Spring A and is reached by a 0.5-mile walk along a well-marked trail leading southeast from Spring A.

GEOLOGY AND HYDROLOGY:

Spring A: Temperature of this spring varied throughout the year's time from 35°C to 37°C. The discharge of the spring was estimated at 60 gpm. The total dissolved solids in the water are 234 mg/l to 252 mg/l. The waters are a calcium bicarbonate-sulfate type.

Spring B: This spring has a temperature of 32°C, and the discharge was not determined. The total dissolved solids in the water are 234 mg/l, and the waters are a calcium bicarbonate type.

Spring C: Not sampled.

Figure 74.--Spring A at Valley View Hot Springs.

Spring D: The temperature of this spring varied throughout the year from 34°C to 36°C. The discharge also varied from 75 to 120 gpm. The total dissolved solids in the water varied from 223 mg/l to 247 mg/l. The waters are a calcium-bicarbonate type.

The waters are associated with the Valley View Fault zone which traverses the east side of the valley in this location (Fig. 76). The bedrock of the area is the Pennsylvanian Minturn and Belden Formations. As shown on Figure 76 these formations are truncated at the Valley View Springs by the Valley View Fault zone along the west side of the Sangre de Cristo Range.

Recent work by John Romero and associates from the Colorado Division of Water Resources showed that the bedrock floor of the valley here is extensively cut by high-angle normal faults, one of which is the Valley View Fault. Reiter (1975) showed the San Luis Valley to have a heat flow in excess of 2.0 heat flow units. Recharge to these springs is probably normal ground waters of the valley that enter the fault zone and then circulate deeply.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Review of the silica solubility and temperature relationships for this system suggests that chalcedony controls the silica content of the hot springs. Therefore, the chalcedony-silica geothermometer was used to estimate the subsurface temperatures. The estimated subsurface temperature with this model is 25°C to 34°C (Table 4). Although this estimate is below the surface temperature of the springs (34°C-37°C), it is within the margin of error inherent in the geothermometer technique.

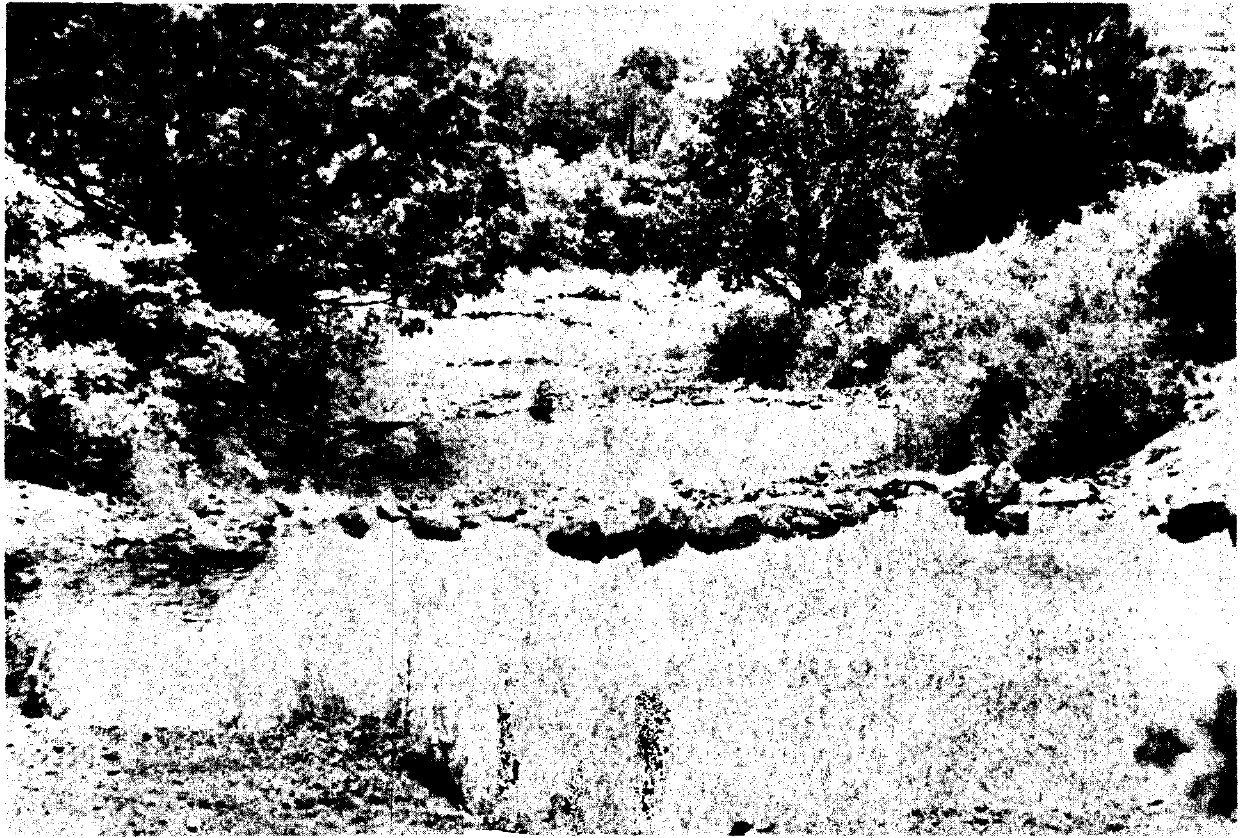


Figure 75.--Spring [illegible] at Valley View Hot Springs.

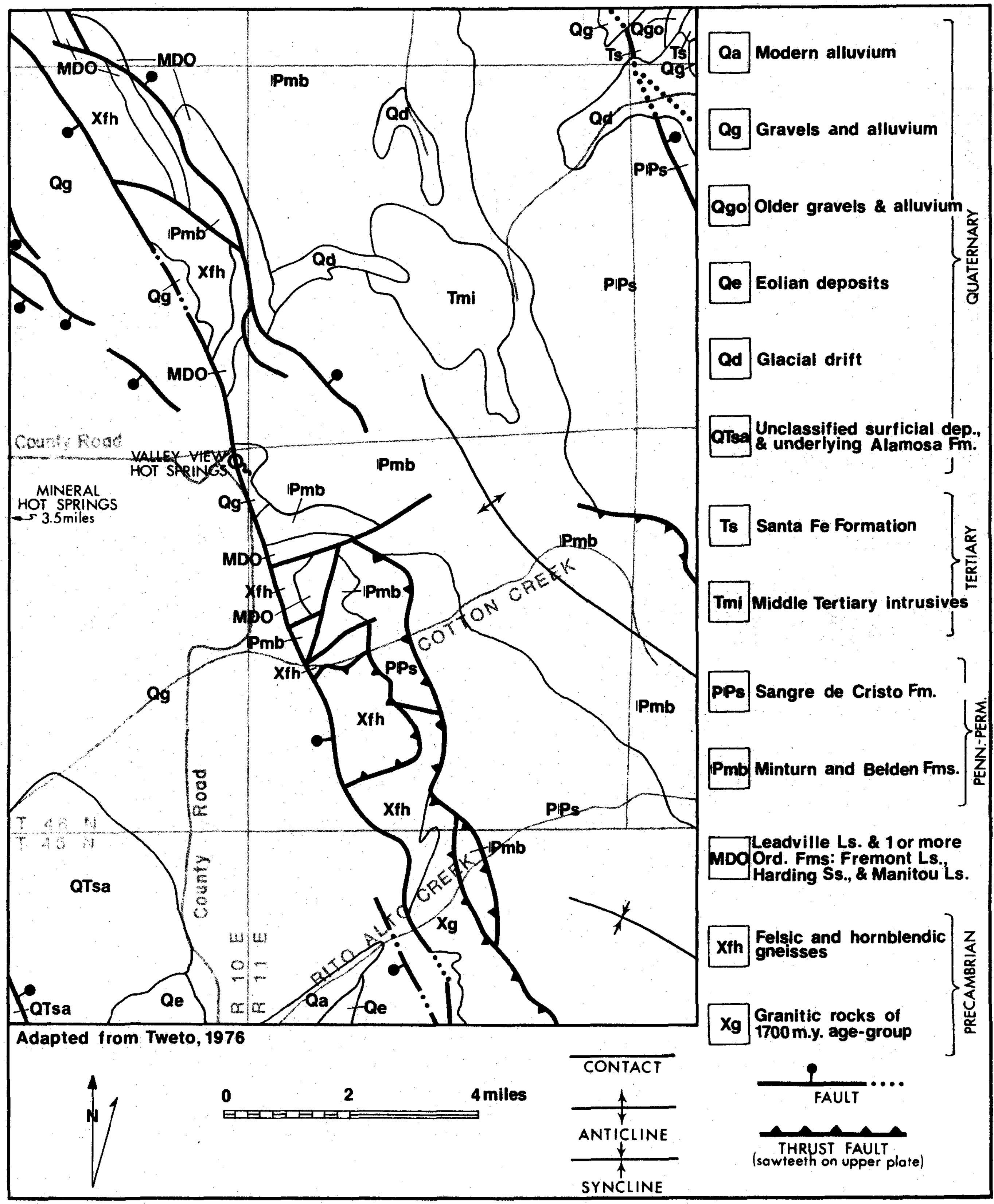


Figure 76.--Geology of Valley View Hot Springs area.

Mixing Model: Since temperature-dependent equilibration between the thermal water and chalcedony apparently controls the silica content of the springs, the chalcedony mixing model is applicable. This mixing model analysis yields a subsurface temperature estimate of 29°C to 37°C, with a cold water fraction of 4 to 33 percent of the spring flow (Table 4).

The cold-water data used in these calculations (Temp.: 6°C; SiO_2: 15 mg/l (Table 6)) may not reflect the actual ground water conditions at depth. Klein (1976) states that ground waters in the San Luis Valley area have exceedingly high silica content. If the assumed silica content of the cold ground waters is below the actual concentration, then the subsurface temperature and cold water-fraction estimates will be too high.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 338°C to 389°C and 10°C to 16°C, respectively. The Na-K geothermometer estimate is too high because the value of the term log Ca/Na is greater than 0.5. The Na-K-Ca geothermometer estimate is obivously incorrect since it is below the surface temperature of the warm springs. This result may be due to the excesssive solution of calcium carbonate by the thermal waters during ascent through numerous caliche zones recently discovered by personnel from the Colorado Division of Water Resources (John Romero, 1976, personal communication).

Conclusion: The high flow rate (250 gpm) and the excellent agreement between the theoretical chalcedony-induced solubility and the silica content of the springs suggest that the temperature at depth in this area is not much greater than the surface temperature. Therefore, the temperature at depth in this area is probably between 40°C and 50°C (Table 4).

#33 SHAWS WARM SPRING

LOCATION: Latitude: 37°45'01"N.; Longitude: 106°19'01"W.; T. 41 N., R. 6 E., Sec. 33 dd, N.M.P.M.; Saguache County; Twins Mnts. SE 7 1/2-minute topographic quadrangle map.

GENERAL: This spring is located approximately 6 miles north of Del Norte. Access is northeast from Del Norte on Colorado Highway 112 for approximately 3.25 miles to the intersection with a dirt road. Turn north on this road and proceed approximately 2.5 miles to a road leading west to some houses and a swimming pool. The spring, located several hundred feet northwest of the swimming pool, is enclosed and inaccessible. Sampling and measuring the waters was achieved by draining the swimming pool and measuring the rate of flow into the pool. The waters are only used in the private swimming pool.

GEOLOGY AND HYDROLOGY: Temperature: 30°C; Discharge: 34 to 50 gpm; Total dissolved solids range from 398 to 424 mg/l; Water is a sodium-bicarbonate type.

This spring is located on the west side of the San Luis Valley and the Rio Grande Rift zone. As shown on the accompanying geologic map (Fig. 77) the bedrock of the area is a complex assemblage of volcanic rocks related to the Summer Coon Volcano and other centers of volcanic activity in the area. All the rocks erupted from the Summer Coon Volcano have been included in the Conejos Formation by Lipman and others (1970).

The geology of the region has been described in detail by Lipman (1968) and Mertzman (1971). As described by these two authors the spring is located well down on the lower southeast flank of the Summer Coon Volcano.

The bedrock of the area is an assemblage of volcanic rocks, tuffaceous sandstones and conglomerates (Fig. 77). Mertzman (1971) noted that the Summer Coon Volcano was active 31.1 to 34.7 million years ago (late Paleocene) and that the volcano became extinct by the time the Rio Grande depression began in early Miocene time.

One fault exists approximately 0.5 mile to the northeast of the spring site, but probably has not affected the occurrence of the spring. It is believed that the waters move downdip through permeable interflow units until they emerge at this site. Recharge probably occurs in the higher ground to the west, and the heat source is probably residual Tertiary volcanic activity in the area.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Review of silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and the amorphous silica may control the silica content of the warm spring.

The amorphous silica geothermometer subsurface temperature estimate is 2°C to 17°C, which is well below the surface temperature of the warm spring (30°C). This low temperature estimate may be caused by mixing of ascending thermal water and dilute ground water or silica precipitation at depth.

Mixing Model: Since temperature-dependent equilibration between the thermal water and amorphous silica may control the silica content of the warm spring, the amorphous silica mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 26°C to 28°C with a cold-water fraction of 19 to 32 percent of the spring flow (Table 4).

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 98°C to 101°C and 83°C to 104°C, respectively. These results are unreliable because the low discharge (45 gpm) and surface temperature (30°C) of this spring are well below the minimum conditions specified for the application of these geothermometers.

CONCLUSION: Geothermometers should be used with caution when applied to Shaw's Warm Spring because most of the assumptions inherent in their use are violated. From review of all data it is believed that the most likely subsurface temperature in this area is between 30°C and 60°C (Table 4).

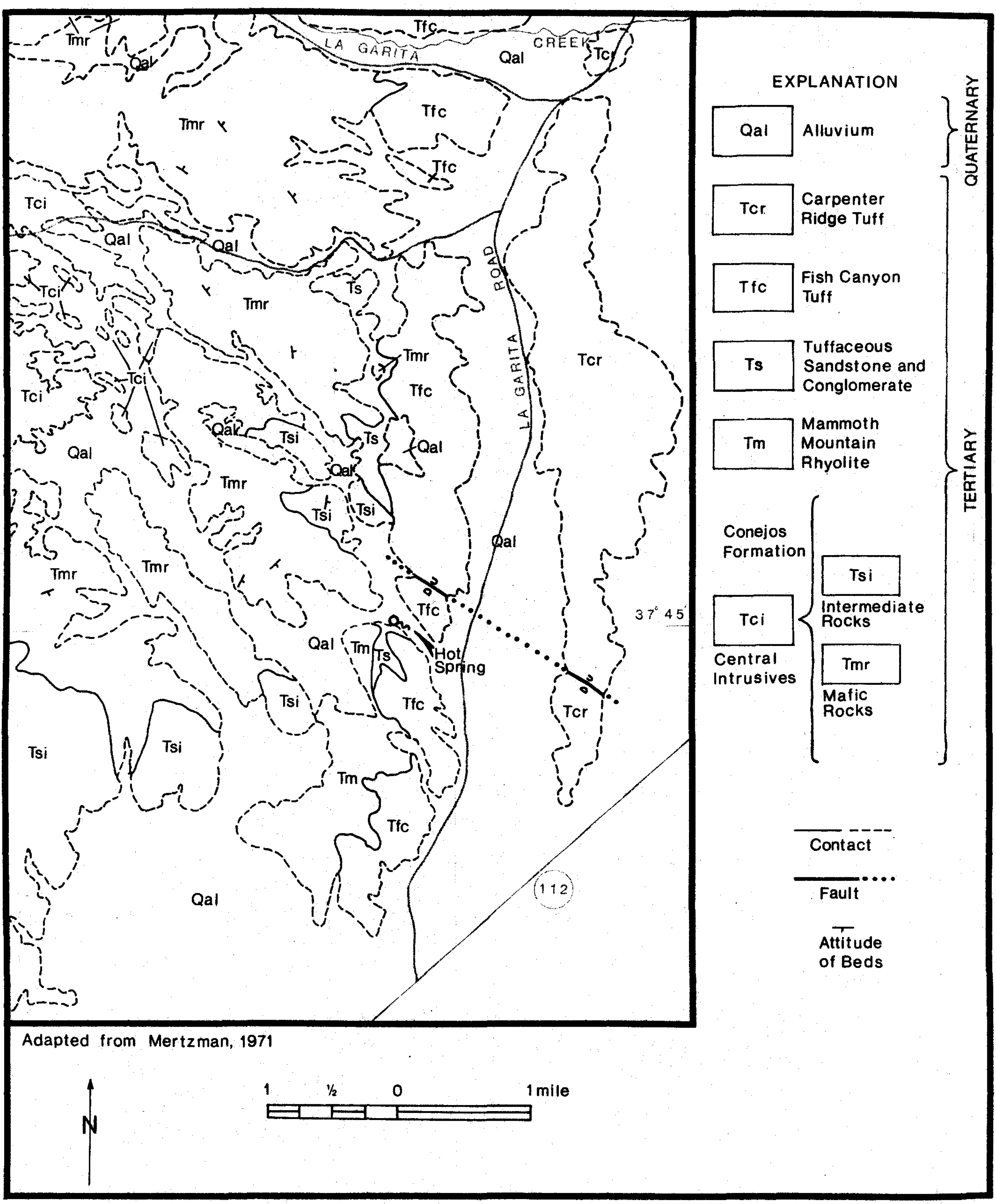


Figure 77.--Geology of Shaws Warm Spring.

#34 SAND DUNES SWIMMING POOL HOT WATER WELL

LOCATION: Latitude: 37°46'42"N.; Longitude: 105°51'20"W.; T. 41 N., R. 10 E., Sec. 27 aa, N.M.P.M.; Alamosa County; Deadman Camp 7 1/2-minute topographic quadrangle map.

GENERAL: This 4,400-ft-deep well is located northeast of Hooper in the San Luis Valley. The well may be reached by Colorado 17 north from Hooper for 1 mile, east on county highway 122 for 1 mile, then north for 1 mile to the well. The well is located west of the road and east of the house (Fig. 78). The thermal waters are used to heat a house and catfish tanks. Until recently (1977) the waters were also used in the swimming pool, but this use has been discontinued. Of the two wells present, the north well is hot, and the south well is cold. The hot well was sampled at the discharge pipe by the pump.

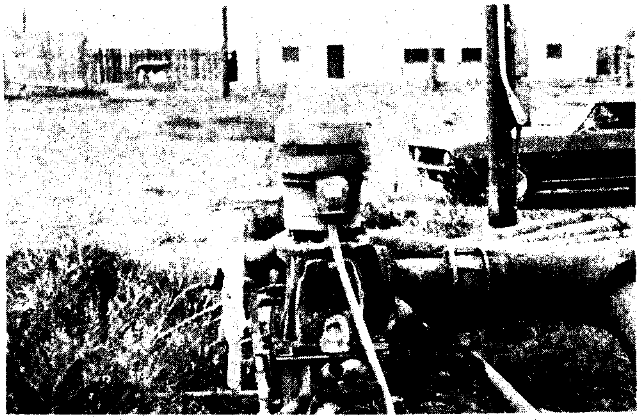


Figure 78.--Sand Dunes Swimming Pool Hot Water Well.

GEOLOGY AND HYDROLOGY: The temperature of the thermal waters was 44°C, with a total dissolved solids of 334 mg/l. The waters are a sodium bicarbonate type with a high silica content.

Chapin (1971), Emery (1971), Emery and others (1971), and Stoughton (1977) have presented detailed discussions of the geology and hydrology of the San Luis Valley and the Rio Grande Rift zone. As shown by Gacia and Karig (1966) and Stoughton (1977) this well is approximately located over the deepest part of the San Luis Valley. Gacia and Karig (1966) showed that the deepest part of the basin contained up to 30,000 ft of valley-fill sediments. Later work by Stoughton (1977) has revised this figure to a maximum of approximately 20,000 ft of valley fill sediments. A deep oil well test was drilled in 1974 in T. 40 N., R. 12 E., Sec. 32, bd, N.M.P.M. by Mapco and Amoco. This well was drilled to a depth of 9,480 ft and had a bottom-hole temperature of 128°C. The geothermal gradient in the well was 38.8°C/km (3.1°F/100 ft). Reiter (1975) has determined that this part of the San Luis Valley has a heat flow of 2.4 heat flow units.

From analysis of all published data it is believed that these thermal waters occur as a result of normal movement of ground water from west to east in the San Luis Valley in an area of above-normal heat flow. While no faults have been mapped in the vicinity, it is believed that the waters are fault controlled.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and amorphous-silica controls the silica content of the hot well. Therefore, the amorphous silica geothermometer yields the most reliable temperature estimate. The amorphous silica geothermometer subsurface temperature estimate is 26°C (Table 4).

Mixing Model: Since temperature-dependent equilibration between the thermal water and amorphous silica may control the silica content of the well, the amorphous silica mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 39°C with a cold-water fraction of 19 percent of the spring flow (Table 4).

The cold water data used in these calculations (T:6°C, SiO^2: 25 mg/L, from Table 6) may not reflect the actual ground water conditions at depth. Klein (1976) states that ground water in the San Luis Valley has an exceedingly high silica content. If the assumed silica content of the cold ground water is below the actual concentration, then the subsurface temperature and cold water-fraction estimates are too high.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 205°C and 187°C, respectively (Table 4).

Conclusion: Geothermometer models yield questionable results when applied to this thermal well because most of the assumptions inherent in their use are violated. The complex geochemistry of this well does not allow an accurate estimation of the subsurface temperature.

#35 SPLASHLAND HOT WATER WELL

LOCATION: Latitude: 37°29'19"N.; Longitude: 105°51'27"W.; T. 38 N., R. 10 E., Sec. 34 dd, N.M.P.M.; Alamosa County; Alamosa East 7 1/2-minute topographic quadrangle map.

GENERAL: This 2,000-ft-deep well is located approximately 200 yards southwest of the Splashland Swimming Pool, 1 mile north of Alamosa on State Highway 17. The waters are used for recreational purposes in the swimming pool.

GEOLOGY AND HYDROLOGY: The waters have a temperature of 40°C and contain 311 mg/l of dissolved elemental mineral matter. The waters are a sodium bicarbonate type. The waters are associated with the valley-fill sediments of the San Luis Valley. Recharge occurs along the west side of the valley with the waters migrating to the east in the subsurface in an area of above-normal geothermal gradients (Reiter, 1975).

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Calculation of the silica solubility showed that amorphous silica controls the silica content of the well. The amorphous-silica geothermometer model yielded a subsurface temperature estimate of 22°C (Table 4).

Mixing Model: Since temperature-dependent equilibration between the thermal equilibration between the thermal water and amorphous silica may control the silica content of the well, the amorphous silica mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 35°C with a cold water fraction of 23 percent of the spring flow (Table 4).

The cold water data used in these calculations (T: 6°C, SiO_2: 25 mg/l Table 6) may not reflect the actual ground-water conditions at depth. Klein (1976) states that ground water in the San Luis Valley has an exceedingly high silica content. If the assumed silica content of the cold ground water is below the actual concentration, then the subsurface temperature and cold water-fraction estimates are too high.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 221°C and 197°C, respectively (Table 4).

Conclusion: Geothermometer models yield questionable results when applied to this thermal well because most of the assumptions inherent in their use are violated. From review of all data it appears that the subsurface temperature in this area is probably between 40°C and 100°C (Table 4).

DEXTER AND McINTYRE WARM SPRINGS

Located on the north side of the San Luis Hills in the southern end of the San Luis Valley are two springs, Dexter and McIntytre, whose occurrence and characteristics are nearly identical. As these springs appear so nearly identical, they will be discussed together.

#36 DEXTER WARM SPRING

Location: Latitude: 37°17'41"N.; Longitude: 105°47'05"W.; T. 35 N., R. 11 E., Sec. 8 ada; Conejos County; Pikes Stockade 7 1/2-minute topographic quadrangle map.

GENERAL:. This group of several unused springs and seeps is located in a marshy area (Fig. 79) on the north side of the San Luis Hills and on the south side of the Conejos River. The springs are reached by going east from Sanford on Colorado Highway 142 for 7.1 miles to a dirt road. Turn north on this road and go approximately 1.75 miles to the springs.

The springs have a temperature of 20°C with a combined discharge of just over 5 gpm. The waters contain 195 mg/l of dissolved solids and are a sodium-bicarbonate type.

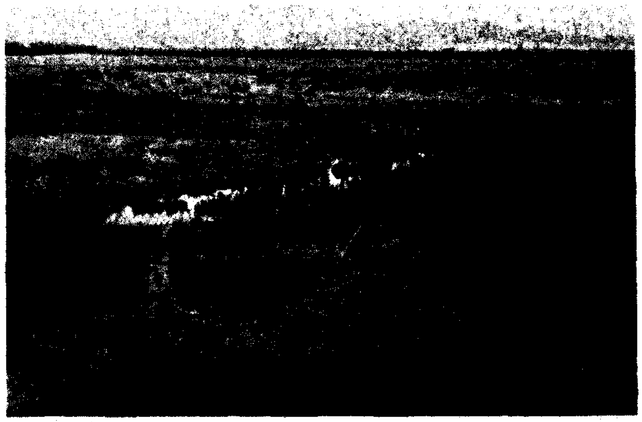


Figure 79.--Photo of Dexter Warm Spring.

#37 McINTYRE WARM SPRING

LOCATION: Latitude: 37°16'48"N.; Longitude: 105°49'07"W.; T. 35 N., R. 11 E., Sec. 18 bcb, N.M.P.M.; Conejos County; Pikes Stockade 7 1/2-minute topographic quadrangle map.

GENERAL: These 10 to 15 unused springs are located on the south bank of the Conejos River south of Alamosa in the San Luis Valley. Access is via a paved county road for 5.3 miles east from Sanford, Colorado, then north and east on a dirt trail for approximately 1 mile. If the Conejos River is at low-flow stage, access may be made by fording the river at Pikes Stockade, and following the dirt road for approximately 1.5 miles southwest to the springs.

While the temperature of these springs (10 to 14°C) is below the minimum temperature used during this investigation, these springs were sampled and measured because of their association with the nearby Dexter Warm Springs. Due to the amount of surface water flowing through the area, it was not possible to measure the discharge of the springs, but it appears to be large. The waters contain 165 mg/l of dissolved solids and are a calcium-bicarbonate type.

GEOLOGY AND HYDROLOGY OF DEXTER AND McINTYRE WARM SPRINGS: As the geological and hydrogeological conditions surrounding each spring are nearly identical, they will be discussed together. The springs are located on the north side of the San Luis Hills and emerge from sediments of the Santa Fe Group (Fig. 80). The San Luis Hills consist of a series of middle to late Tertiary lava flows that rise prominently above the flat surface of the San Luis Valley. The geology of this area has been described in detail by Burroughs (1971). While no faults are shown on the geologic map (Fig. 80), it appears from Burroughs' description that the springs are probably associated with faulting on the north side of the hills.

The origin of the heat for the thermal waters is in doubt but appears to be related to the Pliocene volcanic activity that took place in this area (Burroughs, 1971). Reiter (1975) has mapped the San Luis Valley as having heat flow above 2.5 heat flow units. The origin of the springs is probably due to deep circulation of ground waters in the San Luis Valley ascending through fault zones in an area of above-normal geothermal gradients.

GEOTHERMOMETER ANALYSES FOR DEXTER AND McINTYRE WARM SPRINGS:

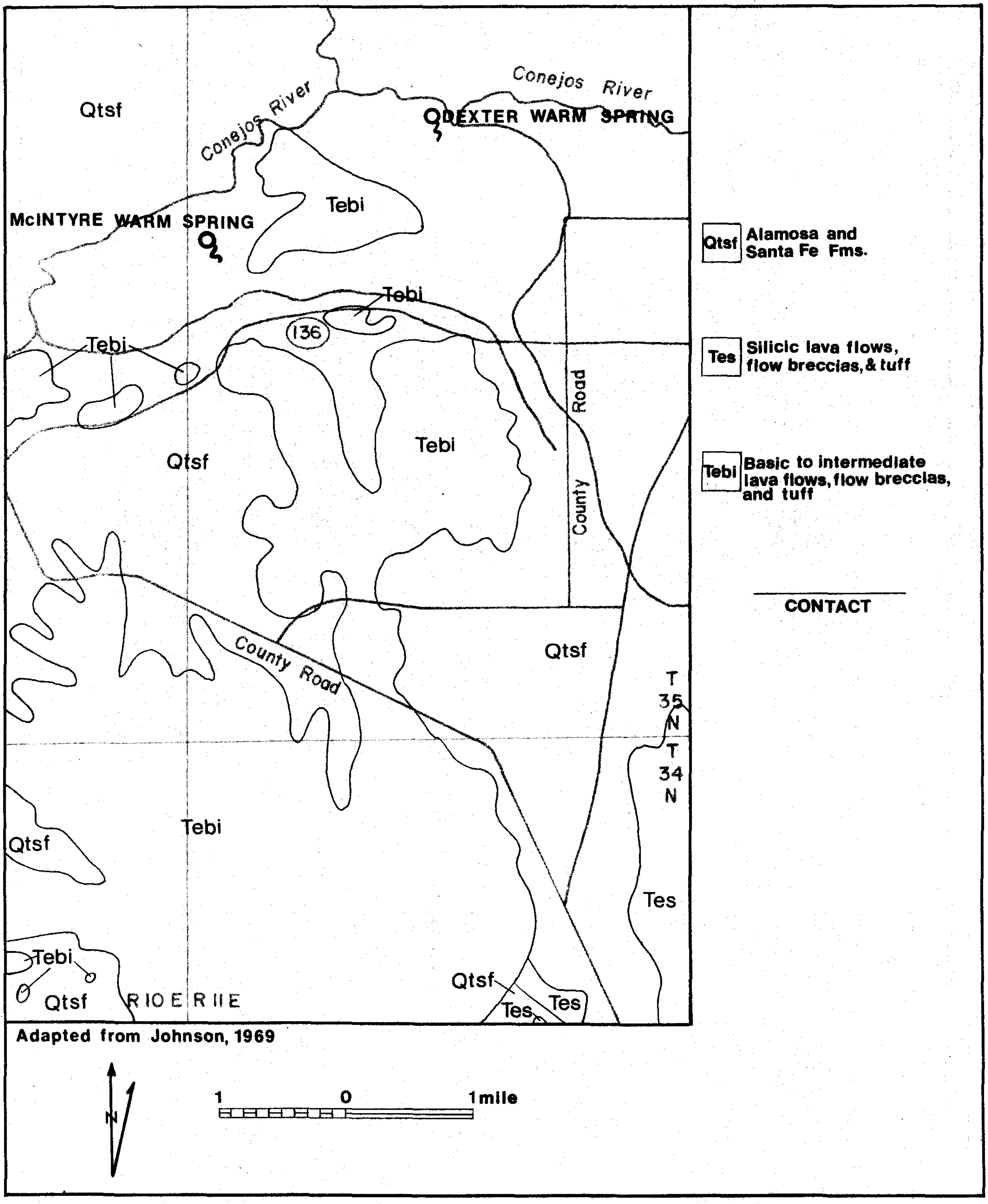
Silica Geothermometer: The silica content of these springs does not approach the solubilities of amorphous silica, chalcedony, cristobalite or quartz. Therefore, application of any of these silica geothermometers will yield unreliable results.

Mixing Model: The amorphous silica solubility at Dexter spring surface temperature (14°C to 20°C) is 94 mg/l to 106 mg/l, which is much higher than the silica content of the warm water (53 mg/l to 65 mg/l).

The amorphous-silica mixing model yields subsurface temperature estimates of 15°C to 19°C, with cold water fractions of 33 to 36 percent of the spring flow.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 278°C to 333°C and 50°C to 91°C, respectively. The Na-K geothermometer results are too high because the value of the term log $\sqrt{Ca}/Na$ exceeds 0.5. The low surface temperature of the warm springs and the lack of substantiation of such high temperatures at depth by the other geothermometers suggest that both the Na-K and Na-K-Ca results are unreliable.

Conclusion: Geothermometer models must be used with caution when applied to McIntyre and Dexter warm springs because most of the assumptions inherent in their use are violated. Any geothermometer estimate for this area is unreliable at best. However, it appears that the temperature at depth is probably between 20°C and 50°C (Table 4).



Adapted from Johnson, 1969

Figure 80.--Geology of Dexter and McIntyre Warm Springs.

#38 STINKING SPRINGS

LOCATION: Latitude: 37°02'05"N.; Longitude: 106°48'25"W.; T. 32 N., R. 1 E., Sec. 2 dd, N.M.P.M.; Archuleta County; Chromo 15-minute topographic quadrangle map.

GENERAL: These unused springs are located approximately 2 miles east of Chromo. Although marshy areas exist near these springs, only one with any distinct flow was located approximately 100 yd south of the road (Fig. 81).

Figure 81.--Stinking Springs.

GEOLOGY AND HYDROLOGY: The spring had a temperature of 27°C with a discharge of 24 gpm. The total dissolved mineral matter solids contained in the waters are 899 mg/l, and the waters are a calcium-sulfate type.

As shown on Figure 82 the springs are located on the crest of the Chromo Anticline on the trace of a small northwest trending fault. The bedrock of the area, Mancos Shale, dips to the southwest off the Continental Divide, which bounds the basin on the east side. It is believed that recharge to this spring occurs along the eastern flank of the San Juan Basin where the waters move downdip until they intersect a fault. They then migrate upward along the fault to the surface. Heating of the waters occurs because this area has above normal heat flow (Reiter, 1975).

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Review of the silica solubility and temperature relationships suggest that chalcedony may control the silica content of the warm spring. Therefore, the chalcedony-silica geothermometer yields the most reliable temperature estimate. The chalcedony-silica geothermometer estimated subsurface temperature is 39°C (Table 4).

Mixing Model: The chalcedony silica mixing model yielded a subsurface temperature estimate of 59°C with a cold water fraction of 61 percent of the spring flow (Table 4). These estimates may be too high because the water sample was taken from a large quiescent pool which might allow evaporative concentration of silica.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 39°C and 41°C, respectively. The Na-K geothermometer estimate is definitely too high because the value of the term log $\sqrt{Ca}/Na$ exceeds 0.5. The Na-K-Ca geothermometer estimate appears to be reasonable and is substantiated by both the mixing model and silica geothermometer.

Conclusion: Geothermometer models must be used with caution when applied to Stinking Springs because most of the assumptions inherent in their use are violated. Moreover, samples of the thermal water had to be taken from a large, quiescent pool. Such sampling situations may exagerate the effects of the surface conditions on the thermal water allowing evaporative concentration of silica and other re-equilibration reactions to occur.

In light of the excellent agreement between the mixing model and the silica and Na-K-Ca geothermometers the subsurface temperature in this area is probably between 40°C and 60°C (Table 4).

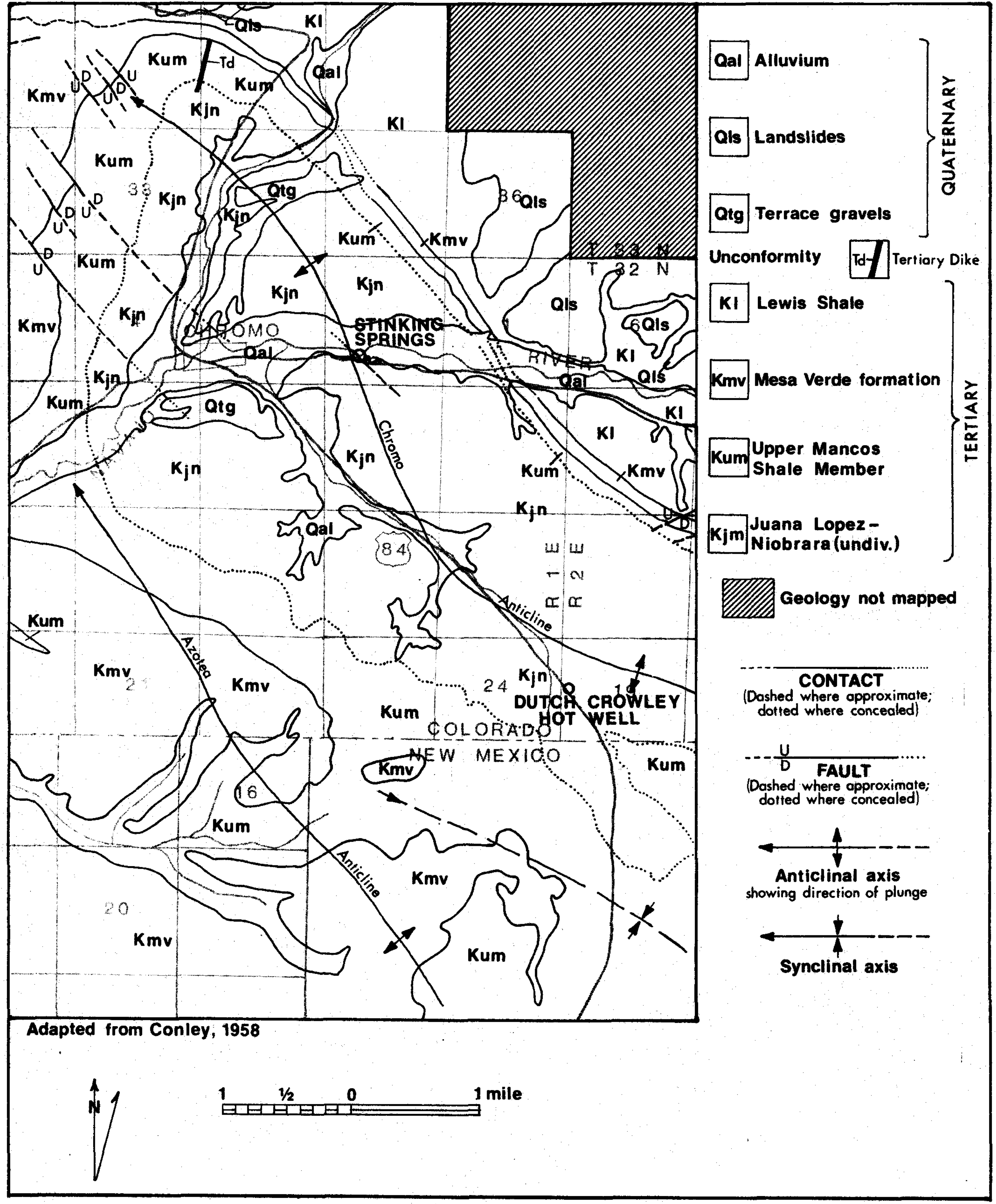


Figure 82.--Map showing geologic conditions around Stinking Springs and Dutch Crowley Artesian Well.

#39 DUTCH CROWLEY ARTESIAN WELL

LOCATION: Latitude: 37°00'01"N.; Longitude: 106°47'03"W.; T. 32 N., R. 2 E., Sec. 18 bbb, N.M.P.M.; Archuleta County; Chromo 15-minute topographic quadrangle map.

GENERAL: This artesian well, which is an old oil well test hole 1,725 ft deep, is located south of Chromo, Colorado, on the Colorado-New Mexico border. Access is via U.S. 84 south from Pagosa Springs to two miles south of Chromo where a dirt trail leads to the east. Turn left on this trail and proceed approximately 1.3 miles until the trail turns south. The well is 0.2 mile south of this turn and approximately 1,000 feet east of the road. The well is used for irrigation purposes.

GEOLOGY AND HYDROLOGY: The waters that flow from the well with a temperature of 70°C are a sodium bicarbonate type and contain 101 mg/l of dissolved solids.

As shown of Figure 82 the well is located on the lower northeast side of the Chromo Anticline. The bedrock of the area is the Juana Lopez Member of the Mancos Shale, and other than minor faulting mapped less than one mile east of the well, no other major structural features have been mapped in the vicinity.

The general dip of the formations in this part of the San Juan basin is to the southwest off the Continental Divide, which bounds the basin on the east. Due to the depth of the well, 1,725 ft, it is believed that the waters come from the underlying Dakota Sandstone. Recharge occurs along the flanks of the Continental Divide where the waters move downdip to the southwest in an area where the heat flow is between 2.0 and 2.5 H.F.U. (Reiter, 1975).

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and chalcedony may control the silica content of the artesian well. Therefore, the chalcedony-silica geothermometer yields the most reliable temperature estimate.

The chalcedony-silica geothermometer estimate of subsurface temperature is 63°C (Table 4). Although this estimte is below the surface temperature of the artesian water (70°C), it is within the margin of error inherent in the geothermometer technique.

Mixing Model: Since temperature-dependent equilibration between the thermal water and chalcedony apparently controls the silica content of the artesian well, the chalcedony mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 65°C with a cold water fraction of 7 percent of the artesian flow (Table 4).

The mixing model should predict a cold-water fraction of 0 percent because of very little opportunity for shallow ground water perculation into a 1,741 ft deep cased well. In addition the subsurface temperature estimate should equal or exceed the surface temperature of the artesian water (70°C).

Based on the expected analytical precision, the silica content of this artesian well (41 mg/l) should vary from 36.9 to 45.1 mg/l (Table 3). If the maximum value of silica (45.1 mg/l) is inserted into the mixing model calculation, the results are 70°C and 0 percent. Therefore, the apparent discrepancy between the expected and actual mixing model results is probably due to analytical error in determining the silica content of the thermal water.

Na-K and Na-K-Ca Geothermometer: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 271°C and 16°C, respectively (Table 4). The Na-K geothermometer esimate is too high because the value of the term log $\sqrt{Ca}/Na$ exceeds 0.5. The Na-K-Ca geothermometer estimate is obviously wrong since it is below the surface temperature of the artesian well. This result may be due to the excessive solution of calcium carbonate by the thermal water during ascent through the anhydrite deposits of the Todilto Limestone.

Conclusion: The rapid flow rate (75 gpm) and the excellent agreement between the mixing model and silica geothermometer suggests that the subsurface temperature is near the surface temperature of the artesian well. Therefore, the temperature at depth in this area is probably between 70°C and 80°C (Table 4).

#40 EOFF ARTESIAN WELL

LOCATION: Latitude: 37°11'26"N; Longitude: 106°59'36" W.; T. 34 N., R. 1 W.; Sec. 7 cdc, N.M.P.M.; Archuleta County; Chromo 15-minute topographic quadrangle map.

GENERAL: This unused, 2,998-ft-deep oil-well test hole is located south of Pagosa Springs. Access is via U.S. Highway 84 south from Pagosa Springs for 5.8 miles, then west on a gravel road for 0.5 mile to a farmhouse. The well is 3.5 miles west of the house along Squaw Canyon.

GEOLOGY AND HYDROLOGY: The waters from this well have a temperature of 39°C and an estimated discharge of 50 gpm. The waters were not sampled for complete analysis of contained mineral matter, but the field measurement of the conductance was 2,500 micromhos, with a pH of 7.0.

This well is located on the east side of the San Juan Basin. The Colorado portion of the basin is bounded on the north and east by the San Juan Mountains and on the south by the Colorado-New Mexico state line. While the central portion of the basin consists of sedimentary formations dipping into the basin, the San Juan Mountains consist of a complex assemblage of varying volcanic rock types. Very little has been published on the geology of the eastern portion of the San Juan Basin. However, while not directly referring to the geologic history or conditions of the San Juan Basin, Lipman (1975) and Steven and Ratte (1960) have discussed in detail the geologic history, especially the volcanic history, of the southeastern San Juan Mountains.

Because this well is approximately 3,000 ft deep, a surface geologic map would not accurately portray the factors controlling the occurrence of the thermal waters. Therefore, no geologic map was prepared for this area.

The bedrock of the area is the Cretaceous Mancos Shale. Formations underlying the Mancos Shale from which the thermal waters could possibly come are, in descending order: Dakota Sandstone, Burro Canyon Formation and the Morrison Formation. It is believed that these thermal waters just represent circulation of ground waters in either the Burro Canyon or some of the sandstone units in the Morrison Formation in an area having above-normal geothermal gradients. Reiter (1975) has shown this area to have a heat flow of between 2.0 and 2.5 heat flow units.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Cristobalite probably controls the silica content of the artesian water. Therefore, the cristobalite-silica geothermometer model will yield the most reliable temperature estimate. This model yielded a subsurface temperature estimate of 47°C.

Mixing Model: Since temperature-dependent equilibration between the thermal water and cristobalite apparently controls the silica content of the hot well, the cristobalite mixing model is applicable. Cristobalite mixing model analysis yields a subsurface temperature estimate of 59°C with a cold water fraction of 38 percent of the total flow.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 221°C and 56°C, respectively. The Na-K geothermometer estimate is too high because the value of the term log $\sqrt{Ca}/Na$ is greater than 0.5. The Na-K-Ca geothermometer estimate is in good agreement with the mixing model results.

Conclusion: The rapid discharge of this well suggests that the temperature at depth is not much higher than the surface temperature of the thermal water (39°C). However, the mixing model and the Na-K-Ca geothermometer suggest a temperature of about 60°C. Therefore, the subsurface temperature in this area is probably between 40°C and 60°C (Table 4).

#41 PAGOSA SPRINGS

LOCATION: Latitude: 37°15'52"N.; Longitude: 107°00'37"W.; T. 35 N., R. 2 W.; Sec. 13 cd, N.M.P.M.; Archuleta County; Pagosa Springs 7 1/2-minute topographic quadrangle map.

GENERAL: This group of several springs and wells, collectively known as Pagosa Springs, are located throughout the downtown area of the town by the same name on U.S Highway 160 and 84 in the southwest part of Colorado. The major spring, Big Spring, is located across from the downtown area (Figure 83) on the south bank of the San Juan River by the Spring Inn Motel. This spring is the second largest spring in the State of Colorado.

Figure 83.--Big Spring at Pagosa Springs.

At the present time at least five producing wells and several abandoned wells are located throughout the downtown area. Thermal waters are used throughout the city for the following: recreational purposes in the swimming pool at the Spa Motel, space heating of the courthouse building, the Spring Inn Motel, the Methodist Church, the Texaco and Standard Oil gas stations west of the courthouse, and for partial space heating of the Rexall Drug store on Main Street, and the Adobe Inn.

GEOLOGY AND HYDROLOGY: Waters from the Big Spring and two wells were sampled and analyzed. Samples were collected from the edge of the Big Spring. This spring had a temperature that ranged throughout the years time from 54°C to 58°C. The discharge varied from a low of 226 gpm to a high of 265 gpm. Due to the diversion of some of the spring water, it was necessary to measure the discharge at several points and then combine them. The main flow was measured in a ditch approximately 200 ft south of the spring, while other flows were measured down along the river below the motel. The waters contain between 3,040 to 3,310 mg/l of dissolved mineral matter and are a sodium-sulfate type.

Waters from the Spa Motel's 500-ft-deep well, which were sampled at the well head, have a temperature of 53°C and contain 3,320 mg/l of dissolved solids. These waters are a sodium-sulfate type.

The Courthouse well, located behind the courthouse, was sampled at the point of outfall from the building. This well has a discharge of 30 gpm, with a temperature of 56°C. The waters contain 3,300 mg/l of dissolved solids and are a sodium-sulfate type.

As shown on Figure 84 the bedrock of the area is the Mancos Shale. Although a major fault lies approximately 1.5 mile southwest of the spring, no obvious controlling structural feature for the occurrence of this spring can be seen. Precipitation of the minerals from the waters has formed a large travertine mound around the Big Spring. The mineral matter found in the thermal waters is derived from the Mancos Shale. While not confirmed by the authors, the top of the reservoir is reported to be at a depth of 400 ft below the downtown section.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: The chalcedony-silica geothermometer yields an estimated reservoir temperature of 76°C to 81°C.

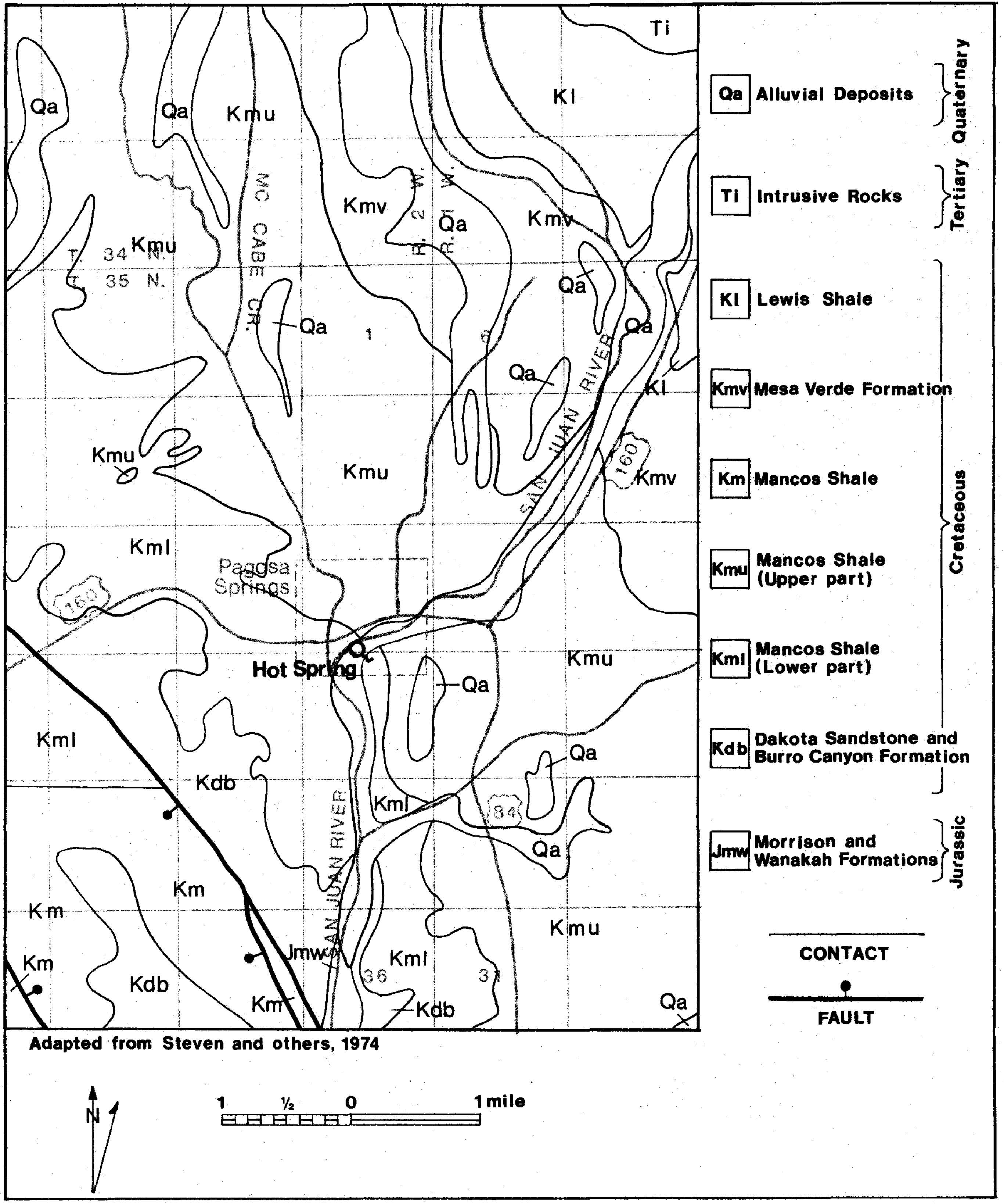
Mixing Model: The chalcedony mixing model yields a subsurface temperature estimate of 113°C to 134°C with a cold water fraction of 54 to 66 percent of the spring flow.

The seasonal flucation of the subsurface temperature estimates suggests that the assumed cold-water analysis and percent-mixing estimates do not adequately represent the hydrological conditions at depth. However, no certain conclusions can be made from these estimates because they are within the range of values that could result from normal analytical error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 207°C to 211°C and 191°C to 195°C, respectively (Table 4).

Extensive travertine deposits occur throughout this area, and the Big Spring currently deposits travertine along the south bank of the San Juan River. The presence of these deposits indicates that the Na-K and the Na-K-Ca geothermometers are too high.

Conclusion: The insignificant variation in surface temperature, mineral content and geothermometer estimates of these hot springs suggests that they are not substantially affected by seasonal meteorological conditions. Morever, the fluctuations of the various geothermometer estimates are well within the range of values that could result from normal analytical error. Consideration of the various geothermometer estimates (Table 4) and the precision of the geothermometers suggests a temperature at depth between 80°C and 150°C (Table 4).



Adapted from Steven and others, 1974

Figure 84.--Geologic map of Pagosa Springs.

#42 RAINBOW HOT SPRING

LOCATION: Latitude: 37°30'34"N.; Longitude: 106°56'52"W.; T. 38 N., R. 1 W., Sec. 9, N.M.P.M.; Mineral County; Spar City 15-minute topographic quadrangle map.

GENERAL: This unused spring is reached by walking approximately 6 miles up the West Fork of the San Juan River. Access is via a dirt road at the base of Wolf Creek Pass that turns from U.S. 160 to the West Fork Campground. Continue past the campground to the end of the road at the Borns Lake cabin area. Near this cabin area a marked foot trail leads to the spring.

GEOLOGY AND HYDROLOGY: When sampled in September 1975, the spring had a temperature of 40°C, a discharge of 45 gpm, contained 161 mg/l of dissolved mineral matter, and was a sodium-bicarbonate type.

As mapped by Steven and Lipman (1973) (Figure 85) the thermal waters emerge along a southeast-trending normal fault that closely follows the valley of Cimarron Creek and the West Fork of the San Juan River. Recharge to the spring is via deep circulation along fault zones in an area of above-normal geothermal gradients that are probably related to the Oligocene volcanic activity that occurred in this region.

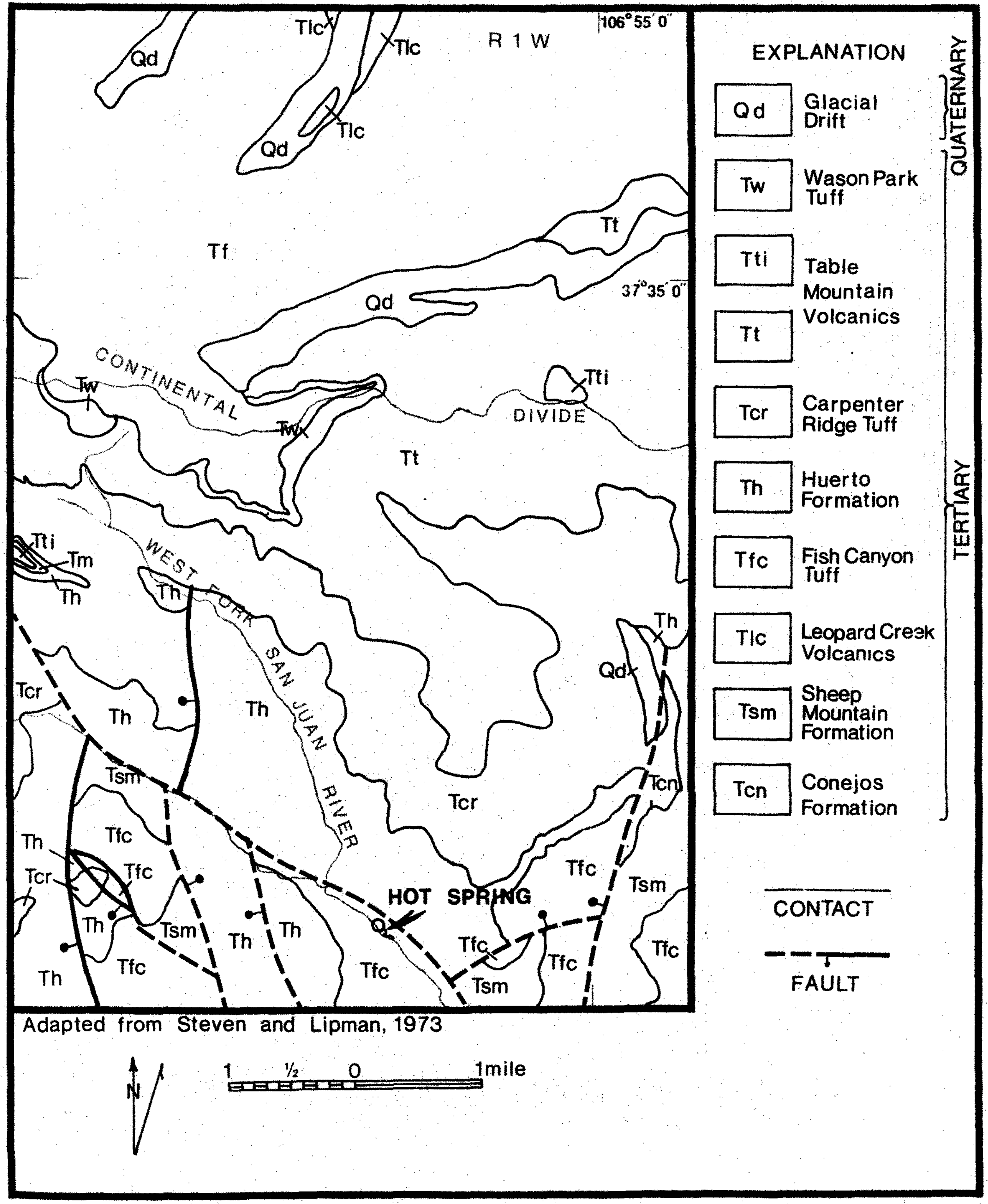
GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Analysis of silica solubility and temperature relationships suggest that cristobalite controls the silica content of the hot spring. Therefore, the cristobalite silica geothermometer was used to estimate the subsurface temperature. The cristobalite-silica geothermometer yielded an estimated subsurface temperature of 41°C, which is very close to the surface temperature of the hot spring (40°C). The high discharge (45 gpm) and the close agreement between the theoretical cristobalite-induced silica solubility (38 mg/l) and the actual silica content of the spring suggest that this geothermometer estimate is close to the actual temperature at depth.

Mixing Model: Since temperature-dependent equilibration between the thermal water and cristobalite apparently controls the silica content of the hot spring, the cristobalite mixing model was used. Cristobalite mixing model analysis yielded a subsurface temperature estimate of 41°C with no shallow, cold ground water contained within the hot spring flow (Table 4).

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 68°C and 22°C, respectively (Table 4). The Na-K geothermometer estimate is too high because the value of the term log $\sqrt{Ca}/Na$ is greater than 0.5. The Na-K-Ca geothermometer estimate is obviously incorrect because it is below the surface temperature of the hot spring. This low estimate may be due to temperature-dependent equilibration between the ascending thermal fluid and the potassium-deficient Fish Canyon Tuff, a quartz-latitic ash flow tuff.

Conclusion: The rapid flow rate and close agreement between the silica geothermometer and mixing model results suggest that the subsurface temperature is not much higher than the surface temperature in this area. Therefore, the subsurface temperature in this area is probably between 40°C and 50°C (Table 4).



Adapted from Steven and Lipman, 1973

Figure 85.--Geologic map of Rainbow Hot Springs.

#43 WAGON WHEEL GAP HOT SPRINGS

LOCATION: Latitude: 37°41'06"N.; Longitude: 106°49'47"W.; T. 41 N., R. 1 E.; Sec. 35 dd, N.M.P.M.; Mineral County; Spar City 7 1/2-minute topographic quadrangle map.

GENERAL: This group of two springs is located approximately 10 miles southeast of Creede. Access is via a dirt road from State Highway 149 approximately 0.5 mile west of the community of Wagon Wheel Gap and along the west side of Goose Creek.

Although these two springs are named for the community of Wagon Wheel Gap, they actually lie over 1 mile south of town along both sides of Goose Creek. One spring, the 4UR, is located on the 4UR Ranch, which is called the Wagon Wheel Gap Ranch on the topographic map. The other spring, here named the CFI Spring, is located on the east bank of Goose Creek approximately 200 yd south of the 4UR Spring. This unused spring is just south of the CFI Mine (Fig. 86).

The spring on the 4UR Ranch is located at the south end of the compound and west-southwest of the old bathhouse building. The spring emerges into a large concrete-lined pool (Fig. 87). Several springs flow into the pool, although the exact number is indeterminable. Since all of these springs are mixed, it was not possible to sample them individually. The waters are used in a new outdoor swimming pool and in a sauna bath.

GEOLOGY AND HYDROLOGY:

4UR Spring: The temperature of the spring varied from 55°C to 57°C throughout the year. The discharge of the spring was an estimated 30 gpm. The total dissolved mineral matter in the water also varied from 1,550 mg/l to 1,620 mg/l. The water is a sodium-bicarbonate type.

CFI Spring: The temperature of the spring varied from 48°C to 51°C throughout the year. The discharge also varied from a low of 48 gpm to 51 gpm. The dissolved elemental mineral matter varied throughout the years time from 1,470 mg/l to 1,540 mg/l. The waters are a sodium-bicarbonate type.

Figure 86.--Photo of CFI Spring at Wagon Wheel Gap.

The Wagon Wheel Gap Hot Springs are located on the southeast side of the central part of the Creede Caldera in the San Juan volcanic field. The geology of the Creede Caldera has been discussed in detail by Steven and Ratte (1973), Steven and Lipman (1973), and others. The authors have shown that this area was the center of extensive volcanic activity in Oligocene time and has had a long and varied geologic history.

While no attempt was made to describe the hydrogeological conditions of the area in detail, it is believed that the springs are recharged in the immediate vicinity where the waters move down through fault zones. The waters may be stored in some of the more permeable intervolcanic beds.

At one time the Creede Caldera may have been quite thermally active. Steven and Ratte (1973) mapped extensive travertine deposits extending from the 4UR Spring northward to the Rio Grande River, west upriver to Creede, then southwest to the edge of the Creede quadrangle. None of these deposits were mapped in the Spar City quadrangle; however, it is believed that from the nature of their occurrence in the Creede quadrangle that they may also extend into the Spar City quadrangle. Steven (1969b) described these deposits to be of cold-water origin. White (1967) on the other hand believes that they were formed by thermal waters.

As shown on the accompanying geologic map (Fig. 88), the waters of both springs emerge through alluvial deposits overlying the Creede Formation, which consists of stream, lake, and pyroclastic deposits (Steven and Lipman, 1973). As shown on the geologic map no faults were mapped in the vicinity of the CFI spring; however, one of the few faults in the area lies within a few hundred yards of the 4UR spring.

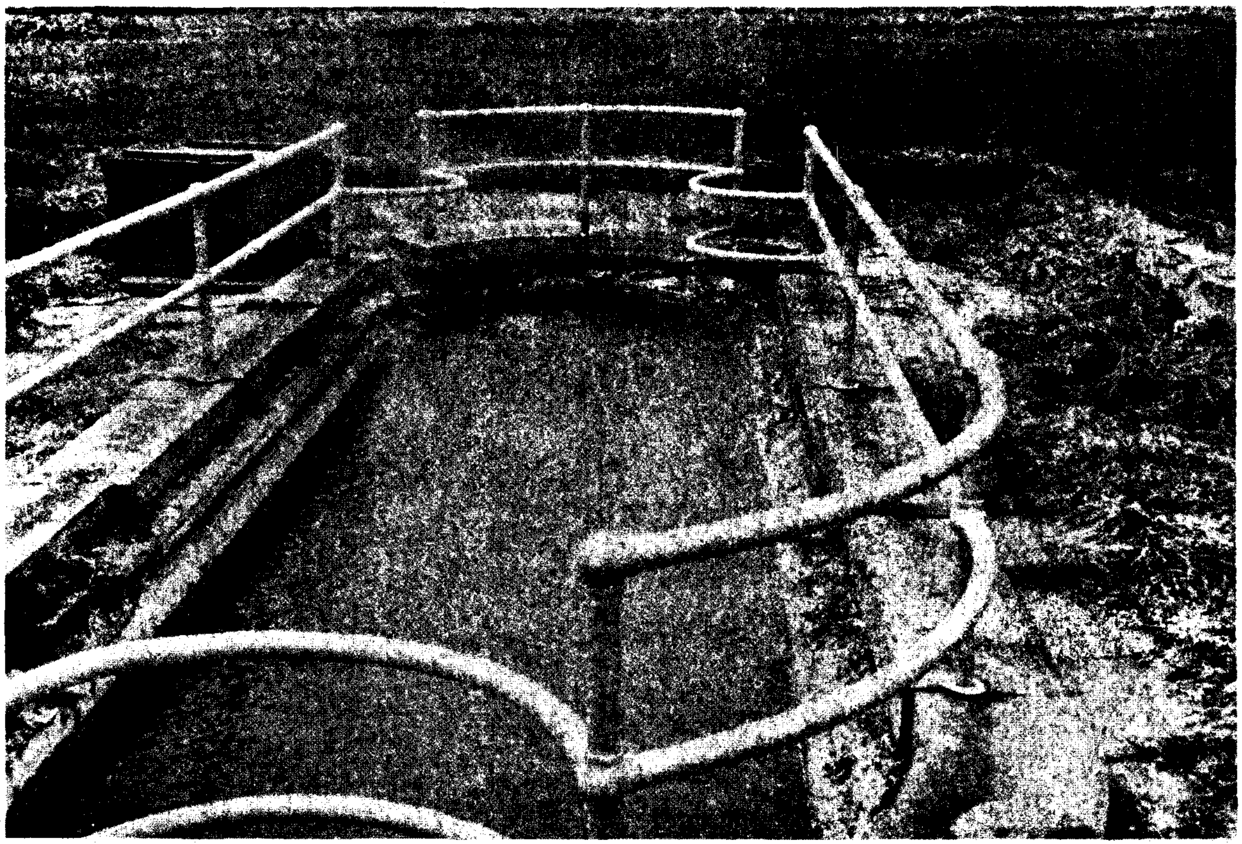
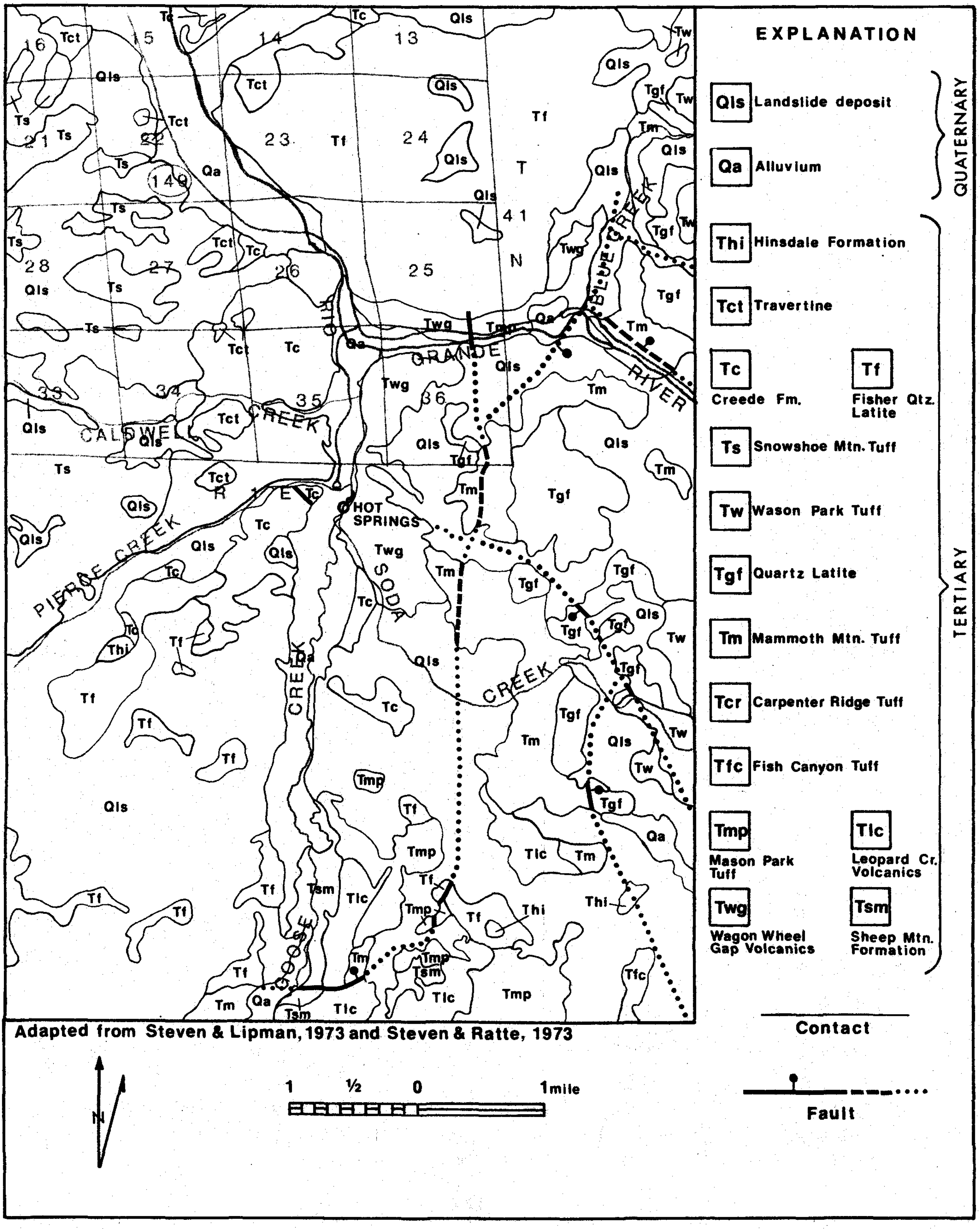


Figure 87.--Photo of 4UR Spring at Wagon Wheel Gap.



Adapted from Steven & Lipman, 1973 and Steven & Ratte, 1973

Figure 88.--Geologic map of Wagon Wheel Gap Hot Springs region.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: The silica content of these springs does not approach the solubility of amorphous silica, chalcedony, cristobalite, or quartz. Therefore, the application of the silica geothermometers will yield questionable results (see application of silica geothermometer).

The amorphous silica geothermometer yields a maximum subsurface temperature estimate of 12°C, which is well below the surface temperature of the warm springs (48°C to 51°C). The cristobalite-silica geothermometer subsurface temperature estimate is 66°C to 81°C (Table 4). However, this estimate is probably too high because the theoretical cristobalite solubility (50 mg/l) at the spring's surface temperature is well below the silica content of the thermal water (67 mg/l to 90 mg/l).

Mixing Model: The solubility of amorphous silica at the surface temperature of the springs is about 190 mg/l. The silica content of the thermal water may be less than the amorphous-silica solubility because of mixing or silica precipitation at depth. The amorphous mixing model yields a subsurface temperature estimate of 43°C with a cold-water fraction of 40 percent. This temperature estimate is also below the surface temperature of the springs; thus, amorphous silica probably does not control the silica content of the thermal water.

The cristobalite mixing model yields a subsurface temperature estimate that ranges from 99°C to 157°C with a cold-water fraction of 56 percent to 76 percent of the spring flow. For the same reason given above, the estimates are probably too high.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 200°C to 206°C and 181°C to 194°C, respectively. Although none of the springs deposit calcium carbonate, considerable calcium carbonate occurs in association with nearby fluorspar and barite deposits. If deposition occurs at depth, then both the Na-K and Na-K-Ca geothermometer estimates are too high.

Conclusion: Emmons and Larson (1913) reported siliceous sinter and opaline silica east of the hot springs. If silica deposition still occurs at depth, then both the silica geothermometers and mixing model results are too low. The opaline silica suggests subsurface temperatures below 100°C. However, the extensive fluorspar deposits indicate temperatures at depth between 119°C and 168°C. If deposition of these minerals still occurs, then the subsurface temperature is probably between 100°C and 168°C. At any rate, the geochemistry of these spring is too complex for a reliable subsurface temperature estimate.

ANTELOPE AND BIRDSIE WARM SPRINGS

Located in the upper reaches of the Rio Grande River valley, west of Creede, Colorado are two small springs whose characteristics and mode of occurrence are nearly identical.

#44 ANTELOPE WARM SPRING

LOCATION: Latitude: 37°44'36"N.; Longitude: 107°02'14"W.; T. 40 N., R. 2 W., Sec. 1 dd, N.M.P.M.; Mineral County; Workman 7 1/2-minute topographic quadrangle map.

GENERAL: Antelope warm spring is located behind a large log building approximately 1 mile north of Colorado 149 and approximately 12 miles west of Creede, Colorado. This unused spring is at the base of a small concrete-lined cistern (Fig. 89).

HYDROLOGY: The spring has a discharge estimated to be 3 gpm with a temperature of 32°C. The total dissolved mineral matter in the waters is 150 mg/l, and the waters are a sodium-bicarbonate type.

#45 BIRDSIE WARM SPRING

LOCATION: Latitude: 37°43'42"N.; Longitude: 107°00'44"W.; T. 40 N., R. 2 W., Sec. 14 abc, N.M.P.M.; Mineral County; Workman 7 1/2-minute topographic quadrangle map.

GENERAL: This unused spring is located along Colorado 149 approximately 14 miles west of Creede, Colorado (Fig. 90).

HYDROLOGY: The discharge of this spring was measured at 15 gpm with a temperature of 30°C. The waters had a conductance of 200 micromhos and a pH of 8.6.

GEOLOGY OF ANTELOPE AND BIRDSIE WARM SPRINGS: These springs are located on the west side of the Creede Caldera, an area of extensive middle Tertiary volcanic activity. The geology of the area has been described in detail by Steven and Ratte (1973).

The geologic map (Fig. 91), based in part on Steven and Ratte (1973), shows Antelope Spring to emerge from glacial drift that overlies volcanic rocks. Birdsie Warm Spring emerges from Tertiary volcanic rocks. These springs do not appear to be fault controlled, for few faults are mapped in the vicinity of the springs (Fig. 91). No attempt was made during this investigation to accurately determine the hydrogeological conditions surrounding these springs. However, the spring may originate from southward down-gradient flow of ground waters through permeable intravolcanic zones that dip into the center of the caldera, an area with above-normal heat flow. Reiter (1975) has shown the upper Rio Grande River valley to have a heat flow in excess of 2.5 heat flow units.

GEOTHERMOMETER ANALYSES OF ANTELOPE AND BIRDSIE SPRINGS:

Silica Geothermometer: Silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and cristobalite controls the silica content of the warm springs. The cristobalite-silica geothermometer, therefore, yields the most reliable temperature estimate. This geothemometer model gave a subsurface temperature estimate of 43°C for Antelope Warm Spring and 52°C for Birdsie Warm Spring (Table 4).

Mixing Model: Since temperature-dependent equilibration between the thermal water and cristobalite apparently controls the silica content of the warm springs, the cristbalite mixing model is applicable. Mixing model analysis of Antelope Warm Spring yields a subsurface temperature estimate of 55°C with a cold water fraction of 44 percent of the spring flow. The mixing model estimate for Birdsie Warm Spring is 91°C with a cold-water fraction of 70 percent. These estimates are within the range of values that could result from normal analytical error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 83°C to 102°C and 35°C to 36°C, respectively (Table 4). The Na-K geothermometer estimate is too high since the value of the term log $\sqrt{Ca}/Na$ exceeds 0.5.

Conclusion: Most geothermometer techniques are not reliable when applied to Antelope and Birdsie Warm Springs because many of the assumptions inherent in their use are violated. The close agreement between the cristobalite-silica and the Na-K-Ca geothermometers suggests subsurface temperatures between 35°C to 52°C (Table 4).

Figure 89.--Antelope Warm Spring.

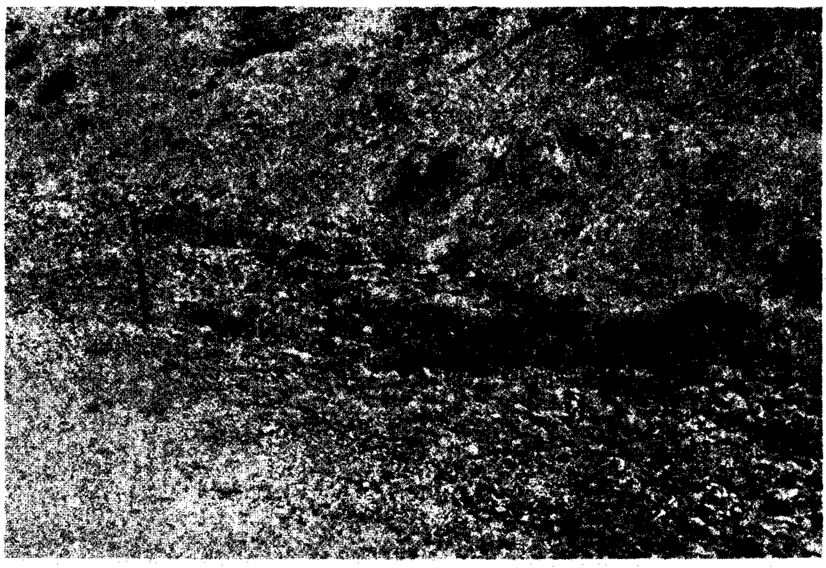
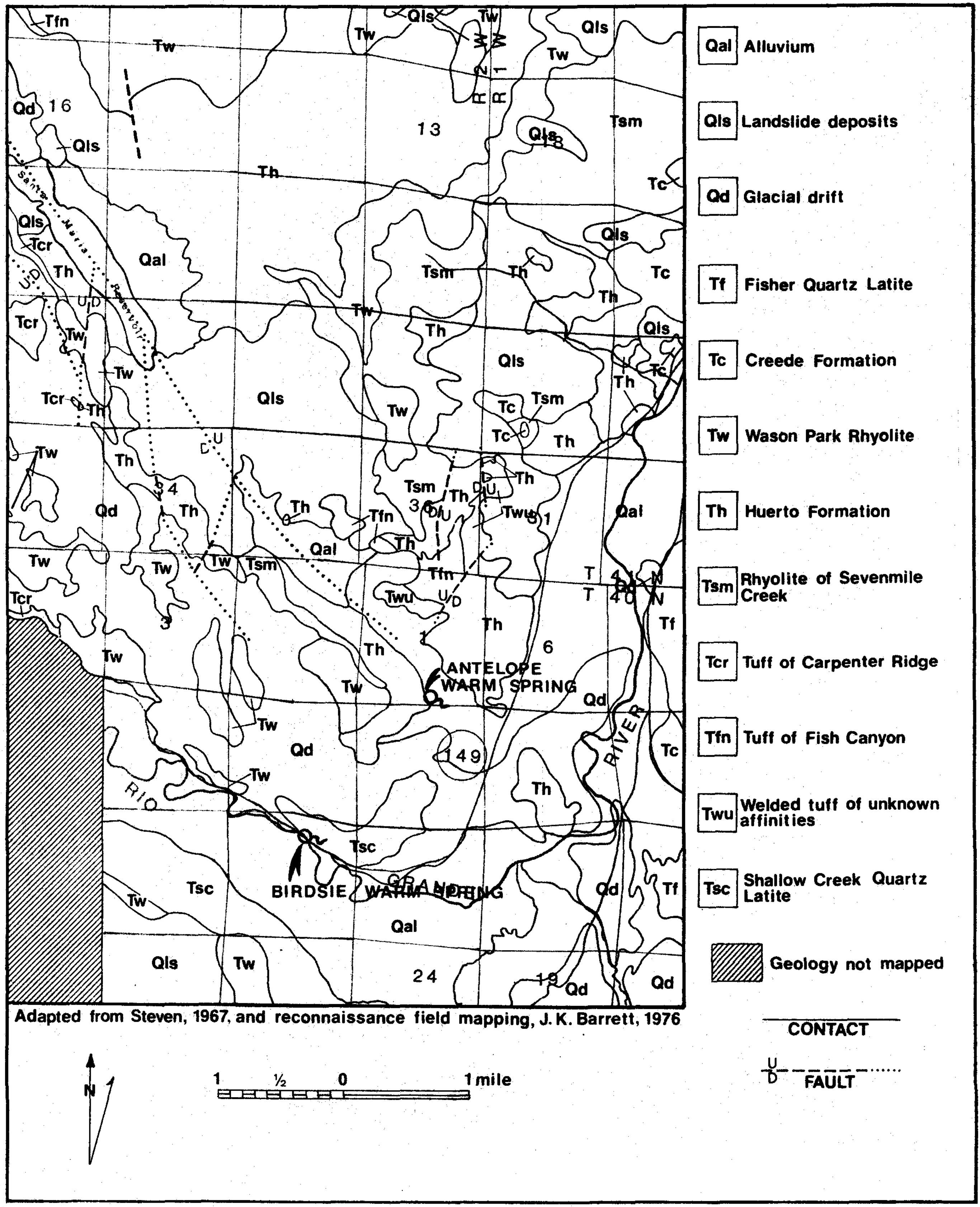


Figure 90.--Birdsie Warm Spring.



Adapted from Steven, 1967, and reconnaissance field mapping, J. K. Barrett, 1976

Figure 91.--Geologic map of Antelope and Birdsie Warm Springs.

#46 UPPER WAUNITA HOT SPRINGS

LOCATION: Latitude: 38°30'50"N.; Longitude: 106°30'27"W.; T. 49 N., R. 4 E., Sec. 11 cc, N.M.P.M.; Gunnison County; Pitkin 7 1/2-minute topographic quadrangle map.

GENERAL: This group of four springs is reached by traveling east from Gunnison, Colorado, on U.S. Highway 50 for 19 miles, and north on a well marked county road for approximately 8 miles. The springs are located on the southeast side of the ranch headquarters building (Fig. 92). Waters from the springs are used for swimming, drinking, and heating the headquarters building.

Spring A, the hottest spring, is located in the gazebo-like structure. This spring is extensively developed with the waters being pumped to the buildings. It was not possible to obtain a sample of the waters for analysis because an iron grill prohibited access.

Spring B is located approximately 75 ft south of A on the same side of the creek. The discharge of this spring was not large, and it was not possible to measure it.

Spring C and D are located on the opposite side of Hot Springs Creek from Springs A and B. Spring C, the largest spring, is located south of the old swimming pool. Spring D flows into the old swimming pool, and due to severe leaking, a discharge measurement could not be obtained. A sample of the water was obtained from the east end of the pool.

GEOLOGY AND HYDROLOGY:

Spring A: Temperature: 76°C; Discharge: not determined; Conductance: 750 micromhos.

Spring B: Temperature: 78°C; Discharge: not determined; Conductance: 720 micromhos.

Spring C: Temperature: 77 to 80°C; Discharge varied throughout the year, measured from 30 gpm to 55 gpm. The total dissolved solids during the period varied from 557 mg/l to 613 mg/l; the water is a sodium-sulfate type.

#46 LOWER WAUNITA HOT SPRINGS

LOCATION: Latitude: 38°31'00"N.; Longitude: 106°30'55"W; T. 49 N., R. 4 E., Sec. 10 bc, N.M.P.M.; Gunnison County; Pitkin 7 1/2-minute topographic quadrangle map.

GENERAL: This large group of unused springs is located approximately 0.5 mile to the west down Hot Springs Creek from the Waunita Hot Springs resort. Access is along a dirt trail from the Waunita Hot Springs resort buildings.

The Lower Waunita Hot Springs consists of three separate (Fig. 93) groups of springs extending over several hundred yards in length. The major spring in each group was selected for measurements.

The northern group (Group A) was named Spring A, the biggest spring on the east side of the group. Group B contains a cistern-like structure and several seeps. Springs in Group C emerge from the old abandoned rock buildings at the south end of the area. Spring C emerges from beneath the old steambath building. Group D is located around the old gazebo along the creek. Spring D is the spring in the gazebo.

HYDROLOGY:

Spring A: Temperature: 75°C; Discharge: estimated at 75 gpm; Conductance: 765 micromhos.

Spring B: Temperature: 70°C; Discharge: estimated at 20 gpm; Total Dissolved Solids: Varied from 528 mg/l to 544 mg/l; Water Type: sodium sulfate-bicarbonate.

Spring C: Temperature: 70°C; Discharge: 8 gpm; Conductance: 780 micromhos.

Figure 92.--Upper Waunita Hot Springs. Spring A is under rock building in center. Other springs are located to the left.

Figure 93.--Lower Waunita Hot Springs. Spring B is located in left center. Spring C is located under building in upper right.

Spring D: Temperature: 62°C; Discharge: not determined; Total Dissolved Solids: 535 mg/l; Water Type: sodium sulfate-bicarbonate.

GEOLOGY OF UPPER AND LOWER WAUNITA HOT SPRINGS: The Waunita Hot Springs are located on the north side of the Tomichi Dome, a Tertiary intrusive that has arched the overlying Mancos Shale. Very litte has been written on the geology of this part of Colorado. The one article describing the geology of the area (Stark and Behre, 1936) describes the Tomichi Dome.

The accompanying geologic map (Fig. 94), taken from Tweto and others (1976), shows that the upper springs are situated on the contact between the Dakota Sandstone and the overlying Mancos Shale. The lower springs are located along a fault zone. It is believed that the upper spring waters migrate up from depth along the contact between the Dakota and Mancos.

GEOTHERMOMETER ANALYSES OF UPPER AND LOWER WAUNITA HOT SPRINGS:

Silica Geothermometer: The quartz-silica geothermometer estimate of subsurface temperature is 143°C to 157°C for Waunita Hot Springs and 123°C to 130°C for Lower Waunita Hot Springs (Table 4).

Mixing Model: Mixing model analysis yields a subsurface temperaure estimate of 209°C to 291°C with a cold-water fraction of 64 to 83 percent for Waunita Hot Springs and a subsurface temperature estimate of 181°C to 208°C with a cold water fraction of 64 to 73 percent for Lower Waunita Hot Springs (Table 4).

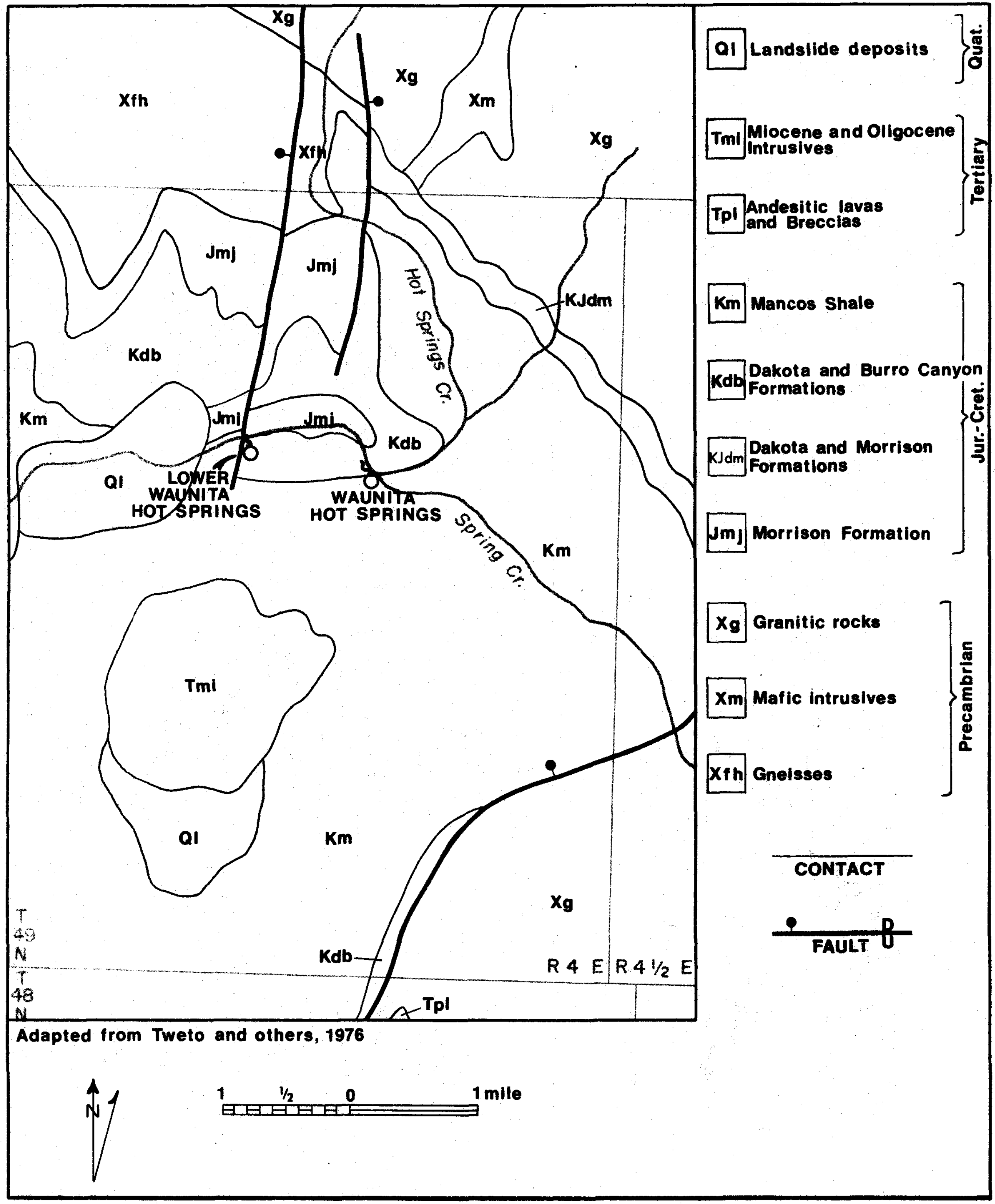
Waunita Hot Spring D and Lower Waunita Hot Spring D, which are the least suitable springs for mixing model analysis but yield the highest subsurface temperature estimates of the group (291°C and 208°C, respectively). Waunita Hot Spring D was sampled from a large, quiescent pool. Lower Waunita Hot Spring D appears to be partially flooded by a nearby stream. Excluding these two springs the subsurface temperature estimates range from 209°C to 247°C for Waunita Hot Springs and 181°C to 197°C for Lower Waunita Hot Springs.

The seasonal fluctuation of the subsurface temperature estimates suggests that the assumed cold water analysis and the percent-mixing estimates do not adequately represent the hydrological condition at depth. However, no certain conclusions can be made from these estimates because they are within the range of values that could result from normal analytical error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 174°C to 179°C and 159°C to 167°C, respectively, for both hot springs groups. The high surface temperature (70°C to 80°C), flow (100 to 200 gpm and close agreement with the mixing model results suggest that the Na-K and Na-K-Ca geothermometer models provide reasonable estimates for this area.

Conclusion: The fluctuation of the various geothermometer estimates is well within the range of values that could result from normal analytical error.

The close agreement between the mixing model and the Na-K-Ca model estimates suggests that these geothermometers adequately reflect the temperature at depth. Therefore, consideration of these results and the precision of the geothermometers suggests temperatures at depth between 110°C and 160°C (Table 4).



Adapted from Tweto and others, 1976

Figure 94.--Geologic map of Waunita Hot Springs region.

#47 CEBOLLA HOT SPRINGS (Formerly known as Powderhorn Hot Springs)

LOCATION: Latitude: 30°16'26"N.; Longitude: 107°05'54"W.; T. 46 N., R. 2W., Sec 4 ab, N.M.P.M.; Gunnison County; Powderhorn 7 1/2-minute topographic quadrangle map.

GENERAL: This group of three fairly large springs is located approximately 30 miles southwest of Gunnison, Colorado, just off Highway 149 along Cebolla Creek. At one time these springs were extensively developed and used, but today all the old buildings and the swimming pool are gone and all that remains are two small wooden buildings (Fig. 95).

The springs are used today for bathing purposes. Two springs emerge into a large cistern-like structure in the southernmost building (left building in Fig. 95), and the other spring is located in the large building approximately 75 ft to the northwest.

GEOLOGY AND HYDROLOGY: Due to modifications of the area around the springs, it was not possible to accurately measure the discharge. However, a fairly reliable discharge of 3 gpm was obtained for one of the two springs in the southern building. All three springs have a temperature of 38°C to 40°C (depending on time of year when measured) with total dissolved mineral matter of 1,450 mg/l. The waters are a sodium-bicarbonate type.

As mapped by Hedlund and Olson (1975) (Fig. 96), these springs are located 300 ft from the southeast trending Cimarron Fault. The bedrock of the area consists of complex assemblages of Precambrian metamorphic rocks, Cambrian and Ordovician intrusives, and Oligocene volcanic-derived rocks. In Oligocene time thermal activity was very extensive in this area, for Hedlund and Olson (1975) mapped extensive Oligocene silicous sinter and travertine deposits along the Valley of Cebolla Creek.

As the Precambrian rock types are not good aquifers, the springs probably originate from deep circulation along the Cimarron Fault system in an area of elevated geothermal gradients. Reiter (1975) has determined that the Cebolla Hot Springs area has a heat flow of just over 2.5 heat flow units.

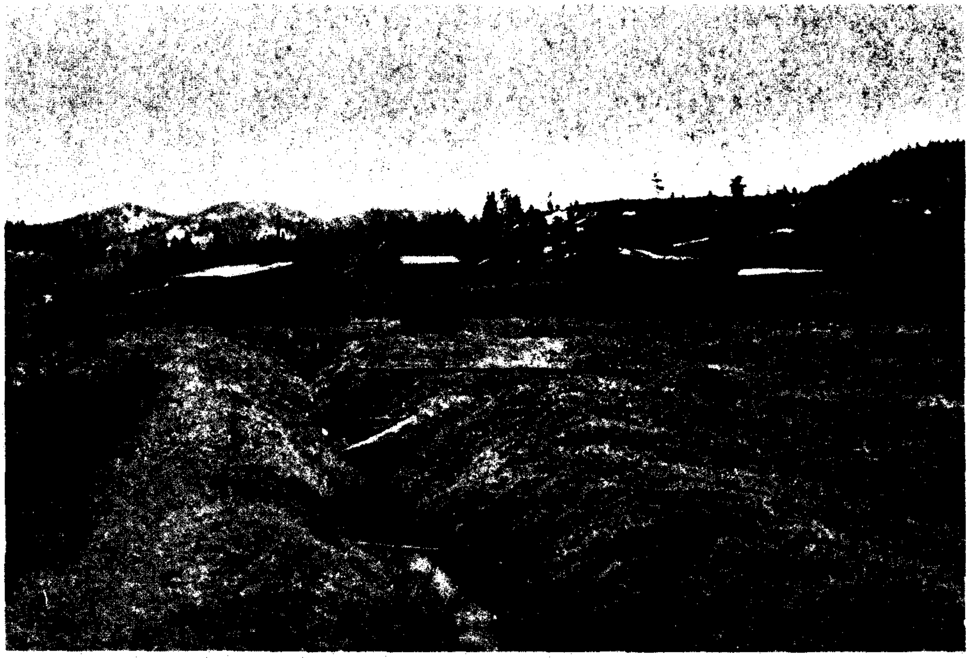


Figure 95.--Cebolla Hot Springs.

GEOTHERMOMETER ANALYSIS:

Due to the three months turn around time between sampling the hot springs and receiving the analytical results it was not known until after the October 1975 sampling date that silica precipitated from solution in the sampling containers. The turn-around time was eventually reduced to 4 to 6 weeks and sample silicas were later diluted 10:1 with deionized water. Samples taken in January, 1976 and April, 1976 were diluted and showed a marked increase in the silica content compared to the earlier analysis.

Silica Geothermometer: Analysis of silica solubility and temperature relationships suggest that cristobalite may control the silica content of the hot springs. Therefore, the cristobalite-silica geothermometer was used to determine the most reliable subsurface temperature estimate.

The cristobalite-silica geothermometer estimate of subsurface temperature is 65°C to 82°C. This estimate is probably too high because the theoretical cristobalite-induced silica solubility (39 mg/l) at the surface temperature of the springs (38°C to 41°C) is well below the silica content of the springs (77 to 92 mg/l).

Mixing Model: Since temperature-dependent equilibration between the thermal water and cristobalite may control the silica content of the springs, the cristobalite mixing model is applicable. Mixing model analysis yields subsurface temperature estimates of 105°C to 185°C with a cold water fraction of 66 to 83 percent of the spring flow (Table 4).

Cristobalite mixing model estimated temperatures based on the January and April, 1976 samples range from 163° to 185°C with a cold-water fraction of 80 to 83 percent of the spring flow (Table 4). These estimates are well within the range of values that could result from normal analytical error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers estimates of 238°C to 278°C and 209°C to 220°C, respectively. Recent travertine deposits mapped in sections 33 and 34, T. 47 N., R. 2 W. and sections 2, 3, 11, 12, T. 46 N., R. 2 W. (Hedlund and Olsen, 1975) suggest that both the Na-K and the Na-K-Ca geothermometer estimates are too high. In addition the geothermometers may yield erroneous results when applied to the high magnesium waters of these springs.

Conclusion: Geothermometer models must be used with caution when applied to Cebolla Hot Springs since most of the assumptions inherent in their use are violated. Moreover, samples of the thermal water had to be taken from large, quiescent pools. Such sampling conditions may exaggerate the effects of the surface conditions on the thermal water, allowing evaporative concentration of the silica content and other reequilibration reactions to occur. The geochemistry of these waters is too complex for an accurate estimation of the temperature at depth.

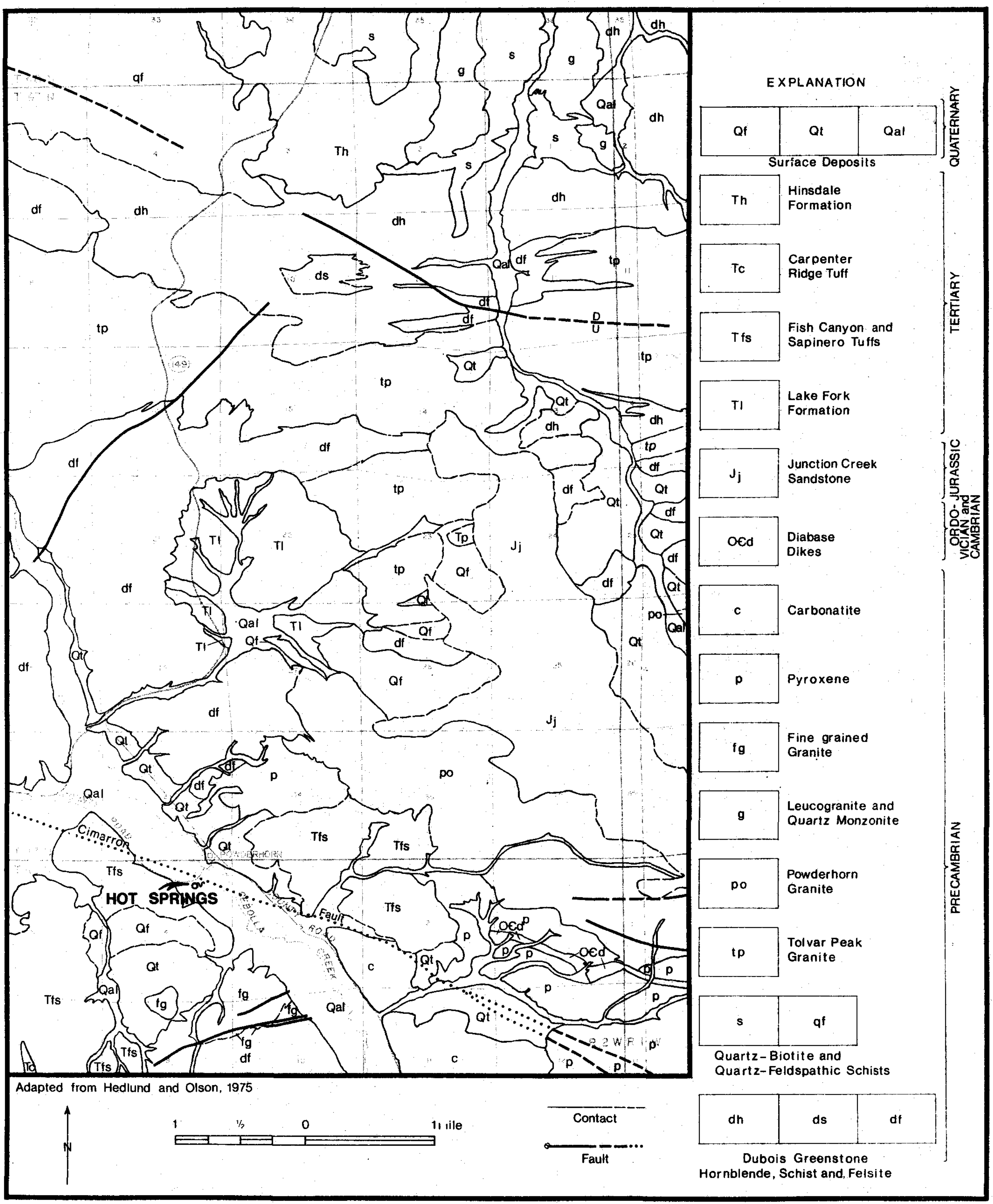


Figure 96.--Geology surrounding Cebolla Hot Springs.

#48 ORVIS HOT SPRING

LOCATION: Latitude: 38°07'59"N.; Longitude 107°44'01"W.; T. 45 N., R. 8 W., Sec. 22 cd, N.M.P.M.; Ouray County; Dallas 7 1/2-minute topographic quadrangle map.

GENERAL: This spring is located on the west side of U.S. Highway 550 approximately 9 miles north of Ouray. Waters from the spring are diverted and piped approximately 200 yd to the north to a building for use in hydrotherapy. The spring is located on a large travertine deposit approximately 50 yd in diameter (Fig. 97).

GEOLOGY AND HYDROLOGY: No water issues from the spring today due to the waters being diverted to the nearby buildings. The spring has a temperature of 52°C and contains approximately 2,300 mg/l of dissolved mineral matter. The waters are a sodium sulfate type with a high concentration of iron.

Although the waters ascend through the alluvial and colluvial deposits of the valley floor, they are associated with the underlying red beds of the Morrison Formation. While geologic mapping (Fig. 98) does not show any possible origin for this spring, it is believed that the waters must move up fracture systems related to the San Juan and La Plata Mountains to the south, for geologic mapping to the west on Dallas Divide (Bush and others, 1956) has shown an extensive network of faults and folds. It is believed that water ascends some fractures that must be present in the vicinity of Orvis Hot Springs. Recharge to this system probably occurs to the south along the flanks of the San Juan Mountains. Reiter (1975) has shown Ouray to be an area of high heat flow (greater than 2.5), and presumably the origin of the heat for the Orvis Hot Springs is related to this high heat flow.

Figure 97.--Orvis Hot Spring.

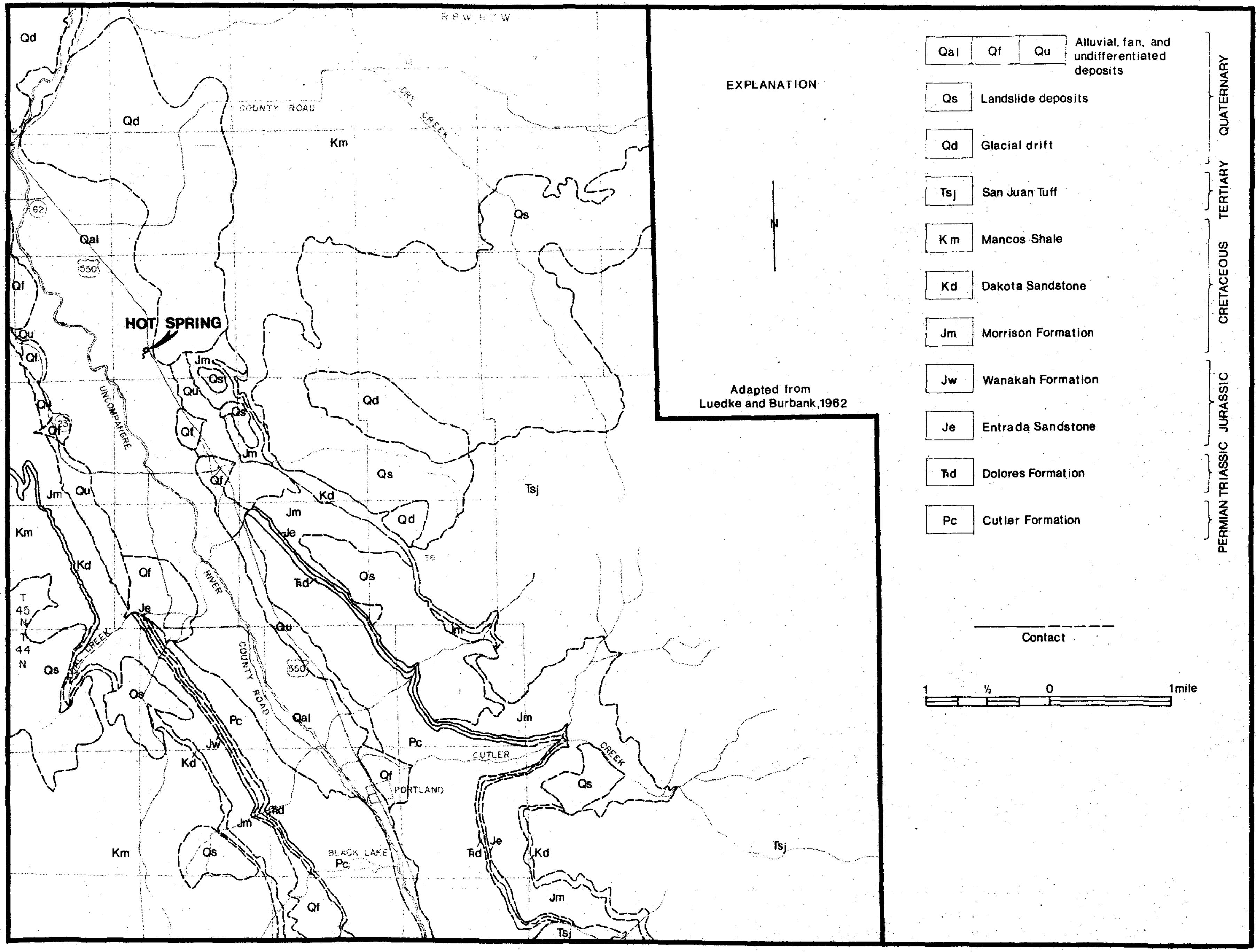


Figure 98.--Geologic map of Orvis Hot Spring.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: The chalcedony geothermometer yields a subsurface temperature estimate of 75°C to 82°C (Table 4).

Mixing Model: The chalcedony mixing model yields a subsurface temperature estimate of 99°C to 127°C with a cold water fraction of 54 to 66 percent of the spring flow (Table 4). These estimates are within the range of values that could result from normal analytical error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 179°C to 187°C and 93°C to 97°C, respectively (Table 4). The Na-K geothermometer estimate is definitely too high because the value of the term log $\sqrt{Ca}/Na$ exceeds 0.5. Extensive travertine deposits, calcium carbonate-cemented gravels, and calcium-depositing seeps near the hot spring suggest that both the Na-K and Na-K-Ca geothermometer estimates are too high.

Conclusion: Geothermometer models must be used with caution when applied to Orvis Hot Spring since most of the assumptions inherent in their use are violated. Samples of the thermal water had to be taken from a large, quiescent pool. Such sampling conditions may exaggerate the effects of the surface conditions on the thermal water, allowing evaporative concentration of the silica content and other re-equilibration reactions to occur.

In light of these deficiencies the best subsurface temperature estimate for this area is 60°C to 90°C (Table 4).

#49 OURAY HOT SPRINGS

In and adjacent to the City of Ouray are a number of hot springs, most of which have small discharges, usually less than 5 gpm. However, the largest and hottest of the springs, the Pool Spring, has a discharge that varies throughout the year from a low of 69 gpm to a high of 200 gpm. This spring is located at the upper reaches of Box Canyon (Fig. 99).

LOCATION OF THERMAL SPRINGS LOCATED AND MEASURED:

Pool Spring: Latitude: 38°01'00"N.; Longitude: 107°40'41"W.; T. 44 N., R. 7 W., Sec. 31, N.M.P.M.; Ouray County; Ouray 7 1/2-minute topographic quadrangle map.

Uncompahgre Hot Spring: Latitude: 38°01'06"N.; Longitude: 107°40'34"W.; T. 44 N., R. 7 W., Sec. 31, N.M.P.M.; Ouray County; Ouray 7 1/2-minute topographic quadrangle map.

Wiesbaden Vapor Caves and Motel Hot Springs: Located in basement of1 Wiesbaden motel at the corner of 6th Avenue and 5th Street.

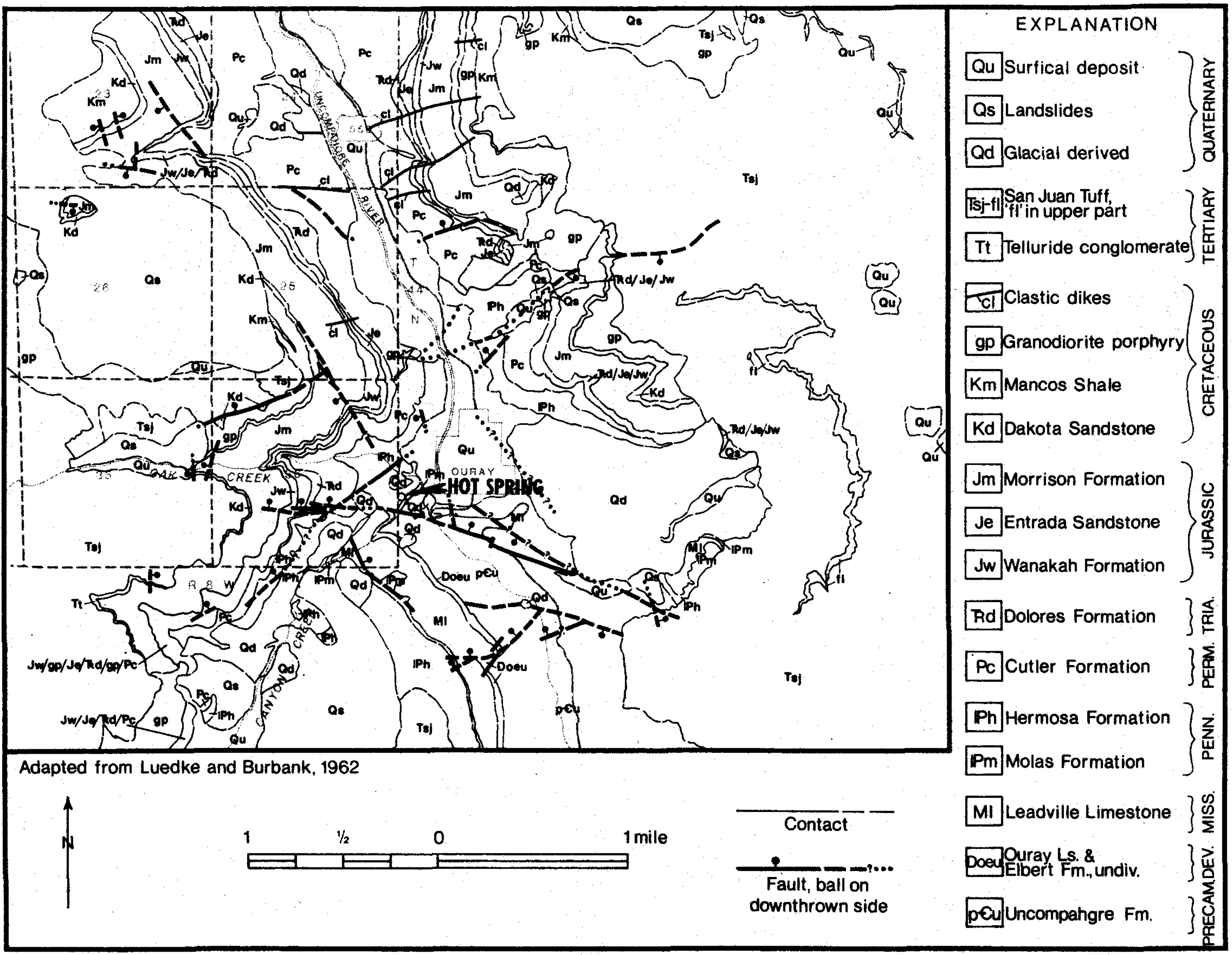
Spring A: Latitude: 38°01'15"N.; Longitude: 107°40'03"W.; T. 44 N., R. 7 W., Sec. 31, N.M.P.M.; Ouray County; Ouray 7 1/2-minute topographic quadrangle map.

Spring B: Latitude: 38°01'15"N.; Longitude: 107°40'03"W.; T. 44 N., R. 7 W., Sec. 31, N.M.P.M.; Ouray County; Ouray 7 1/2-minute topographic quadrangle map..

Spring C: Latitude: 38°01'15"N.; Longitude: 107°40'03"W.; T. 44 N., R. 7 W., Sec. 31, N.M.P.M.; Ouray County; Ouray 7 1/2-minute topographic quadrangle map.

GENERAL: With the exception of the Uncompahgre Hot Spring, several seeps in Box Canyon, and the springs at the rear of Box Canon Motel, all the thermal waters in the Ouray vicinity are used. The waters from the Pool Hot Spring are piped from Box Canyon to the swimming pool on the north end of town. Waters from the Wiesbaden Springs are used for the motel's mineral baths, swimming pool, and space heating.

Figure 99.--Pool Hot Spring at Ouray.



Adapted from Luedke and Burbank, 1962

Figure 100.--Geology of Ouray area.

GEOLOGY AND HYDROLOGY: As stated earlier, the discharge of the Pool Spring varies throughout the year from a low of 60 gpm to a high of 200 gpm. The temperature of the waters is a very consistent, 67°C to 69°C. The waters contain approximately 1,650 mg/l of dissolved solids and are a calcium-sulfate type. The concentration of radiochemical elements, Radium^{226} and Radium^{228}, in the Pool Spring exceeds the U.S. Environmental Protection Agency Protection Agency limits for drinking water supplies. Due to the alterations at both the swimming pool and the spring site, it was only possible to obtain water samples when the pipeline dumps into a concrete cistern near Oak Creek.

The Uncompahgre Hot Spring has a discharge of 5 gpm with a temperature of 49°C. The waters contain 1,570 mg/l of dissolved solids and are a calcium sulfate type. The spring was sampled on the Uncompahgre River, below a sheer cliff approximately 100 yd upstream from the 3d Ave. bridge.

The Wiesbaden Motel Hot Springs are located in vapor caves beneath the motel at the corner of 6th Ave. and 5th St. Spring A has a temperature of 53°C and contains 910 mg/l of dissolved solids. The waters are a calcium-sulfate type. This spring was sampled from the cistern just to the left inside the cave entrance. Spring B was sampled at the back of the cave from a ledge about 8 ft above the floor. The spring has an estimated discharge of 2 gpm. The waters contain 410 mg/l of dissolved solids and are a calcium sulfate type. Spring C, located in the furthest corner of the cave, has a discharge which varies between one gpm and 30 gpm throughout the year. The waters from this spring contain approximately 800 mg/l of dissolved solids and are a calcium-sulfate type.

Due to the complexity of the geological conditions in the area, no definitive statements can be made regarding the geological conditions controlling the occurrence of these springs (Fig. 100). All the springs appear to be associated with one or more fault systems, and they apparently represent deep circulation of ground water through the fault systems of the region.

Since field work completion, thermal springs have been reported in the Red Mountain Pass area (Kevin McCarthy, 1977, oral communication). These springs have not been located or sampled yet.

GEOTHERMOMETER ANALYSES:

Due to the extensive modifications made to most of the hot springs for recreation and space heating, only data from Pool Hot Spring will be discussed in the following sections. Geothermometer results for Pool Hot Spring and the other hot springs in this area are listed in Table 4.

Silica Geothermometer: Silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and chalcedony controls the silica content of the hot spring. Therefore, the chalcedony-silica geothermometer was used. This geothermometer yielded a subsurface temperature of 69°C to 71°C, which is very near the surface temperature of the spring (67°C to 69°C).

Mixing Model: Since temperature-dependent equilibration between the thermal water and chalcedony apparently controls the silica content of the hot spring, the chalcedony mixing model was used. Mixing model analysis yields a subsurface temperature estimate of 77°C to 79°C with a cold water fraction of 15 to 16 percent of the spring flow. These estimates are well within the range of values that could result from normal analytical error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 184°C to 192°C and 39°C, respectively (Table 4). The Na-K geothermometer estimate is definitely too high because the value of the term log $\sqrt{Ca}/Na$ is greater than 0.5. The Na-K-Ca geothermometer estimate is incorrect because the result is below the surface temperature of the hot spring.

Conclusion: The insignificant variation in mineral content and surface temperature of Pool Hot Spring sugggests that it is not materially affected by seasonal metereological conditions. Moreover, the fluctuation of the various geothermometer estimates is well within the range of values that could result from normal analytical error.

The high flow (approximately 175 gpm) of this hot spring and close agreement between the silica geothermometer and mixing model estimates suggests temperatures at depth between 70°C and 90°C (Table 4).

#50 LEMON HOT SPRING

LOCATION: Latitude: 38°51'00"N.; Longitude: 108°03'11"W.; T. 44 N., R. 11 W., Sec. 34 dd, N.M.P.M.; San Miguel County; Placerville 7 1/2-minute topographic quadrangle map.

GENERAL: This unused spring is located in a tunnel driven into the Dolores Formation on the west bank of the San Miguel River in the community of Placerville 17 miles northwest of Telluride on Highway 145.

GEOLOGY AND HYDROLOGY: The spring has a discharge of 8 to 10 gpm at a temperature of 31 to 33°C. The waters contain from 2,740 to 2,810 mg/l of dissolved solids and are a mixed sodium bicarbonate-sulfate type. The surrounding area is geologically very complex, for the area is a transition zone between the Uncompahgre Plateau to the north and the La Plata Mountains to the south. A number of large north-trending fault zones and grabens intersect northwest-trending fault zones paralleling the San Miguel River. These north-south structures die out at the San Miguel River. Although none of these structures are mapped on the south side of the river (Fig. 101), one of them, the Sheep Draw Graben and associated faults, are on trend with the Lemon Warm Spring. The spring itself is located at the intersection and termination of one small and one large fault. Even though these faults are not apparent within the tunnel at the spring site, it is believed that they control the origin of the spring. It is believed that the waters migrate up these faults from depth. The waters come from the red beds of the Triassic Dolores Formation (Fig. 101). Recharge is probably to the south and west along the flanks of the La Plata Mountains.

GEOTHERMOMETER ANALYSES

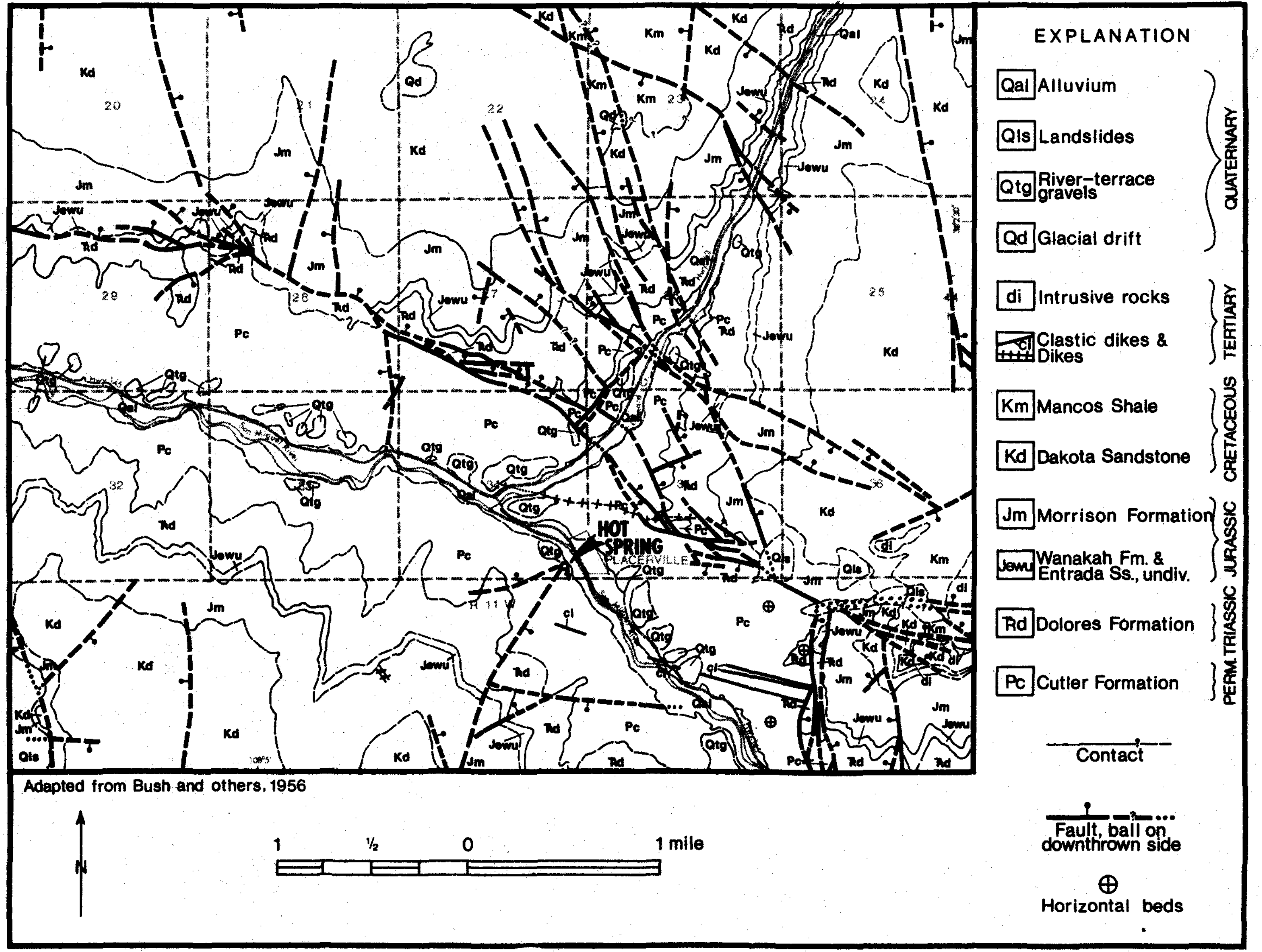
Silica Geothermometer: Calculation of the silica solubility shows that the amorphous-silica geothermometer yields the most reliable subsurface temperature estimate. The amorphous-silica geothermometer estimate of subsurface temperature is 14°C to 17°C, which is below the surface temperature of the hot spring (31°C to 33°C). This low estimate may be caused by dilution of the ascending thermal water by shallow ground water.

Mixing Model: Since temperature-dependent equilibration between the thermal water and amorphous silica apparently controls the silica content of the hot spring, the amorphous-silica mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 29°C to 31°C with a cold-water fraction of 15 to 17 percent of the spring flow. Although the subsurface temperature estimate is below the surface temperature of the hot spring (33°C) it is well within the expected margin of error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 203°C to 210°C and 192°C to 198°C, respectively. The nearby occurrence of travertine deposits, calcium carbonate-cemented river gravels and the lack of substantiation of such high temperature estimates by the other geothermometers suggest that these estimates are excessive.

Conclusion: The insignificant variation in flow, surface temperature and mineral content of this hot spring suggests that it is not materially affected by seasonal metereological conditions. Moreover, the fluctuation of the various geothermometer estimates is well within the range of values that could result from normal analytical error.

The low surface temperature and flow of this hot spring renders geothermometer analysis to be unreliable.



Adapted from Bush and others, 1956

Figure 101.--Geologic conditions of the Lemon Hot Springs.

#51 DUNTON HOT SPRING

LOCATION: Latitude: 37°46'18"N.; Longitude 108°05'38"W.; T. 41 N., R. 11 W.; Sec. 32, N.M.P.M.; Dolores County; Dolores Peak 7 1/2-minute topographic quadrangle map.

GENERAL: This spring is located at the old mining town of Dunton, which is now a resort area northwest of Rico. Access is via a dirt road which turns off of Colorado 145 approximately 2 miles north of Rico or alternatively via a dirt county road up the West Dolores River starting a few miles west of Stoner. The spring is located at the base of the hill east of the main buildings (Figs. 102 and 103). The waters are piped approximately 30 yd to a building where they empty into a large pool and are used for bathing. The waters are drained from this pool to the West Dolores River.

GEOLOGY AND HYDROLOGY: The waters of these springs are a calcium bicarbonate type with a strong concentration of iron (up to 2,300 mg/l) and manganese (average concentration of 1,800 mg/l). The temperature of the spring is 42°C with a discharge of 25 gpm. The surrounding bedrock are the red sandstones, siltstones, and shales of the Dolores Formation. The red color and high iron content of the spring water confirm that the waters are associated with the Dolores Formation.

The surface of the ground is mantled with a veneer of red sandstones and shales which makes difficult the determination of the true geologic conditions of the area. As shown on the accompanying geologic map (Fig. 104), several major north-northwest trending faults, with major displacement, pass through or are located only a short distance from Dunton. The fault on which the Dunton Hot Spring is located has dropped the Morrison Formation down into contact with the Entrada and Dolores Formations.

The recharge area of these springs is unknown but is probably to the south with the spring resulting from deep circulation along fault zones in an area of high geothermal gradients.

Figure 102.--Dunton Hot Springs.

Figure 103.--Dunton Hot Springs.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and chalcedony may control the silica content of the spring. Therefore, the chalcedony-silica geothermometer yields the most reliable temperature estimate. The chalcedony-silica geothermometer estimate of subsurface temperature is 51°C to 54°C (Table 4).

E. Bastin (1922) visited the Emma Mine (approximately 0.5 mile south of Dunton Hot Spring) and reported a warm spring 3000 ft within the main portal. His analysis of the warm spring is:

Temperature	82°F (28°C)
SiO_2	42 mg/l
Na^{+2}	55 mg/l
K^+	29 mg/l
Ca^{++}	74 mg/l

At the time the analysis was made (1913) the warm spring was gaseous (CO_2 and H_2S) and was precipitating calcium carbonate and epsomite ($MgSO_4 \cdot 7H_2O$).

Mixing Model: Since temperature-dependent equilibration between the thermal water and chalcedony apparently controls the silica content of the hot spring, the chalcedony mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 65° to 69°C with a cold-water fraction of 39 to 43 percent of the spring flow (Table 4).

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 328°C to 342°C and 47°C to 52°C respectively (Table 4). The Na-K geothermometer estimate is definitely too high because the value of the term log $\sqrt{Ca}/Na$ exceeds 0.5. If the calcium carbonate-depositing spring within the Emma Mine is representative of conditions at depth in Dunton Hot Spring, then both the Na-K and Na-K-Ca geothermometer estimates are too high. In any case, the magnesium content causes the results of these calculations to be questionable.

Conclusion: The insignificant variation in flow, mineral content, and surface temperature of Dunton Hot Spring implies that it is not materially affected by seasonal metereological conditions. Moreover, the fluctuation of the various geothermometer estimates is well within the range of values that could result from normal analytical error.

The subsurface temperature in this area is probably between 50°C and 70°C (Table 4).

#52 GEYSER WARM SPRING

LOCATION: Latitude: 37°44'48"N; Longitude: 108°07'02"; T. 40 N., R. 11 W., Sec. 6 N.M.P.M.; Dolores County; Rico 7 1/2-minute topographic quadrangle map.

GENERAL: This spring, as implied by its name, is a true geyser, the only true geyser in the State of Colorado. Although the frequency of the eruption varies, 30 minute intervals are most common. The geyser action is slight and boils only 12 to 15 in. above the quiescent level of the spring.

The spring is reached via a 2-mile foot trail that starts approximately 1.5 miles south of Dunton and approximately 0.5 mile north of the Paradise Ranch buildings. The trail crosses the West Dolores River and runs east.

GEOLOGY AND HYDROLOGY: Due to the physical make up of the area around the spring and the geyser action, it was not possible to accurately measure the spring's discharge, but it is estimated to be 25 to 200 gpm. The temperature of the spring is 28°C, and the waters are a sodium-bicarbonate type. The waters contain 1,620 mg/l of dissolved solids.

Bush and Bromfield (1966) have mapped the location of this spring near the intersection of two faults (Fig. 104), a postulated northeast-trending fault and a postulated northwest-trending fault. The waters emerge from the Dolores Formation, which overlies the Pennsylvanian Cutler Formation. The Dolores Formation consists of red siltstones, sandstone, shale, and a few limestone-pebble conglomerate beds (Bush and Bromfield, 1966). The intense faulting in the area makes reliable predictions of the recharge areas difficult.

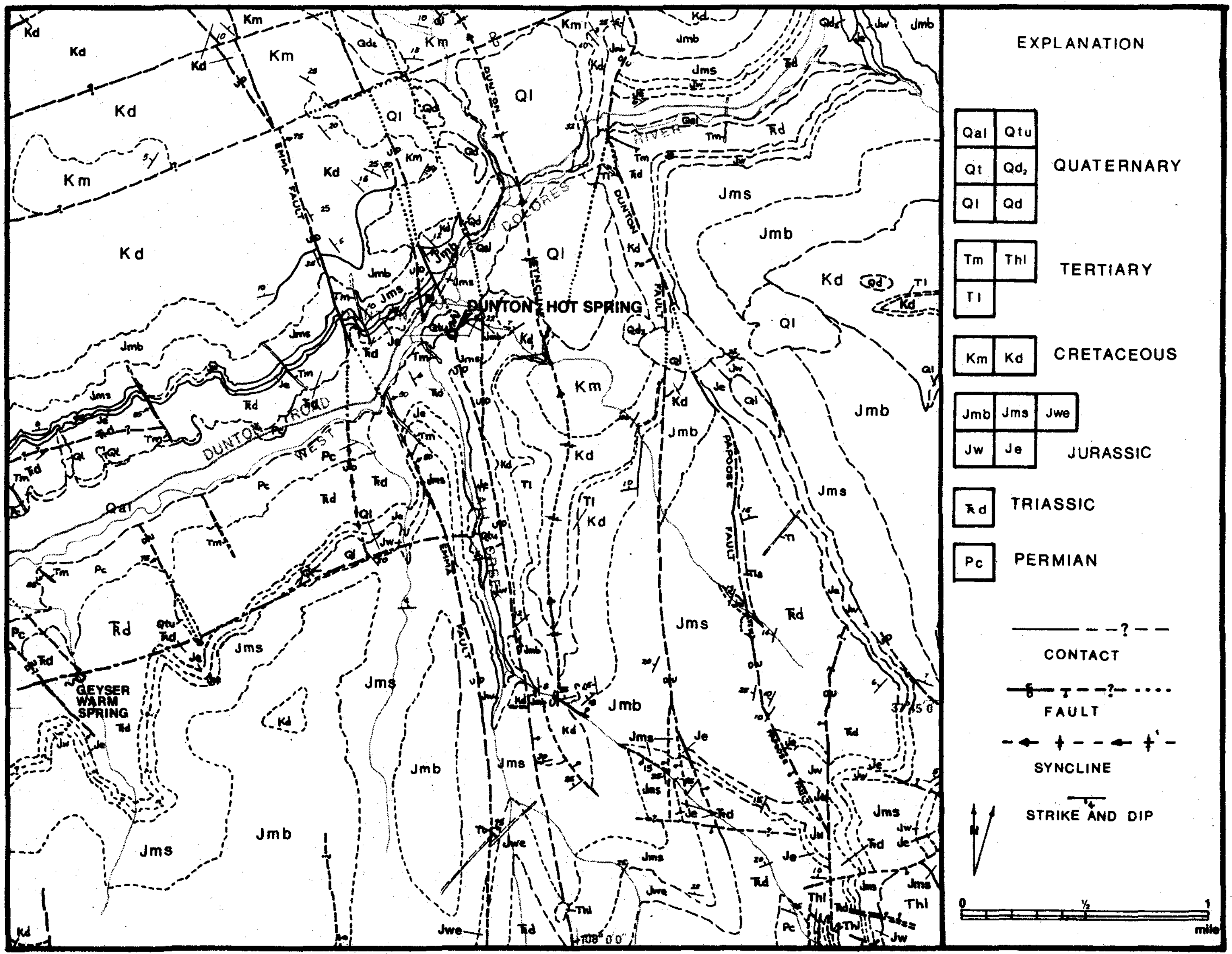
GEOTHERMOMETER ANALYSES

Silica Geothermometer: The chalcedony-silica geothermometer yields a subsurface temperature estimate of 58°C.

Mixing Model: Cristobalite mixing model analysis yields a subsurface temperature estimate of 113°C with a cold water fraction of 80 percent of the spring flow.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 183°C and 160°C, respectively. Travertine deposits near the warm spring and the lack of substantiation of such high temperatures by the other geothermometers suggest that these estimates are too high.

Conclusion: The mixing model and silica geothermometers yield the most reliable estimates of subsurface temperature for Geyser Warm Spring. The subsurface temperature suggested by these geothermometers is between 60°C and 120°C (Table 4).



Adapted from Bush and Bromfield, 1966 and Pratt and others, 1969

Figure 104.--Geologic map of Dunton and Geyser Hot Springs.

#53 PARADISE WARM SPRING

LOCATION: Latitude: 37°45'15"N.; Longitude: 108°07'53"W.; T. 40 N., R. 12 W., Sec. 1, N.M.P.M.; Dolores County; Groundhog Mountain 7 1/2- minute topographic quadrangle map.

GENERAL: This spring is located approximately 2.6 miles south of Dunton, Colorado on the northeast bank of the West Dolores River. Access is via the paved and dirt county road from State Highway 145 along the West Dolores River. The main spring is located in the large log building at the ranch headquarters (Fig. 105). Several seeps are reported in the pasture between the buildings and the river, but they were not located. The spring in the building flows into a large concrete cistern and is used privately by the owners for mineral baths. Evidently the thermal waters were used in the past to heat the large swimming pool just south of the log building.

GEOLOGY AND HYDROLOGY: The waters of this spring have a temperature that ranges throughout the year from 40°C to 46°C. The total dissolved solids varied from a low of 6,070 mg/l to a high of 6,530 mg/l. The waters are a sodium chloride type with a discharge of 26 to 34 gpm. When it was possible to gain access to the building, the spring was sampled from the edge of the cistern. Other times it was sampled from the outfall discharge pipe on the south side of the building.

Since no previously published geologic map exists for this area, no geologic map was prepared for this report. Detailed geologic mapping has not been done near this spring, but one can assume that some of the faults mapped in the quadrangle to the north (see Dunton Hot Spring, No. 51) extend into the vicinity of this spring. The waters emerge through West Dolores River alluvium which overlies the red sandstones, shales, and siltstones of the Dolores Formation.

Figure 105.--Paradise Hot Spring. Spring is in log building.

GEOTHERMOMETER ANALYSES:

Silica Geothermometer: Computation of the silica solubility and temperature relationships for this spring suggest that amorphous silica may control the silica content of the warm waters. Therefore, the amorphous silica geothermometer was used and gave an estimated subsurface temperature of 39°C to 56°C (Table 4).

Mixing Model: Since temperature-dependent equilibration between the thermal water and amorphous silica apparently controls the silica content of the hot spring, the amorphous silica mixing model is applicable. Mixing model analysis yields a subsurface temperature estimate of 43°C to 45°C with a cold water fraction of 1 to 4 percent of the spring flow.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 245°C to 247°C and 248°C to 252°C, respectively. These estimates should be treated skeptically for the magnesium content (30 mg/l) of the spring may be effecting the geothermometers.

Conclusion: Geothermometer models must be used with caution when applied to Paradise Warm Spring because most of the assumptions inherent in their use are violated. The ambiguous nature of the geochemistry precludes any reliable subsurface temperature estimtes.

#54 RICO

Just to the north of Rico, Colorado, along the east bank of the Dolores River are, or were, four core-drill holes that have been described as springs. These holes and their locations are as follows:

LOCATION:

Diamond Drill Hole: Latitude: 37°42'05"N.; Longitude: 108°01'45"W.; T. 40 N., R. 11 W., Sec. -, N.M.P.M.; Dolores County; Rico 7 1/2-minute topographic quadrangle map.

Big Geyser Warm Spring: Latitude: 37°42'00"N.; Longitude: 108°01'44"W.; T. 40 N., R. 11 W., Sec.-, N.M.P.M.; Dolores County; Rico 7 1/2-minute topographic quadrangle map.

Geyser Warm Spring: Latitude: 37°42'02"; Longitude: 108°01'44"W.; T. 40 N., R. 11 W., Sec.-, N.M.P.M.; Dolores County; Rico 7 1/2-minute topographic quadrangle map.

Little Spring: Latitude: 37°42'04"N.; Longitude: 108°01'44"W.; T. 40 N., R. 11 W., Sec.-, N.M.P.M.; Dolores County; Rico 7 1/2-minute topographic quadrangle map.

GENERAL: All the above thermal waters are located along the east side of the dirt road leading into the Argentine Mine on the east side of the Dolores River 0.2 to 0.3 mile above the bridge across the Dolores River. While these are called "springs", they are actually drill holes. Two of the springs have geyser action, the waters from the Big Geyser attaining the greatest height of approximately 6 ft (Fig. 106). These features may no longer exist by the time this report is published because of plans to plug the wells. All the thermal waters are within 200 yd of each other, and the waters are unused. The depths of these wells are unknown.

GEOLOGY AND HYDROLOGY:

Diamond Drill Hole: Temperature: 44°C; Discharge: 15 gpm; Total Dissolved Solids: 2,250 mg/l; and the waters are a calcium bicarbonate-sulfate type with a large concentration of manganese.

Big Geyser Warm Spring: Temperature: 34 to 36°C; Discharge: 8-12 gpm; Total Dissolved Solids: 2,750 mg/l; and the waters are a calcium-bicarbonate type with large concentrations of iron and manganese.

Geyser Warm Spring: Temperature: 38°C; Discharge: 14 gpm; Total Dissolved Solids: 2,790 mg/l; and the waters are a calcium-bicarbonate type with large concentrations of iron and manganese.

Little Spring: Temperature: 38°C; Discharge: 13 to 15 gpm; Total Dissolved Solids: 2,745 mg/l average; and the waters are a calcium bicarbonate-sulfate type with large concentrations of iron and manganese.

Geyser Warm Spring contained 38 picocuries/liter of Radium226, the highest of any thermal waters in Colorado, and 11 picocuries/liter of Radium228, the highest in Colorado.

The geological conditions in the Rico area are very complex (Fig. 107) for the area is cut by numerous faults and fractures. The bedrock varies from Precambrian metamorphic rocks to Mississippian and younger sedimentary rocks. The "hot springs" are located on the crest of the Rico Dome, a large anticlinal-type feature that extends from several miles west of Rico to the east of Rico.

No complete appraisal of the hydrogeological conditions of the area was possible, but the waters may represent deep circulation along some of the various fault systems in the area with the heating resulting from radioactive disintegration and residual heat from the magma chamber that supplied the Tertiary volcanic rocks.

Due to a high carbon dioxide content, the waters have a frothy appearance. This gas drives the water and gives the geyserlike activity to the waters.

GEOTHERMOMETER ANALYSES:

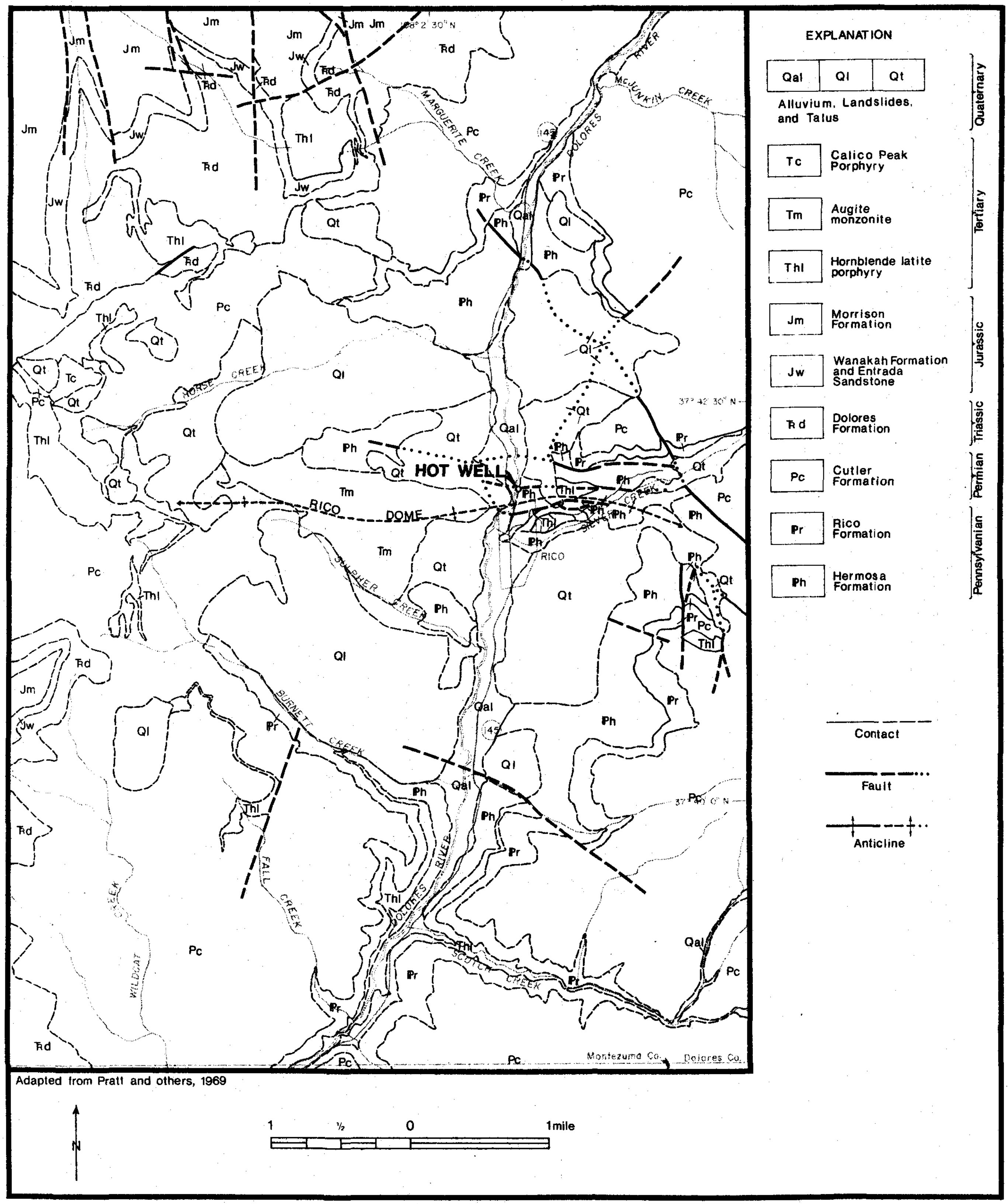
Silica Geothermometer: Silica solubility and temperature relationships suggest that temperature-dependent equilibration between the thermal water and amorphous silica controls the silica content of the thermal water. Thus, the amorphous silica geothermometer yields the most reliable subsurface temperature estimate. This geothermometer gives an estimated subsurface temperature of 22°C to 35°C (Table 4) which is below the surface temperature of the thermal water (36°C to 44°C). This low estimate may be caused by shallow ground water dilution of the ascending thermal water.

Mixing Model: The amorphous-silica mixing model was used here also. This model yielded a subsurface yielded a subsurface temperature estimate of 31°C to 39°C with a cold-water fraction of 1 to 19 percent of the total flow (Table 4). Although the subsurface temperature estimate is below the surface temperature of the thermal water (36°C to 44°C), it is within the expected margin of error.

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 185°C to 315°C and 17°C to 59°C respectively, (Table 4). The Na-K geothermometer estimate is too high because the value of the term log $\sqrt{Ca}/Na$ exceeds 0.5. Excluding the September 16, 1975, analysis of Rico Little Spring the Na-K-Ca geothermometer yields temperature estimates of 56°C to 59°C. The high magnesium content of the springs renders these results unreliable.

Conclusion: Geothermometer models should be used with caution when applied to the Rico area because most of the assumptions inherent in their use are violated. Any geothermometer estimate is for this group of springs is at best unreliable due to the ambiguous geochemistry of the waters.

Figure 106.--Big Geyser Spring at Rico.



Adapted from Pratt and others, 1969

Figure 107.--Geologic map of Rico, Colorado region.

#55 PINKERTON HOT SPRINGS

Located approximately 14 miles north of Durango along U.S. Highway 550 at the Golden Horeshoe Resort are a group of springs known as the Pinkerton Hot Springs.

LOCATION: The location of the following springs were determined:

Spring A: Latitude: 37°26'50"N.: Longitude: 107°48'17"W.; T. 37 N., R. 9 W., Sec. 25 ab, N.M.P.M.; La Plata County; Hermosa 7-1/2 minute topographic quadrangle map.

Spring B: Latitude: 37°27'58"N.: Longitude: 107°48'18"W.; T. 37 N., R. 9 W., Sec. 25 a, N.M.P.M.; La Plata County; Hermosa 7-1/2 minute topographic quadrangle map.

Mound Spring: Latitude: 37°27'07"N.: Longitude: 107°48'20"W.; T. 37 N., R. 9 W., Sec. 25 ba, N.M.P.M.; La Plata County; Hermosa 7-1/2 minute topographic quadrangle map.

Little Mound Spring: Latitude: 37°27'09"N.; Longitude: 107°48'21"W.; T. 37 N., R. 9 W., Sec. 25 ba, N.M.P.M.; La Plata County; Hermosa 7-1/2 minute topographic quadrangle map.

General: Spring A (Fig. 108) is located just east of the highway right-of-way and to the south of the resort buildings. Spring B was located 900 to 1,200 ft west of Spring A in the trees and bushes. Mound Spring is located approximately 1,500 ft northwest of Spring A. As the name implies, mound spring flows from the top of a large mound approximately 100 ft above the road (Fig. 109). Little Mound Spring is located several hundred feet north of Mound Spring. The new section of U.S. 550 under construction in 1977 passes the base of Mound and Little Mound Springs. The construction of this new section of road has destroyed Spring B.

Geology and Hydrology: Spring A was sampled in the fall of 1975, January, 1976, and April 1976. The temperature remained a constant 32°C, and its discharge was 54 gpm. The dissolved solids of the waters varied from a low of 3,700 mg/l to a high of 3,990 mg/l, and the waters are a mixed sodium-calcium, chloride-bicarbonate type with a high concentration of iron.

Figure 108.--Pinkerton Hot Spring. Spring A.

Spring B was sampled only once. Its temperature was 33°C with a discharge of 20 gpm. The dissolved solids was not determined, but the field measurement of conductance was 6,000 micromhos. The waters are a sodium-bicarbonate type with a very high concentration of iron.

Mound Warm Spring: The waters of this spring have a temperature of 32°C and the discharge of the spring is 54 gpm. The waters contain approximately 3,800 mg/l of dissolved solids with a high iron content.

Little Mound Spring: The waters of this spring were not sampled for complete chemical analysis of dissolved solids. Field measurements showed that the spring had a temperature of 26°C, an estimated discharge of 2 gpm, a pH of 7.0, and a conductance of 5,500 micromhos.

Surrounding all four springs are large aprons of iron-rich sediments.

These springs are located on the south side of the La Plata Mountains and Coal Bank Hill, a pass in the La Plata Mountains. The waters emerge from colluvial and alluvial deposits overlying the Mississippian Leadville Limestone.

The La Plata Mountains and the San Juan Mounains, immediately to the east, were centers of extensive volcanic activity in middle Tertiary time. Although no volcanic rocks are found near these springs, they occur only a few miles to the north. While not shown on the accompanying geologic map (Fig. 110), the Leadville Limestone appears to be faulted in the vicinity of the springs. Moyer and others (1961) state that the waters emerge from a fault transverse to the valley. Any explanation of the occurrence of these thermal waters must explain the high concentration of dissolved iron and evaporite mineral matter in the waters. Kilgore and Clark (1961, p. 235) have shown that a thin section of early Paleozoic limestones and sandstones underlies the Pinkerton Hot Springs, none of which contain large amounts of readily soluble minerals, especially iron. However, the overlying red sandstones, shales, siltstones of the Hermosa Group do. In addition, formations within the Hermosa group contain large amounts of evaporite minerals. Contact of the thermal waters with these units would explain the origin of the mineral matter in the thermal waters.

Figure 109.--Mound Spring at Pinkerton Hot Springs.

Reiter (1975) has shown this part of western Colorado to have a heat flow between 2.0 and 2.5 heat flow units. The source of the heat is unknown but may be related to the volcanic rocks found in the La Plata and San Juan Mountains. Recharge of the thermal water is believed to occur via deep circulation along fault zones from the La Plata Mountains.

GEOTHERMOMETER ANALYSIS OF SPRING A AND MOUND SPRING:

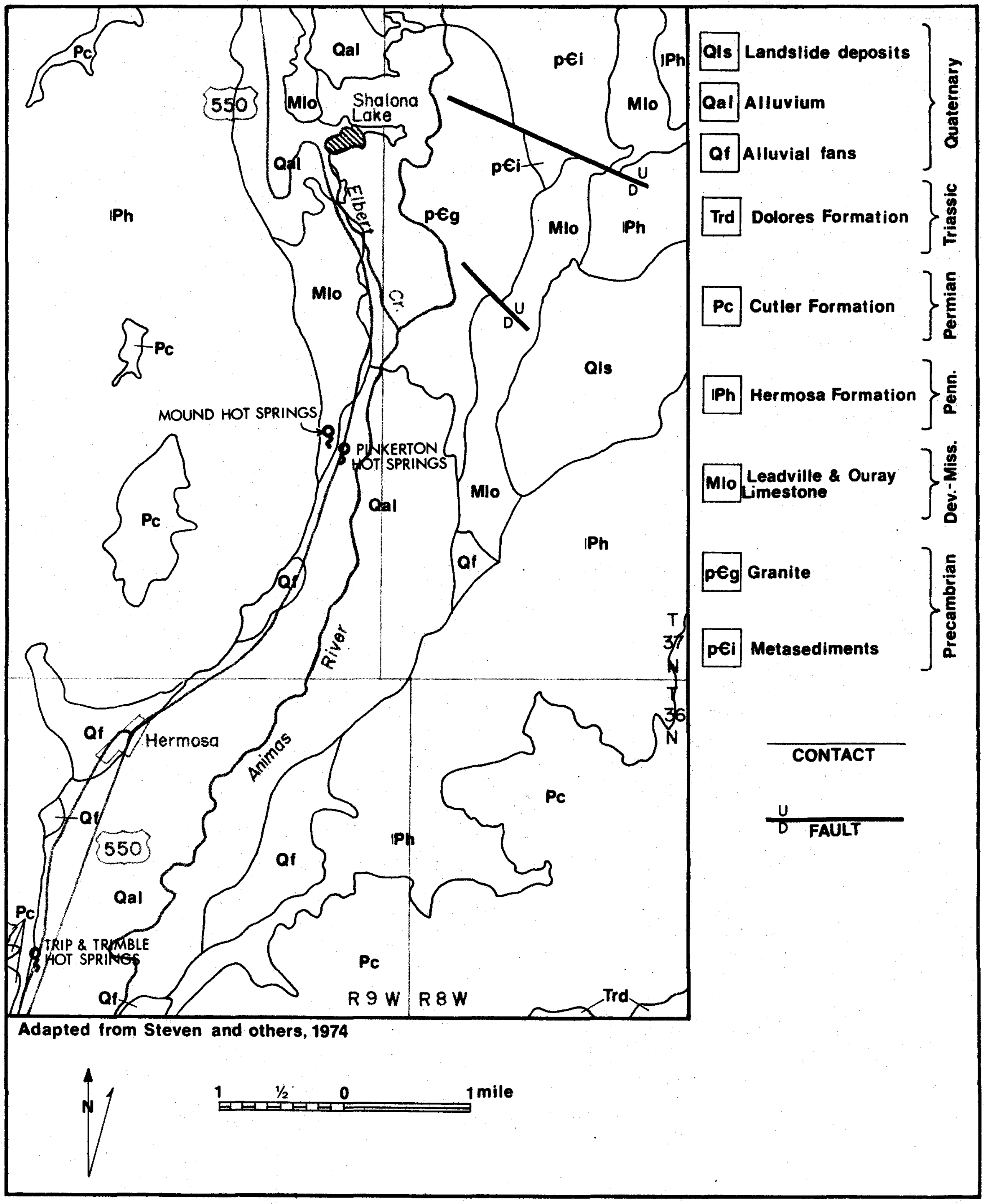
Silica Geothermometer: The quartz-silica geothermometer yields an estimated temperature of 78°C for Spring A and Mound Spring.

Mixing Model: Since temperature-dependent equilibration between the thermal waters and quartz may control the silica content of the spring, the quartz mixing model is applicable. Use this model for Spring A yields an estimated subsurface temperature of 127°C to 133°C with a cold-water fraction of 81 to 82 percent. A temperature of 139°C with a cold-water fraction of 84 percent was estimated for Mound Spring (Table 4). The estimated values are within the range of values that could result from normal analytical error.

Na-K and Na-K-Ca Geothermometers: The Na-K geothermometer yielded a subsurface temperature estimate of 231°C to 234°C for Spring A, and 234°C to 235°C for Mound Spring. The Na-K-Ca geothermometer yielded an estimated temperature of 202°C to 206°C for Spring A and 206°C to 207°C for Mound Spring. In both instances the Na-K estimate is too high because the value of the term, log $\sqrt{Ca}/Na$ is greater than 0.5. In addition, large travertine and calcium carbonate deposits near the hot springs suggest that both the Na-K and Na-K-Ca geothermometer estimates are too high.

Conclusion: The insignificant variation in flow, mineral content, and surface temperature of the warm spring suggests that it is not materially affected by seasonal metereological conditions. Moreover, the fluctuations of the various geothermometer model estimates are well within the range of values that could result from normal analytical errors.

Consideration of the mixing model and silica geothermometer results and mixing model precision suggests subsurface temperatures between 75° and 125°C (Table 4).



Adapted from Steven and others, 1974

Figure 110.--Geologic conditions of Pinkeron, Mound, Tripp, and Trimble Hot Springs areas.

#56 TRIPP AND TRIMBLE WARM SPRINGS

#56 TRIMBLE HOT SPRING

LOCATION: Latitude: 37°23'28"N.; Longitude: 107°50'52"W.; T. 36 N., R. 9 W., Sec. 15 bb, N.M.P.M.; La Plata County; Hermosa 7 1/2-minute topographic quadrangle map.

GENERAL: Trimble Hot Spring is located approximately 9.25 miles north of Durango just off U.S. Highway 550. At the present time the spring is unused and just barely flows. In the past this spring fed the large swimming pool located to the south. The spring is inside a small rock house (Fig. 111).

GEOLOGY AND HYDROLOGY: This spring had a temperature of 36°C and a discharge of less than one gpm. The waters contained 3,340 mg/l of dissolved mineral matter and are a calcium sulfate type.

The waters, although issuing from colluvial deposits at the base of the cliff, are associated with the underlying red beds of the Paradox Formation (Fig. 110).

Moyer and others (1961) have described a northeast-trending fault, downthrown on the northwest side, crossing the valley near the springs. They state that the springs emerge along this fault zone. Kilgore and Clark (1961) show this and other faults in the vicinity reaching to basement rocks. The origin of these thermal waters is unknown but may result from deep circulation and updip flow along faults in the San Juan basin.

#56 TRIPP HOT SPRING

LOCATION: Latitude: 37°23'30"N.; Longitude: 107°50'52"W.; T. 36 N., R. 9 W., Sec. 10 cc, N.M.P.M.; La Plata County; Hermosa 7 1/2-minute topographic quadrangle map.

Figure 111.--Trimble Hot Springs. Spring is inside rock house.

GENERAL: This spring is located less than 200 ft north of the Trimble Hot Spring, approximately 9.25 miles north of Durango off U.S. Highway 550. The spring is located in the big tin building behind the house (Fig. 112). The spring was sampled from a concrete-lined trough in the metal building.

GEOLOGY AND HYDROLOGY: Temperature: 44°C; Discharge: not determined; Total Dissolved Solids: 3,240 mg/l; Calcium-sodium sulfate type.

Like the Trimble Hot Spring waters, these waters come from colluvial deposits overlying the red beds of the Paradox Formation.

GEOTHERMOMETER ANALYSES OF TRIMBLE AND TRIPP HOT SPRINGS:

Silica Geothermometer: The silica content of these springs does not approach the solubilities of amorphous silica, chalcedony, cristobalite, or quartz. Therefore, application of any of these silica geothermometers will yield unreliable results.

Mixing Model: The amorphous silica solubility at the warm springs surface temperature (36°C to 44°C), 143 to 164 mg/l, is much higher than the silica content of the thermal water (69 to 72 mg/l). This discrepancy may be caused by mixing of the thermal water and relatively dilute groundwater.

The amorphous-silica mixing model yields a subsurface temperature estimate of 30°C to 40°C with a cold-water fraction of 39 to 47 percent of the spring flow (Table 4).

Na-K and Na-K-Ca Geothermometers: The Na-K and Na-K-Ca geothermometers yield subsurface temperature estimates of 197°C to 198°C and 97°C to 99°C, respectively (Table 4). The Na-K geothermometer estimate is too high because the term log $\sqrt{Ca}/Na$ exceeds 0.5. In addition, the low surface temperature and flow (less than 1 gpm) and the lack of substantiation of such high subsurface temperatures by the other geothermometers suggest that both the Na-K and Na-K-Ca estimates are unreliable.

CONCLUSION: Geothermometer models must be used with caution when applied to Tripp and Trimble warm springs because most of the assumptions inherent in their use are violated. Any geothermometer estimate for this area is unreliable at best; however, the subsurface temperature is probably between 45°C and 70°C (Table 4).

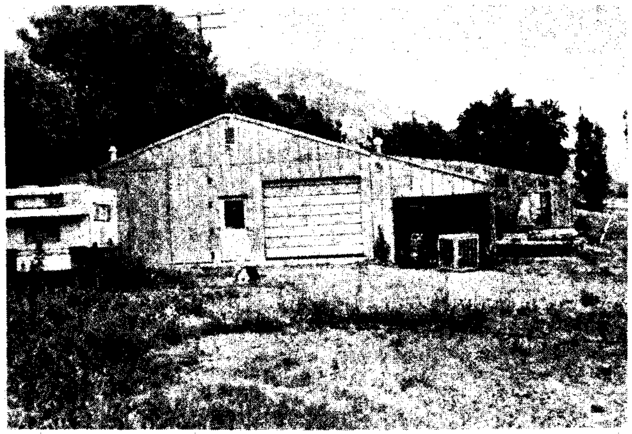


Figure 112.--Tripp Hot Springs. Spring is inside metal buildings.

HISTORICAL TRENDS OF SUBSURFACE TEMPERATURE ESTIMATES

To determine what, if any, changes might be occurring in in the geo-thermal reservoir, a study was made to find all historical analytical water-chemistry data. Ms. Rebecca Goodman researched the historical files and found that nearly one hundred years ago seven springs--Glenwood Springs, Hot Sulphur Springs, Hortense Hot Spring, Idaho Springs, Mt. Princeton Hot Springs, Pagosa Springs, and Poncha Springs--were sampled and the results published (Crofutt, 1885; Fossett, 1880; Horn, 1870; McCauley, 1878; Patrick, 1880; and Wheeler, 1875).

When the silica content of the springs, as reported by the above authors, were applied to the silica geothermometer models (Figs. 113-119), it was found that the estimated temperatures of Hot Sulphur Springs, Hortense Hot Spring, Idaho Springs, Mt. Princeton Hot Springs, and Poncha Springs have increased with time. The estimated temperature of the other two springs--Glenwood Springs and Pagosa Springs--peaked and are now decreasing. While this appraisal may have significance, it should be pointed out that the data cannot be considered conclusive because many factors may have affected the chemistry of the waters over the last 100 years. Such factors as different sampling points, analytical techniques, and natural and man-made alteration in the spring flow may individually or collectively have changed the data substantially. Some questions may be raised regarding the reliability of the historical data analysis. It is believed that the historical analysis are reasonable and are an accurate measurement of the dissolved silica in the thermal waters.

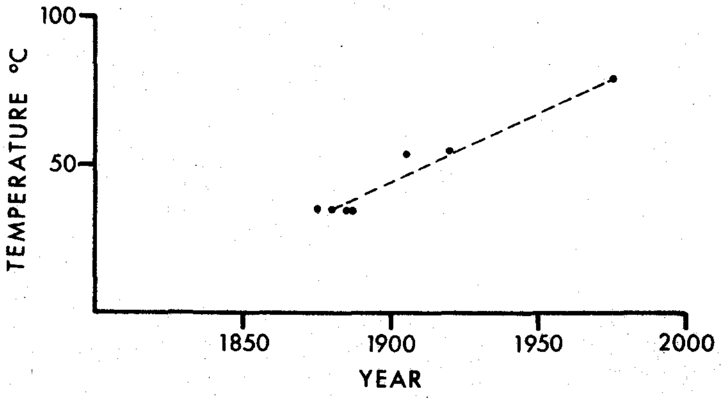


Figure 113.--Estimated temperature of Idaho Springs with time.

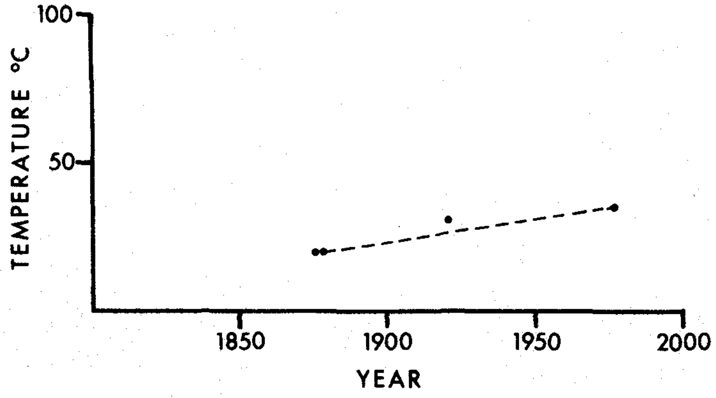


Figure 114.--Estimated temperature of Hot Sulphur Springs with time.

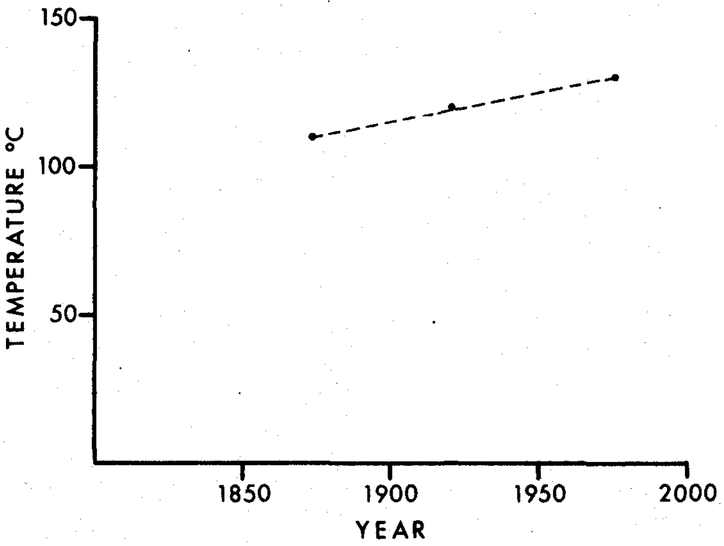


Figure 115.--Estimated temperature of Hortense Hot Spring with time.

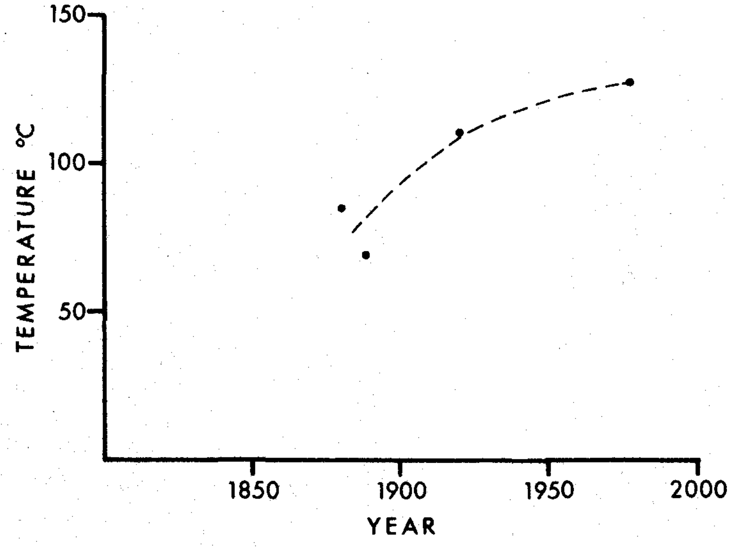


Figure 116.--Estimated temperature of Mount Princeton Hot Springs with time.

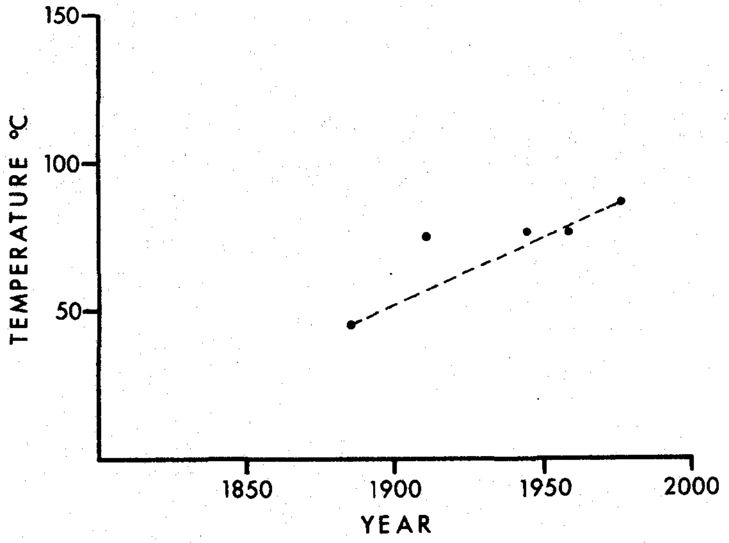


Figure 117.--Poncha Springs estimated temperature with time.

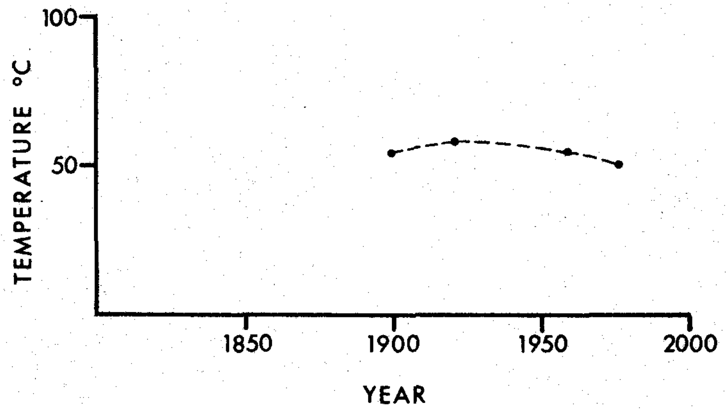


Figure 118.--Glenwood Springs estimated temperature with time.

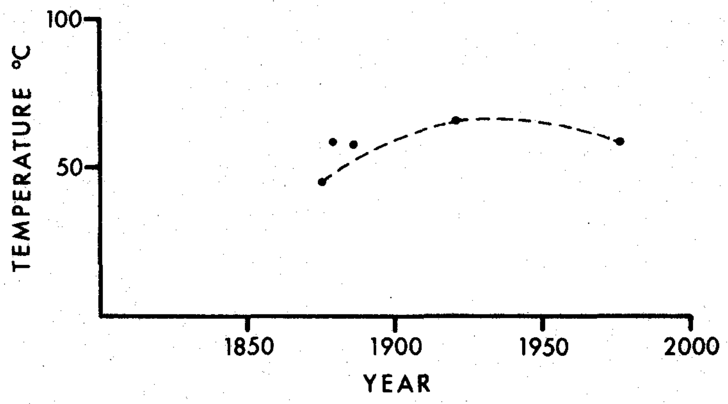


Figure 119.--Pagosa Springs estimated temperature with time.

SUMMARY

Colorado's geothermal resources potential is expressed in the 127 thermal springs and wells (temperatures in excess of 20°C) found throughout the western one-half of the state. While these springs and wells are found in all geological environments, the majority of them are associated with the Rio Grande Rift of the San Luis Valley and Upper Arkansas Valleys, and with the San Juan and La Plata Mountains of the southwestern part of Colorado. The discharge of the waters ranges from less than 1 gpm to a high of 2,263 gpm at the Big Spring in Glenwood Springs. The temperature ranges from a low of 20°C to 83°C at Hortense Hot Spring in the Chalk Creek Valley southwest of Buena Vista.

During the course of the investigation, the amount of mineral matter contained in the waters was determined by wet-chemical and spectrographic methods. In addition radiochemical analyses of radon, radium, uranium, and thorium were determined. In all but one instance, the levels of radioactivity were below accepted U.S. Environmental Protection Agency limits.

To aid in appraising the geothermal resources of Colorado, four geothermometer models were utilized to estimate the subsurface reservoir temperatures of the various spring areas. The models used were: Silica, Mixing Model 1, Na-K, and Na-K-Ca. Probable subsurface temperatures range from low of 20°C to 50°C at Dexter Warm Spring in the southern San Luis Valley to high of 150°C to 200°C at both Cottonwood Hot Springs and Mount Princeton Hot Springs area.

REFERENCES

American Geological Institute, 1962, Dictionary of geological terms: Garden City, N.Y., Doubleday and Co., 545 p.

Barrett, J.K., and Pearl, R.H., 1976, Hydrogeological data of thermal springs and wells in Colorado: Colorado Geol. Survey Inf. Ser. 6, 124 p.

Barrett, J.K., Pearl, R.H., and Pennington, A.J., 1976, Map showing thermal springs, wells and heat-flow contours in Colorado: Colorado Geol. Survey Inf. Ser. 4, 1 pl., scale 1:1,000,000.

Bass, N.W. and Northrop, S.A., 1963, Geology of Glenwood Springs quadrangle and vicinity, northwestern Colorado: U.S. Geol. Survey Bull. 1142-J, 74 p.

Bastin, E.S., 1922, Silver enrichment in the San Juan Mountains, Colorado: U.S. Geol. Survey Bull. 735, 129 p.

Bedinger, M.S., Pearson, F.J., Jr., Reed, J.E., Sniegocki, R.T., and Stone, C.J., 1974, The waters of Hot Springs National Park, Arkansas - Their origin, nature and mangement: U.S. Geol. Survey Open-File Report, 102 p.

Berthoud, E.L., 1866, Description of the hot springs of Soda Creek, their location, number, temperature, and altitude, and the geological features of the surrounding locality, together with the remarkable discovery of a human skeleton and a fossil pine tree in the boulder and gravel formation of Soda Bar, Oct. 13th, 1860: Philadelphia Acad. Nat. Sci. Proc. v. 18, p. 342-345.

Boos, C.M., and Boos, M.F., 1957, Tectonics of eastern flank and foothills of Front Range, Colorado: Am. Assoc. Petroleum Geologists Bull., v. 41, no. 12, p. 2603-2676.

Brogden, R.E., and Giles, T.F., 1976, Availability and chemical quality of ground water in the Crystal River and Cattle Creek drainage basins near Glenwood Springs, west-central Colorado: U.S. Geol. Survey Water Resources Inv. 76-70, sheet 1 (geologic map scale 1:125,000).

Bryant, Bruce, 1969, Geologic map of the Maroon Bells quadrangle, Pitkin and Gunnison Counties, Colorado: U.S. Geol. Survey Geol. Quad. Map CQ-788.

______1970, Geologic map of the Hayden Peak quadrangle, Pitkin and Gunnison Counties, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-863.

Burroughs, R.L., 1971, Geology of the San Luis Hills, south-central Colorado, in Guidebook of the San Luis Basin, Colorado: New Mexico Geol. Soc. 22d Field Conference, p. 277-287.

Bush, A.L., and Bromfield, C.S., 1966, Geologic map of the Dolores Peak Quadrangle, Dolores and San Miguel Counties, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-536.

Bush, A.L., Bromfield, C.S., and Pierson, T.L., 1956, Preliminary geologic map of the Placerville quadrangle, Colorado: U.S. Geol. Survey Mineral Inv. Field Studies Map MF-96.

Chapin, C.E., 1971, The Rio Grande Rift, part I-Modifications and additions, in Guidebook of the San Luis Basin, Colorado: New Mexico Geol. Soc. 22d Field Conference, p. 191-201.

Chronic, John, 1964, Geology of the southern Mosquito Range, Colorado: Mtn. Geologist v. 1, no. 3, p. 103-113.

Conley, C.D., 1958, Geology of the Chromo anticline, Archuleta County, Colorado and Rio Arriba County, New Mexico: Colorado School Mines Master Sci. Thesis T-879.

Craig, Harmon, 1961a, Standard for reporting concentrations of deuterium and oxygen-18 in natural waters: Science, v. 131, p. 1833-1834.

______1961b, Isotopic variations in meteoric waters: Science, v. 133, p. 1702-1703.

Crofutt, G.A., 1885 [repr. 1966], Grip-sack guide of Colorado: Golden, Colo., Cubar Associates, p. 131.

DeVoto, R.H., 1971, Geologic history of South Park and geology of the Antero Reservoir quadrangle, Colorado: Colorado School Mines Quart., v. 66, no., 3, 90 p.

Dick, J.D., 1976, Geothermal reservoir temperatures in Chaffee County, Colorado: Northeast Louisiana Univ., Dept. of Geology, Master Sci. thesis, 171 p.

Emery, P.A., 1971, Water resources of the San Luis Valley, Colorado, *in* Guidebook of the San Luis Basin, Colorado: New Mexico Geol. Soc. 22d Field Conference, p. 129-132

Emery, P.A., Boettcher, A.J., Snipes, R.J., and McIntyre, H.J., Jr., 1971, Hydrology of the San Luis Valley, south-central Colorado: U.S. Geol. Survey Hydrol. Inv. Atlas HA-381.

Emmons, W. H., and Larsen, E.S., 1913, The hot springs and mineral deposits of Wagon Wheel Gap, Colorado: Econ. Geology, v. 8, p. 235-246.

Epis, R.C., and Chapin, C.E., 1968, Geologic history of the Thirtynine Mile Volcanic field, *in* Cenozoic volcanism in the Southern Rocky Mountains: Colorado School Mines Quart., v. 63, no. 3, p. 51-85.

Ettinger, Morris, 1964, Geology of the Hartsel area, South Park, Colo.: Mt. Geologist, v. 1, 1no. 3, p. 127-139.

Fossett, Frank, 1880, Colorado, its gold and silver mines, farms and stock ranges, and health and pleasure resorts-Tourists guide to the Rocky Mountains, 2d ed.: New York, C.G. Crawford, 592 p.

Fournier, R.O., 1973, Silica in thermal waters-Laboratory and field investigations, *in* Proceedings of International Symposium on Hydrogeochemistry and Biogeochemistry, Japan, 1970, v. 1-- Hydrogeochemistry: Washington, J.W. Clark, p. 122-139.

_____,1977, Chemical geothermometers and mixing models for geothermal systems: Geothermics, vo. 5, p. 41-50.

Fournier, R.O., and Rowe, J.J., 1966, Estimation of underground temperatures from the silica content of water from hot springs and wet-steam wells: Am. Jour. Sci., v. 264, p. 685-697.

Fournier, R.O., and Truesdell, A.H., 1972, Chemical indicators of subsurface temperature applied to hot spring waters of Yellowstone Natinonal Park, Wyoming, U.S.A.: Geothermics, Spec. Issue 2, p. 529-535.

______1973, An empirical Na-K-Ca geothermometer for natural waters: Geochim. et Cosmochim. Acta, v. 37, p. 1255-1275.

______1974, Geochemical indicators of subsurface temperatures, part 2-- Estimation of temperature and fraction of hot water mixed with cold water: U.S. Geol. Survey Jour. Research, v. 2, no. 3, p. 263-270.

Fournier, R.O., White, D.E., and Truesdell, A.H., 1974, Geochemical indicators of subsurface temperatures, part 1-Basic assumptions: U.S. Geol. Survey Jour. Research, v. 2, no. 3, p. 259-262.

Gaca, J.R., and Karig, D.E., 1966, Gravity survey in the San Luis Valley area, Colorado: U.S. Geol. Survey open-file rept., 26 .

George, R.D., Curtis, H.A., Lester, O.C., Crook, J.K., and Yeo, J.M., 1920, Mineral Waters of Colorado: Colorado Geol. Survey Bull. 11, 474 p.

Grose, L.T., 1971, Geothermal energy--Geology, exploration and developments, part 1: Colorado School Mines Mineral Indsutries Bull. v. 14, no. 6, 14 p.

_______1972, Geothermal energy--Geology, exploration, and developments, part 2: Colorado School Mines Mineral Industries Bull. v. 15, no. 1, 16 p.

______1974, Summary of geology of Colorado related to geothermal energy potential; *in* Proceedings of a symposium on geothermal energy and Colorado: Colorado Geol. Survey Bull. 35, p. 11-29.

Hail, W.J., Jr., 1965, Geology of northwestern North Park, Colorado: U.S. Geol. Survey Bull. 1188, 133 p.

______1972, Reconnaissance geologic map of the Hotchkiss area, Delta and Montrose Counties, Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I-698 (scale 1:48,000).

Harrison, J.E., and Wells, J.D., 1959, Geology and ore deposits of the Chicago Creek area, Clear Creek County, Colorado: U.S. Geol. Survey Prof. Paper 319, 92 p.

Hedlund, D.C., and Olson, J.C., 1975, Geologic map of the Powderhorn quadrangle, Gunnison and Saguache Counties, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-1178.

Horn, T.G., 1877, Report on the mineral springs of Colorado, in Colorado State Board of Health, Annual Report: Denver, Colorado Bd. Health, p. 43.

Hunter, Z.M., 1955, Geology of the foothills of the Front Range in northern Colorado: Rocky Mtn. Assoc. Geologists, 2 maps (scale 1: 48,000).

Izett, G.A., 1968, Geology of the Hot Sulphur Springs quadrangle, Grand County, Colorado: U.S. Geol. Survey Prof. Paper 586, 79 p.

Izett, G.A., and Barclay, C.S.V., 1964, Preliminary geologic map of the Hot Sulphur Springs SW quadrangle, Grand County, Colorado: U.S. Geol. Survey Mineral Inv. Field Studies Map MF-291.

Izett, G.A., and Hoover, D.L., 1963, Preliminary geologic map of the Hot Sulphur Springs SE quadrangle, Grand County, Colorado: U.S. Geol. Survey Mineral Inv. Field Studies Map MF-271.

Johnson, R.B., 1969, Geologic map of the Trinidad quadrangle, south-central Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I-558.

Keenan, J.H., Hill, P.G., and Moore, J.G., 1969, Steam tables (International Edition-Metric Units): New York, John Wiley.

Kilgore, L.W, and Clark, P.E., 1961, Animas Valley cross section, in Berg, R.R., and Rold, J.W., eds., Symposium on Lower and Middle Paleozoic rocks of Colorado--12th Field Conf.: Rocky Mtn. Assoc. Geologists, p. 235.

Klein, J.M., 1976, Chemistry of silica in the ground water of the San Luis Valley, Colorado [abs.]: Geol. Soc. America Abs. with Program, 89th Ann. Mtg., v. 8, no. 6, p 956-957.

Knepper, D.H., Jr., 1974, Tectonic analysis of the Rio Grande rift zone: Colorado School Mines, Ph.D. Thesis T-1593.

______1976, Late Cenozoic structure of the Rio Grande Rift Zone, central Colorado, in Epis, R.C., and Weimer, R.J., eds., Studies in Colorado field geology: Colorado School Mines Prof. Contr. 8, p. 421-430.

Knepper, D.H., Jr., and Grose, L.T., 1976, Structure, volcanism, and geothermal features of the northern Rio Grande Rift zone, Colorado; in Epis, R.C., and Weimer, R.J., eds., Studies in Colorado field geology: Colorado School Mines Prof. Contr. 8, p. 403-420.

Kruger, Paul, and Otte, Carel, eds., 1973, Geothermal energy--resources, production, stimulation: Stanford Univ. Press, 360 p.

Lawrence Berkeley Laboratory, 1976, Proceedings Second United Nations Symposium on the development and use of geothermal resources; San Francisco, California, USA, 20-29 May 1975: U.S. Govt. Printing Office, vol. 1-3, 2466 p.

Lewis, E.L., 1966, The thermal springs of Colorado--A resource appraisal: Univ. Colorado Dept. Geography, Master Sci. Thesis, 91 p.

Limbach, F. W., 1975, The geology of the Buena Vista area, Chaffee County, Colorado: Colorado School Mines Master Sci. Thesis, T-1692, 98 p.

Lipman, P.W., 1968, Geology of the Summer Coon volcanic center, eastern San Juan Mountains, Colorado, in Epis, R.C., ed., Cenozoic volcanism in the southern Rocky Mountains: Colorado School Mines Quart., v. 63, no. 3, p. 211-236.

______1975, Evolution of the Platoro Caldera complex and related volcanic rocks, southeastern San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 852, 128 p.

Lipman, P.W., Steven, T.A., and Mehnert, H.H., 1970, Volcanic history of the San Juan Mountains, Colorado, as indicated by potassium-argon dating: Geol. Soc. America Bull., v. 81, p. 2329-2352.

Lovering, T.S., and Goddard, E.N., 1950, Geology and ore deposits of the Front Range, Colorado: U.S. Geol. Survey Prof. Paper 223, 319 p.

Luedke, R.G., Burbank, W.S., 1962, Geologic map of the Ouray quadrangle, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-192.

Mallory, E.C., Jr., and Barnett, P.R., 1973, Chemical and spectrochemical analyses of selected ground waters in Colorado: U.S. Geol. Survey open- file rept., 47 p.

McAvoy, R.L., Erdman, D.E., [no date], The precision and accuracy which can be expected when analyzing natural water samples, U.S. Geol. Survey unpub. rept.

McCauley, C.A.H., 1878, Report on the San Juan reconnaissance of 1877: U.S. War Dept. Chief Engineer, Ann. Rept., 1878, app. ss, p. 1753-1852.

McFarlan, A.C., 1961, Outline of the geology of the Cement Creek area, Gunnison County, Colorado, in Berg, R.R., and Rold, J.W., eds., Symposium on Lower and Middle Paleozoic rocks of Colorado-12th Field Conf.: Rocky Mtn. Assoc. Geologists, p. 125-132.

Mertzman, S.A., Jr., 1971, The Summer Coon volcano, eastern San Juan Mountains, Colorado, in Guidebook of the San Luis Basin, Colorado: New Mexico Geol. Soc. 22d Field Conference, p. 265-275.

Moench, R.H., and Drake, A.A., Jr., 1966, Economic geology of the Idaho Springs district, Clear Creek and Gilpin Counties, Colorado: U.S. Geol. Survey Bull. 1208, 19 p.

Moyer, J.L., Ansberry, L.E., Mallory, W.W., Loomis, F., and Baars, D.L., 1961, Road log, in Berg, R.R., and Rold, J.W., eds., Symposium on Lower and Middle Paleozoic rocks of Colorado--12th Field Conf.: Rocky Mtn. Assoc. Geologists, p. 229-235.

Patrick, G.E., 1880, [Chemical analysis of Hortense Hot Spring], in Denison, Charles, Rocky Mountain health resorts: Boston, Houghton, Osgood and Co.

Pearl, R.H., 1972, Geothermal Resources of Colorado: Colorado Geol. Survey Spec. Pub. 2, 54 p.

Pearl, R. H., ed., 1974, Proceedings of a symposium on geothermal energy and Colorado: Colorado Geol. Survey Bull. 35, 102 p.

Pratt, W.P., McKnight, E.T., and DeHon, R.A., 1969, Geologic map of the Rico quadrangle, Dolores and Montezuma Counties, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-797.

Reed, M.J., 1975, Chemistry of thermal water in selected geothermal areas of California: California Div. Oil and Gas Rept. TR15.

Reiter, Marshall, 1975, Terrestrial heat flow along the Rio Grande Rift, New Mexico and southern Colorado: Geol. Soc. America Bull, v. 86, p. 811-818.

Renner, J.L., White, D.E., and Williams, D.L., 1975, Hydrothermal convection systems, in Assessment of geothermal resources of the United States, 1975: U.S. Geol. Survey Circ. 726, p. 5-57.

Scott, G.R., 1964, Geologic map of the Northwest and Northeast Pueblo quadrangles, Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I-408.

______1969, Geologic map of the Southwest and Southeast Pueblo quadrangles, Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I-597.

______1973, Reconnaissance geologic map of the Owl Canyon quadrangle, Pueblo County, Colorado: U.S. Geol. Survey Misc. Field Studies Map MF-547.

______1975, Reconnaissance geologic map of the Buena Vista quadrangle Chaffee and Park Counties, Colorado: U.S. Geol. Survey Misc. Field Studies Map MF-657 (scale 1:62,500).

Scott, G.R., Taylor, R.M., Epis, R.C., and Wobus, R.A., 1976, Geologic map of the Pueblo 1° x 2° quadrangle, south-central, Colorado: U.S. Geol. Survey Misc. Field Studies Map MF-775 (scale 1:187,500).

Scott, G.R., Van Alstine, R.E., and Sharp, W.N., 1975, Geologic map of the Poncha Springs quadrangle, Chaffee County, Colorado: U.S. Geol. Survey Misc. Field Studies Map MF-658 (scale 1:62,500).

Sears, J.D., 1924, Geology and oil and gas prospects of part of Moffat County, Colorado, and southern Sweetwater County, Wyoming: U.S. Geol. Survey Bull. 751-G, p. 269-319.

Sharp, W.N., 1970, Extensive zeolitization associated with hot springs in central Colorado, in Geological Survey research 1970: U.S. Geol. Survey Prof. Paper 700-B, p. B14-B20.

Spurr, J.E., Garrey, G.H., and Bull, S.H., 1908, Economic geology of the Georgetown quadrangle (together with the Empire district) Colorado: U.S. Geol. Survey Prof. Paper 63, 422 p.

Stark, J.T., and Behre, C.H., Jr., 1936, Tomichi dome flow: Geol. Soc. America Bull. v. 47, no. 1, p. 101-110.

Steven, T.A., 1969, Geologic map of the Bristol Head quadrangle, Mineral and Hinsdale Counties, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-631.

______1969b, Possible relation of mineralization to thermal springs in Creede district, San Juan Mountains, Colorado: A discussion: Econ. Geol. v. 64, p. 696-698.

Steven, T.A., and Lipman, P.W., 1973, Geologic map of the Spar City quadrangle, Mineral County, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-1052.

Steven, T.A., Lipman, P.W., Hail W.J., Jr., Barker, F., and Luedke, R.G., 1974, Geologic map of the Durango quadrangle, southwestern Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I-764.

Steven, T.A., and Ratte, J.C., 1960, Geology and ore deposits of the Summitville District, San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 343, 70 p.

_______1973, Geologic map of the Creede quadrangle, Mineral and Saguache Counties, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-1053.

Stoughton, Dean, 1977, Interpretation of seismic reflection data from the San Luis Valley, south-central Colorado: Colorado School Mines, Dept. Geophysical Engineering, Master Sci. Thesis T-1960, 100 p.

Taylor, R.B., and Scott, G.R., 1973, Reconnaissance geologic map of the Wetmore Quadrangle, Custer and Pueblo Counties, Colorado: U.S. Geol. Survey Misc. Field Studies Map MF-548.

Taylor, R.B., Scott, G.R., and Wobus, R.A., 1975, Reconnaissance geologic map of the Howard quadrangle, central Colorado: U.S. Geol. Survey Mis. Geol. Inv. Map I-892 (scale 1:62,500).

Taylor, R.B., Scott, G.R., Wobus, R.A., and Epis, R.C., 1975, Reconnaissance geologic map of the Royal Gorge quadrangle, Fremont and Custer Counties, Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I-869.

Trimble, D.E., 1975, Geologic map of the Niwot quadrangle, Boulder County, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-1229.

Truesdell, A.H., Fournier, R.O., 1975, Calculation of deep reservoir temperatures in geothermal systems from the chemistry of boiling spring waters of mixed origin, in Proc. 2nd U. N. Symposium on the Development and Use of Geothermal Resources: San Francisco, California, p. 837-844.

_____,1977, Procedure for estimating the temperature of a hot water component in a mixed water using a plot of dissolved silica vs enthalpy, in Geol. Survey Research 1977: U.S.Geol. Survey Jour. Research v. 5, no. 1, p. 49-52.

Truesdell, A.H., Fournier, R.O., and Thompson, J.M., 1973, Mixture, a computer program for the calculation of hot water temperature and mixing fractions of large volume warm springs of mixed water origin: Natl. Tech. Inf. Service Rept. PB-220 732, 12 p.

Tweto, Ogden, 1975, Preliminary geologic map of the Craig 1° x 2° quadrangle, northwestern Colorado: U.S. Geol. Survey Misc. Field Studies Map MF-666 (Available as U.S.G.S. I-972).

_______1976, Preliminary geologic map of Colorado: U.S. Geol. Survey Misc. Field Studies Map MF-788.

Tweto, O., Steven, T.A., Hail, W.J., Jr., and Moench, R.H., 1976, Preliminary geologic map of the Montrose 1° x 2° quadrangle, southwestern Colorado: U.S. Geol. Survey, Misc. Field Studies Map MF-761.

Van Alstine, R.E., 1970, Allochthonous Paleozoic blocks in the Tertiary San Luis-Upper Arkansas graben, Colorado, in Geological Survey research 1970: U.S. Geol. Surv. Prof. Paper 700-B, p. B43-B51.

______1974, Geology and mineral deposits of the Poncha Springs SE quadrangle, Chaffee County, Colorado: U.S. Geol. Survey Prof. Paper 829, 17 p.

Van Alstine, R.E., and Cox, D.E., 1969, Fluorspar mines and prospects, in Geology and mineral deposits of the Poncha Springs NE quadrangle, Chaffee County, Colorado: U.S. Geol. Survey Prof. Paper 626, p. 38-43.

Walton, G.E., 1883, Mineral springs of the United States and Canada: Philadelphia, D. Appleton and Co., p. 305.

Waring, G.A., 1965, Thermal springs of the United States and other countries of the world--A summary, revised by R.R. Blankenship and Ray Bentall: U.S. Geol. Survey Prof. Paper 492, 383 p.

Wehlage, E.F., 1976, The basics of applied geothermal engineering: West Covina, California, Geothermal Information Services, 211 p.

Wheeler, G.M., 1875, Report upon the geographical and geological explorations and surveys west of the 100th Meridan: U.S. Army Engineer Dept., pts. 1-5, v. 3, p. 478-487.

White, D.E., 1965, Geothermal energy: U.S. Geol. Survey Circ. 519, 17p.

______1967, Mercury and base metal deposits with associated thermal water, in Geochemistry of hydrothermal ore deposits: Holt, Rinehart, and Winston, Inc., p. 575-671.

______1968, Hydrology, activity, and heat flow of the Steamboat Springs thermal system, Washoe County, Nevada: U.S. Geol. Survey Prof. Paper 458-C, 109 p.

______1972, Geochemistry applied to the discovery, evaluation, and exploitation of geothermal energy resources, in Proceedings of U.N. Symposium on the Development and Utilization of Geothermal Resources, Pisa: Geothermics Spec. Issue 2, v. 2, pt. 1.

White, D.E., Barnes, Ivan, and O'Neill, J.R., 1973, Thermal and mineral waters of nonmeteoric origin, California Coast Ranges: Geol. Soc. America Bull., v. 84, p. 547-560.

Zohdy, A.A.R., Hershey, L.A., Emery, P.A., and Stanley, W.D., 1971, Resistivity sections, upper Arkansas River Basin, Colorado: U.S. Geol. Survey open-file rept., 16 p.

APPENDIX A

TABLE 1

STATISTICAL SUMMARY OF THERMAL WATERS IN COLORADO

Summary derived from data presented
by Barrett and Pearl (1976)

	No. of Spls.	High	Low	Mean	Std. Dev.
FIELD VALUES					
Sp. Cond. (micromhos)	103	36800	135	4753	8653
Discharge (gallons/minute)	101	2263	1	88	266
Temp. (°C)	125	83	20	45	15
CHEMICAL ANALYSES					
Arsenic (ug/l)	96	240	0	28	51.32
Boron (ug/l)	102	3200	8	580	798
Cadmium (ug/l)	97	2	0	-	0.21
Calcium (mg/l)	104	770	1	174	-
Chloride (mg/l)	103	11000	1	1060	2805
Fluoride (mg/l)	102	20	0	5.32	5.13
Iron (ug/l)	103	8500	10	553	1559
Lithium (ug/l)	97	9600	10	864	1340
Magnesium (mg/l)	103	150	0	29	33
Manganese (ug/l)	103	4400	0	248	564
Mercury (ug/l)	97	0.2	0	0.026	0.056
Nitrogen (mg/l)	101	6.5	0	0.155	0.646
Phosphate					
Ortho. diss. as P (mg/l)	101	1.4	0	0.06	0.15
Ortho. (mg/l)	102	4.3	0	0.18	0.472
Potassium (mg/l)	102	380	0	45.20	68.17
Selenium (ug/l)	97	4	0	0.09	0.46
Silica (mg/l)	101	200	1	54.54	36.33
Sodium (mg/l)	103	7000	3	792	1660
Sulfate (mg/l)	102	2000	2	441	478
Zinc (ug/l)	97	1000	0	23.77	101
Alkalinity (mg/l)					
$CaCO_3$	103	2780	15	531	494
Bicarbonate	103	3390	18	643	601
Total Diss. Solids (mg/l)	101	21500	91	2967	5055
SPECTROGRAPHIC ANALYSES					
Aluminum (ug/l)	60	650	5	100	113
Barium (ug/l)	60	1000	1	93	134
Beryllium (ug/l)	60	20	0	3.36	4.69
Bismuth (ug/l)	60	150	0	15.57	25.13
Chromium (ug/l)	60	100	0	13.88	20.88
Cobalt (ug/l)	60	90	1	12.33	18.10
Copper (ug/l)	60	20	0	4.38	4.60
Gallium (ug/l)	60	50	0	6.74	9.71
Germanium (ug/l)	60	100	1	16.15	22.75
Lead (ug/l)	60	100	1	14.33	20.82
Nickel (ug/l)	60	90	1	12.45	18.04
Silver (ug/l)	60	10	0	1.40	2.17
Strontium (ug/l)	60	12000	10	2734	3050
Tin (ug/l)	60	150	0.7	16.18	26.09
Titanium (ug/l)	60	50	0	7.14	9.78

TABLE 1 (Cont.)

	No. of Spls.	High	Low	Mean	Std. Dev.
Vanadium (ug/l)	60	90	0.3	11.80	17.35
Zirconium (ug/l)	60	200	1	22.88	35.81
RADIOCHEMICAL ANALYSES.	Values reported in Picocuries/liter (Pci/l)				
Radon	16	2100	72	756	615
Radium	38	38	0.11	6.61	10.05
Radium	23	36	0.58	5.24	7.99
Uranium	39	15	0.025	1.53	3.76
Uranium	30	0.25	0.0062	0.034	0.058
Uranium	39	6.5	0.018	0.63	1.41
Thorium	39	0.16	0.0069	0.038	0.035
Thorium	39	0.46	0.0043	0.033	0.072

TABLE 2

ALPHABETICAL LIST OF THERMAL SPRINGS AND WELLS IN COLORADO

	Spring Number in Report	County
Antelope Hot Spring	44	Mineral
Birdsie Warm Spring	45	Mineral
Brands Ranch Artesian Well	5	Jackson
Brown's Canyon Warm Spring	22	Chaffee
Brown's Canyon Grotto Warm Spring	22	Chaffee
Canon City Warm Spring	26	Fremont
Cebolla Hot Springs	47	Gunnison
Cement Creek Warm Spring	16	Gunnison
Chimney Hill Warm Water Well	22	Chaffee
Clark Artesian Well	30	Pueblo
Colonel Chinn Hot Water Well	14	Delta
Conundrum Hot Springs	15	Pitkin
Cottonwood Hot Springs	20	Chaffee
Craig Warm Water Well	2	Moffat
Dexter Warm Spring	36	Conejos
Don K Ranch Artesian Well	29	Pueblo
Dotsero Warm Spring	10	Eagle
Dunton Hot Spring	51	Dolores
Dutch Crowley Artesian Well	39	Archuleta
Eldorado Springs	8	Boulder
Eoff Artesian Well	40	Archuleta
Florence Artesian Well	28	Fremont
Fremont Natatorium Hot Spring	27	Fremont
Geyser Warm Spring	52	Dolores
Glenwood Springs	11	Garfield
Hartsel Hot Springs	19	Park
Haystack Butte Warm Water Well	7	Boulder
Hortense Hot Spring	21	Chaffee
Hortense Hot Water Well	21	Chaffee
Hot Sulphur Springs	6	Grand
Idaho Hot Springs	9	Clear Creek
Juniper Hot Springs	1	Moffat
Jump-Steady Hot Spring	20	Chaffee
Lemon Hot Spring	50	San Miguel
Little Mound Spring	55	La Plata
McIntyre	37	Conejos
Merrifield Hot Water Well	20	Chaffee
Mineral Hot Spring	31	Saguache
Mound Hot Spring	55	La Plata
Mt. Princeton Hot Springs	21	Chaffee
Orvis Hot Spring	48	Ouray
Ouray Hot Spring	49	Ouray
Pagosa Springs	41	Archuleta
Paradise Hot Spring	53	Dolores
Penny Hot Springs	13	Pitkin
Pinkerton Hot Springs	55	La Plata
Poncha Hot Springs	23	Chaffee
Rainbow Hot Spring	42	Mineral
Ranger Hot Spring	17	Gunnison
Rhodes Warm Spring	18	Park
Rico	54	Dolores
Routt Hot Springs	3	Routt

TABLE 2 (Cont.)

	in Report	County
Sand Dunes Swimming Pool, Hot Water Well	34	Saguache
Shaws Warm Spring	33	Saguache
South Canyon Hot Spring	12	Garfield
Splashland Hot Water Well	35	Alamosa
Steamboat Springs	4	Routt
Stinking Springs	38	Archuleta
Swissvale Warm Spring	25	Fremont
Trimble Hot Spring	56	La Plata
Tripp Hot Spring	56	La Plata
Valley View Hot Springs	32	Saguache
Wagon Wheel Gap Hot Springs	43	Mineral
Waunita Hot Springs, Upper and Lower	46	Gunnison
Wellsville Warm Spring	24	Fremont
Woolmington Warm Water Well	21	Chaffee
Wright Water Wells	21	Chaffee
Young Life Hot Water Well	21	Chaffee

TABLE 3

PRECISION AND ACCURACY OF WATER ANALYSES
(McAvoy and Endmann)

Constituent	Range in Concentration (mg/l)	% Relative Deviation (2)
HCO_3	30-50	10
	50-100	4
	>100	7
Ca	3-10	14
	10-50	7
	50-100	5
Cl	1-5	32
	5-25	7
	25-100	3
	>100	6
Dissolved Solids	100-300	4
	>300	3
F	0.1-1.0	31
	1.0-5.0	15
Mg	0.1- 1.0	80
	1.0-10.0	11
	10-25.0	6
NO_2+ NO_3	0.2- 1.0	70
	1.0-12.0	13
K	0.75-2.0	22
	2.0-7.0	17
	7-25	16
SiO_2	4-10	8
	10-40	8
Na	3-10	14
	10-25	6
	25-100	5
	>100	4
SO_4	21-50	8
	50-100	8
	>100	9
pH (pH units)	7.7-8.8	4

TABLE 4

ESTIMATED RESERVOIR TEMPERATURES (°C) AND GEOCHEMICAL DATA

(Geochemical data from Barrett and Pearl, 1976)

Geothermometer Models

q = quartz
c = chalcedony
a = amorphous
cr = cristobalite

Hot Spring	Spring Number	Date Sampled	Silica G.T.	Mixing Model T.	Mixing Model %	Na-K G.T.	Na-K-Ca G.T.	Most Likely Sub. Temp.	Discharge gpm.	T.D.S. mg/l	pH	Si mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	B ug/l
Antelope W.S	44	8/75						35-52	3E	151	--	41	44	0.1	4	0.3	130
		10/75	41	49	36 cr	83	35		3E	150	8.9	39	43	0.3	1.7	0.6	130
Birdsie W.S.	45	8/76	52 cr	91	70 cr	102	36	35-52	15	168	8.6	50	42	0.5	4.0	0.1	140
Brands Ranch	5	7/76	42 c	43	1 c	199	171	42-55	80E	262	6.0	26	78	7.5	10	2.6	50
Brown's Grotto W.S.	22	6/76	49 cr	129	87 cr	123	89	50--100	3E	494	8.0	47	160	3.3	7.6	0.1	80
Canon City H.S.	26	9/75	35 c	40	3 c	187	70	--	5	1,230	6.3	22	190	15	190	62	190
		1/76	34 c	38	12 c	187	68		1	1,220	6.2	21	180	16	190	55	200
		4/76	34 c	38	12 c	188	72		2	1,210	6.1	21	190	15	170	61	200
Cebolla Hot Springs																	
Spring "A"	47	7/75	71 cr	125	72 cr	278	216	--	--	1,450	--	74	310	63	120	50	1,100
		10/75	65 cr	105	66 cr	248	215		3	1,440	6.8	66	310	64	120	50	1,100
		1/76	78 cr	163	80 cr	238	209		3	1,470	6.9	85	330	58	120	0	1,100
		4/76	82 cr	185	83 cr	252	220		3	1,450	6.4	92	310	66	120	--	1,100
Spring "B"	47	7/75	73 cr	145	78 cr	249	217		--	1,460	--	77	310	64	120	50	1,100
Spring "C"	47	7/75	74 cr	143	76 cr	250	217	--	--	1,460	--	79	300	63	130	51	1,100
Cement Ck. W.S.	16	7/75	30 c	53	61 c	232	45	30-60	--	401	--	19	36	5.8	75	22	60
		10/75	25 c	27	0 c	225	48		80	389	7.2	17	41	6	69	18	60
		1/76	25 c	27	0 c	225	46		60	398	7.0	17	40	6	73	18	70
		4/76	28 c	29	6 c	238	49		60	382	7.2	18	36	6.4	68	20	80
Chalk Creek H.S. Area:																	
Mt. Princeton H.S. "A"	21	7/75	110 q	194	78 q	149	56	150-200	--	245	--	60	57	2.1	11	0.5	20
		10/75	108 q	190	77 q	148	58		18	248	8.6	58	58	2.1	10	0.2	20
		1/76	105 q	186	77 q	151	58		20	244	7.9	56	57	2.2	11	0.9	20
		4/76	127 q	236	81 q	150	59		23	248	7.8	59	58	2.2	10	0.8	20
Mt. Princeton H.S. F	21	7/75	107 q	201	81 q	150	51	150-200	12	229	--	57	50	1.9	12	0.5	10
Hortense H.S.	21	7/75	118 q	164	57 q	146	94	150-200	--	340	--	72	93	3.2	4.5	0.5	40
		10/75	116 q	156	54 q	144	93		18	336	8.5	68	94	3.1	4.4	0.1	50
		1/76	120 q	164	56 q	141	97		18	351	8.2	74	100	3.1	4.0	0	40
		4/76	129 q	186	61 q	145	93		17	341	8.2	88	94	3.2	4.7	0	40
Hortense Hot Water Well	21	7/75	118 q	164	56 q	144	80	150-200	--	318	--	72	84	2.8	6.4	1	30

TABLE 4 (Cont.)

Hot Spring	Spring Number	Date Sampled	Silica G.T.	Mixing Model		Na-K G.T.	Na-K-Ca G.T.	Most Likely Sub. Temp.	Discharge gpm.	T.D.S. mg/l	pH	Si mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	B ug/l
				T.	%												
Chalk Creek Area Cont.																	
Woolmington Hot Water Well	21	8/75	--	---	--	156	47	150-200	--	143	--	1	40	1.7	11	0.6	20
Wright Hot Well(E.)	21	8/75	103 q	152	62 q	148	62	150--200	--	234	--	53	61	2.1	8.3	0.3	20
Wright Hot Well(W.)	21	7/75	116 q	172	64 q	145	77	150-200	--	313	--	68	73	2.5	5.8	0.3	30
Young Life Hot Well	21	7/75	116 q	188	71 q	135	68	150-200	--	259	--	71	60	2.3	8.5	0.3	20
Clark Artesian Well	30	9/75	40 q	61	65 q	280	159	25-50	12	1,210	6.8	11	250	18	75	45	100
Colonel Chinn Hot Water Well	14	4/76	41 c	43	1 c	183	170	--	--		6.5	25	570	41	110	32	1,700
Conundrum H.S.	15	9/75	40 cr	41	6 cr	187	4	40-50	50	1,910	--	38	44	3.4	500	1.4	30
Cottonwood H.S. Area:																	
Cottonwood H.S.	20	6/75	110 q	174	70 q	132	84	150-200	10E	370	--	60	110	2.8	6.2	0.5	90
Jumpsteady H.S.	20	6/75	108 q	180	74 q	133	79	150-200	--	356	--	58	100	2.6	6.4	0.6	90
		10/75	105 q	174	74 q	131	85		90	364	6.0	54	110	2.7	5.6	0.3	90
		1/76	109 q	182	74 q	131	83		50	368	8.2	58	110	2.7	5.9	0.3	110
		4/76	--	---	--	135	83		50	302	8.5	13	100	2.7	5.8	0	80
Merrifield Hot Water Well	20	6/75	97 q	174	77 q	141	68	150-200	--	301	8.8	48	81	2.5	9.5	0.8	80
Craig Warm Water Well	2	1/76	58 q	70 35	50 q 20 c	100	104	40-70	24	896	8.2	19	360	4.1	5.8	0.9	210
Dexter W.S.	36	4/76	--	19	36 a	278	91	20-50	50E	--	7.9	--	--	--	--	--	--
Don K. Ranch Artesian Well	29	9/75	42 cr	63	61 cr	219	190	--	25	1,700	6.5	40	400	50	160	66	560
Dotsero W.S.	10	9/75	--	--	--	104	113	32-45	500E	--	--	--	3,500	44	230	62	210
		1/76	16 c	27	36 c	135	144		525E	10,400	7.2	13	3,500	95	260	79	210
		4/76	16 c	29	26 c	104	112		800E	9,940	7.0	13	3,500	44	240	65	220
S. Dotsero W.S.	10	12/75	16 c	29	26 c	102	109	32-45	1,000E	9,040	7.0	13	3,100	37	250	54	190
Dunton H.S.	51	9/75	54 c	69	40 c	329	50	50-70	26	1,260	--	34	35	19	330	45	90
		1/76	51 c	65	39 c	328	47		25	1,340	7.0	32	34	21	360	43	110
		4/76	53 c	69	43 c	342	52		25	1,300	6.4	33	34	21	340	45	90
Dutch Crowley Artesian Well	39	8/76	63 c	65	7 c	271	16	70-80	75E	--	7.0	--	--	--	--	--	---
Eldorado Springs																	
Spring "A"	8	9/75	23 c	27	8 c	314	43	26-40	--	101	6.9	16	6.9	3.2	15	4.8	20
Spring "B"	8	9/75	21 c	26	10 c	320	45	26-40	--	84	6.7	15	6.3	3.1	12	2.9	20
		2/76	21 c	26	19 c	254	57		--	91	6.6	15	7.3	3.3	11	3.3	10
		4/76	21 c	26	1 c	311	46		--	84	6.6	15	6.7	3.0	11	3.0	30

TABLE 4 (Cont.)

Hot Spring	Spring Number	Date Sampled	Silica G.T.	Mixing Model T.	Mixing Model %	Na-K G.T.	Na-K-Ca G.T.	Most Likely Sub. Temp.	Discharge gpm.	T.D.S. mg/l	pH	Si mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	B ug/l
Eoff Artesian Well	40	8/76	47 cr	59	38 cr	221	56	40-60	50E	---	7.0	--	--	--	--	--	--
Florence Artesian Well	28	9/75	34 c	41	40 c	212	178	34-50	130	1,480	6.3	21	270	32	180	78	160
Fremont Natatorium H.S.	27	9/75	23 c	32	23 c	172	72	35-50	20	1,370	6.9	16	220	13	150	70	90
		1/76	21 c	32	23 c	174	73		20	1,300	6.8	15	210	13	140	67	80
		4/76	21 c	32	23 c	171	71		18	1,330	6.7	15	210	12	140	67	90
Geyser W.S.	52	9/75	58 c	113	80 c	183	160	60-120	25-200E	1,620	--	37	400	29	170	40	120
Glenwood Springs Area:																	
Big Spring	11	7/75	51 c	59	18 c	133	148	--	2,263	20,200	6.3	32	6,900	180	510	91	890
Drinking Spring	11	7/75	51 c	59	18 c	133	147	--	--	20,300	6.3	32	7,000	180	510	90	910
		10/75	47 c	49	3 c	131	145		--	20,200	6.5	29	6,900	170	530	88	880
		1/76	48 c	51	0 c.	168	186		161	20,500	6.4	30	7,000	380	500	82	920
		4/76	48 c	51	0 c	135	149		140	18,800	6.4	30	6,600	180	480	15	870
Vapor Caves, Men's H.S.	11	9/75	45 c	49	3 c	129	143	--	5E	18,000	6.7	28	6,300	150	440	40	870
Graves Spring	11	9/75	51 c	77	46 c	133	144	--	5	21,500	7.0	32	7,000	180	770	150	1,000
Spring "A"	11	7/75	48 c	73	46 c	134	149	--	2-3E	17,600	6.3	30	6,000	160	410	88	800
Spring "B"	11	7/75	48 c	51	0 c	135	149	--	75	18,300	6.5	30	6,300	170	450	86	760
		10/75	44 c	47	9 c	131	145		75	18,400	7.0	27	6,400	160	490	79	830
		1/76	45 c	49	6 c	133	165		100	17,700	6.7	28	6,500	190	49	76	840
		4/76	45 c	49	6 c	135	151		110	17,800	7.0	28	6,300	170	360	86	840
Spring "D"	11	7/75	48 c	51	2 c	133	147	--	74	18,000	6.4	30	89	160	450	82	810
Railroad Spring	11	1/76	47 c	49	6 c	143	158	--	75	18,400	7.1	29	6,100	200	460	80	850
		4/76	47 c	49	6 c	138	152		75	18,200	6.5	29	6,200	180	460	86	890
Hartsel Hot Springs Spring "A"	19	6/75	63 c	85	44 c	162	152	55-85	--	2,280	--	41	680	33	120	20	560
Spring "B"	19	6/75	59 c	73	33 c	163	152	55-85	--	2,140	--	38	650	32	120	20	550
		10/75	55 c	79	46 c	163	153		40	2,260	7.0	35	670	33	110	20	540
		1/76	56 c	83	51 c	161	152		48	2,310	6.6	36	710	34	120	19	510
		4/76	58 c	87	53 c	163	153		50	2,330	6.6	37	670	33	120	21	380
Haystack Butte Warm Water Well	7	9/75	47 c	57	53 c	52	62	50	4E	1,200	8.0	29	510	1.3	2.5	0.7	740
Hot Sulphur Springs Spring "A"	6	7/75	86 q	109	63 q	169	171	75-150	--	1,200	6.6	35	430	25	14	3.7	570
		10/75	81 q	97	59 q	166	166		12	1,210	7.1	31	440	23	15	3.6	560
		1/76	81 q	97	59 q	165	165		12	1,220	6.9	31	450	23	15	3.2	480
		4/76	84 q	103	64 q	169	168		13	1,160	6.9	33	420	23	15	3.9	560
Spring "B"	6	7/75	86 q	113	67 q	169	169	75-150	1	1,200	6.7	35	430	24	15	3.1	570
Spring "C"	6	7/75	86 q	115	69 qr	170	170	75-150	3	1,210	6.8	35	440	25	15	3.5	530
		10/75	81 q	99	64 q	165	164		15	1,190	7.1	31	430	22	15	3.2	560

TABLE 4 (Cont.)

Hot Spring	Spring Number	Date Sampled	Silica G.T.	Mixing Model T.	Mixing Model %	Na-K G.T.	Na-K-Ca G.T.	Most Likely Sub. Temp.	Discharge gpm.	T.D.S. mg/l	pH	Si mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	B ug/l
Hot Sulphur Springs Cont.																	
Spring "D"	6	10/75	80 q	97	63 q	167	166	75-150	23	1,190	7.1	30	430	23	16	3.0	570
Idaho Hot Springs																	
Spring "A"	9	7/75	66 cr	109	64 cr	231	210	--	21	2,020	--	68	500	80	140	36	350
		10/75	59 cr	95	63 cr	231	210		--	2,110	6.9	58	530	84	150	40	360
		2/76	71 cr	141	76 cr	225	204		--	1,950	6.7	74	490	71	130	34	300
		4/76	78 cr	171	81 cr	228	207		--	1,940	6.9	60	500	76	130	36	470
Spring "B"	9	7/75	66 cr	--	--	230	210	--	--	2,070	--	68	520	82	130	50	370
Spring "C"	9	7/75	47 cr	--	--	235	206	--	1	1,070	--	45	260	44	77	23	170
Lodge Well	9	10/75	59 cr	81	48 cr	231	210	--	30	2,070	6.9	58	520	82	150	38	360
Juniper H.S.	1	7/75	53 c	81	59 c	75	80	50-75	13	1,150	7.8	33	460	2.3	3.7	0.8	540
		10/75	47 c	73	61 c	67	76		14	1,160	8.0	29	480	2.0	2.9	0.4	550
		1/76	50 c	73	55 c	70	78		13	1,160	8.2	31	470	2.2	3.9	0.3	480
		4/76	51 c	81	61 c	69	78		18	1,150	7.9	32	460	2.1	3.3	0.3	520
Lemon H.S.	50	9/75	15 a	29	17 a	210	198	--	8	2,760	--	95	730	84	140	11	2,600
		1/76	17 a	31	15 a	203	192		10	2,810	6.5	100	780	80	150	10	490
		4/76	14 a	29	25 a	207	195		10	2,740	6.2	94	760	84	150	11	2,500
McIntyre W.S.	37	4/76	--	15	33 a	333	50	20-50	5E	---	7.9	--	--	--	--	--	--
Mineral Hot Springs																	
Spring "A"	31	6/75	70 c	87	38 c	206	90	70-90	100	643	--	48	130	14	57	14	360
		10/75	67 c	79	30 c	202	90		167	663	6.5	45	140	14	60	13	350
		1/76	69 c	83	34 c	199	89		70	658	7.0	47	140	15	57	13	370
		4/76	69 c	83	34 c	202	90		95	639	6.8	47	140	14	59	13	450
Spring "C"	31	6/75	72 c	93	43 c	197	91	70-90	--	723	--	50	150	14	60	14	370
Spring "D"	31	6/75	70 c	89	41 c	202	92	70-90	--	665	--	48	140	14	55	13	370
		10/75	67 c	79	30 c	198	91		--	690	6.5	45	150	14	59	13	350
		1/76	68 c	81	32 c	195	87		5E	657	6.5	46	140	14	56	13	340
		4/76	69 c	83	34 c	202	90		--	648	7.3	47	140	14	58	13	400
Orvis H.S.	48	9/75	73 c	99	54 c	179	93	--	-1	2,270	--	51	420	28	260	19	1,000
		1/76	82 c	127	66 c	183	97		-1	2,490	6.5	60	460	33	290	18	990
		4/76	75 c	107	54 c	187	93		-1	2,270	6.6	53	390	30	280	19	1,000
Ouray Hot Springs																	
Wiesbaden Vapor Caves "A"	49	9/75	61 c	51	4 c	196	32	70-90	--	1,580	--	40	120	11	350	8	150
Wiesbaden Vapor Caves "B"	49	9/75	47 c	111	75 c	198	32	70-90	2E	695	--	29	53	5	150	8.3	60
Wiesbaden Vapor Caves "C"	49	9/75	60 c	99	56 c	299	28	70--90	1E	1,380	--	39	110	8.9	300	8.8	160
		1/76	60 c	161	83 c	190	41		30E	1,430	--	39	110	9.1	310	8.5	170
		4/76	60 c	93	51 c	192	43		5E	1,390	7.1	39	110	9.4	310	8.9	170
Pool H.S.	49	9/75	69 c	77	16 c	191	39	70-90	125	1,650	6.7	47	110	9.2	370	8.9	200
		1/76	71 c	79	15 c	184	39		60	1,660	6.5	49	120	8.8	360	8.5	200
		4/76	71 c	79	15 c	192	39		200	1,640	7.3	49	110	9.4	360	8.8	200

TABLE 4 (Cont.)

Hot Spring	Spring Number	Date Sampled	Silica G.T.	Mixing Model T.	Mixing Model %	Na-K G.T.	Na-K-Ca G.T.	Most Likely Sub. Temp.	Discharge gpm.	T.D.S. mg/l	pH	Si mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	B ug/l
Ouray Hot Springs Cont.																	
Uncompahgre H.S.	49	4/76	66 c	109	58 c	192	40	70-90	5	1,570	7.7	44	110	9.4	350	9.2	200
Pagosa Spgs,																	
Big Spg	41	8/75	76 c	113	54 c	209	194	80-150	265	3.200	6.5	54	790	90	230	25	1,800
		10/75	--	--	-	209	194		226	--	6.9	--	780	87	210	23	1,700
		1/76	80 c	133	64 c	207	191		241	3,310	6.6	58	800	87	240	2.6	2,000
		4/76	81 c	139	66 c	210	193		260	3,040	6.5	59	730	85	230	24	2,300
Courthouse hot water well	41	8/75	74 c	113	56 c	210	193	75-125	30	3,300	6.5	52	780	89	250	25	1,800
Spa Hot Water Well	41	8/75	73 c	117	60 c	211	195	75-125	--	3,320	6.5	51	780	91	230	24	1,900
Paradise Hot Spring	53	9/75	39 a	45	4 a	247	252	--	26	6,070	--	150	1,800	360	160	27	9,300
		1/76	56 a	53	7 a	247	248		34	6,530	6.9	200	1,900	380	240	30	1,000
		4/76	39 a	43	1 a	245	250		30	6,180	6.8	150	1,900	370	170	28	4,300
Penny Hot Springs	13	9/75	15 a	35	25 a	199	93	60-90	10	2,820	--	96	400	38	410	50	700
		1/76	3 a	35	48 a	197	89		10	2,820	6.3	74	390	36	420	51	640
		4/76	39 a	45	2 a	202	92		10	2,750	6.3	150	380	38	390	53	690
Granges Spring	13	1/76	7 a	41	50 a	198	90	60-90	12	2,960	9.2	81	400	38	440	55	650
Pinkerton H.S. Area:																	
Spring "A"	55	9/75	78 q	127	81 q	231	205	75-125	54	3,990	--	28	750	120	510	79	3,000
		1/76	78 q	127	81 q	231	202		54	3,880	6.5	28	690	110	560	69	2,800
		4/76	78 q	133	82 q	234	206		54	3,770	6.4	29	720	120	530	72	2,800
Spring "B"	55	9/75	--	--	--	234	206	75-125	20	----	--	--	720	120	530	71	3,000
Mound Spring	55	9/75	79 q	139	84 q	234	206	75-125	8E	3,940	--	29	730	120	550	74	3,000
		1/76	78 q	137	85 q	235	206		5E	3,880	6.5	28	710	120	550	68	3,000
		4/76	78 q	137	85 q	235	207		5E	3,840	6.4	28	710	120	550	72	2,900
Poncha Hot Springs																	
Spring "A"	23	6/75	126 q	173	63 q	155	99	115-145	--	667	--	81	190	8	20	0.7	80
		10/75	119 q	157	60 q	154	140		--	678	8.0	71	200	8.1	17	0.5	70
		1/76	137 q	201	69 q	154	141		--	697	7.7	100	200	8.3	17	0.2	80
		4/76	137 q	201	69 q	159	145		200	654	7.5	77	190	8.7	17	0.2	60
Spring "B"	23	6/75	127 q	183	68 q	154	139	115-145	30E	655	--	83	190	7.8	18	0.5	70
Spring "C"	23	6/75	126 q	185	70 q	157	96	115-145	2	670	--	81	190	8.3	24	0.8	80
		10/75	119 q	169	68 q	156	142		3	660	8.0	71	190	8.1	17	0.4	70
		1/76	130 q	195	72 q	154	141		2	685	7.5	88	200	8.3	17	0.3	60
		4/76	136 q	209	73 q	158	144		4	655	7.5	79	190	8.6	17	0.4	150
Rainbow Hot Spring	42	9/75	41 cr	41	0 cr	68	22	40-50	45	161	--	39	45	0.2	2.1	0.2	50
Ranger Warm Spring	17	7/75	32 c	67	71 c	214	56	30-60	132	461	--	20	59	7.2	73	22	80
		10/75	28 c	29	1 c	216	66		250E	465	7.1	18	61	7.7	70	20	80
		1/76	30 c	45	49 c	218	60		225E	466	6.9	19	62	8.1	72	20	80
		4/76	30 c	45	49 c	217	60		175E	474	7.1	19	63	8.2	71	23	80

TABLE 4 (Cont.)

Hot Spring	Spring Number	Date Sampled	Silica G.T.	Mixing Model T.	Mixing Model %	Na-K G.T.	Na-K-Ca G.T.	Most Likely Sub. Temp.	Discharge gpm.	T.D.S. mg/l	pH	Si mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	B ug/l
Rhodes W.S.	18	6/75	10 c	21	65 c	240	2	25-35	--	186	8.2	11	5.5	1	33	21	30
		10/75	13 c	23	41 c	222	10		200	194	6.5	12	8.6	1.2	32	19	20
Rico																	
Diamond Drill Hole	54	1/76	26 a	39	18 a	307	56	--	15	2,250	7.0	120	66	28	590	82	70
Big Geyser W.S.	54	9/75	22 a	31	19 a	297	57	--	8	2,750	--	110	78	30	680	98	80
		4/76	35 a	37	1 a	315	56		12	2,740	6.8	140	67	31	690	93	70
Geyser W.S.	54	9/75	22 a	35	15 a	301	59	--	14	2,790	--	110	80	32	680	100	80
Little Spring	54	9/75	26 a	35	15 a	305	58	--	13	2,790	--	120	76	5.6	620	110	90
		1/76	26 a	37	10 a	185	17		15	2,700	7.0	120	77	32	690	92	70
Routt Hot Springs																	
Spring "A"	3	7/75	136 q	225	75 q	170	154	125-175	33	552	7.6	97	160	9	13	0.4	280
		10/75	125 q	199	71 q	165	154		50	518	6.5	80	160	8.3	7.3	0.2	290
		1/76	129 q	209	73 q	167	155		25	521	9.3	86	160	8.5	7.7	0.1	260
		4/76	131 q	213	73 q	169	157		35	527	7.8	89	160	8.8	7.7	0.1	280
Spring "B"	3	7/75	136 q	231	76 q	170	159	125-175	30	539	7.1	98	160	9.1	7.8	0.5	280
Sand Dunes Hot Well	34	8/75	26 a	39	19 a	205	187	--	--	334	8.3	120	81	8.6	3.2	0.4	510
Shaws W.S.	33	8/75	8 a	26	32 a	101	103	30-60	34	406	9.3	83	130	1.5	0.9	0.6	130
		10/75	2 a	26	32 a	98	104		34	402	9.3	73	130	1.4	0.5	0.3	140
		1/76	17 a	28	19 a	101	83		52	424	9.0	100	130	1.5	2.7	0.7	120
		4/76	4 a	26	32 a	100	102		40	398	8.9	76	130	1.5	0.9	0.1	270
South Canyon H. S.																	
Spring "A"	12	7/75	66 c	123	67 c	138	137	100-130	12	794	7.1	44	280	8.2	7.0	1.0	210
		10/75	60 c	103	60 c	137	135		7	800	7.6	39	280	8.0	7.7	1.4	260
		1/76	67 c	127	68 c	140	137		9	783	--	45	270	8.2	7.9	2.2	290
		4/76	63 c	115	65 c	140	137		17	772	7.3	41	270	8.2	7.8	0.9	260
Spring "B"	12	7/75	65 c	119	66 c	139	137	100-130	1E	757	7.1	43	260	7.8	7.1	0.9	230
Splashland Hot Well	35		22 a	35	23 a	221	197	40-100	--	311	8.3	110	72	9.9	4.1	0.4	340
Steamboat Springs																	
Heart Spring	4	4/76	101 q	179	81 q	148	141	125-130	140	903	8.0	49	300	11	18	1	700
Sulphur Cave	4	4/76	60 q	79	79 q	181	188	125-130	10	4,530	6.5	18	1,600	110	90	24	2,900
Steamboat Spring	4	4/76	66 q	93	76 q	176	187	125-130	20	6,170	6.7	21	2,200	140	110	31	3,200
Stinking Springs	38	9/75	39 c	59	61 c	339	41	40-60	24	899	--	24	20	12	210	27	60
Swissvale Warm Spgs.																	
Spring "A"	25	6/76	32 cr	35	22 cr	214	48	35-50	125	--	7.0	-	-	-	-	-	-
Spring "F"	25	6/76	31 cr	47	69 cr	2	44	35-50	20	--	7.0	-	-	-	-	-	-
Trimble H.S.	56	9/75	--	34	47 a	197	97	45-70	1E	3,340	--	72	510	47	510	42	1,400
Tripp H.S.		9/75	--	30	39 a	198	99	45-70	--	3,240	--	69	500	47	470	41	1,500

TABLE 4 (Cont.)

Hot Spring	Spring Number	Date Sampled	Silica G.T.	Mixing Model T.	Mixing Model %	Na-K G.T.	Na-K-Ca G.T.	Most Likely Sub. Temp.	Discharge gpm.	T.D.S. mg/l	pH	Si mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	B ug/l
Valley View Hot Spgs.																	
Spring "A"	32	6/75	34 c	37	4 c	356	12	40-50	--	252	--	21	3.5	2.5	51	15	8
		10/75	32 c	35	9 c	356	14		60E	249	6.5	20	3.7	2.6	50	14	10
		1/76	32 c	35	5 c	352	15		--	243	6.8	20	3.9	2.7	50	14	7
		4/76	32 c	35	9 c	375	15		--	234	7.5	20	3.3	2.8	50	14	310
Spring "B"	32	6/75	30 c	31	12 c	338	11	40-50	--	234	--	19	3.7	2.2	46	14	8
Spring "D"	32	10/75	25 c	29	33 c	360	11	40-50	120E	229	6.0	17	3.2	2.4	49	12	9
		1/76	28 c	31	25 c	346	16		75E	247	6.5	18	4.3	2.8	51	13	20
		4/76	28 c	31	29 c	389	10		75E	223	7.5	18	2.6	2.5	50	13	220
Wagon Wheel Gap																	
4UR Spring	43	10/75	75 cr	113	56 cr	206	194	--	30E	1,580	7.0	81	480	51	61	15	2,500
		1/76	81 cr	137	66 cr	204	191		30E	1,550	7.0	90	460	48	60	14	1,300
		4/76	77 cr	119	59 cr	200	188		28E	1,620	6.7	84	490	48	66	15	2,600
CF & I Spring	43	8/75	71 cr	117	64 cr	205	181	--	30	1,510	--	74	450	48	67	16	2,600
		10/75	66 cr	99	56 cr	203	184		50	1,520	6.4	68	460	47	68	15	2,500
		1/76	80 cr	157	76 cr	203	175		30	1,540	6.5	88	450	46	66	15	1,300
		4/76	66 cr	99	57 cr	206	181		32	1,470	6.4	67	430	46	68	15	2,600
Waunita Hot Springs																	
Spring "C"	46	7/75	143 q	213	66 q	179	163	175-225	--	557	--	110	150	10	11	0.2	70
		10/75	143 q	209	64 q	176	166		30	579	8.4	110	160	10	5.9	0	60
		1/76	157 q	247	71 q	174	159		55	613	8.5	140	160	9.8	11	0.3	60
		4/76	148 q	225	68 q	178	167		50	575	7.9	120	150	10	5.8	7.3	60
Spring "D"	46	7/75	153 q	291	83 q	175	165	175-225	--	594	--	130	160	10	6.0	0	70
Lower Waunita H.S.																	
Spring "B"	46	7/75	130 q	197	67 q	178	165	110-160	--	544	--	88	150	9.9	7.8	0.7	70
		10/75	123 q	181	64 q	176	163		20E	549	8.0	77	160	10	8.6	0.4	60
		4/76	129 q	195	67 q	179	165		25E	528	7.7	86	150	10	8.5	1.0	60
Lower Waunita H.S.																	
Spring "D"	46	7/75	129 q	209	73 q	179	166	110-160	--	535	--	86	150	10	6.9	0.5	70
Wellsville W.S.	24	6/75	32 cr	33	2 cr	213	49	35-50	--	470	--	32	51	6.2	79	24	100
		10/75	30 cr	33	7 cr	214	49		160	484	7.0	30	50	6.1	76	27	100
		1/76	31 cr	33	15 cr	216	48		175	482	7.1	31	49	6.3	81	25	100
		4/76	31 cr	33	15 cr	213	50		200	482	7.2	31	52	6.3	76	26	90

TABLE 6

FIELD DATA OF COLD WATER DATA USED FOR MIXING MODEL

Hot Spring	Cold Water Temp. °C	Cold Water SiO_2 Content, mg/l
Antelope W.S.	2	25
Birdsie W.S.	2	25
Brands Ranch	3	15
Brown's Grotto	5	25
Canon City	10	7
Cebolla	6	31
Cement Creek	9	10
Clark Artesian Well	5	7
Colonel Chinn Well	11	15
Conundrum	5	25
Cottonwood H.S.	5	8
Jumpsteady H.S.	5	8
Merrifield Well	5	8
Craig Well	6	15
Dexter	6	25
Don K. Ranch	5	10
Dotsero	8	6
S. Dotsero	8	6
Dunton	5	15
Dutch Crowley	6	25
Eldorado Spring	13	10
Eoff Well	6	25
Florence Well	10	7
Fremont Natatorium	10	7
Geyser	5	20
Glenwood Springs Area	8	6
Hartsel H.S.	6	12
Haystack Butte	11	25
Hot Sulphur Springs	4	22
Idaho H.S.	6	25
Juniper H.S.	6	15
Lemon H.S.	4	25
McIntyre	6	25
Mineral	11	19
Mt. Princeton Area	11	8
Orvis	10	25
Ouray H.S. Area	2	6
Pagosa Springs	7	12
Paradise H.S.	5	25
Penny H.S.	8	25
Pinkerton H.S.	8	15
Mound W.S.	8	15
Poncha H.S.	6	25
Rainbow	2	25
Ranger	9	10
Rhodes	10	11
Rico	4	25
Routt	5	8
Sand Dunes	6	25
Shaws	5	25
Splashland Well	6	25
S. Canyon	8	6
Steamboat	4	15
Stinking Springs Chromo	6	15

TABLE 6 (Cont.)

Hot Spring	Cold Water Temp. °C	Cold Water Sio Content, mg/l
Swissvale W.S.	8	25
Trimble	8	15
Tripp	8	15
Valley View	6	15
Wagon Wheel Gap	10	25
Waunita	2	7
Lower Waunita	2	7
Wellsville	8	25

TABLE 9

ENTHALPIES OF LIQUID WATER AND AMORPHOUS SILICA SOLUBILITIES AT SELECTED TEMPERATURES AND PRESSURES

Temperature °C	Enthalpy[1] cal/gm	Silica[2] mg/l
16	16.0	98
20	20.0	106
24	24.0	114
28	28.0	123
32	32.0	133
36	36.0	143
40	40.0	153
44	44.0	164
48	48.0	175
50	50.0	181
55	55.0	196
60	60.0	211
65	65.0	228
70	70.0	245
75	75.0	263

[1] Keenan and others, 1969.
[2] Values generated from equations derived by R.O. Fournier (in Reed, 1975).

TABLE 10

ENTHALPIES OF LIQUID WATER AND CHALCEDONY SOLUBILITIES AT SELECTED TEMPERATURES AND PRESSURES

Temperature (°C)	Enthalp[1] (cal/gm)	Silica[2] mg/l
25	25.0	17
30	30.0	19
35	35.0	22
40	40.0	25
45	45.0	28
50	50.0	31
75	75.0	53
100	100.1	84
125	125.4	125
150	151.0	177
175	177.0	243
200	203.6	321

[1] Keenan and others (1969).
[2] Values generated from equations derived by R.O. Fournier (in (Reed, 1975).

TABLE 11

ENTHALPIES OF LIQUID WATER AND CRISTOBALITE SOLUBILITIES AT SELECTED TEMPERATURES AND PRESSURES

Temperature (°C)	Enthalpy [1] (cal/gm)	Silica [2] (mg/l)
25	25.0	26
30	30.0	30
35	35.0	34
40	40.0	38
45	45.0	43
50	50.0	48
75	75.0	80
100	100.1	125
125	125.4	185
150	151.0	260
175	177.0	352
200	203.6	462

[1] Keenan and others (1969).

[2] Values generated from equations derived by R.O. Fournier (in Reed, 1975).

TABLE 16

ISOTOPE DATA FOR MOUNT PRINCETON THERMAL AREA

Hot Springs and Wells	O[1] (0/00, mills)	D[2] (00/0, mills)	Tritium[3] (Tritium Units)
1 Jumpsteady H.S. Loc. 38°48'48"N., 106°13'20"W.	-17.8	-130.8	19.7 ± 1.7
2 Cottonwood H.S. Loc. 38°48'48"N., 106°13'21"W.	-17.8	-131.1	17.0 ± 1.6
3 Merrifield Hot Well Loc. 38°48'40"N., 106°13'21"W.	-18.0	-131.1	150.0 ± 5
4 Mt. Princeton H.S. "A" Loc. 38°43'58"N., 106°09'40"W.	-16.4	-117.1	75.0 ± 3.6
5 Hortense H.S. Loc. 38°43'59"N., 106°10'26"W.	-16.4	-119.4	32.1 ± 2.0
Cold Water			
6 S. Cottonwood Ck. Loc. 38°46'59"N., 106°15'45"W.	-17.5	-128.2	128.0 ± 6
7 Poundstone Cold Sp. Loc. 38°47'47"N., 106°14'53"W.	-17.9	-130.4	176.0 ± 8
8 Abernathy C.S. Loc. 38°48'17"N., 106°14'40"W.	-17.0	-128.4	212.0 ± 10
9 Silver Cliff C.S. Loc. 38°47'17"N., 106°14'34"W.	-17.5	-127.2	145.0 ± 7
10 Cold Spring #8 Loc. 38°48'53"N., 106°20'36"W.	-19.2	-138.1	256.0 ± 12
11 E. Cottonwood Pass C.S. Loc. 38°49'08"N., 106°24'17"W.	-18.4	-133.3	130.0 ± 6
12 W. Cottonwood Pass C.S. Loc. 38°49'56"N., 106°24'44"W.	-18.1	-131.5	127.0 ± 6
13 Cold Well #13 Loc. 38°43'31"N., 106°10'35"W.	-16.8	-120.6	188.0 ± 9
14 Cold Well #14 Loc. 38°43'13"N., 106°11'10"W.	-17.0	-123.0	207.0 ± 10
15 Tin Cup Pass C.S. Loc. 38°42'27"N., 106°25'54"W.	-20.0	-143.0	166.0 ± 8

1. Geochron Laboratories Inc (1976)
2. L.D. White, Analyst (1977)
3. F.J. Pearson (1977)

APPENDIX B

GEOTHERMOMETER MODEL PROGRAMS FOR PROGRAMMABLE TEXAS INSTRUMENTS SR-52 AND HEWLETT PACKARD HP 25 CALCULATORS

SR-52 PROGRAMMABLE CALCULATOR

SILICA GEOTHERMOMETER MODEL - T.I. SR-52

Procedure: Load program; enter silica values as expressed in mg/l; press A; press RUN; value displayed will be estimated temperature in degrees C. If the calculated temperature could be either adiabatic or conductive the display will be in the following format: 100,000,xxx.xx (x=temperature). If the calculated temperature is below the point where the curve divides into two parts the display will be: xxx.xx (x= temperature).

The following examples demonstrates the use of the program. 1). A spring has a silica content of 88 mg/l. Enter this value as described above. First value displayed 100,000,130.3(conductive) Press RUN for second value of 100,000,126.9 (adiabatic)

2). A spring has a silica content of 35 mg/l. Enter this value as described above. Value displayed: 86.03

```
LOC   CODE   KEY      LOC   CODE   KEY      LOC   CODE   KEY

000    53    (        025    00    0        050    95    =
       01    1               02    2               42    STO
       03    3               53    (               00    0
       00    0               01    1               03    3
       09    9               05    5               43    RCL

005    55    DIV      030    02    2        055    00    0
       53    C               02    2               01    1
       05    5               55    DIV             75    -
       93    .               53    (               05    5
       01    1               05    5               09    9

010    09    9        035    93    .        060    95    =
       75    -               07    7               80    IF POS
       43    RCL             05    5               32    SIN
       00    0               75    -               43    RCL
       01    1               43    RCL             00    0

015    28    106      040    00    0        065    02    2
       54    )               01    1               81    HLT
       95    =               28    LOG             46    LBL
       54    )               54    )               32    SIN
       75    -               95    =               43    RCL

020    02    2        045    54    )        070    00    0
       07    7               75    -               02    2
       03    3               02    2               85    +
       95    =               07    7               01    1
       42    STO             03    3               00    0
```

Silica Geothermometer Model Cont.

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
075	00	0	095	03	3			
	00	0		43	RCL			
	00	0		00	0			
	00	0		03	3			
	00	0		81	HLT			
080	00	0	100	46	LBL			
	00	0		11	A			
	95	=		42	STO			
	81	HLT		00	0			
	01	1		01	1			
085	00	0	105	81	HLT			
	00	0		86	RST			
	00	0						
	00	0						
	00	0						
090	00	0						
	00	0						
	00	0						
	44	SUM						
	00	0						

SODIUM-POTASSIUM-CALCIUM GEOTHERMOMETER MODEL - T I SR 52

Procedure: Load program; enter sodium values as expressed in mg/l; press A; enter potassium values as expressed in mg/l; press B; enter calcium values as expressed in mg/l; press C; press Run; value displayed will be estimated temperature in degree C.

LOG	CODE	KEY	LOG	CODE	KEY	LOG	CODE	KEY
000	46	LBL	035	94	+I	070	43	RCL
	11	A		49	PROD		00	0
	42	STO		00	0		·03	3
	00	0		02	2		30	X
	01	I		02	2		55	DIV
005	81	HLT	040	93	.	075	43	RCL
	46	LBL		04	4		00	0
	12	B		09	9		01	1
	42	STO		05	5		95	=
	00	0		52	EE		28	LOG
010	02	2	045	05	5	080	42	STO
	81	HLT		94	+/-		00	0
	46	LBL		49	PROD		05	5
	13	C		00	0		65	X
	42	STO		03	3		93	.
015	00	0	050	22	INV	085	03	3
	03	3		52	FIX		03	3
	81	HLT		43	RCL		03	3
	04	4		00	0		95	=
	93	.		01	I		42	STO
020	03	3	055	55	DIV	090	00	0
	05	5		43	RCL		06	6
	52	EE		00			43	RCL
	05	5		02	2		00	0
	94	+/-		95	=		05	5
025	49	PROD	060	28	I06	095	65	X
	00	0		85	+		01	1
	01	I		02	2		93	.
	02	2		93	.		03	3
	93	.		02	2		03	3
030	05	5	065	04	4	100	03	3
	05	5		95	=		95	=
	07	7		42	STO		42	STO
	52	EE		00	0		00	0
	05	5		04	4		07	7

Sodium-Potassium-Calcium Geothermometer Model Cont.

LOG	CODE	KEY
105	01	1
	06	6
	04	4
	07	7
	55	DIV
110	53	(
	43	RCL
	00	0
	04	4
	85	+
115	43	RCL
	00	0
	06	6
	54	)
	95	=
120	75	-
	02	2
	07	7
	03	3
	95	=
125	42	RCL
	00	0
	08	8
	01	1
	06	6
135	00	0
	07	7
	85	+
	43	RCL
	00	0
140	04	4
	54	(
	95	=
	75	-
	02	2
145	07	7
	03	3
	95	=
	42	STO
	00	0
150	09	9
	43	RCL
	00	0
	05	5
	80	HLT
155	32	SIN
	43	RCL
	00	0
	08	8
	81	HLT
160	46	LBL
	32	SIN
	43	RCL
	00	0
	09	9
165	75	-
	01	1
	00	0
	00	0
	95	=
170	180	HLT
	33	COS
	43	RCL
	00	0
	09	9
175	81	HLT
	46	LBL
	33	COS
	43	RCL
	00	0
180	08	8
	81	HLT
	00	0

MIXING MODEL NO. 1 GEOTHERMOMETER PROGRAM - T I SR 52

Procedure: Load program; enter temperature of warm spring; press A; enter temperature of cold spring; press B; enter silica content of the warm spring; press C; enter silica content of the cold spring; press D; enter beginning temperature; press E. To calculate estimated reservoir temperature in degress C, press RUN. To calculate percent of cold water present, press RUN.

```
LOC    CODE    KEY        LOC    CODE    KEY        LOC    CODE    KEY

000     46     LBL        030     46     LBL        060     01      1
        11      A                 32     SIN                09      9
        42     STO                02      2                 75      -
        00      0                 44     SUM                01      1
        01      I                 00      0                 03      3

005     81     HLT        035     05      5         065     00      0
        46     LBL                43     RCL                09      9
        12      B                 00      0                 55     DIV
        42     STO                05      5                 53      (
        00      0                 95      =                 43     RCL

010     02      2         040     65      X         070     00      0
        81     HLT                01      1                 05      5
        46     LBL                93      .                 85      +
        13      C                 00      0                 02      2
        42     STO                08      8                 07      7

015     00      0         045     75      -         075     03      3
        03      3                 04      4                 54      )
        81     HLT                93      .                 54      )
        46     LBL                02      2                 54      )
        14      D                 95      =                 42     STO

020     42     STO        050     42     STO        080     00      0
        00      0                 00      0                 07      7
        04      4                 06      6                 53      (
        81     HLT                53      (                 43     RCL
        46     LBL                01      1                 00      0

025     15      E         055     00      0         085     06      6
        42     STO                45     yx               75      -
        00      0                 53      (                 43     RCL
        05      5                 05      5                 00      0
        81     HLT                93      .                 01      1
```

Mixing Model No. 1 Cont.

LOG	CODE	KEY	LOG	CODE	KEY	LOG	CODE	KEY
090	54	)	110	43	RCL	130	00	0
	55	DIV		00	0		08	8
	53	(		03	3		95	=
	43	RCL		54	)		22	INV
	00	0		55	DIV		80	IF POS
095	06	6	115	53	(	135	32	SIN
	75	-		43	RCL		43	RCL
	43	RCL		00	0		00	0
	00	0		07	7		05	5
	02	2		75	-		81	HLT
100	54	)	120	43	RCL	140	43	RCL
	95	=		00	0		00	0
	42	STO		04	4		08	8
	00	0		54	)		81	HLT
	08	8		95	=			
105	53	(	125	42	STO			
	43	RCL		00	0			
	00	0		09	9			
	07	7		75	-			
	75	-		43	RCL			

HEWLETT PACKARD H.P. 25 CALCULATOR PROGRAMS

QUARTZ-SILICA GEOTHERMOMETER PROGRAM - H. P. 25

This program computes the quartz-silica geothermometer estimate of subsurface temperature for both the adiabatic and conductive cooling cases The silica content (milligrams/liter) of the hot spring is stored in register 0 (STO 0). The program is executed by keying f, PRGM and RS. When the silica content of the hot spring equals or exceeds 59 mg/l, the conductive cooling estimate is flashed for two seconds, then the adiabatic cooling estimate is displayed continuously. The conductive cooling estimate is displayed exclusively for silica concentrations below 59 mg/l.

Line	Code	Key Entry	Comments	Registers
01	01	1		R_0 Warm Spring Silica Content
	03	3		
	00	0		
	09	9		
05	24 00	RCL 0		
	14 08	f, LOG		
	05	5		
	73	.		
	01	1		
10	09	9		
	41	-		
	32	CHS		
	71	÷		
	02	2		
15	07	7		
	03	3		
	41	-		
	14 01	f, INT		
	23 01	STO 1		
20	14 74	f, PAUSE	Conductive cooling answer	
	14 74	f, PAUSE		
	24 00	RCL 0		
	05	5		
	09	9		
25	14 51	f, X ≥ Y		
	13 46	GTO 46		
	01	1		
	05	5		
	02	2		

Quartz-Silica Geothermometer Model Cont.

Line	Code	Entry	Comments	Registers
30	02	2		
	24 00	RCL 0		
	14 08	f, LOG		
	05	5		
	73	.		
35	07	7		
	05	5		
	41	-		
	32	CHS		
	71	÷		
40	02	2		
	07	7		
	03	3		
	41	-		
	14 01	f, INT	adiabatic	
			cooling	
45	13 00	GTO 00	answer	
	24 01	RCL 1	Conductive	
	13 00	GTO 00	cooling answer	

SODIUM-POTASSIUM-CALCIUM GEOTHERMOMETER PROGRAM - H. P. 25

This program computes the Na-K-Ca geothermometer estimate of subsurface temperature. The sodium, potassium, and calcium contents (mg/l) of the hot spring are stored in registers 0, 1, and 2, respectively (STO 0, STO 1, STO 2). The factors for converting the sodium, potassium, and calcium contents from milligrams/liter to moles/liter are stored in registers 3, 4, and 5, respectively (STO 3, STO 4, STO 5). Storage registers 6 and 7 contain constants used in the calculation (equations 25 and 26). After all data and constants are stored, the program is initiated by keying f, PRGM and RS; the subsurface temperature estimate is displayed continuously at the end of the calculation.

```
                           KEY
LINE        CODE           ENTRY         COMMENTS     REGISTERS

 01          24 03         RCL  3                     R
          23 61 00         STO  x  0                  Na mg/l
             24 04         RCL  4
          23 61 01         STO  x  1                  R
                                                      K  mg/l
05           24 00         RCL  0
             24 01         RCL  1                     R
             71              ÷                        Ca mg/l
             14 08         f, LOG
             23 01         STO  1                     R
                                                      4.35 x 10
10           24 02         RCL  2
             24 05         RCL  2                     R               Converts
             61            X                          2.557 x 10      from mg/l
             14 02         f,   x                                     to moles/l
             24 00         RCL  0                     R
                                                      2.495 x 10
15           71              ÷
             14 08         f, LOG                     R
             03            3                          1647
             71              ÷
             23 02         STO  2                     R
                                                      2.24
20           15 51         g, X ≥  0
             13 31         GTO  31
             24 01         RCL  1
             24 02         RCL  2
             51            +

25           24 07         RCL  7
             51            +
             24 06         RCL  6
             21            X ⇆ Y
             71              ÷
```

Sodium-Potassium-Calcium Geothermometer Model Cont.

LINE	CODE	KEY ENTRY	COMMENTS	REGISTERS
30	13 46	GTO 46		
	04	4		
	61	X		
	24 01	RCL 1		
	51	+		
35	24 07	RCL 7		
	51	+		
	24 06	RCL 6		
	21	X ⇆ Y		
	71	÷		
40	03	3		
	07	7		
	03	3		
	21	X ⇆ Y		
	14 51	X > Y		
45	13 22	GTO 22		
	02	2		
	07	7		
	03	3		
	41	-	Subsurface Temperature	

QUARTZ-MIXING MODEL I GEOTHERMOMETER PROGRAM - H.P. 25

This program computes the quartz mixing model I estimate of subsurface temperature and the cold water fraction contained in the thermal spring The temperature (°C) and silica content (mg/l) of the warm spring is stored in registers 0 and 1, respectively (STO 0, STO 1). The temperature and silica content of the cold spring is stored in registers 2 and 3, respectively (STO 2, STO 3). Registers 6 and 7 (STO 6, STO 7) contain constants used in equation 1 described below.

The program first calculates the quartz-induced silica solubility (equation 1) and enthalpy (equation 2) at a given temperature. Equation 2 approximates the relationship between enthalpy and water temperature. The error introduced into the subsurface temperature estimates by this approximation is very small (less than 5%).

Eq 1: Silica Solubility $SiO_2 = 10^{5.19 - (1309/t + 273)}$

Eq 2: Enthalpy $E = 1.08\,t - 4.2$

Where:

SiO_2 = quartz-induced silica solubility (mg/l)
t = temperature (°C)
E = enthalpy calories/gram

The result of equation 1 is inserted into equation 12, and the result of equation 2 is inserted into equation 11 with the appropriate field data to determine the values of X_{si} and X_t, respectively.

Eq 11: $X_t = \dfrac{E_h - T_{ws}}{E_h - T_{cs}}$

Eq 12: $X_{si} = \dfrac{Si_h - Si_{ws}}{Si_h - Si_{cs}}$

Where:

E = enthalpy of hot water (calories/gram)
Si_h = silica content of hot water (mg/l)
T_{ws} = surface temperature of warm spring (°C)
T_{cs} = surface temperature of cold spring (°C)
Si_{ws} = silica content of warm spring (mg/l)
Si_{cs} = silica content of cold spring (mg/l)

The values of X_t and X_{si} are then compared to each other at 2°C temperature increments starting at 51°C. If X_{si} is greater than X_t, then the temperature is increased by 2°C and equations 1, 2, 11, and 12 are recalculated. When X_{si} becomes equal to or less than X_t the computation is finished and the estimate of subsurface temperature is displayed. Keying RS yields the cold water fraction of the warm spring. Depending upon the magnitude of the subsurface temperature estimate, this program may require .25 to 5 minutes to run.

Line	Code	Key Entry	Comments
01	05	5	
	01	1	
	23 04	STO 4	
	24 07	RCL 7	
05	24 06	RCL 6	
	24 04	RCL 4	
	02	2	
	07	7	
	03	3	
10	51	+	
	71	÷	
	41	-	
	15 08	g, 10^x	
	24 01	RCL 1	
15	21	X ⇄ Y	
	41	-	
	15 51	g, X ≥ 0	
	13 43	GTO 43	
	24 03	RCL 3	
20	14 73	f, LAST X	
	41	-	
	71	÷	
	24 04	RCL 4	
	01	1	
25	73	.	
	00	0	
	08	8	
	61	X	
	04	4	
30	73	.	
	02	2	
	41	-	
	24 00	RCL 0	
	21	X ⇄ Y	
35	41	-	
	24 02	RCL 2	
	14 73	f, LAST X	
	41	-	
	71	÷	
40	15 03	g, ABS	
	14 41	f, X < Y	
	13 46	GTO 46	
	02	2	
	23 51 04	STO + 4	
45	13 04	GTO 04	Displays Subsurface Temperature Key R/S for X, % cold water
	24 04	RCL 4	
	74	R/S	
	22	R↓	
	13 00	GTO 00	

Registers

R_0 Temp W.S.

R_1 SiO_2 W.S.

R_2 Temp C.S.

R_3 SiO_2 C.S.

R_4 subsurface temperature (in use)

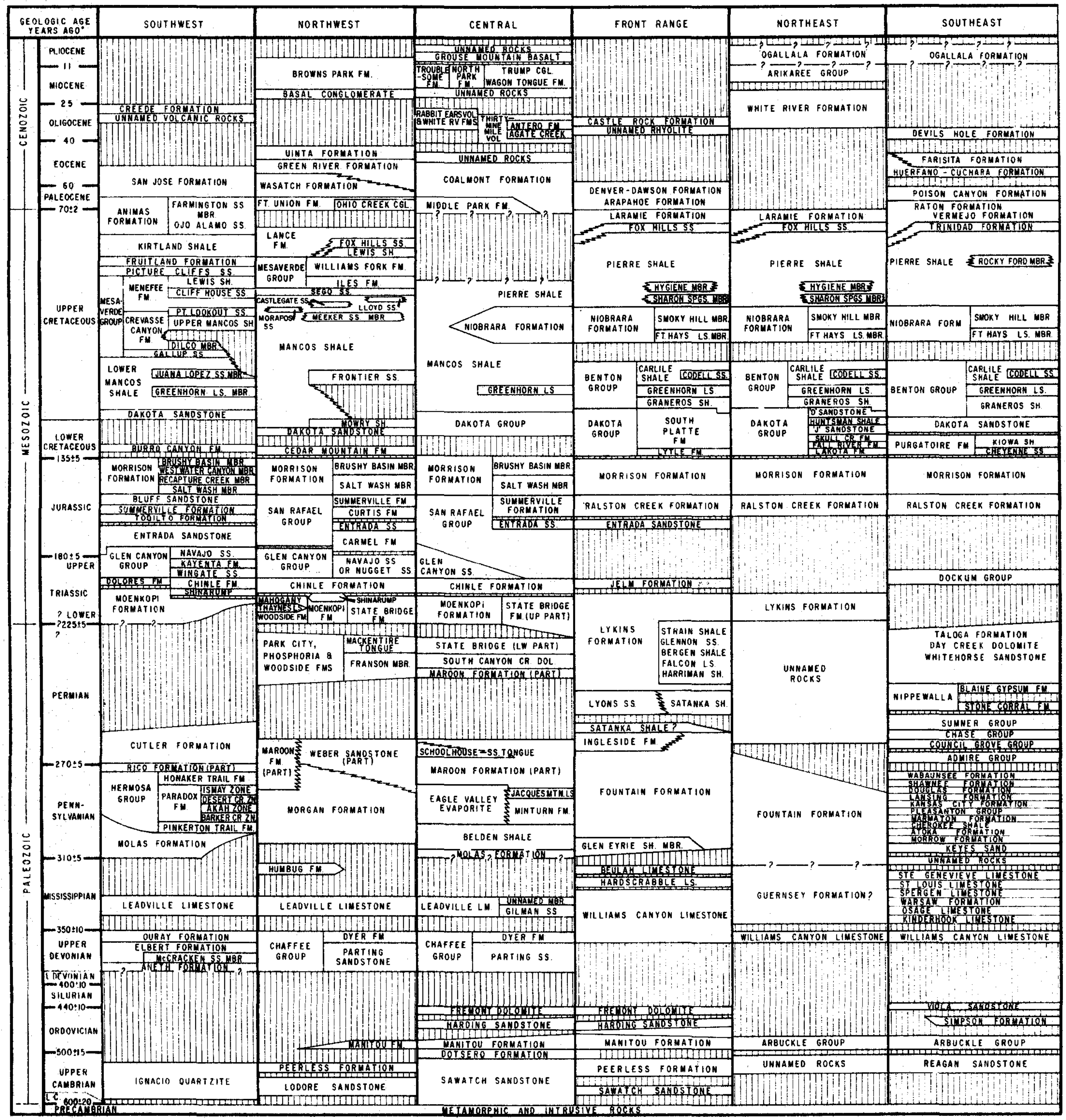
R_5 Not used

R_6 1309

R_7 5.19

COLORADO STRATIGRAPHIC CORRELATION CHART

COLORADO GEOLOGICAL SURVEY



Compiled by Richard Howard Pearl and D. Keith Murray (August 1974).
*Millions of years before present (Source: Geochron Laboratories, Inc.)

Source of data: Geologic Atlas of the Rocky Mountain Region (RMAG, 1972) and other publications. Reviewed by selected members of the RMAG.

Figure 120