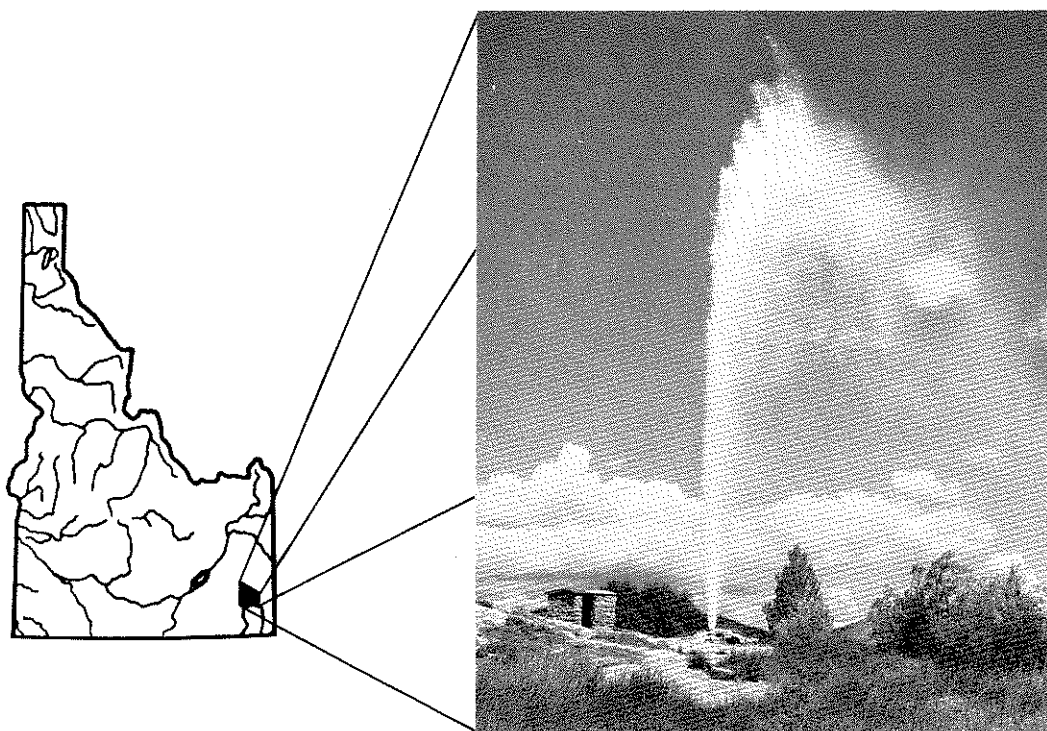


GEOHERMAL INVESTIGATIONS IN IDAHO

PART 6 GEOCHEMISTRY AND GEOLOGIC SETTING OF THE THERMAL AND MINERAL WATERS OF THE BLACKFOOT RESERVOIR AREA, CARIBOU COUNTY, IDAHO



IDAHO DEPARTMENT OF WATER RESOURCES
WATER INFORMATION BULLETIN NO. 30
AUGUST 1976

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Part 6

**Geochemistry and Geologic Setting of the
Thermal and Mineral Waters of the Blackfoot Reservoir Area,
Caribou County, Idaho**

by

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**Prepared and published by
Idaho Department of Water Resources
R. Keith Higginson
Director**

August 1976

PREFACE

Geothermal energy (the natural heat energy of the earth) is receiving nationwide attention. The increasing involvement of many parties in exploration for and development of this energy source has been accelerated by four factors:

1. Ecologically, geothermal energy appears to be a better alternative than other methods of power generation such as nuclear, fossil fuel, or hydroelectric.
2. Economically, it competes favorably with hydroelectric and fossil fuel power generation, and may be cheaper than nuclear methods.
3. Enormous reserves of geothermal resources have been identified and can be developed if the effort is made to utilize them.
4. Efficient use of all energy sources is now recognized as necessary if present energy shortages are to be alleviated and future shortages avoided.

Published information on the geothermal potential in Idaho consists mostly of numerous reports that briefly describe or mention thermal water occurrences in particular areas or regions of the state. Seven reports (Stearns and others, 1937; Waring, 1956; Ross, 1971; Nichols and others, 1972; Warner, 1972; and Young and Mitchell, 1973; and Warner, 1975) have been written on Idaho's geothermal potential. Three of the reports are mainly compilations of pre-existing data collected by various investigators over an extended time interval of approximately 50 to 60 years. Waring (1965, p. 26-31) essentially updates the data of Stearns and others (1937, p. 136-151). Godwin and others (1971) classified approximately 15 million acres (60,705 square kilometers) of land in Idaho as being valuable prospectively for geothermal exploration. Ross (1971) published geologic and chemical information on 380 thermal water occurrences, and presented brief evaluations of the geothermal potential of different regions of the state. Nichols and others (1972) identified non-power uses and the economic impact of these uses on Idaho. Warner (1972 and 1975) dealt with Idaho's geothermal potential based on its regional geologic setting.

In Idaho, the prospects for early development of geothermal energy as a power source appear excellent. The regional geologic setting appears favorable for the existence of large geothermal fields although little is known of the full potential of this resource. A great deal more must be learned of geothermal occurrence, development, utilization, and regulation. The Idaho Department of Water Resources initiated a study of geothermal potential to generate interest in development of the resource and to properly perform the Department's

regulatory function. Part 1 of the study, prepared jointly with the U.S. Geological Survey, located twenty-five areas in Idaho (fig. 1) where indications of potential for power development utilizing geothermal energy were found. Parts 2, 3 and 4, prepared by the U.S. Geological Survey, studied areas in west-central and southwest Idaho. Parts 5, 6 and 7, prepared by the Idaho Department of Water Resources, studied areas in south-central and southeastern Idaho. Part 8, prepared jointly by the Idaho Department of Water Resources and the Southern Methodist University, describes the heat flow regime in and around the Snake River Plain.

There are four objectives common to each of the studies: (1) to encourage the development of the resource through public knowledge of its occurrence, characteristics, origin, and properties; (2) to develop the expertise within the Department to properly perform its function of regulation of the resource; (3) to protect the ground and surface waters of the state from deleterious effects which might be brought about by large-scale geothermal development efforts by public or private parties; (4) to protect the geothermal resource from waste and mismanagement because of lack of knowledge of its occurrence, characteristics, and properties.

This study, part 6, summarizes a part of the effort to obtain additional data on the properties, origin, occurrence, and characteristics of this resource in Idaho.

ACKNOWLEDGMENTS

Many people have contributed to this study in the hope that the information will be of benefit to the people of the State of Idaho.

The Idaho Nuclear Energy Commission granted financial support for the chemical analyses necessary in collection of data. Aerojet Nuclear Company, a prime contractor of the Energy Resource and Development Administration, made available laboratory facilities, personnel, and equipment for neutron-activation analyses at the Idaho National Engineering Laboratory at a very minimal cost. The Bureau of Reclamation made available personnel and laboratory facilities for standard water-quality analyses.

The Department of Geology at Idaho State University provided x-ray laboratory facilities at no cost for the mineral identification study. The Department of Chemistry at Idaho State University made available, also at no charge, glass-blowing laboratory facilities as part of the neutron activation studies.

All of these cooperative efforts are gratefully acknowledged and appreciated; without such generous support, this study could not have been accomplished.

COVER PHOTO

THE SODA SPRINGS GEYSER

Soda Springs, Idaho

Soda Springs boasts the only man-made geyser in the world which erupts from a carbon dioxide gas.

The geyser is 2 feet in diameter and leaps upward to a height of 70 feet. It resembles in many respects "Old Faithful" of Yellowstone Park. The water is very hot, but because of a cavity of carbon dioxide gas through which the geyser passes, the water cools before it reaches the surface. The geyser spouts an estimated 2,000 gallons of heavily mineralized water and gas per minute. The water is laden with dissolved constituents and is undesirable for drinking and culinary use.

The geyser came into being when a group of Soda Springs businessmen attempted to drill for hot water in anticipation of securing water for a swimming pool. The depth drilled was 315 feet and was completed on November 30, 1937. An adequate control has been placed on the mechanism which is operated by the City police who turn it on at the request of tourists.

The geyser is owned by the Soda Springs Geyser Co., Inc., and is located on Soda Mound west of Main Street on 1st South at the end of the Civic Center.

(Photo and caption courtesy of the Idaho Historical Society.)

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ABSTRACT

Geologic evidence of geothermal activity is abundant in the Blackfoot Reservoir area. The Intermountain Seismic Belt passing through the area coincides with a zone of high heat flow manifested by numerous thermal springs. A geothermal gradient of 1°C per 25 meters has been reported for the area. Basalt flows less than 700,000 years old exist west and south of the Blackfoot Reservoir. Gravity and magnetic data reveal a geologically very young volcanic collapse structure (caldera) or a mass of low density intrusive rocks near the center of the area. Rhyolite cones reportedly 100,000 years old, thermal springs, spring deposits, and geyser activity indicate the presence of geothermal activity. An audio-magnetotelluric survey, conducted during 1973 indicated that shallow, low conductive zones do not exist in the survey area at a depth of less than 2 kilometers. If any geothermal reservoirs or aquifers exist in the area, they are probably very deep (greater than 2 kilometers).

The silica geochemical thermometers indicates that the thermal waters of the Blackfoot Reservoir area are not from high temperature reservoirs or aquifers. Higher temperatures were predicted by the sodium-potassium-calcium (Na-K-Ca) geochemical thermometers; however, in many cases active travertine deposition influenced the reliability of the calculated Na-K-Ca aquifer temperatures.

Published estimates of geothermal gradient suggest these waters could be ascending from depths as shallow as 1 kilometer along normal faults closely associated with the springs. Deep reservoirs could be assessed only by deep exploration techniques such as deep resistivity, deep drilling, heat flow, and seismic monitoring. Geothermal water at shallow depths for use in small scale, low temperature applications might be discovered by prospecting along fault zones associated with travertine deposits which cover extensive areas in the Blackfoot Reservoir area.

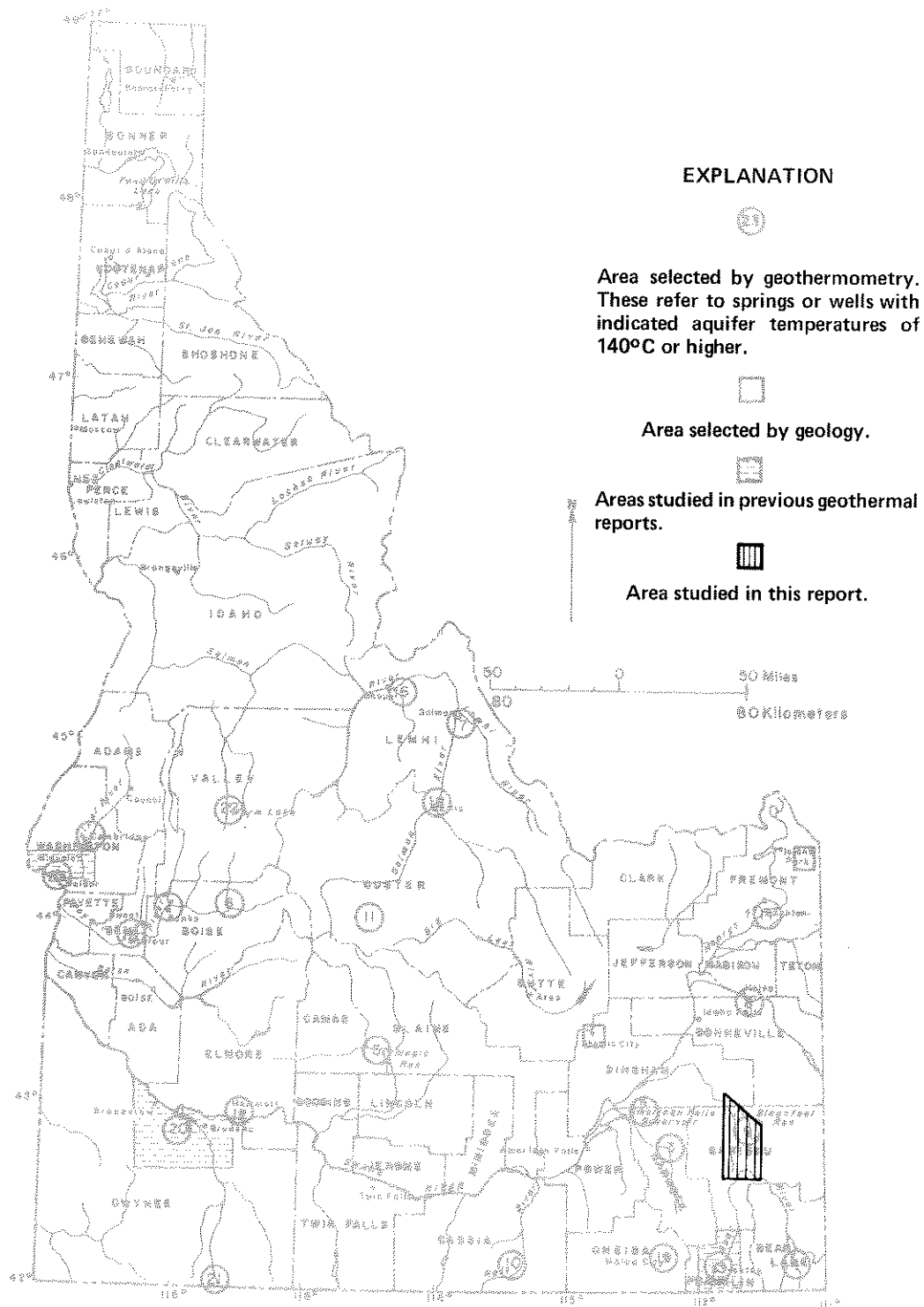


FIGURE 1. Index map of Idaho showing area of this report and areas selected for study by Young and Mitchell (1973).

GENERAL INTRODUCTION

Purpose and Scope

Reconnaissance geochemical sampling of geothermal waters within Idaho has given indications of at least 25 areas that may have potential for geothermal energy utilization (Young and Mitchell, 1973). The Blackfoot Reservoir region was one of the 25 areas (fig. 1). This region was chosen for further evaluation of its geothermal potential for four reasons:

1. Preliminary geochemical sampling and application of the silica (Si) and sodium-potassium-calcium (Na-K-Ca) geochemical thermometers at several sites indicated the possibility that temperatures might be high enough for power generation at depth in this area.
2. Numerous thermal and mineralized springs with easy access meant additional data could be inexpensively and rapidly obtained.
3. An environment favorable to the possible existence of a geothermal field makes up the geologic framework of the area.
4. A built-in market for electrical energy without long distance power transmission exists; the world's largest known phosphate reserve is located in the immediate area. A prerequisite for large-scale development of this phosphate reserve is an inexpensive, abundant power source. Such development would have worldwide impact.

The purpose of this report is to further examine and evaluate the geothermal potential of the Blackfoot Reservoir area by obtaining more thermal-water chemistry data from existing springs and wells; obtaining pertinent geological, geophysical, and hydrological data from the literature; presenting the field-work data; describing the occurrence and chemical characteristics of the thermal waters; interpreting the existing and newly acquired data and relating it to the geothermal potential; developing the information necessary to formulate regulatory strategies if and when deep drilling in the area commences; and recommending areas of additional work where needed.

Previous Work

Publications on the geothermal potential of the Blackfoot Reservoir area do not exist, although many reports contain useful information pertaining to that subject. These

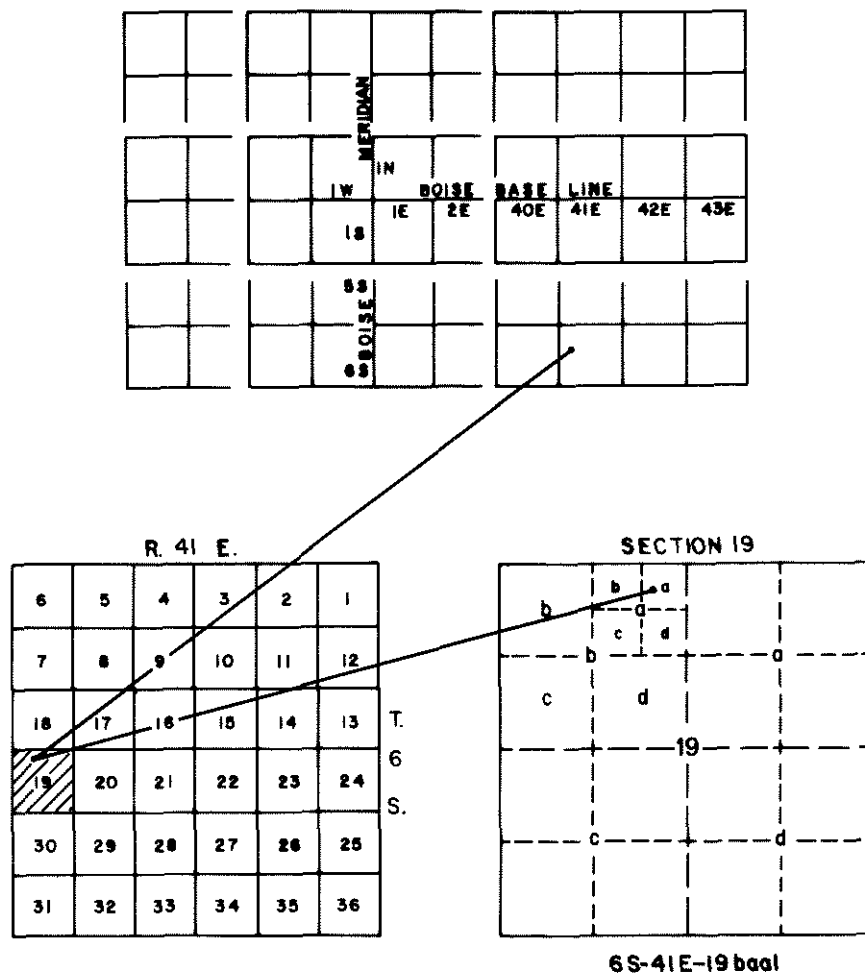


FIGURE 2. Diagram showing the well and spring numbering system.
(Using well 6S-41E-19baa1.)

publications principally research the extensive phosphate reserves found in nearby areas. Mansfield (1972) wrote a detailed treatise on the geography, geology, and mineral resources of a part of southeastern Idaho and included the Henry and adjacent quadrangles. Armstrong (1953) published a generalized composite stratigraphic section for the Soda Springs quadrangle and adjacent areas and in 1969 published a geologic map of the Soda Springs quadrangle. Armstrong and Cressman (1963) reported on the Bannock thrust zone in southeastern Idaho. Mitchell and others (1965) produced an aeromagnetic map of the Pocatello-Soda Springs area. Mabey and Oriel (1970) published gravity and magnetic data on the Soda Springs area.

Little work has been done pertaining to the hydrology of the area. Dion (1969) made a hydrologic reconnaissance of the Bear River basin in southeastern Idaho, and Dion (1974) also studied underground leakage from the Blackfoot Reservoir into the Bear and Portneuf river drainage areas. Many other publications and much unpublished data exists pertaining principally to the geology and geophysics of adjacent areas, but which include data on the Blackfoot Reservoir area.

Well- and Spring-Numbering System

The numbering system used by the Idaho Department of Water Resources and the U.S. Geological Survey in Idaho indicates the location of wells or springs within the rectangular subdivision of the public lands, with reference to the Boise baseline and meridian. The first two segments of the number designate the township and range. The third segment gives the section number, followed by three letters and a numeral, which indicate the quarter section, the 40-acre tract, the 10-acre tract, and the serial number of the well within the tract, respectively. Quarter sections are lettered a, b, c, and d in counterclockwise order from the northeast quarter of each section (fig. 2). Within the quarter sections, 40-acre and 10-acre tracts are lettered in the same manner. Well 6S-41E-19baa1 is in the NE $\frac{1}{4}$ NE $\frac{1}{4}$ NW $\frac{1}{4}$ Sec. 19, T. 6 S., R. 41 E., and was the first well inventoried in that tract. Springs are designated by the letter "S" following the last numeral; for example, 9S-41E-12add1S.

Use of Metric Units

The metric or International System (SI) of units is used in this report to present water chemistry data. Concentrations of chemical substances dissolved in the water are given in milligrams per liter (mg/l) rather than in parts per million (ppm) as in some previous Water Information Bulletins. Numerical values for chemical concentrations are essentially equal whether reported in mg/l or ppm for the range of values reported in this report. Water temperatures are given in degrees Celsius ($^{\circ}$ C). Figure 3 shows the relation between degrees Celsius and degrees Fahrenheit.

Linear measurements (inches, feet, yards, miles) are given in their corresponding metric units (millimeters, meters, kilometers). Weight and volume measurements are also given in

FIGURE 3. Graph showing Celsius-Fahrenheit temperature relationship.

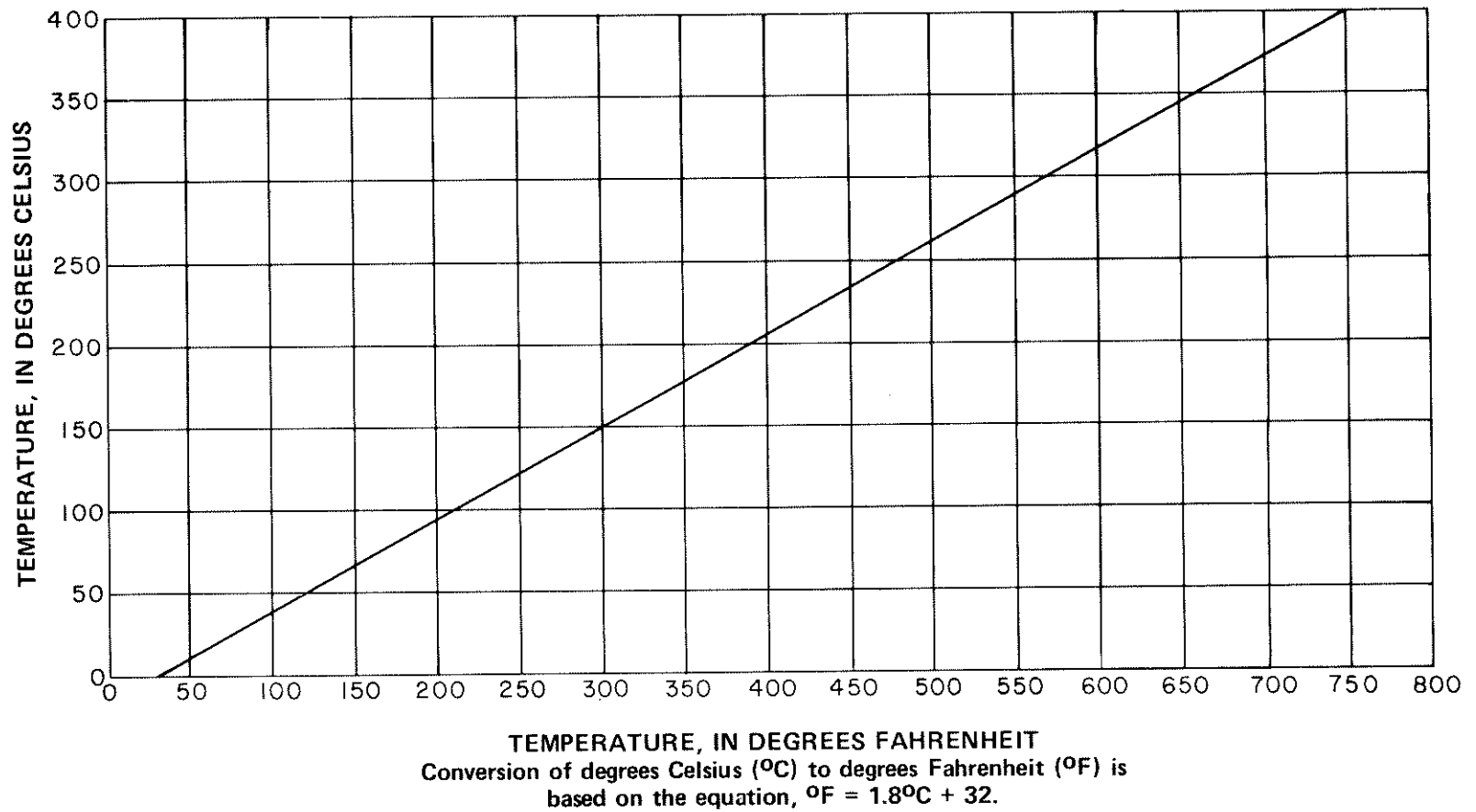


TABLE 1
TABLE OF CONVERSION FACTORS

To Convert from	To	Multiply by
inches	centimeters	2.540
feet	meters	0.305
yards	meters	0.914
miles	kilometers	1.609
sq. miles	sq. kilometers	2.589
gallons	liters	3.785
ounces	grams	28.349
centimeters	inches	0.394
meters	feet	3.281
meters	yards	1.094
kilometers	miles	0.621
sq. kilometers	sq. miles	0.386
liters	gallons	0.264
grams	ounces	0.035

their corresponding metric units. Table 1 gives conversion factors for these units. Area measurements are listed in both SI and English units except when referring to areas described by official rectangular subdivision of public lands.

Collection of Water Chemistry Data

All known accessible thermal-water occurrences in the Blackfoot Reservoir area were visited. Several thermal-water samples were collected from each spring system to insure that representative samples were obtained for chemical analysis. Field data collected included measurement of pH, water temperature, and conductivity. The discharge rate from each spring vent or flowing well was measured or estimated. These measurements were made as close as possible to each spring vent or well discharge pipe.

A standard chemical analysis was run on each thermal-water sample taken. Trace metal analyses were conducted using neutron activation methods. Separate samples were taken for silica analysis and diluted in the field with distilled water (one part sample to nine parts distilled water) to prevent silica polymerization.

Carbonate and bicarbonate determinations were performed potentiometrically in the field because gas—believed to consist mostly of carbon dioxide (CO₂)—was being evolved from many spring vents and sample holding time was considered to be too short for reliable laboratory analysis of these constituents.

In addition, thermal-water deposit samples were collected from each spring or well (where active deposition was noted). The mineral constituents were identified using x-ray diffraction and field identification methods.

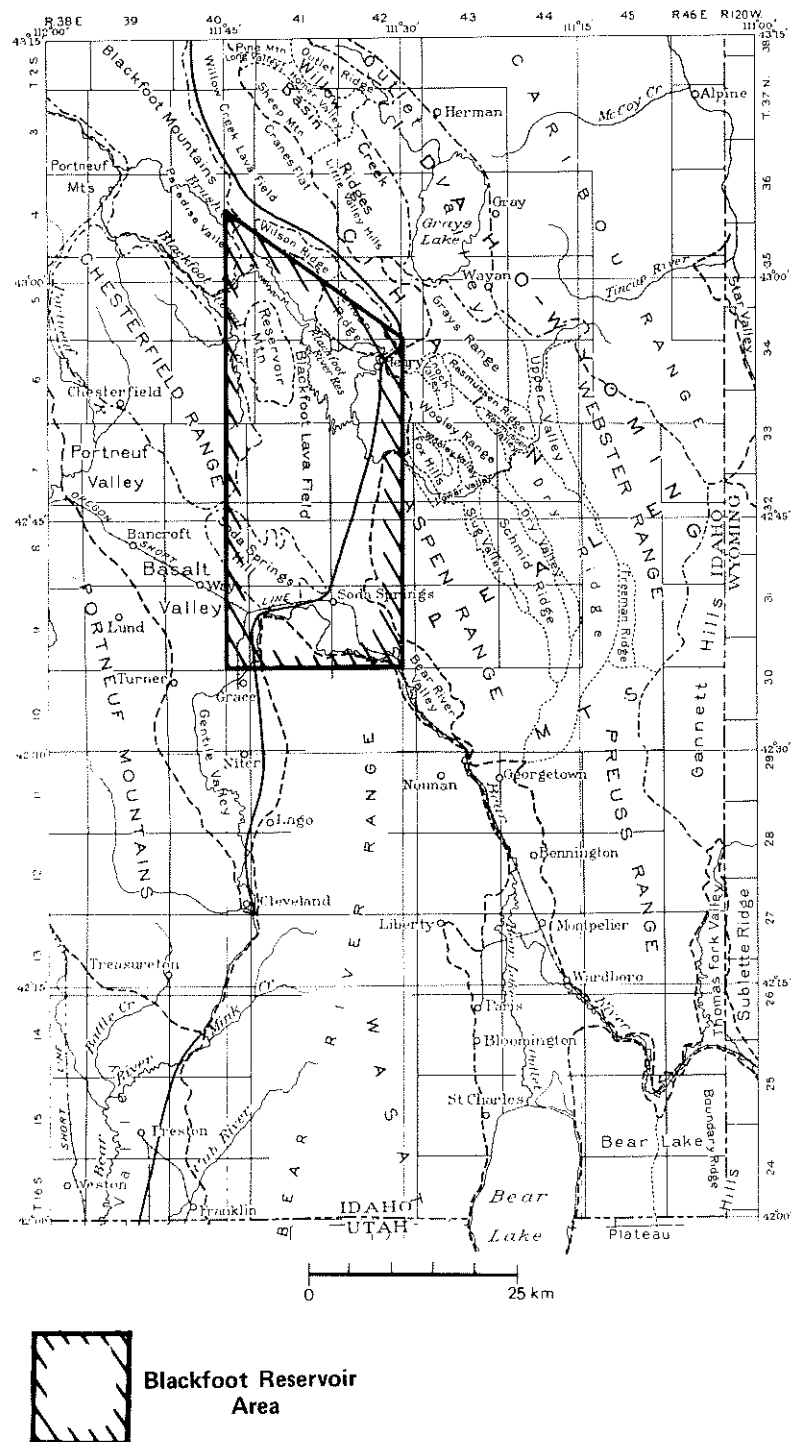


FIGURE 4. Map of southeastern Idaho and adjacent regions, showing the principal physiographic features. The heavy solid line is the boundary between the Rocky Mountain (right) and basin and range provinces. (From Mansfield, 1927.)

GEOLOGY

Location and General Features

The Blackfoot Reservoir area is located in southeastern Idaho (figs. 1 and 4) near the town of Soda Springs (population 2,977 in 1970) and comprises an area of approximately 1,165 square kilometers (45 square miles). It includes all of the Henry quadrangle, narrow strips of the Portneuf and Slug Creek quadrangles on the west and east, and the northern half of the Soda Springs quadrangle on the south. The main industries are elemental phosphorous and phosphate fertilizer production; and agriculture, principally wheat, barley, oats, and livestock raising.

The area lies near the intersection of the three physiographic provinces, the Basin and Range, Northern Rocky Mountain, and the Columbia River Plateau. Physiographic characteristics of each of these provinces are found within the study area. According to Mansfield (1927, p. 15) the dividing line between the Northern Rocky Mountain Province on the east and the Basin and Range Province on the west passes through the central portion of the area. The southern edge of the Snake River section of the Columbia River Plateau Province lies only 30 kilometers (km) north and west of the study area. The area lies along the Intermountain Seismic Belt, a zone of earthquake activity described by Smith and Sbar (1974).

An irregularly shaped, high mountain valley (1,800 meter average elevation), or gently undulating plain characterizes the central portion of the study area with mountain ranges flanking the valley on nearly all sides. These ranges include the Bear River Range to the south; the Aspen, Fox Hills, and Wooley ranges on the east; Pelican Ridge and Reservoir Mountain on the north and northwest; and the Chesterfield Range and Soda Springs Hills on the west.

The principal drainage systems are the Blackfoot and Bear rivers. The Blackfoot River enters the area through a broad valley separating the Fox Hills and Aspen mountain ranges, flows northwest and is impounded behind Blackfoot Dam. The river leaves the area through a 30 meter (m) deep, narrow gorge cut into basalt rock and eventually discharges into the Snake River.

The Bear River enters through a narrow valley and flows westward across the extreme southern portion where it is impounded by Alexander Dam and forms Soda Point Reservoir. The Bear River exits the area by abruptly turning south around Soda Point through a narrow gorge eroded into basalt. This river eventually empties into the Great Salt Lake.

As the whole of the Blackfoot Reservoir area lies at an elevation above 1,800 m, severe cold winters and short moderate summers are the rule. Mean annual precipitation on the valley floor rarely exceeds 50 centimeters (cm), and the climate can be considered semiarid. The mean annual temperature is 5°C at Soda Springs. Winter snows account for most of the water available in the hydrologic network. Summer rainfall is sufficient to sustain dry farming of wheat, barley, oats and hay. No fruits or vegetables are grown commercially due to the short frost-free growing season of approximately 80 to 90 days.

Generalized Geology

The Blackfoot Reservoir area lies near the eastern margin and within a long narrow curvilinear zone of earthquake activity stretching from Las Vegas, Nevada, on the south to Flathead Lake, Montana, on the north, known as the Intermountain Seismic Belt (Smith and Sbar, 1974). This zone is interpreted to be a boundary between subplates of the greater North American crustal plate, where differential movements between the Basin and Range and Colorado Plateau-Rocky Mountain provinces are taking place (Sbar and others, 1972). Plate and subplate boundaries are considered by most geothermal authorities to be excellent areas for prospecting for geothermal resources. Youthful magmatic activity, areas of high heat flow, and thermal spring activity are known to occur along the Intermountain Seismic Belt.

The area can be divided into three geologic realms with lower-middle Paleozoic marine sedimentary rocks on the west, upper Paleozoic and Mesozoic sedimentary rocks on the east, and the Quaternary Blackfoot lava field occupying the central portion of the area (fig. 5). This lava field is an extensive area of basaltic lava flows which were erupted late Pleistocene Epoch (Armstrong, 1969, sheet 1). The Blackfoot lava field is, according to Mansfield (1927, p. 36), an example of the interfingering of the Snake River lava plain with its bordering mountains. Mabey and Oriel (1970, p. E10) report two cycles of vulcanism and associated deformation in the central part of the Blackfoot lava field, as suggested by reverse remanent magnetization of these flows. These authors believe this reverse magnetization indicates an age greater than 700,000 years for that portion of the lava field west of the Blackfoot Reservoir at which time the last major reversed period ended (Cox and others, 1967). Mabey and Oriel (1970, p. E10) state that during the second phase of vulcanism a thick sequence of normally magnetized basalt accumulated in depressions south and west of the Blackfoot Reservoir and some of these flows extended into Gem Valley on the west and Bear River Valley on the south.

Near the center of the Blackfoot lava field, three prominent volcanic cones, China Hat, North Cone and South Cone, are situated along a northeast linear trend. These cones, dated by Armstrong and others (1975, p. 226-243) to be about 100,000 years old are composed chiefly of rhyolite, and are thought to be older than the basalts of the Blackfoot lava field which surround them.

Bordering the Blackfoot lava field on the east are the Aspen, Fox Hills, Wooley, and Webster mountain ranges. These northwest trending ranges are composed chiefly of late Paleozoic and Mesozoic marine limestones, dolomites, siltstones, and shales.

The north-south trending Bear River Range, in the southern part of the area, consists principally of early Paleozoic marine quartzites, limestones, and dolomites, with subordinate volumes of shale and Tertiary continental sediments.

STRUCTURAL FEATURES

The structural framework of the Blackfoot Reservoir area is highly complex. The area lies near a structural pivot or line of flexure, where the prevailing north-south trending mountain ranges to the south abruptly change direction and trend approximately northwest-southeast.

The eastern geologic realm consists of various flanking mountain ranges which have been folded into northwest trending synclines and anticlines and are cut by at least three types of faults. This eastern part is now thought to be within a zone of westward dipping imbricate thrust faults some tens of kilometers wide first described by Richards and Mansfield (1912) to be one continuous overthrust sheet which they called the Bannock overthrust. This single overthrust concept has been interpreted by Armstrong and Cressman (1913, p. J1) as a series of thrusts ranging in age from Late Jurassic to post-Early Cretaceous, being progressively younger from west to east. Armstrong and Cressman recommended referring to these thrusts as the Bannock thrust zone and dropping the older usage, the Bannock overthrust.

According to the work of Armstrong (1969, sheet 1) the faulted and thrust mountain ranges are upthrown fault blocks (horsts) and at least the southern half of the Blackfoot lava field is a complex downthrown fault block (graben). Armstrong indicates displacements along these normal faults of at least 1,200 meters. Armstrong also mapped the Paris thrust fault, apparently to explain the older marine sedimentary sequence exposed in the mountains to the west of the Blackfoot lava field and the rapid facies change between rock units exposed in the mountains on the both sides of the valley. As mapped by Armstrong, this thrust carried lower Paleozoic formations up over lower Triassic formations. The trace of the thrust fault strikes northwest, extending through the south central part of the Blackfoot lava field in the Soda Springs quadrangle.

Mabey and Oriel (1970, p. E3) report that faults transverse to the mountain ranges apparently are strike-slip faults and that they offset major thrust slices. The offset suggests tear faulting formed at a late stage of thrusting or the strike-slip faults formed later than the thrusts. Armstrong and Cressman (1913, plate 4) mapped many of these transverse faults as left lateral strike-slip faults.

The central geologic realm, consisting of the Blackfoot lava field, contains three prominent hills, China Hat, North Cone and South Cone. These hills are composed predominantly of rhyolitic volcanic rocks. Mansfield (1927, p. 127) thought that the alignment of these rhyolitic cones marked a fissure, or the intersection of northeast trending

fissures with a set of northwest trending fissures. The fissure intersections may have been the focal point of the magma extrusions which formed the rhyolite cones. Very young (less than one million years) rhyolitic volcanic rocks are thought by many geothermal experts to be a favorable indicator of geothermal resources due to their theoretical mode of formation. The rhyolitic cones may represent a volcanic episode which would be young enough to provide a potential heat source should a cooling magma chamber (from which these surface flows could have been derived) exist in the area.

Mabey and Oriel (1970, p. E10) report a possible collapsed volcanic structure (caldera) related to withdrawal of molten rock at depth and subsequent lava extrusion on the surface. Existence of this caldera, some 18 km across, is indicated by a compound circular negative gravity anomaly, the general abundance of craters, cones, and large magnetic anomalies, and the spatial relations between basalt flows and gravity depressions. The caldera center corresponds approximately with the three rhyolite cones: China Hat, North Cone and South Cone.

An alternate hypothesis (Mabey and Oriel, 1970, p. E10) proposes that a part of each of the compound gravity anomalies is produced by an underlying low density granitic intrusive body. Both interpretations are suggested by the rhyolite cones. Either interpretation would appear favorable toward geothermal power development as the cooling magmatic mass may represent a potential heat source, hot enough and at shallow enough depth to produce high enthalpy waters, provided a suitable reservoir exists. The collapsed rock debris filling the caldera could be sufficiently porous and permeable to constitute a good geothermal reservoir if sufficient heat is available.

Examination of false color infrared satellite imagery gives no visible indication of single or compound circular surface features which would indicate the existence of a caldera in the vicinity of the magnetic and gravity anomalies. It would appear from this evidence that the alternate hypothesis may be the better explanation for these anomalies.

The western geologic realm in the Blackfoot Reservoir area is structurally somewhat simpler, being distinguished mainly by homoclinal strata cut by several sets of late Cenozoic normal faults, with the mountain ranges being horsts. Transverse faults in this area are also thought to be strike-slip faults.

Spring Deposits

Spring deposits (travertine cones, mounds, and terrace structures) cover extensive areas particularly along the margins of the Blackfoot lava field adjacent to mountain fronts, generally contacting limestones of various ages (fig. 5). Mansfield (1927, p. 112) referred to the deposits as calcareous sinter (travertine) which appear intimately associated with noteworthy faults. Mansfield (1972, p. 113) further states that travertine deposition probably began during the crustal disturbance that marked the close of the Tertiary Period and this deposition has continued with varying intensity until the present. Deposition now is on a much less extensive scale. Many of the travertine deposits (especially the more extensive ones) are associated with active springs while other deposits are associated with

extinct springs. The following description of these deposits is taken from Mansfield (1927, p. 113).

. . . The travertine is generally a white, gray, or buff porous rock, locally deeply ferruginous, that forms rounded, ledgy hills, mounds, or cones that mark the sites of springs that have probably been long extinct. Elsewhere it forms more or less extensive areas of basins and terraces, . . . and cones with apertures, where the springs are still active or only recently extinct (pl. 60, B). The texture in some places is coarse, open, or even cavernous; in other places it is dense, fine, and banded. Locally casts of stems of grasses and gastropod shells occur in the deposits. The rock forms successive layers that give a concentric, shelly structure to cones or that form inclined beds in some of the larger mounds or ledges. The more massive and dense ledges resemble some of the Tertiary limestones and are locally difficult to distinguish from them. . . .

X-ray diffraction studies indicate that the deposits are nearly amorphous (devoid of crystal structure) but contain quantities of calcite and quartz. X-ray diffraction traces on all samples tested, both from the Blackfoot Reservoir and northern Cache Valley areas, were wearisomely uniform.

Some thermal-water sources deposit travertine very rapidly as shown by well 6S-41E-19bac2 drilled in 1968 to a depth of 56.2 meters. This well water built a large, circular, buff colored, travertine mound 23 meters in diameter and 1.5 meters high over a 6-year period. The well, along with others in the section, has now been plugged. The springs and wells forming travertine deposits occur in conjunction with warm calcium bicarbonate type waters from which large volumes of CO₂ gas evolve.

Geothermal Gradient and Heat Flow

Although not extremely reliable as predictors of drilling depth, geothermal gradient measurements have been used in geothermal investigations to establish boundary conditions or possible limits to which one might reasonably expect water to be circulating.

The heat content of the thermal waters of the Blackfoot Reservoir area may be attributable to the geothermal gradient (rate of increase in temperature with increased depth). In the region of southeastern Idaho, where both igneous and sedimentary rocks are found, a geothermal gradient of 1°C per 25 m would be a reasonable assumption (Mansfield 1927, p. 320). This value is intermediate between a normal geothermal gradient of 1°C per 35 m found in most sedimentary rocks, and a gradient of 1°C per 5 to 16 m which Mansfield reported to be found in volcanic terrains in western Idaho. Using the 1°C per 25 m (40°C/km) gradient and a 5°C mean annual temperature, Mansfield calculated that the waters (having an average surface temperature of 48°C) could have come from a depth of 1,000 m. If the gradient continued to 3,000 m, rock temperatures approaching 150°C might be encountered.

The greater reliability of heat flow measurements over simple temperature gradient measurements or calculations in assessing an areal geothermal potential is well known. The geothermal gradient may be viewed as the potential difference between the earth's deeper layers and that found at the surface, and is dependent on the ability of the intervening rock layers to conduct heat (thermal conductivity). Heat flow measurements take this thermal

conductivity into account, and therefore, are uniform with depth while abrupt and sometimes large variations in geothermal gradient occur with depth due to changes in thermal conductivity. A high heat flow, therefore, may indicate the presence of an intense heat source (regional or local) in the subsurface, while a high geothermal gradient may only reflect a lower thermal conductivity.

Although the thermal conductivity of the intervening rock layers in the Blackfoot Reservoir area is not exactly known, reasonable heat flow assumptions can be made by simply knowing the limits of thermal conductivity of the types of rocks found in the area. For example, thermal conductivity of Snake River Plain Basalt rocks range from 3.5 to 5 millicalories/cm/°C sec (3.5 to 5 TCU - thermal conductivity units) giving a heat flow, in heat flow units (HFU), of from $40^{\circ}\text{C}/\text{km} \times 3.5 \text{ TCU} = 1.5 \mu\text{cal}/\text{cm}^2/\text{sec}$ - microcalories/cm²/sec (1.5 HFU) as a lower limit and $40^{\circ}\text{C}/\text{km} \times 9 \text{ TCU} = 3.6 \text{ HFU}$ as an upper limit. A heat flow of 1.5 HFU would be similar to that found in most of the United States and is considered normal while that approaching 3 HFU would be more typical of the Snake River Plain Region (Brott and others, 1976, in press).

Since part of the area is in the Basin and Range Province, a heat flow of 2½ to 3 HFU would be a reasonable assumption. This above-normal heat flow would be high enough to reasonably expect that the thermal waters in the area could be reaching maximum temperature through deep circulation.

THERMAL AND MINERAL SPRINGS AND WELLS AND THEIR GEOCHEMISTRY

Location and General Description

Thermal and mineral springs and wells are widely distributed throughout the Henry and northern half of the Soda Springs quadrangles, being, in general, found along the margins of the Blackfoot lava field where the thermal waters generally issue near limestones (fig. 5). Mansfield (1927, p. 317) described these spring waters of the Henry and six neighboring quadrangles but gave no pertinent chemical analyses. He separated the waters into five categories according to the mineral species being deposited, or on the dissolved chemical constituents. These five classes were: (1) normal springs, characterized by being not noticeably saline to the taste and forming no mineral deposits; (2) calcareous, distinguished by forming deposits of travertine; (3) sulphurated; (4) chalybeate, or iron bearing; and (5) saline springs. In the Henry and Soda Springs quadrangles only the first three classes are found.

Corral Creek Wells

These wells merit additional description since reliable data concerning them were obtained by FMC geologists during drilling operations related to phosphate exploration. Holes were drilled from 1966 to 1970 to an average depth of 57 meters on a broad, north-northwest trending anticline which has been offset some hundred meters east from the normal structure in the area. The anticline is cut off at the north end by an east-west trending strike-slip fault along which the offset block slipped. Another fault, some hundred meters south, is more or less parallel to this major fault but of much less magnitude (H. N. Hurst, written communi.). A map showing bore hole and water sample locations as well as subsurface geology is given in figure 6. Selected geologic cross sections are given in figure 7. The map indicates that the thermal water from these artesian wells is coming from a restricted area of only a few acres. The well discharge waters, although only warm, falsely appear to be vigorously boiling due to large volumes of gas being evolved from them. Analyses performed to identify this gas for FMC Corporation indicate it consists of over 99 percent CO₂ (carbon dioxide). The ground surrounding the flowing wells is saturated with CO₂ gas; the gas appears as tiny bubbles when the ground is water saturated, as after a rainstorm. According to J. S. Spalding (1972, written communi.), both the water and CO₂ gas from the wells were encountered in phosphatic shales which constitute the Meade Peak member of the Phosphoria formation. Spalding further comments that of the 13 bore holes he found flowing on September 9, 1970, seven were found flowing on February 21, 1971. Including the nonflowing bore holes which with one exception were small volume, cooler ones, Spalding estimated discharge reduction between the above two dates to be about 50

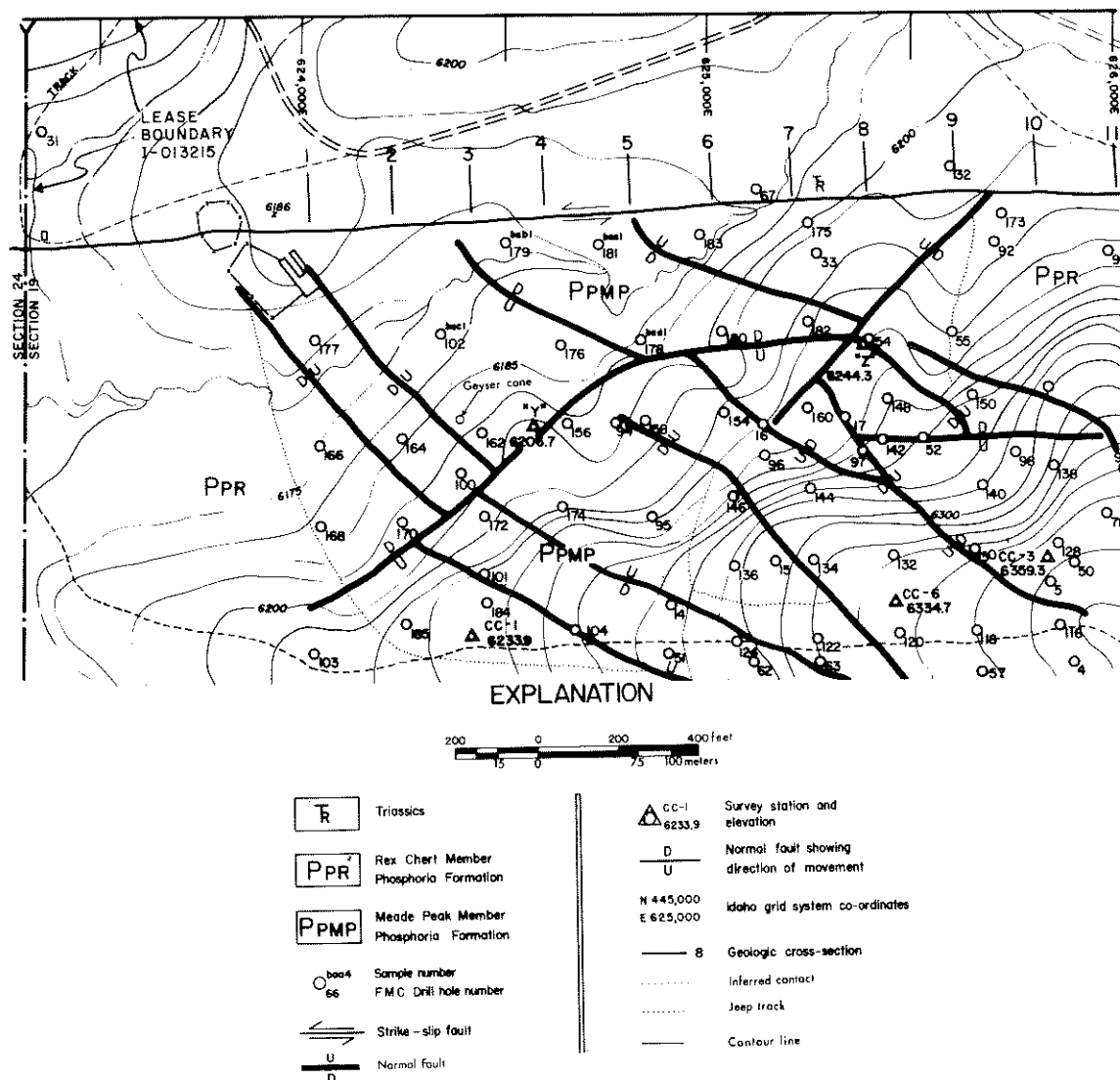


FIGURE 6. Suballuvial geologic map of the Corral Creek well area, Caribou County, Idaho. (Courtesy of FMC, Mineral Development Department, Inorganic Chemicals Division, Pocatello, Idaho.)

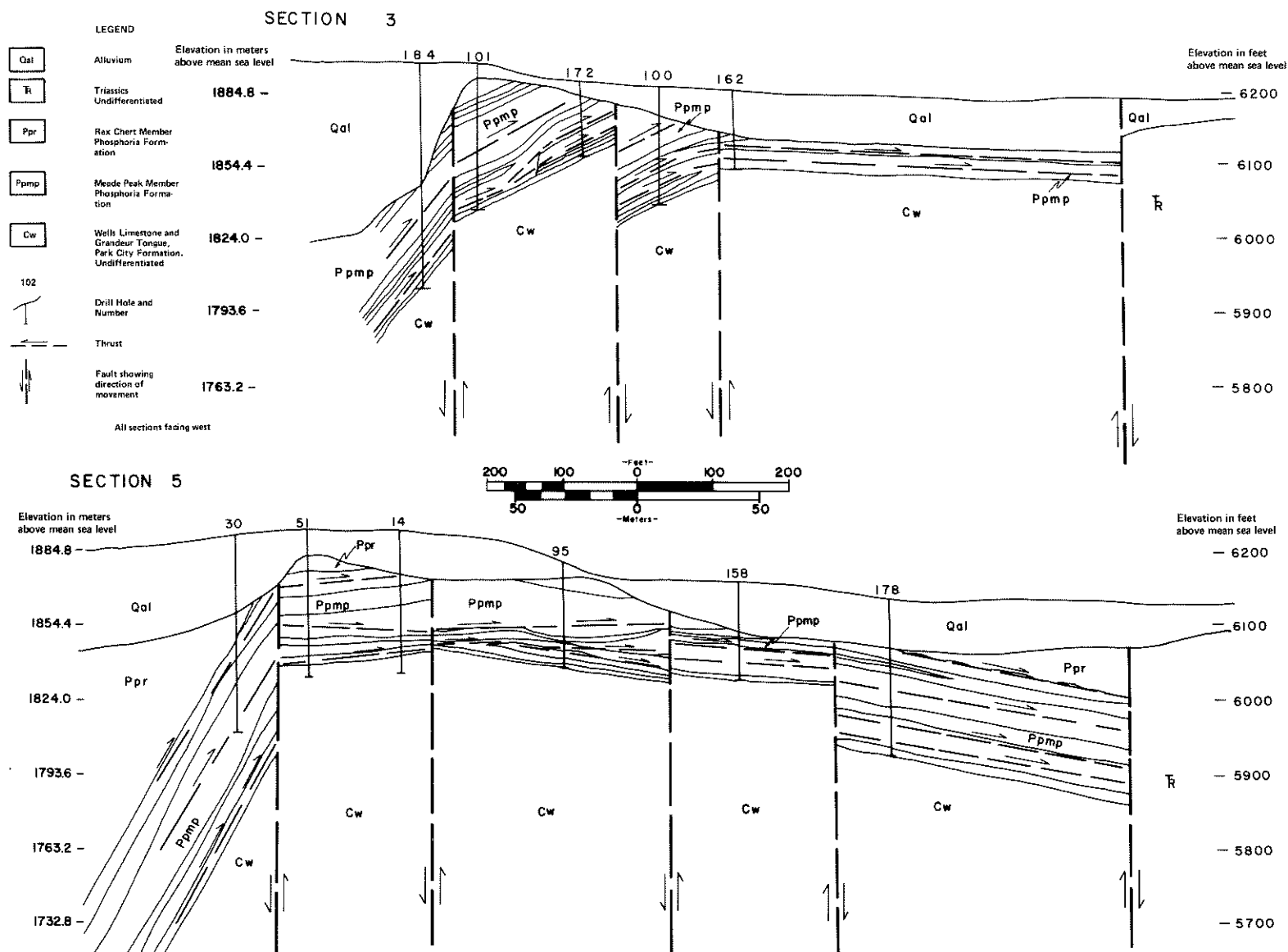


FIGURE 7. Selected north-south geologic cross sections of the Corral Creek well area, Caribou County, Idaho. (Courtesy of FMC Corp. Mineral Development Department, Inorganic Chemicals Division, Pocatello, Idaho.)

percent. Depthwise, between 15 and 20 additional centimeters (cm) of travertine had been deposited around drill hole 102 (6S-41E-19bac1) located near the old warm spring. Spalding made no statement as to why such a discharge reduction had taken place in so short a time, but it could be due to self-sealing of the bore holes by travertine deposition rather than depletion of the water-bearing structure.

Water coming from the "still flowing" bore holes is also copiously precipitating CaCO_3 in the form of travertine. One bore hole (164) was discharging water in spurts through a 5 cm diameter pipe to heights of about 6 m above land surface.

Surface temperature isotherms were constructed by FMC Corporation (fig. 8). A temperature high which corresponds closely to the "still flowing" bore holes of February 21, 1971, is located just north of and on the downthrown side of a northeast trending normal fault shown on figure 6. With the exception of only four holes (numbered 94, 158, 172, and 174), all holes that have discharged thermal waters, as well as the old spring, are located on the downthrown side of this fault block. Cold water was encountered in many of the drill holes to the southeast of this fault. The faulting appears to be related to the larger Pelican Fault mapped by Mansfield (1927, plate 3). All bore holes have now been plugged. During plugging operations the effects of plugging bore hole 181 were observable in bore hole 166 as reddish muddy water discharge. This would indicate structural control in a northeast-southwest direction. (R. J. Hayden, personal communi.)

The restricted flow area and proximity to faulting indicates that waters are ascending along fault planes, and that bore holes are not penetrating a large thermal aquifer. This is borne out by a resistivity survey conducted by the regional geophysics branch of the U.S. Geological Survey during 1973.

The following is a brief statement on the audio-magnetotelluric (AMT) work in the Blackfoot lava field area by Donald B. Hoover:

Several days during August were spent with the AMT system in the Blackfoot lava field to evaluate the geothermal potential of the region. A series of soundings were made from the warm artesian wells on the west side of Reservoir Mountain southeast through China Hat dome to state route 34, and two stations north to the village of Henry where there is a hot spring.

The results of the work indicate that there is no low resistivity region such as we see in other potential geothermal areas within the depth of exploration of the equipment. Typical resistivities at 8 Hertz were 100 to 200 ohm-meters so our skin depth was about 2 kilometers. I interpret this as indicating that the warm wells and springs occupy a very restricted volume within the upper 2 kilometers of rock, and that if any geothermal potential exists it must be deeper than 2 kilometers.

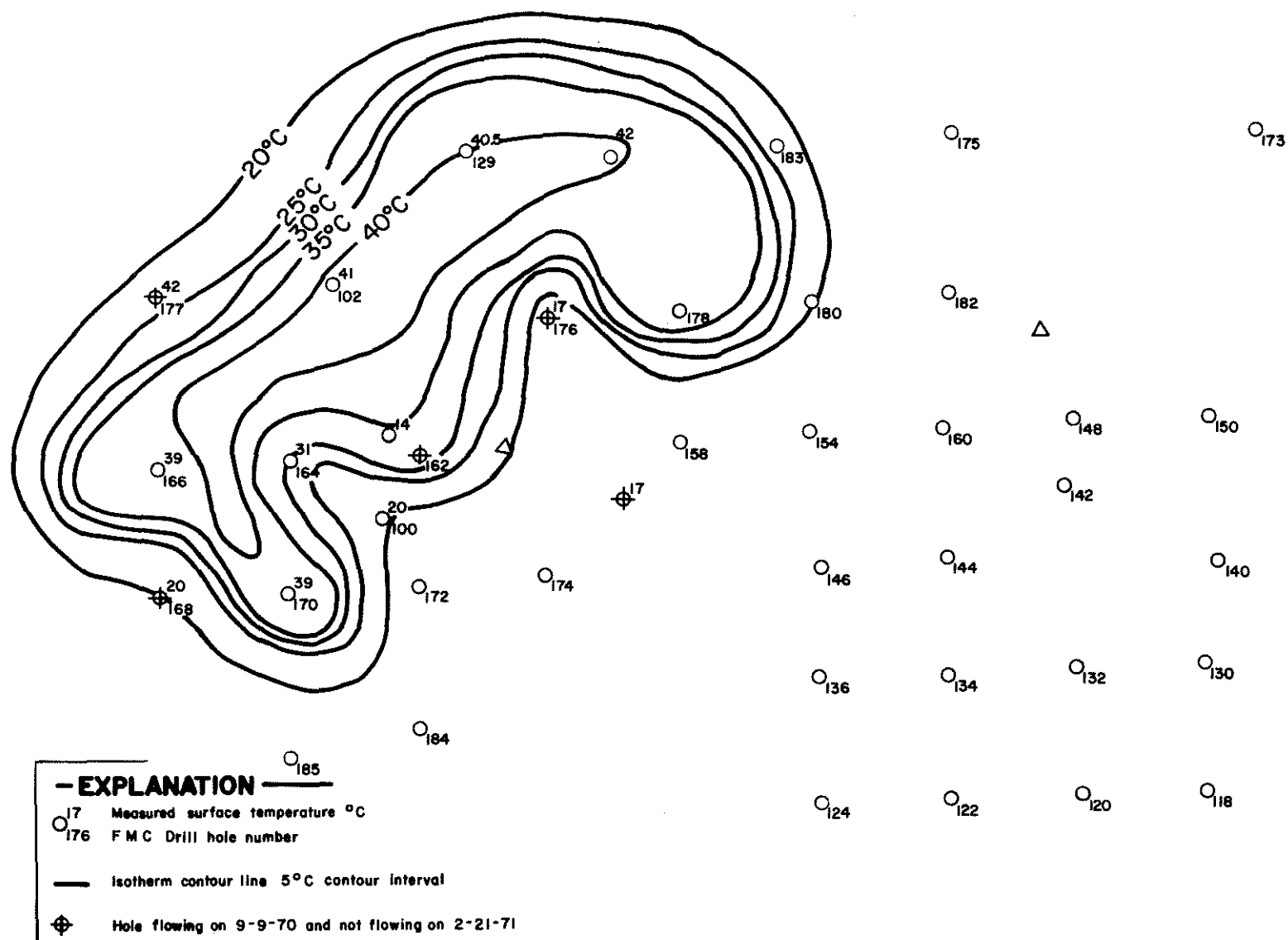


FIGURE 8. Isotherm contour map of flowing wells on Corral Creek. (Courtesy of FMC, Mineral Development Department, Inorganic Chemicals Division, Pocatello, Idaho.)

Major Chemical Constituents

Present day classification of geothermal water is based primarily on the dominant dissolved chemical species found in the waters. Chemical analyses from eight springs and four wells in the Blackfoot Reservoir area are shown in table 2. All springs and wells sampled, both thermal and nonthermal (except Sulfur Springs - 9S-42E-14aad1S), can be classed as calcium bicarbonate ($\text{Ca}[\text{HCO}_3]_2$) or calcium-magnesium bicarbonate ($\text{Ca, Mg} [\text{HCO}_3]_2$) type waters. The sampled springs and wells evolve large quantities of CO_2 gas, and have associated voluminous deposits of travertine. However, the Corral Creek wells (6S-41E-19baa1-4) and Soda Springs Geyser (9S-41E-12add1) are the only active travertine depositors. Sulfur Springs evolves hydrogen sulfide (H_2S), and carbon dioxide (CO_2) gas. Free sulfur can be seen in suspension in the waters of the few spring vents which are still active. Sulfur deposits are associated with gypsum deposits along a north-south trending fault zones (Staley and Prater, 1945). Free sulfur may be formed by oxidation-reduction reactions between the H_2S and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$).

In general, measured surface temperatures were low in the Blackfoot Reservoir area with the highest recorded being 42°C from an artesian well (6S-41E-19baa1) drilled on a phosphate lease held by Food Machinery Corporation (FMC) located near Corral Creek west of Reservoir Mountain.

Discharge of the various springs and flowing wells ranged from 3 liters per minute (l/min) to 950 l/min. Discharge averaged 215 l/min.

Silica content is noted to be fairly low and relatively uniform throughout the entire area. The highest values, 84 and 75 milligrams per liter (mg/l) are from the coldest waters, i.e., Hooper (8S-41E-36dda1S) and Sulfur springs, respectively. High silica values, however, are to be expected in springs of these types (see appendix).

Magnesium and calcium concentrations are high while sodium and chloride concentrations are relatively low compared to the other dissolved constituents. The pH of the waters range from 4.3 Sulfur Springs to 6.8 at Woodall Springs (7S-42E-34baa1S), the least mineralized spring sampled.

Trace Metals

Trace metal analyses performed by neutron-activation techniques are listed in table 3. These give an insight into the likelihood of mineral extraction from thermal waters in the area. Valuable metals are known to be associated with geothermal brines in certain parts of the world. Knowledge of trace metal constituents are also valuable in engineering design for hot water extraction and utilization methods. Certain elements may represent potential pollution hazards if present in sufficient quantities.

Low concentration of nearly all analyzed trace elements were, however, found in these thermal waters. Iron and Strontium were the only trace metals of noteworthy concentration found in any of the waters of the Blackfoot Reservoir area. Iron occurred in the mg/l range in both Hooper and Sulfur springs and in Soda Springs geyser waters. Strontium occurred in the milligram per liter range in all sampled springs and wells except Hooper and Sulfur springs. None of the thermal waters of the area contained any detectable antimony. Other elemental concentrations are in the micrograms per milliliter range.

TABLE 2
CHEMICAL ANALYSES OF THERMAL AND MINERAL WATERS FROM THE BLACKFOOT RESERVOIR AREA,
CARIBOU COUNTY, IDAHO
(Chemical constituents in milligrams per liter)

Spring or well identification number and name	Measured surface temperature (°C)	Reported well depth below land surface (meters)	Discharge (l/min)	Silica (SiO ₂)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Carbonate (CO ₃)	Sulfate (SO ₄)	Phosphate (PO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)	Boron (B)	Ammonia (NH ₃)	Specific conductance (field)	pH (field)	Dissolved solids (calculated) (TDS)	Sodium adsorption ratio (SAR)
5S-40E-15bdc1S	14			25	662	251	145	196	2,382	0	1,122	0.01	68.0	2.4	0.39	0.47	0	434	6.1	4,630	1.2
5S-40E-14bcc1S	26		5	33	674	245	147	217	2,357	0	1,132	0	110.0	3.7	0.06	0.42	1.3	470	6.2	4,665	1.2
5S-41E-1daa1S	23		570	25	232	58	26	14	956	0	70	0	28.0	2.3	0.03	0.04	0	146	6.2	1,370	0.4
Corral Creek Well 6S-41E-19baa1	42	39.5	600	28	701	263	101	237	2,845	0	898	0	41.0	2.3	0.16	0.52	1.2	4,519	6.5	4,849	0.8
Corral Creek Well 6S-41E-19bad1	36	63.8	40	30	649	253	99	233	2,803	0	884	0	40.0	2.5	0.15	0.53	1.2	4,399	6.6	4,728	0.8
Corral Creek Well 6S-41E-19bac1	41	56.2	80	30	697	263	101	233	2,723	0	896	0	40.0	2.4	0.14	0.52	1.3	4,589	6.6	4,720	0.8
Corral Creek Well 6S-41E-19bab1	41	36.5	400	30	620	246	97	242	2,763	0	908	.01	43.0	3.5	0.24	0.47	1.9	4,519	6.8	4,677	0.8
Woodall Springs 7S-42E-34baa1S	12			34	162	44	3	0.2	664	0	31	.01	2.8	0.5	0.10	0.09	0	1,019	6.8	907	0.1
Hooper Springs 8S-41E-36dda1S	10		40	84	141	106	33	13	1,001	0	48	.13	14.0	0.4	0.13	0.10	0.4	1,409	5.9	1,343	0.5
Soda Springs Geyser 9S-41E-12add1	28		5	35	851	193	12	23	2,613	0	801	0	5.7	1.6	0.21	0.05	0.1	1,959	6.5	4,475	0.1
Sulfur Springs 9S-42E-14aad1S	5		5	75	543	73	18	12	67	0	1,593	.21	6.0	0.4	0.12	0.06	0.4	2,419	4.8	2,300	0.2

Analyses by: U.S. Bureau of Reclamation

TABLE 3
TRACE METAL ANALYSES OF THERMAL AND MINERAL WATERS
FROM THE BLACKFOOT RESERVOIR AREA,
CARIBOU COUNTY, IDAHO
 (Chemical constituents in milligrams per liter)

Spring or well identification number & name	Scandium (Sc)	Chromium (Cr)	Iron (Fe)	Cobalt (Co)	Zinc (Zn)	Rubidium (Rb)	Strontium (Sr)	Silver (Ag)	Antimony (Sb)	Barium (Ba)	Cesium (Cs)
	X10 ⁻⁴	X10 ⁻²		X10 ⁻³	X10 ⁻²	X10 ⁻²		X10 ⁻³		X10 ⁻²	X10 ⁻⁴
5S-40E-15b1S	1.0	0.12	0.19	0.27	1.5	17	3.9	7.3	0	0	10
-14bcc1S	1.4	.47	.60	.32	2.9	11	2.5	0	0	10	2.8
Hooper Springs											
8S-41E-36dda1S	1.2	.30	6.1	4.5	1.4	2.4	.38	3.5	0	11	.24
Corral Creek Well											
6S-41E-19bac1	.07	.04	.80	.19	1.0	6.8	1.1	2.7	0	0	3.6
Soda Spring Geyser											
9S-41E-12add1	.22	.44	2.8	.54	2.1	3.2	2.2	7.6	0	7.0	2.1
Sulfur Springs											
9S-42E-14aad1S	44	1.4	11	4.9	12	2.7	.73	.83	0	7.9	.42

Analyses by Idaho National Engineering Laboratory.

Geochemical Thermometers and Atomic Ratios

Preliminary evaluations of geothermal systems are being successfully conducted using geochemical thermometers. In the Raft River Valley of southeastern Idaho the reliability of these thermometers has been tested by deep drilling. The silica, and Na-K-Ca predicted aquifer temperatures (Young and Mitchell, 1973) and mixing model calculations (Young and Mitchell, 1973, unpublished data) agreed very closely (within 10°C) with temperatures found at depth (Kunze, 1975). This proven reliability in the Raft River Valley gives some measure of confidence in applying the same methods to other similar areas of the state.

The degree of reliance to be placed on a geochemical thermometer depends on many factors. A detailed description of the basic assumptions, cautions, and limitations for these geochemical thermometers is included in the appendix. The basic assumption is that the chemical character of the water obtained by temperature dependent equilibrium reactions in the thermal aquifer is conserved from the time the water leaves the aquifer until it reaches the surface. The concentration of certain chemical constituents dissolved in the thermal waters can, therefore, be used to estimate aquifer temperatures.

Aquifer temperatures calculated from the silica, the Na-K-Ca geochemical thermometers, and mixing models, as well as the atomic ratios of selected elements found in the thermal waters of the Blackfoot Reservoir area are given in table 4. These were calculated from values of concentration found in table 2. Observations from table 4 significant to the area's geothermal potential are:

1. Silica temperatures (T_1) based on equilibrium with quartz are notably low and fairly uniform throughout the area with the exception of Hooper and Sulfur springs.
2. Na-K-Ca temperatures (T_4) are notably high in the north.
3. Temperatures of mixing (T_6 and T_7) are generally low throughout with the exception of Woodall Springs.
4. Na/K temperatures are unreasonably high.
5. $\text{Cl}/\text{CO}_3 + \text{HCO}_3$ ratio is fairly constant except at the extreme north and south (see table 4).

Discussion of Geochemical Data

The geochemical data suggest that the thermal waters in the Blackfoot Reservoir area are from low temperature systems. The chalcedony equilibrium geochemical thermometer (T_4 table 4) is considered the most reliable and representative of actual aquifer temperatures in most cases because of nine considerations:

1. Precipitation of silica is sluggish below 180°C, therefore, precipitation of silica as a cause of the low predicated quartz equilibrium aquifer temperatures (T_1 and T_2) is considered unlikely.
2. In most cases, amorphous silica is not the mineraloid controlling silica concentration in the thermal water. The below-zero temperatures predicted by

TABLE 4
ESTIMATED AQUIFER TEMPERATURES AND ATOMIC RATIOS
OF SELECTED CHEMICAL CONSTITUENTS

Spring or well identification number and name	Discharge (l/min)	Measured Surface Temperature (°C)	Aquifer temperatures from geochemical thermometers rounded to 5°C (see footnotes)									Atomic Ratios											
												Sodium Potassium	Sodium Calcium	Magnesium Calcium	Calcium Bicarbonate	Chloride Carbonate + Bicarbonate	Chloride Fluoride	Chloride Boron	Ammonia Chloride	Ammonia Fluoride	$\sqrt{\text{Calcium} + \text{Sodium}}$	Chloride Sulfate	Calcium Fluoride
			T ₁	T ₂	T ₃	T ₄	T ₅	T ₆	T ₇	T ₈	%	Na/k	Na/Ca	Mg/Ca	Ca/HCO ₃	Cl/CO ₂ +HCO ₃	Cl/F	Cl/B	NH ₃ /Cl	NH ₃ /F	$\sqrt{\text{Ca}/\text{Na}}$	Cl/SO ₄	Ca/F
5S-40E-15bdc1S	-	14	70	75	-40	40	320	999	999	260	-	1.26	.038	0.62	0.42	0.05	15.19	44.08	0.00	0.01	20.38	0.16	130.
5S-40E-14bcc1S	5	26	85	85	-30	50	330	999	149	70	91	1.15	.38	.60	.44	.08	15.93	79.79	.02	.39	20.28	.26	86.3
5S-41E-1daa1S	3,500	23	70	75	-40	40	45	530	999	999	-	3.16	.20	.41	.37	.05	6.52	213.26	0	0	67.27	1.08	47.8
Corral Creek Well 6S-41E-19baa1	600	42	75	80	-35	50	360	999	999	60	-	0.72	.25	.62	.38	.02	9.55	24.02	.06	.58	30.10	.12	144
Corral Creek Well 6S-41E-19bad1	40	36	80	85	-30	50	365	999	999	60	-	.72	.27	.64	.35	.02	8.58	22.99	.06	.54	29.55	.12	123
Corral Creek Well 6S-41E-19bac1	80	41	80	85	-30	30	360	999	999	70	-	.74	.25	.62	.39	.03	8.93	23.43	.07	.60	30.02	.12	137
Corral Creek Well 6S-41E-19bab1	400	41	80	85	-30	50	370	999	999	70	-	.68	.27	.65	.34	.03	6.58	27.87	.09	.61	29.48	.13	83.9
Woodall Springs 7S-42E-34baa1S	-	12	85	85	-30	55	45	105	999	110	-	39.33	.04	.45	.37	.01	3.13	9.48	0	0	395.03	.24	159
Hooper Springs 8S-41E-36dda1S	400	10	125	125	10	100	55	430	999	999	-	4.32	.41	1.24	.21	.02	17.45	42.65	.06	1.12	41.32	.79	155
Soda Springs Geyser 9S-41E-12add1	5	58	85	90	-25	55	30	999	999	90	-	.89	.02	.37	.50	0	1.91	34.73	.02	.04	279.16	.02	252
Sulfur Springs 9S-42E-14aad1S	5	5	120	120	5	95	25	615	999	999	-	2.55	.06	.22	12.34	.15	8.93	30.47	.15	1.36	148.66	.01	715

T₁ = Silica temperatures assuming quartz equilibrium and conductive cooling (no steam loss).

T₂ = Silica temperatures assuming quartz equilibrium and adiabatic expansion at constant enthalpy (maximum steam loss).

T₃ = Silica temperatures assuming equilibrium with amorphous silica.

T₄ = Silica temperatures assuming equilibrium with chalcedony.

T₅ = Na-K-Ca temperatures.

T₆ = Na-K temperatures.

T₇ = Fournier-Truesdell mixing model 1 temperatures (no steam loss).

T₈ = Fournier-Truesdell mixing model 2 temperatures (maximum steam loss).

% = Percent of cold water in T₇ calculation.

+ = Molar ratio.

- = Discharge measurement or estimate not possible.

999 = Temperature estimate not possible.

the amorphous silica thermometer indicate that the thermal waters are considerably undersaturated with silica with respect to this phase. The exceptions are Hooper and Sulfur springs, where amorphous silica is highly suspect as the controlling mineraloid. These cold water springs are of the typical sodium bicarbonate and acid sulfate, low chloride waters, respectively. Agreement between the amorphous silica aquifer temperatures and the surface temperature indicates amorphous silica as the controlling phase for dissolved silica in these two springs.

3. No unusual conditions suggestive of mixed hot and cold waters, such as cold spring seeps in the vicinity of the hot springs or wells, were observed.
4. Discharges were, in general, very low throughout the area indicating little, if any, mixing taking place. Exceptions to the low discharges are found only in drilled holes.
5. Mixing models, in general, predict aquifer temperatures not significantly higher than quartz equilibrium predicted aquifer temperatures or, in many cases, give no prediction at all (table 4 and fig. 3 of the appendix). No prediction by the mixing model may mean a basic assumption is wrong. In this case, the wrong assumption may be equilibrium with quartz.
6. The high Na-K-Ca predicted aquifer temperatures can in all cases be attributable to deposition of travertine and evolution of CO₂ gas. In cases where the Na-K-Ca thermometer predicts low aquifer temperatures, the predicted temperature is in general agreement with measured surface temperatures. These are cases where little or no surface deposition of travertine is taking place and CO₂ gas evolution is minimal. This agreement may indicate that no precipitation of CaCO₃ is occurring in the subsurface in these nondepositing spring vents. The low predicted Na-K-Ca aquifer temperatures show good agreement with chalcedony equilibrium aquifer temperatures.
7. Magnesium content and magnesium/calcium ratios are very high indicating the waters are of low temperature.
8. The depths postulated as necessary to give rise to the measured surface temperature (Mansfield, 1927) are reasonable for the origin of these waters.
9. Arnórsson (1970, p. 537, 1975, p. 763) found that chalcedony generally controls silica concentration in Icelandic thermal waters when aquifer temperatures are below 100-110°C. Chalcedonic equilibrium aquifer temperatures, and in most cases, quartz equilibrium aquifer temperatures, are below Arnórsson's upper limit. Chalcedony equilibrium is, therefore, indicated if this criteria is applicable to the Blackfoot Reservoir area.

Travertine deposition as an indicator of low temperature waters may or may not be valid for southeastern Idaho due to the presence of abundant limestone, and in this report this criterion is not used to substantiate low temperature waters.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Geologic evidence of geothermal activity is abundant in the Henry and Soda Springs quadrangles. The Intermountain Seismic Belt, related to plate and subplate boundaries, passes through the area. A known zone of high heat flow coincides with the seismic zone, and is manifested by numerous thermal springs. Mansfield reports a high geothermal gradient. The Pleistocene basalt flows, thought to be less than 700,000 years old, exist west and south of the Blackfoot Reservoir. Possibly present is a geologically young volcanic collapse structure (caldera) or low density granitic intrusive (heat source?). The extremely young (less than 100,000 years old) rhyolite structures (China Hat, North Cone and South Cone) exist near the center of the area surrounded by the somewhat younger basalts. Evident are thermal springs deposits, warm springs and geyser activity. All are strong geologic evidence of large-scale geothermal potential.

The audio-magnetotelluric (AMT) survey indicates that no shallow, low-conductive zone (typical of geothermal systems) exists to depths approaching 2 km. This indicates the absence of geothermal reservoirs to 2 km depths in the survey area.

The geochemical thermometers indicate that the thermal waters of the Blackfoot Reservoir area probably have never reached high temperatures (above 50°C).

Published estimates of temperature gradients suggest that the thermal springs could emerge from depths as shallow as 1,100 m. The close association of these springs and wells with normal faults indicates that the waters are probably meteoric waters circulating to shallow depths along faults and re-emerging as thermal springs or wells. Water ascending from shallow depths may provide little information concerning any deep thermal systems which, in this area, would be the real exploration target.

The geochemistry of the thermal waters, the results of the AMT survey, and the speculative geothermal gradient and heat flow estimates from the Blackfoot Reservoir area indicate little potential for geothermal power generation from shallow depths (less 2 km). The possibility of deeper geothermal resources is, however, attested to by the favorable geologic framework. The possible deep reservoirs would not be accessible to exploration or development except by very expensive techniques such as deep resistivity, heat flow, or deep test drilling.

Heat flow measurements taken from three or four strategically placed 300 m deep drill holes would indicate the approximate intensity of any deep heat source in the area, and

consequently may be the better and less expensive method of exploration. This activity should be deferred until other, more accessible geothermal systems in Idaho have been assessed.

The Blackfoot Reservoir area does, however, represent a unique region where prospecting for geothermal water for low temperature use might be successfully conducted by local individuals, small businessmen, or corporations who wish to make use of low temperature geothermal energy but who lack large amounts of speculative investment capital. Local water well drillers might locate hot water in areas of obvious faulting where surface deposits of travertine are found. If the extinct springs have ceased to flow because of self-sealing due to CaCO_3 deposition, rather than regional cooling or more arid conditions than formerly existed, substantial amounts of low temperature water (less than 75°C) might be found by drilling into fault zones associated with travertine deposits. Self-reliant, enterprising individuals may even devise methods of scaling control, a potential hazard in geothermal water utilization in this area.

The moderately high dissolved solids in these waters precludes their use for irrigation purposes or stockwatering. Their low temperatures suggests uses such as mushroom growing, balneological baths, soil warming, recreational usages, warm water for winter mining operations or de-icing. Space heating for vegetable greenhouses or animal husbandry may be practical if efficient heat pumps were utilized.

The saline waters may challenge engineers who work toward their utilization. Activities related to the large-scale withdrawal and use of these waters must be very carefully monitored. Cooperation between those individuals making use of the water, as well as state and local officials, is necessary to avoid potential thermal and saline pollution, which could be a danger due to the higher temperatures and salinity of these waters should large-scale withdrawal be attempted.

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GEOCHEMICAL THERMOMETERS

Young and Mitchell (1973) gave a brief review of the then available geochemical thermometers. Their summary is as follows:

"Summary of Geochemical Thermometers Available

In recent years the concentrations of certain chemical constituents dissolved in thermal waters have been used to estimate water temperatures in the thermal aquifer. However, these geochemical thermometers are useful only if the geothermal system is of the more common hot-water type rather than of the vapor-dominated or steam type, none of which is known to occur in Idaho.

Geochemical thermometers that are useful in describing and evaluating geothermal systems (excluding the sodium-potassium-calcium thermometer) have been summarized by White (1970). Part of his summary is as follows:

'Chemical indicators of subsurface temperatures in hot-water systems.

Indicator	Comments
1) SiO ₂ content	Best of indicators; assumes quartz equilibrium at high temperature, with no dilution or precipitation after cooling.
2) Na/K	Generally significant for ratios between 20/1 to 8/1 and for some systems outside these limits; see text.
3) Ca and HCO ₃ contents	Qualitatively useful for near-neutral waters; solubility of CaCO ₃ inversely related to subsurface temperatures; see text and ELLIS (1970).
4) Mg; Mg/Ca	Low values indicate high subsurface temperature, and vice versa.
5) ***	***
6) Na/Ca	High ratios may indicate high temperatures (MAHON, 1970) but not for high-Ca brines; less direct than 3?
7) Cl/HCO ₃ + CO ₃	Highest ratios in related waters indicate highest subsurface temperatures (FOURNIER, TRUESDELL 1970) and vice versa.
8) Cl/F	High ratios may indicate high temperature (MAHON, 1970) but Ca content (as controlled by pH and CO ₃ ²⁻ contents) prevents quantitative application.
9) ***	***

10) Sinter deposits

Reliable indicator of subsurface temperatures (now or formerly) $> 180^{\circ}\text{C}$.

11) Travertine deposits

Strong indicator of low subsurface temperatures unless bicarbonate waters have contacted limestone after cooling.'

The general principles and assumptions on which the use of geochemical thermometers (White, 1970) is based are: (1) the chemical reactions controlling the amount of a chemical constituent taken into solution by hot water are temperature dependent; (2) an adequate supply of these chemical constituents is present in the aquifer; (3) chemical equilibrium has been established between the hot water and the specific aquifer minerals which supply the chemical constituents; (4) hot water from the aquifer flows rapidly to the surface; and (5) the chemical composition of the hot water does not change as it ascends from the aquifer to the surface.

The fact that these principles and assumptions more often than not can not readily be verified in a field situation requires that the concept of geochemical thermometers be applied with caution and in full recognition of the uncertainties involved. With that understanding, geochemical thermometers provide a useful point of departure for reconnaissance screening and provisional evaluation of thermal areas.

Silica Geochemical Thermometer

The silica method of estimating aquifer temperatures (Fournier and Rowe, 1966) appears to be the most accurate and useful proposed to date. Experimental evidence has established that the solubility of silica in water is most commonly a function of temperature and the silica species being dissolved, (fig. 1).

Practical use of the silica geochemical thermometer assumes that there is

equilibration of dissolved silica with quartz minerals in high-temperature aquifers and that the equilibrium composition is largely preserved in the silica-bearing thermal waters during their ascent to the surface. White (1970) stated that while equilibrium is generally attained at high aquifer temperatures, silica may precipitate rapidly as waters cool to about 180°C and, therefore, the silica method commonly fails to predict actual aquifer temperatures much above 180°C . The rate of precipitation of silica decreases rapidly as the temperature cools below 180°C .

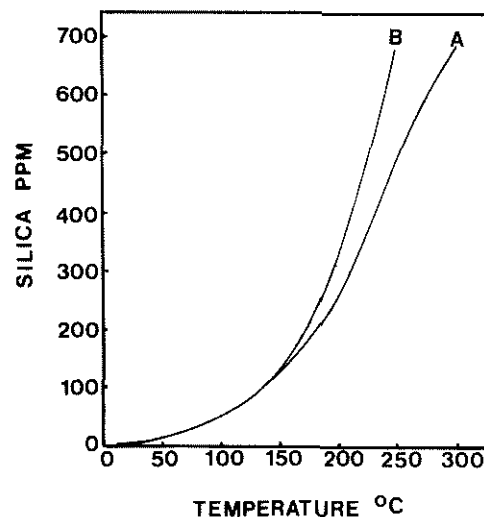


Figure 1. Silica concentration in geothermal water vs. estimated temperature of last equilibration. Curve A applies to waters cooled entirely by heat conduction. Curve B applies to waters cooled entirely by adiabatic expansion at constant enthalpy. (From Fournier and Rowe, 1966.)

White (1970) also cautioned against using the silica geochemical thermometer in acid waters which have a low chloride concentration, because at temperatures near or below 100°C these waters are actively decomposing silicate minerals and thereby releasing highly soluble amorphous SiO_2 . In this case, the basic assumption of equilibration with quartz would be rendered invalid."

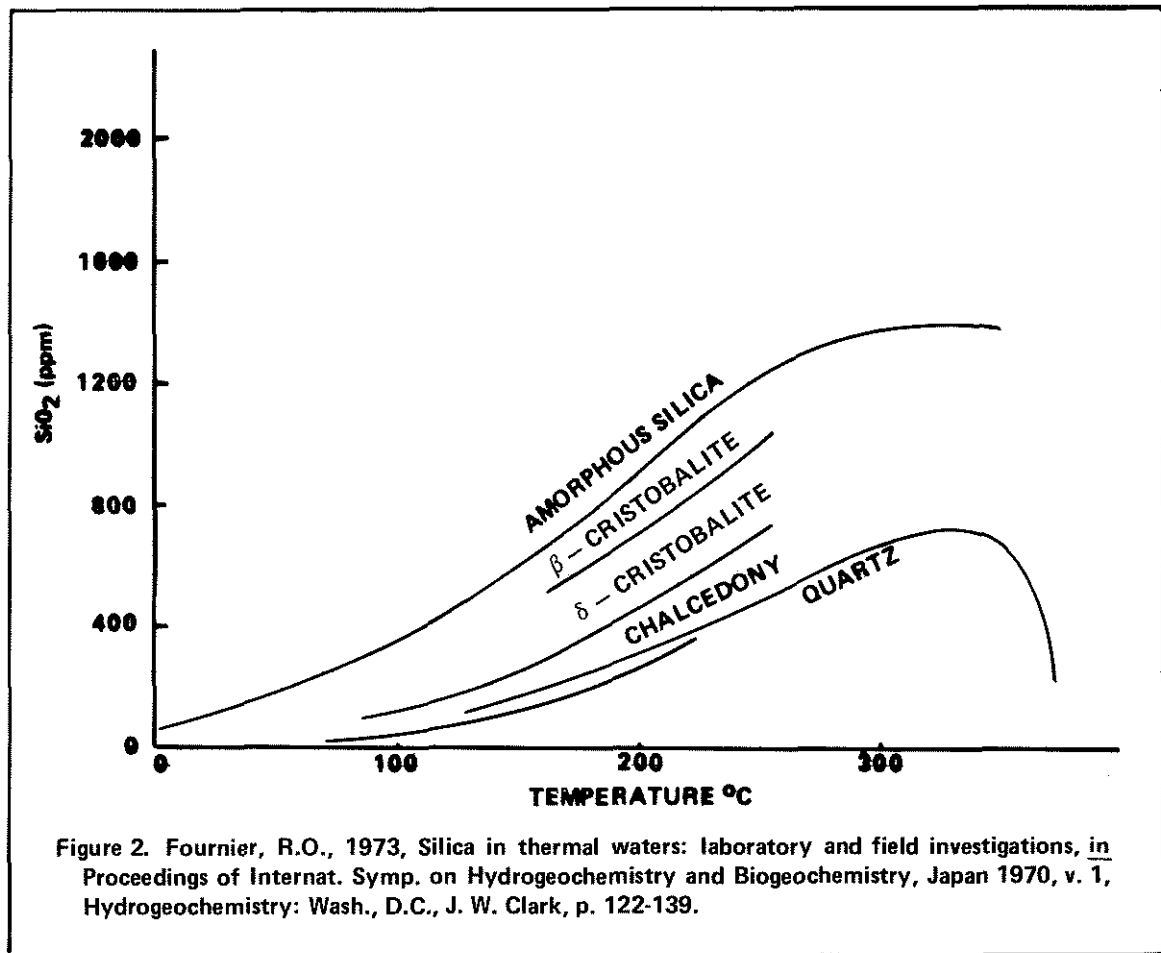
The amorphous silica curve (fig. 2) would give more accurate aquifer temperature predictions in acid waters.

Arnórsson (1970, p. 537, 1975, p. 763) found that chalcedony generally controls silica concentration in Iceland's thermal waters when aquifer temperatures are below 100-110°C. The chalcedony curve

(fig. 2) probably should be given consideration when the silica method using the quartz curve indicates temperatures about 10-20°C above Arnórsson's 110°C upper limit.

"The Sodium-Potassium and Sodium-Potassium-Calcium Geochemical Thermometers

The sodium-potassium (Na/K) geochemical thermometers plots the log of the atomic ratios of Na/K against the reciprocal of the absolute temperature. White (1970) stated that ratios are of general significance only in the ratio range between 8/1 and 20/1. He also reported that Na/K temperatures are not significant



for most acid waters, although a few acid-sulfate chloride waters yield reasonable temperatures. Fournier and Truesdell (1973) point out that Ca enters into silicate reactions in competition with Na and K and the amount of Ca in solution is greatly dependent upon carbonate equilibria. Calcium concentration from carbonates decreases as temperature increases, and may increase or decrease as the partial pressure of carbon dioxide increases, depending on pH considerations. Therefore, the Na/K ratio should not be used for purposes of geochemical thermometry when partial pressures of carbon dioxide are large, as higher carbon dioxide partial pressures may permit more Ca to remain in solution and consequently a smaller Na/K ratio. Fournier and Truesdell (1973) suggest that this ratio should not be used when the $\sqrt{M_{Ca}/M_{Na}}$ (square root of molar concentration of calcium/molar concentration of sodium) is greater than 1.

The sodium-potassium-calcium (Na-K-Ca) geochemical thermometer devised by Fournier and Truesdell (1973) is a method of estimating aquifer temperatures based on the molar concentrations of Na, K, and Ca in natural thermal waters. Accumulated

evidence suggests that thermal, calcium-rich waters do not give reasonable temperature estimates using Na/K atomic ratios alone, and that the Ca concentration must be given concentration.

Fournier and Truesdell (1973) showed that molar concentrations of Na-K-Ca for most geothermal waters cluster near a straight line when plotted as the function $\log K^* = \log (Na/K) + \beta \log (\sqrt{Ca}/Na)$ versus the reciprocal of the absolute temperature, where β is either 1/3 or 4/3, depending upon whether the waters equilibrated above or below about 100°C and where K^* is an equilibrium constant. For most waters they tested, the Na-K-Ca method gave better results than the Na/K method. It is generally believed that the Na-K-Ca geochemical thermometer will give better results for calcium-rich environments provided calcium carbonate has not been deposited after the water has left the aquifer. Where calcium carbonate has been deposited, the Na-K-Ca geochemical thermometer may give anomalously high aquifer temperatures. Fournier and Truesdell (1973) caution against using the Na-K-Ca geochemical thermometer in acid waters that are low in chloride."

Dilution Effects, the Use of the Geochemical Thermometers and Mixing Models

Dilution effects caused by mixing of thermal with nonthermal waters can be a cause of erroneous temperature estimates. Cool groundwaters containing low silica concentrations that mix with thermal waters rich in silica would effectively lower the silica concentration of the thermal water, and a lower aquifer temperature would be indicated. Generally, the possible effect of both dilution and enrichment of thermal waters on the temperature calculated using any geochemical thermometer must be considered.

Fournier and Truesdell (1974a) suggested several starting assumptions to apply to the interpretation of chemical data for hot springs and wells where little information on hydrologic conditions is available. They emphasized that these assumptions are not hard, fast rules applicable to every situation. Their recommended procedures are based on: (1) the discharge of the spring or well, and (2) the recorded surface temperature, as outlined below.

	Small Discharge	Large Discharge
Boiling Springs	Assume mostly conductive cooling. Apply chemical indicators assuming little or no steam loss (adiabatic cooling).	Assume steam loss (adiabatic cooling). Assume maximum steam loss, apply geochemical thermometers accordingly.
Springs below boiling	Probably no clearcut interpretation. May be (1) water that has never been very hot, (2) mixed water from different sources at different temperatures, (3) hot water cooled by conduction. Indicated temperatures most likely, minimum.	Assume no conductive cooling. Geochemical thermometers, particularly Na-K-Ca, if within +25°C of measured surface temperature may be suggestive of equilibrium conditions. Higher indicated temperatures suggests a mixed water.

Small discharge was defined to be less than 200 l/min for single isolated spring, and 20 l/min for single spring vents of larger groups.

Fournier and Truesdell (1974b, in press) have developed a method of testing thermal waters to determine if mixing may be taking place. They maintain that mixing should be suspect where: (1) regular variations in surface temperatures with chloride, boron, or other nonreactive chemical constituents from several springs of an area are observed, (2) the Na-K-Ca geochemical thermometer indicates nonequilibrium conditions (Na-K-Ca indicated temperatures varies from the observed surface temperature by more than 20°C).

Under ideal conditions, Fournier and Truesdell's mixing models allow prediction of the temperature of the hot water before mixing. The models assume that enthalpy (heat content - H_c) of the cold water multiplied by the fraction of cold water (X) plus the enthalpy of the hot water (H_h) multiplied by the fraction of the hot water (1-X) is equal to the enthalpy of the emerging spring water (H_{spg}). Stated mathematically:

$$(H_c)(X) + (H_h)(1-X) = H_{spg} \quad (1)$$

Similarly,

$$(Si_c)(X) + (Si_h)(1-X) = Si_{spg} \quad (2)$$

Where Si_c is the silica content of cold spring, Si_{spg} is the silica content of the hot spring water and Si_h is the enthalpy value for silica in hot water (table 1 - equation 5). Equations 1 and 2 are each solved for the unknown X by simple algebraic rearrangement to give equations 3 and 4.

Fournier and Truesdell's suggested graphical method of solution for mixing model 1, in which the enthalpy of the hot water plus separated steam which heats cold water is the same as the initial enthalpy of hot water before steam separates (no steam loss by system; hence, no evaporative concentration), is as follows:

- "1. Assume a series of values of temperature of hot water and using this corresponding enthalpy values listed in table 1 calculate X_t for each one, using equation 3.

$$X_t = \frac{(\text{Enthalpy of hot water}) - (\text{temp of warm spg})}{(\text{Enthalpy of hot water}) - (\text{temp of cold spg})} \quad (3)$$

2. Plot the calculated values of X_t vs. the assumed temperatures from which the hot water enthalpy values were derived. (See fig. 3, curve A for sample plot.)

3. Using a series of silica contents of hot water appropriate for the temperatures listed in table 1 evaluate X_{Si} for each silica content using equation 4.

$$X_{Si} = \frac{(\text{Silica in hot water}) - (\text{Silica in warm spg})}{(\text{Silica in hot water}) - (\text{Silica in cold spg})} \quad (4)$$

4. On the same graph previously used, plot the calculated values of X_{Si} vs. the temperatures for which the silica contents were obtained (see fig. 3, curve B)."

Table 1¹

Enthalpies of liquid water and quartz solubilities at selected temperatures and at pressures appropriate for steam and liquid water to coexist. Enthalpies from Keenan et al. (1969). Quartz solubilities at and below 225°C from Morey et al. (1962); above 225°C from unpublished data of R. O. Fournier.

Temperature °C	Enthalpy cal/gm	Silica ppm
50	50.0	13.5
75	75.0	26.6
100	100.1	48
125	125.4	80
150	151.0	125
175	177.0	185
200	203.6	265
225	230.9	365
250	259.2	486
275	289.0	614
300	321.0	692

¹Table from Fournier and Truesdell, 1974.

Table 2 gives the calculated X_t and X_{Si} values at selected temperatures and silica concentrations for this mixing model from sampled springs and wells in the northern Cache Valley area.

The intersection of the two curves represent the percent of cold water mixing with the hot (read directly below intersection point on the horizontal axis of the graph) and the temperature of the hot water component before mixing (read on the vertical axis of the graph directly to the left of the intersection point.)

Their solution for mixing model 2, in which the enthalpy of hot water in the zone of mixing is less than the enthalpy of the hot water at depth, due to escape of steam during ascent is as follows:

1. Use the atmospheric boiling temperature for the value of H_h in equation 2 and calculate the corresponding value of X .
2. Use that value of X in equation 3 to estimate the residual silica content of the hot water at t_g .
3. Use the calculated residual silica content and curve A of Fournier and Rowe (1966, fig. 5) to estimate the original subsurface temperature before separation of steam. Curve A of Fournier and Rowe is roughly approximated by the equation

$$-\log C = \frac{1522}{t_{oC} - 273} - 5.75 \quad (5)$$

where C is the silica concentration, and t is temperature in degrees Celsius."

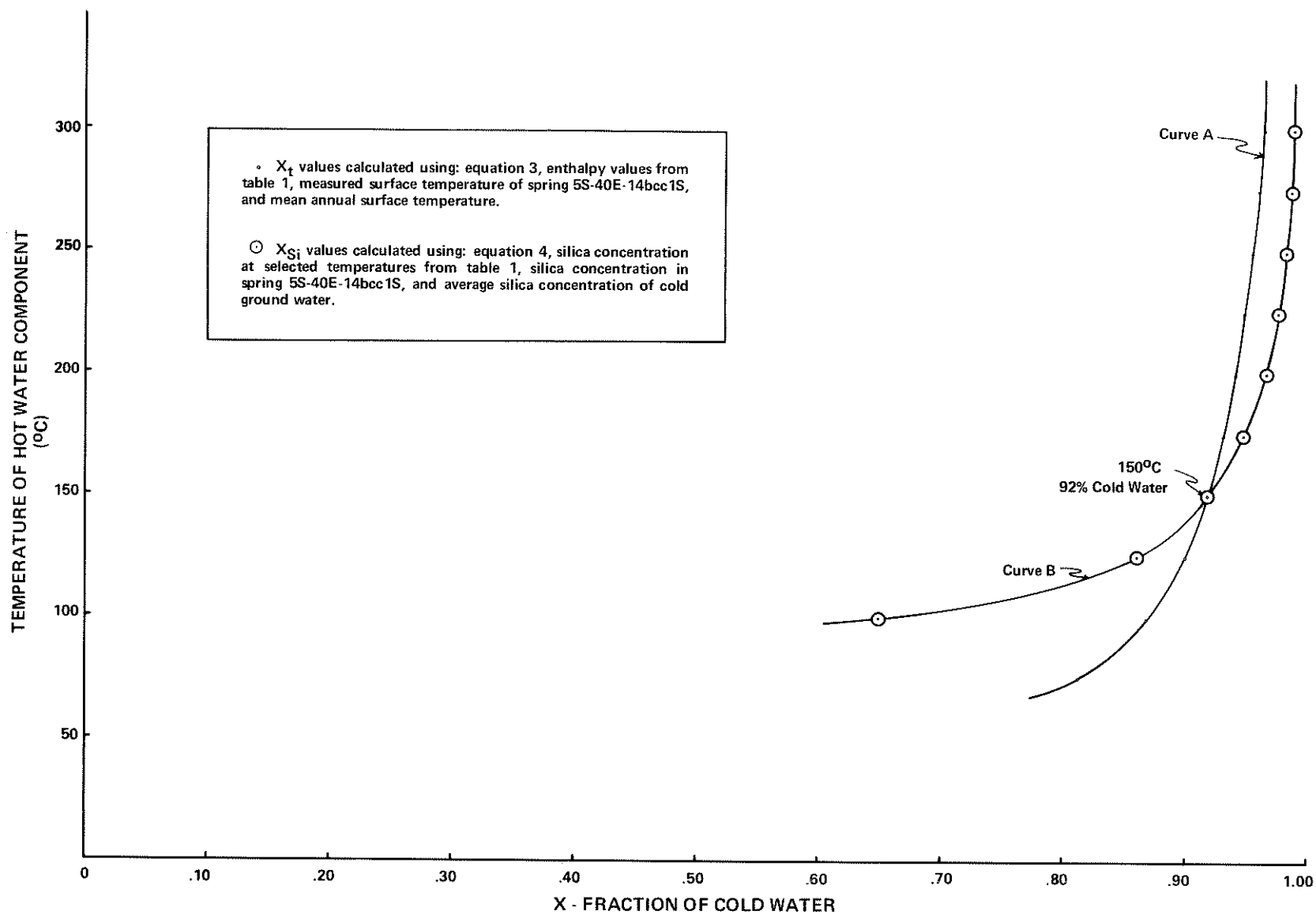


FIGURE 3. Fraction of cold water relative to temperature for spring 5S-40E-14bcc1S.

TABLE 2
 X_t AND X_{Si} VALUES AT SPECIFIED TEMPERATURES AND SILICA CONCENTRATIONS FOR
 THERMAL AND MINERAL WATERS OF THE BLACKFOOT RESERVOIR AREA
 (Temperatures °C)

Spring No. 5S-40E-15bdc1S			Spring No. 5S-41E-1daa1S			Well No. 6S-41E-19bad2		
Surface temperature = 14° Silica = 25 mg/l Background silica = 25 mg/l Background temperature = 15° Boiling temperature = 93°			Surface temperature = 23° Silica = 25 mg/l Background silica = 25 mg/l Background temperature = 15° Boiling temperature = 93°			Surface temperature = 36° Silica = 30 mg/l Background silica = 25 mg/l Background temperature = 15° Boiling temperature = 93°		
T	X_t	X_{Si}	T	X_t	X_{Si}	T	X_t	X_{Si}
75	-	1.000	75	0.867	1.000	75	0.650	-
100	-	1.000	100	.906	1.000	100	.753	0.783
125	-	1.000	125	.928	1.000	125	.810	.914
150	-	1.000	150	.941	1.000	150	.846	.950
175	-	1.000	175	.951	1.000	175	.870	.969
200	-	1.000	200	.958	1.000	200	.889	.979
225	-	1.000	225	.963	1.000	225	.903	.985
250	-	1.000	250	.967	1.000	250	.914	.989
275	-	1.000	275	.971	1.000	275	.923	.992
300	-	1.000	300	.974	1.000	300	.931	.993
Hot water temperature calculation not possible.			Hot water temperature calculation not possible.			Temperature of unmixed hot water = 98°. Percent of cold water = 74.		
Spring No. 5S-40E-14bcc1S			Well No. 6S-41E-19baa1			Well No. 6S-1E-19bac1		
Surface temperature = 26° Silica = 33 mg/l Background silica = 25 mg/l Background temperature = 15° Boiling temperature = 93°			Surface temperature = 42° Silica = 28 mg/l Background silica = 25 mg/l Background temperature = 15° Boiling temperature = 93°			Surface temperature = 41° Silica = 30 mg/l Background silica = 25 mg/l Background temperature = 15° Boiling temperature = 93°		
T	X_t	X_{Si}	T	X_t	X_{Si}	T	X_t	X_{Si}
75	0.817	-	75	0.550	-	75	0.567	-
100	.871	0.652	100	.683	0.870	100	.694	0.783
125	.900	.862	125	.755	.948	125	.764	.914
150	.919	.920	150	.801	.970	150	.809	.950
175	.932	.950	175	.833	.981	175	.840	.969
200	.942	.967	200	.857	.987	200	.862	.979
225	.949	.976	225	.875	.991	225	.880	.985
250	.955	.982	250	.889	.993	250	.894	.989
275	.960	.986	275	.901	.995	275	.905	.992
300	.964	.988	300	.912	.996	300	.915	.993
Temperature of unmixed hot water = 149°. Percent of cold water = 91.			Temperature of unmixed hot water = 93°. Percent of cold water = 67.			Temperature of unmixed hot water = 96°. Percent of cold water = 67.		

Well No. 6S-41E-19bab1

Surface temperature = 41°
 Silica = 30 mg/l
 Background silica = 25 mg/l
 Background temperature = 15°
 Boiling temperature = 93°

T	X _t	X _{Si}
75	0.567	-
100	.694	0.783
125	.764	.914
150	.809	.950
175	.840	.969
200	.862	.979
225	.880	.985
250	.894	.989
275	.905	.992
300	.915	.993

Temperature of unmixed hot water = 96°.
 Percent of cold water = 67.

Spring No. 7S-41E-34baa1S

Surface temperature = 12°
 Silica = 34 mg/l
 Background silica = 25 mg/l
 Background temperature = 15°
 Boiling temperature = 93°

T	X _t	X _{Si}
75	-	-
100	-	0.609
125	-	.845
150	-	.910
175	-	.944
200	-	.962
225	-	.974
250	-	.980
275	-	.985
300	-	.987

Hot water temperature calculation not possible.

Spring No. 8S-41E-36dda1S

Surface temperature = 10°
 Silica = 84 mg/l
 Background silica = 25 mg/l
 Background temperature = 15°
 Boiling temperature = 93°

T	X _t	X _{Si}
75	-	-
100	-	-
125	-	-
150	-	0.410
175	-	.631
200	-	.754
225	-	.826
250	-	.871
275	-	.900
300	-	.912

Hot water temperature calculation not possible.

Well No. 9S-41E-12add1

Surface temperature = 28°
 Silica = 35 mg/l
 Background silica = 25 mg/l
 Background temperature = 15°
 Boiling temperature = 93°

T	X _t	X _{Si}
75	0.783	-
100	.847	0.565
125	.882	.828
150	.904	.900
175	.920	.938
200	.931	.958
225	.940	.971
250	.947	.978
275	.953	.983
300	.958	.985

Temperature of unmixed hot water = 154°.
 Percent of cold water = 90.

Spring No. 9S-42E-14aad1S

Surface Temperature = 5°
 Silica = 75 mg/l
 Background silica = 25 mg/l
 Background temperature = 15°
 Boiling temperature = 93°

T	X _t	X _{Si}
75	-	-
100	-	-
125	-	0.138
150	-	.500
175	-	.688
200	-	.792
225	-	.853
250	-	.890
275	-	.915
300	-	.925

Hot water temperature calculation not possible.

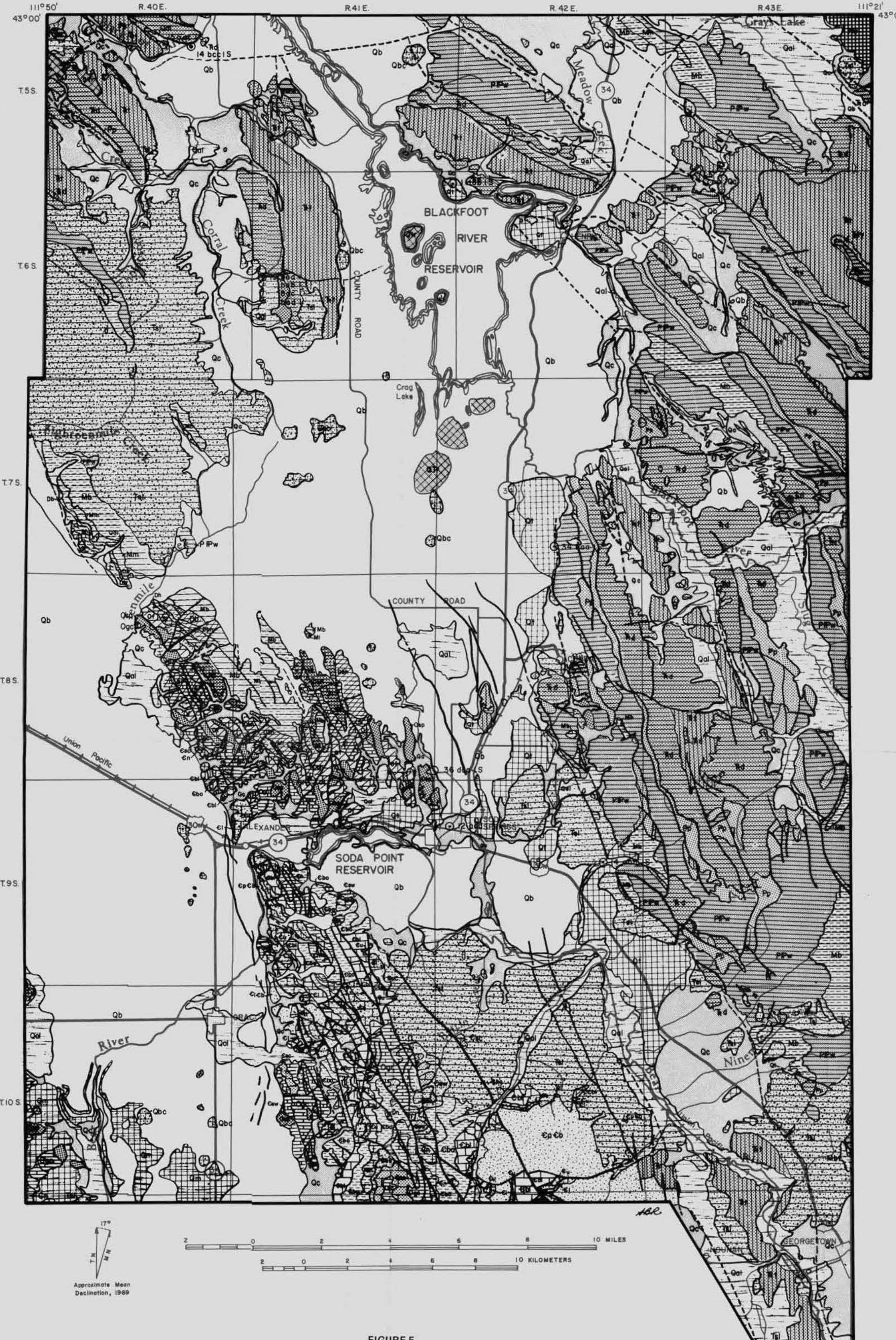


FIGURE 5
GEOLOGIC MAP OF THE BLACKFOOT RESERVOIR AREA, CARIBOU COUNTY, IDAHO

Modified from
Don R. Mabey and Steven S. Oriel
Department of the Interior
United States Geological Survey
Professional Paper 646-E
1970

EXPLANATION

Quaternary

Holocene

Pleistocene

Pliocene

Tertiary

Cretaceous

Jurassic

Triassic(?) and Jurassic(?)

Triassic

Permian

Pennsylvanian

Mississippian

Carboniferous

Unconsolidated gravel, sand, and mud.

Colluvium
Includes hillwash, talus, loess, and alluvium in tributary valleys.

Tufa
Porous to spongy white, buff, and yellow calcium carbonate.

Basaltic cinders

Basalt
Dark finely to medium crystalline vesicular, porphyritic, and coarsely crystalline massive olivine basalt. Maximum observed thickness about 90 meters.

Main Canyon Formation of Bright (1967)
Poorly consolidated to unconsolidated silt and marl grading into sand and gravel near valley margins. Maximum thickness exceeds 180 meters.

Rhyolite

Salt Lake Formation
Very light gray to white poorly consolidated tuffaceous calcareous siltstone, claystone, sandstone, and conglomerate. About 300 meters thick.

Wayan Formation
Red calcareous mudstone and red, buff, and white sandstone and conglomerate. Several (undetermined) hundred meters thick.

Gannett Group

Kgu, upper part. Includes an upper unnamed red mudstone and siltstone unit, a middle thin- to medium-bedded aphanitic gray limestone (Draney Limestone), and a lower conglomeratic unit (Bechler Conglomerate) of red and white conglomerate and sandstone and red mudstone. About 600-910 meters thick.

Kg, lower part. Includes medium to massive beds of pale-gray and pastel aphanitic limestone (Peterson Limestone) and red conglomerate, red and tan sandstone, and purple, red, and green mudstone (Ephraim Conglomerate). About 365-600 meters thick.

Stump Sandstone and Preuss Redbeds
Gray, white, and pale-green calcareous sandstone, quartzite, and sandy limestone, underlain by purplish-red and maroon siltstone and fine-grained sandstone. About 300-600 meters thick.

Twin Creek Limestone
Gray to dark-gray thin- to medium bedded silty to shaly limestone. About 750-1500 meters thick.

Nugget Sandstone
Tan, pink, and red quartzitic and partly calcareous sandstone; weathers mainly to brown manganese-oxide-coated talus. About 275-485 meters thick.

Ankareh Formation
As mapped includes Wood Shale Tongue of Ankareh Formation, Deadman Limestone, and Higham G. Consists mainly of red siltstone and mudstone. About 60-150 meters thick.

Thaynes Limestone

Timothy Sandstone Member; gray to olive-gray fine- to coarse-grained calcareous sandstone. About 75-300 meters thick.

agillaceous and silty limestone, calcareous muddy siltstone, and calcareous sandstone. About 760-975 meters thick.

Dinwoody Formation
Light grayish-brown to olive-brown claystone, gray limestone, and brown- to black-weathering siltstone. About 300-600 meters thick.

Phosphoria Formation and associated rocks
Mainly cherty mudstone, phosphatic mudstone, chert, phosphorite, limestone, and dolomite. About 130-170 meters thick.

Wells Formation
Sandstone, mainly quartzitic but partly calcareous, fine to very fine grained; limestone and dolomite; includes some red mudstone near base assigned to the Amsden Formation farther east. 450-600 meters thick.

Brazier Limestone of Mansfield (1927)
485-600 meters thick.

Madison Limestone
Thin- to medium-bedded cherty fine-grained to coarsely bioclastic limestone. 200-300 meters thick.

Beirdneau Formation
Gray, tan, pink silty and andy limestone and calcareous sandstone, and gray to dark-gray limestone and dolomite. 125-260 meters thick.

Hyrum Dolomite
Dark blue-gray, brown-weathering, petroliferous smelling laminated dolomite and light-gray dolomite with interbeds of limestone. 120-500 meters thick.

Beirdneau Formation and Hyrum Dolomite undifferentiated.

Laketown Dolomite
Very light to medium gray, white-weathering, medium- to thick-bedded dolomite. 150-300 meters thick.

Fish Haven Dolomite
Dark-gray, brown-weathering, fetid thin- to medium-bedded dolomite. 150-300 meters thick.

Iwan Peak Quartzite
Well-sorted very fine to fine grained medium-bedded to massive quartzite. 150-365 meters thick.

Garden City Limestone
Medium-gray dolomite and dark-gray chert in upper part, grading downward to dark-gray thin- to medium-bedded limestone with bioclastic, oolitic, and intraformational conglomeratic beds. 350-410 meters thick.

St. Charles Limestone

Cac, upper part. Light- to medium-gray and brown dolomite and dark-gray limestone. 210-275 meters thick.

Csw, Worm Creek Quartzite Member. Light-gray vitreous quartzite and white to pink quartzitic arkose with interbedded light- to medium-gray dolomite. 60-75 meters thick.

Nounan Limestone
Medium- to light-gray dolomite and dark-gray silty limestone and intraformational limestone conglomerate. 210-320 meters thick.

Boomington Formation
Shaly micaceous green mudstone and claystone with interbeds and nodules of pastel aphanitic limestone and oolitic and intraformational conglomeratic limestone. About 300 meters thick.

Hacksmith Limestone
Medium-gray to buff medium- to thick-bedded limestone, partly oolitic and partly silty. 230-290 meters thick.

Rocks in the Bancroft area

Cbn, upper limestone unit. Thin- to medium-bedded medium-gray partly silty and noddled limestone. 150 meters thick.

Cib, middle shale unit. Mainly green, partly dark-gray to black, mudstone and light- to medium-gray limestone. 120 meters thick.

Ctk, lower limestone and quartzite unit. Medium- to dark-gray medium- to thick-bedded oolitic and Girvanella-bearing limestone, and brown-weathering porous sandstone and green quartzite interbedded with limestone in lower part. 180 meters thick.

Ute Limestone and Langston Formation

Cu, Ute Limestone. Thin-bedded light- to bluish gray argillaceous partly oolitic limestone; partings and interbeds of green shaly claystone. 250 meters thick.

Cl, Langston Formation. Light-gray coarsely crystalline dolomite, weathering brown to reddish brown, that grades laterally into units of dark-gray partly oolitic limestone and green and dark-gray claystone. 75-180 meters thick.

Brigham Quartzite
Mainly light-gray to tan and green very poorly sorted partly conglomeratic quartzite with units of tan, green, and brown argillite; grades downward into purple quartzite. More than 760 meters thick; base not exposed in area.

Contact
Dotted where concealed.

Fault
Dotted where concealed.

Cones and collapse depressions in basalt.