MONTANA STATE UNIVERSITY

Geology and hydrology of hot springs in the Jefferson Valley, Montana
by Daniel Peter OHaire

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Earth Science
Montana State University
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Abstract:
This report discusses the origin of Silver Star, Renova, Pipestone and New Biltmore hot springs in the upper Jefferson Valley of southwest Montana. Thermal water circulation was examined using geologic mapping, geochemical sampling, and shallow resistivity and seismic data.

Cold meteoric water is believed to circulate by hydrothermal convection to depths of 2 or 3 km in fractured crystalline rock or deeply buried aquifers where it warms to the temperature of the local geothermal gradient. The hot water ascends rapidly to the surface in fault zones or aquifers. A regionally high heat flow and geothermal gradient, in combination with numerous high angle faults with significant vertical permeability, provide a setting where hydrothermal convection may develop. Cenozoic block faults bound the valleys, which contain thick sequences of Tertiary basin fill.

The geothermal gradient may be increased locally by the blanketing effect of relatively low thermal conductivity basin fill.

Geothermal potential of the hot spring systems in the upper Jefferson Valley appears to be limited because of low estimated base temperatures, probable small reservoir capacity, and the prohibitively high cost of drilling and extraction. The present use of the hot waters for space heating and bathing is appropriate.

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Date Dec 14, 1977

GEOLOGY AND HYDROLOGY OF HOT SPRINGS IN THE JEFFERSON VALLEY, MONTANA

by

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A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

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ABSTRACT

This report discusses the origin of Silver Star, Renova, Pipestone and New Biltmore hot springs in the upper Jefferson Valley of southwest Montana. Thermal water circulation was examined using geologic mapping, geochemical sampling, and shallow resistivity and seismic data.

Cold meteoric water is believed to circulate by hydrothermal convection to depths of 2 or 3 km in fractured crystalline rock or deeply buried aquifers where it warms to the temperature of the local geothermal gradient. The hot water ascends rapidly to the surface in fault zones or aquifers. A regionally high heat flow and geothermal gradient, in combination with numerous high angle faults with significant vertical permeability, provide a setting where hydrothermal convection may develop. Cenozoic block faults bound the valleys, which contain thick sequences of Tertiary basin fill. The geothermal gradient may be increased locally by the blanketing effect of relatively low thermal conductivity basin fill.

Geothermal potential of the hot spring systems in the upper Jefferson Valley appears to be limited because of low estimated base temperatures, probable small reservoir capacity, and the prohibitively high cost of drilling and extraction. The present use of the hot waters for space heating and bathing is appropriate.

CHAPTER 1

INTRODUCTION

Objectives and Procedure

This paper discusses the origin of hot springs in the upper Jefferson Valley, Montana. The thermal springs of the upper Jefferson Valley are of interest because of a regional concentration of hot springs and because the area lies astride a north-south trending line of hot springs in a deep and narrow valley along the eastern margin of the Boulder batholith. Silver Star and Renova hot springs received detailed attention while Pipestone and New Biltmore hot springs were the objects of brief reconnaissance.

A primary objective of this investigation was the establishment of a pattern for the circulation of thermal water. A preliminary assessment of the geothermal potential of the upper Jefferson Valley was a secondary objective. Conclusions are based on field evidence and a review of the scientific literature.

Geologic maps of the Silver Star and Renova areas were prepared. In addition, shallow subsurface geophysical investigations were conducted in the two areas. Dr. Robert Leonard of the United States Geological Survey investigated the geochemistry of these and other hot springs.

Location and Physiography of Study Area

Field investigations for this report were confined to the upper Jefferson River Valley, Montana, and adjacent hills between Pipestone and Twin Bridges, a distance along the valley of about 40 km (Fig. 1). The valley may be viewed in profile from Interstate 90 near Whitehall. The Tobacco Root Mountains border the valley on the east; the mountain front rises abruptly in a nearly straight line from the valley. The Highland Mountains rise gently on the west.

An alluvial fan complex slopes from the mountains to the valley. Hidden under the fan complex is a range front fault along which the mountains were uplifted and the valley dropped down. The upper Jefferson River meanders north through the valley along the edge of the alluvial fan to join the Missouri River at Three Forks, Montana.

Gullies have formed on the fan complex. During the Oligocene and Phiocene, a deposition dominated over erosion and the fan complex achieved a great size (Thornbury, 1965). In the Quaternary, erosion has exceeded deposition. Lesser cycles of deposition and erosion account for smaller features such as benches.

The physiography is similar in many ways to the block faulted terrain of the Basin and Range province. Block faulting, erosion, and deposition have worked to create the landscape which we see today. If not for the intervening Snake River Plain and differences of climate, the upper Jefferson Valley and adjacent parts of southwest Montana

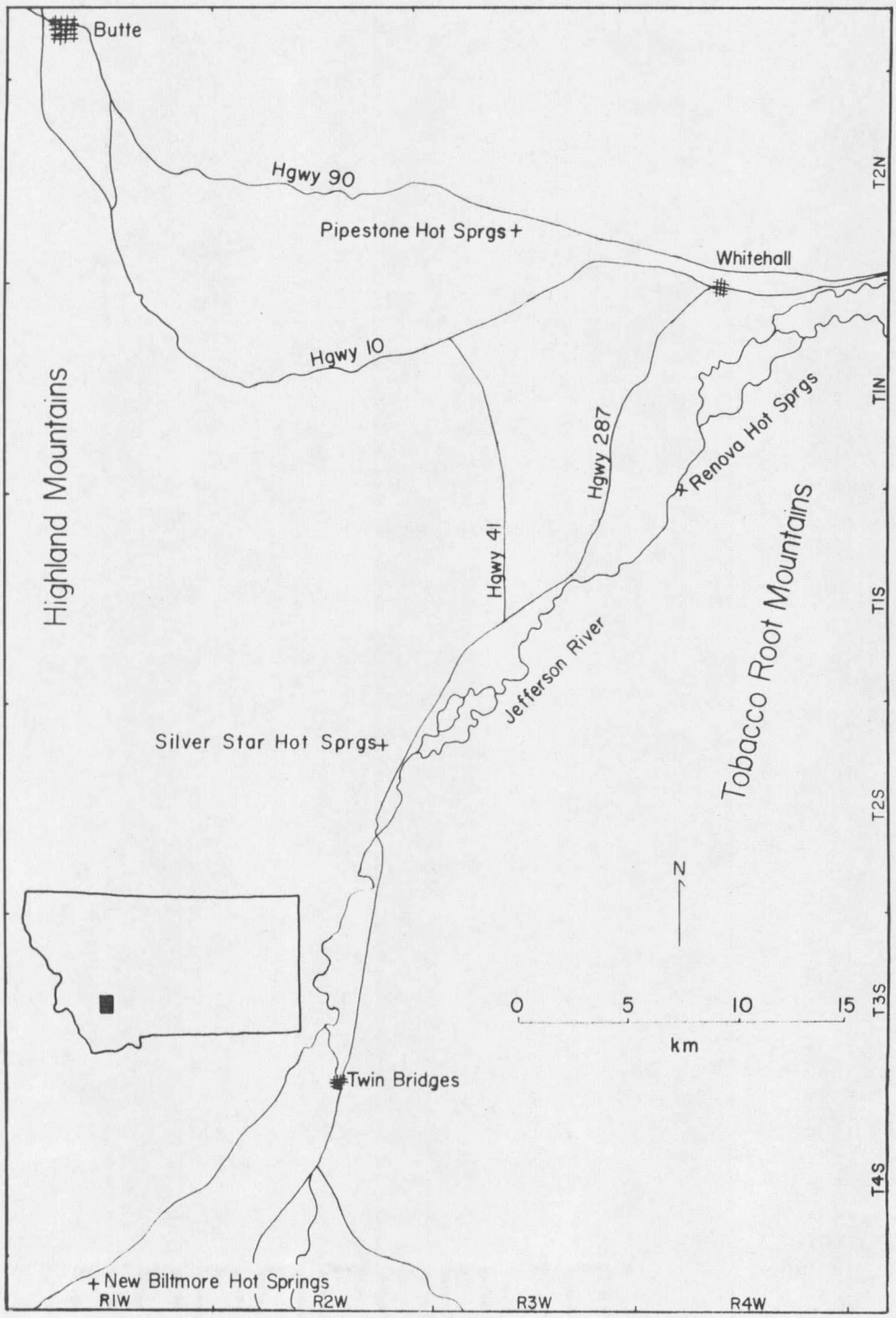


Figure 1. Index Map Showing Location of Hot Springs Studied and Geographic Features.

might well be included in the Basin and Range physiographic province. The relationship can be seen on the geologic map of the United States. That "army of caterpillars marching north out of Mexico" (first described by Fenneman, 1931) can be seen to project under the Snake River Plain and into southwest Montana.

The climate of the upper Jefferson Valley is temperate and semi-arid. Average annual precipitation is 25-35 cm. The temperature varies from an average of -7°C in January to an average of 18°C in July. The adjacent mountain ranges are cooler and receive more moisture than the valley. Elevations range from about 1500 m on the valley floor to 3000 m on the mountain peaks.

The most important economic activity in the upper Jefferson Valley is agriculture. Ranchers raise cattle and feed crops such as hay and alfalfa.

Previous Investigations

Tansley, Schafer and Hart (1933) discussed the structural geology and geologic history of the Tobacco Root Mountains and vicinity. Their work still serves as a good general reference for the area. Later reports on the northern Tobacco Root Mountains and vicinity include papers by Reid (1957) and Schmidt (1975). Berg (1959) in a masters thesis described the geology of the area around Renova Hot Springs. The geology of the Jefferson Valley was

investigated by Kuenzi and Fields (1971). Their work was based on the Tertiary stratigraphy and paleontology.

Geophysical investigations of the basin fill include a regional gravity survey by Burfeind (1967), a seismic study by Wilson (1962) and a resistivity study by Malik (1977) in the vicinity of Silver Star Hot Springs. Localized shallow seismic and d.c. resistivity surveys were conducted by Montana State University personnel (1976 and 1977, unpublished data) near Silver Star and Renova hot springs. A soil temperature survey was conducted by M.S.U. personnel at Silver Star in 1975.

The Highland Mountains and its mining districts were described by Sahinen (1950). Fritzche (1935) and McMillan (1939) reported on the geology of the Silver Star Mining District in masters theses.

The Boulder batholith was described by Pinckney (1958), Hamilton and Myers (1967) and Klepper, Robinson and Smedes (1971).

Hot springs in southwest Montana have been the subject of reports by Williams (1971), on the Bearmouth area, and Struhsacker (1976), on the Gardiner area; Kaczmarek (1974) reported on the geochemistry of selected hot springs, and Galloway (1977) investigated the circulation of hot water in fractured crystalline rock.

The geochemistry and structural controls of selected Montana hot springs were discussed by Chadwick and Kaczmarek (1975). Geochemical data on Montana thermal springs has been provided by White and

Williams (1975), Mariner and others (1976), Leonard (unpublished) and others of the U.S. Geological Survey.

CHAPTER 2

GENERAL PRINCIPLES OF HOT SPRINGS

In order to decipher the pattern of thermal circulation and to assess the geothermal resource, an understanding of basic hot spring principles is required. A discussion of hydrothermal convection and of the probable heat source is presented here for the reader.

Hydrothermal Convection Systems

In a hydrothermal convection system, heat is transferred primarily by the convection of water or steam, rather than by conduction through solid rock. In Fig. 2, heated water rises buoyantly because it is less dense while cooler; more dense water sinks to take its place.

Most hydrothermal convection systems are believed to contain liquid water rather than steam as the dominant pressure-controlling fluid (Renner, White and Williams, 1975). In these systems, water transfers most of the heat. Some vapor may be present, however, as bubbles in the more shallow parts of the system.

Surface temperatures of hot springs generally do not exceed the boiling point of water, which is 100°C at sea level and slightly less at higher elevations. An exception is a group of springs in Yellowstone National Park which are superheated by 1° to 2°C. Nearly all hot springs in Montana have surface temperatures below 80°C.

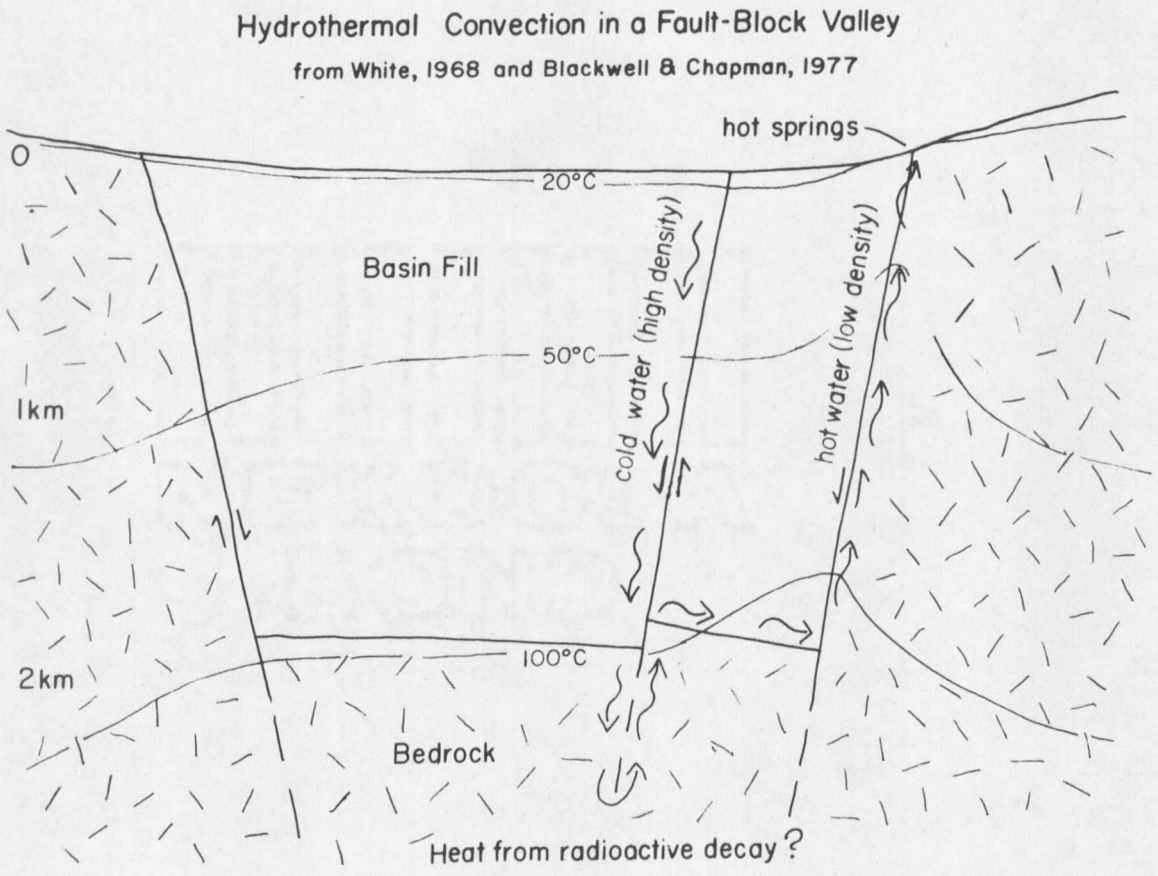


Figure 2. Hypothetical Cross Section Showing Hydrothermal Convection in a Fault-block Valley.

Density differences are the principal driving force in a hydrothermal convection system and are nearly all due to the thermal expansion of water. Density differences due to compaction by pressure are no greater than 1%, and the presence of 2500 ppm dissolved solids will increase the density of water by approximately 0.2%. These density differences are slight compared to the thermal expansion of water; pure water at 50°C is 6% more dense than water at 150°C (White, 1968).

Piezometric head may be present in a hydrothermal convection system in addition to thermal density differences and may provide additional driving force to the system. If recharge occurs at a higher elevation than discharge, piezometric head will be present. This is important to systems within folded structures on the flanks of mountains. Here, water recharging permeable rock formations in uplands flows down through the rock under the force of gravity.

Seeps and springs are the principal way to detect hydrothermal convection systems but do not necessarily accompany all of them. Other convections systems probably exist undetected at depth; discovery awaits more sophisticated exploration techniques. A convection system might not discharge water at the surface if overlying impermeable rocks denied outlet; dilution by cold surface water could also mask a thermal seep.

Source of Heat

The Geothermal Gradient

If we know precisely the value of the geothermal gradient, then we may predict the temperature of the rocks at any specific depth. At present, only a rough approximation of the geothermal gradient in Montana is available, because it varies from place to place and few measurements have been taken. Values in river valleys are indeterminate because of perturbations caused by the movement of ground water. Based upon a few scattered measurements, mostly in granitic rock, a value of 30°C / km is employed for southwest Montana (Blackwell, 1969).

The geothermal gradient is related to crustal heat flow and the thermal conductivity of the rock as expressed in the following equation:

geothermal gradient = heat flow/thermal conductivity

For a given heat flow, the geothermal gradient will be higher in low thermal conductivity rocks. In general, poorly consolidated valley fill has a lower thermal conductivity than bedrock. The geothermal gradient is, therefore, expected to be higher in the valley fill than in the bedrock.

Blackwell and Chapman (1977) have modeled a block faulted valley where the valley fill has a relatively low thermal conductivity and

the surrounding bedrock a relatively high thermal conductivity. A typical Basin and Range heat flow of 2.0 microcalories per cm^2 per sec (H.F.U.) is employed (Blackwell, 1969). The thermal gradient is calculated to be 29°C / km in the bedrock and 57°C / km in the valley fill. The presence of a valley margin hydrothermal convection system causes heating of near surface rocks by ascending thermal water and a consequent local increase in the geothermal gradient (Fig. 2).

The geothermal gradient and heat flow of western Montana are somewhat greater than the world average. The region lies within a zone of abnormally high heat flow known as the Cordilleran Thermal Anomaly with an average conductive heat flow of 2.2 H.F.U. (Blackwell, 1969; Blackwell and Robertson, 1973). The zone includes the Basin and Range and much of Montana and Idaho. This is greater than the worldwide average heat flow of 1.5 H.F.U. (Lee and Uyeda, 1965).

If the high regional heat flow is viewed in combination with the regional tectonic framework, then it is possible to postulate a mechanism which logically will account for the large number of hot springs in southwest Montana. Thermal waters employ fault zones as conduits and acquire their elevated temperatures primarily by conduction of heat from hot rocks two or more kilometers deep.

Negative Evidence for Magmatic Heat Source

Hot igneous bodies at depth have been cited as a source of heat for hot springs elsewhere (Smith and Shaw, 1975). With the exception of hot springs in and near Yellowstone National Park and the Snake River Plain, hot springs in Montana probably do not derive their heat from a shallow magmatic source.

Two types of evidence support this line of reasoning. First is the absence of recent volcanism. Geothermal resource areas with high (greater than 200°C?) base temperatures are often associated with recent volcanism and associated magma at depth (Smith and Shaw, 1975). Quaternary volcanism, with the exception of Yellowstone and the Snake River Plain, is not present in Montana (Smith and Shaw, 1975). On the other hand, older Tertiary volcanics are common in the region. Whether there is residual heat from Tertiary volcanism is uncertain, but it seems unlikely that it would contribute significantly to the region's geothermal resource. Smith and Shaw, 1975, estimate that the heat from a 10 km thick magma chamber would dissipate within 10 million years.

Second, the close grouping of estimated geothermal aquifer temperatures argues against the presence of igneous heat sources (Chadwick and Kaczmarek, 1975). Igneous bodies of different sizes and degrees of cooling, intruded into different levels of the crust,

would probably impart greatly different temperatures to thermal waters associated with them.

Heat Production by Radioactive Decay

Radioactivity from an underlying granitic mass may account in part for the regionally high heat flow, in particular near the Boulder batholith. Fehn and Cathles (1976) have calculated the heat generated by radioactivity in a pluton similar to the Conway Granite of New Hampshire (thickness 7 km, diameter 33 km, top 3 km below the surface). In their model, the country rock is assumed to generate no heat, while the heat generation rate of the pluton is 20×10^{-3} cal / cm^3 / sec (20 H.G.U.). Surface heat flow above the center of the pluton is 2.3 H.F.U. and above the edge of the pluton it is 1.8 H.F.U. The authors conclude that "A mass of water equal to the mass of the intrusive is convected through the intrusive in 60×10^6 years if the permeability is 0.05 md and in 13×10^6 years if the permeability is 0.5 md." These calculations indicate that abnormal radioactivity, if present, may contribute significantly to the occurrence of hydrothermal convection systems within and adjacent to a granitic pluton.

A study of the Idaho batholith (Swanberg, 1972) suggests that heat generation in a pluton decreases exponentially with depth. If this is so, then values for the Boulder batholith based only on surface measurements may be somewhat overestimated.

Granitic intrusive rocks may underlie much of southwest Montana. The Idaho, Boulder and Tobacco Root batholiths are exposed over large areas and are probably even more extensive at depth. These intrusives are mostly of late Cretaceous and early Tertiary age and share a similar composition. If they are derived from a common parent magma, then granitic rocks may underlie the areas between and even adjacent to these batholiths. Burfeind (1967) concludes on the basis of a regional gravity survey that granitic rocks underlie much of southwest Montana at depths ranging from approximately 5,000 to 10,000 m. He suggests that mountain ranges such as the Madison, Bridger, Gallatin and Ruby ranges may have granitic cores at depth. This hypothesis might be tested by a survey of heat flows to determine if the area thought to be underlain by granitic rock demonstrates a higher heat flow than adjacent areas.

Measurements of heat production in the Boulder batholith range from 7.0 to 15.2 H.G.U. in the volumetrically predominate younger rocks of the pluton (Tilling and Gottfreid, 1969). This represents a contribution to the regionally high heat flow and may account at least in part for the concentration of hot springs in the region. Roy, Blackwell and Decker (1972) determined that the average measured heat flow for the Boulder batholith is 1.98 H.F.U., with about 0.6 H.F.U. derived from radiogenic decay in the crust and about 1.4 H.F.U.

derived from the mantle. The presence of abandoned uranium mines in the area further supports this idea.

The line of hot springs along the eastern margin of the Boulder batholith may be due in part to heat produced by radioactive decay. From north to south, Helena, Alhambra, Boulder, Pipestone and Silver Star hot springs lie along the eastern margin of the Boulder batholith.

In conclusion, the hot springs in the study area probably do not derive their heat from hot magma or cooling igneous rock. Instead, deep circulation of meteoric water by hydrothermal convection in a region characterized by Cenozoic faulting and a regionally high geothermal gradient may account for the hot water.

CHAPTER 3

THERMAL SPRINGS OF SOUTHWEST MONTANA

Montana is characterized by an unusual concentration of thermal springs, with nearly 70 springs discharging water hotter than 20°C. About 25 of these are above 38°C and can be considered "hot" springs. Compared to the worldwide average, this concentration is unusually high.

Oxygen isotope data suggest that the spring waters are meteoric (Mariner, Presser and Evans, 1976). This argues against the possibility that the waters are juvenile.

Kaczmarek (1974) concluded that the geothermal aquifer temperatures of Montana thermal springs, based on silica and Na-K-Ca thermometry, fell into two categories, which he described as follows:

> The low-temperature group of base temperatures averages 20°C and usually results from circulation in shallow structures on the flanks of uplifts. The high temperature group of base temperatures averages 100°C to 120°C and results from deep circulation in major faults or in deep regional structures.

The concentration of hot springs in southwest Montana is an order of magnitude greater than that of northwest Montana, which is also mountainous. This probably reflects the different tectonic settings of the two regions. Northwest Montana is characterized by thrust faults and is dominated at the surface by Precambrian Belt sedimentary rocks. Southwest Montana contains numerous granitic

intrusions and Precambrian gneiss and has been undergoing more extensive block faulting in the Cenozoic (McMannis, 1965).

If the geothermal gradient is 30°C / km (see discussion on "Source of Heat"), and the mean annual temperature is 10°C, then at a depth of 3 km, rock will be at a temperature of 100°C. Faults, or possibly folds, may allow the circulation of water to that depth, where the water warms to the temperature of the host rock, 100°C. The hot water is buoyant and so rises to the surface by the most expedient route, commonly along a fault.

The thermal springs of southwest Montana may be classified according to the lithology of the aquifer. Following is a grouping modified from that used by Kaczmarek: 1) springs whose waters circulate at depth within fractured crystalline rock, 2) springs which issue from the Tertiary basin fill and 3) springs whose waters circulate within folded sedimentary rocks. The following three sections include a description of each type of hot springs in turn.

Thermal Springs in Crystalline Rock

A large number of hot springs in southwest Montana are known to issue from fractured crystalline rock. The crystalline rock may be either gneiss and schist or granitic intrusive.

Included in this category are Elkhorn, Gregson, Alhambra, Boulder, Broadwater and Potosi hot springs. Alhambra can be cited as typical.

Alhambra Hot Springs issues from fractures in the Boulder batholith where the Alhambra Fault crosses Warm Springs Valley. Hot water circulates in the fault zone and rising, emerges in the valley, issuing directly from joints in the quartz monzonite (Chadwick and Kaczmarek, 1975). A mechanism such as faulting is necessary to maintain permeability of the crystalline rock at depth by creation of a system of fractures (Galloway, 1977).

The waters of hot springs issuing from fractured crystalline rock are typically dilute. Surface discharge temperatures vary from 50 to 70°C. The waters are generally neutral to slightly alkaline. The principal dissolved constituents are sodium bicarbonate, silica and sulfate plus lesser amounts of calcium, magnesium, potassium chloride and fluoride. The chemistry of these waters is typical of ground water circulating in siliceous rocks. Reservoir storage capacity is probably restricted to fractures for these systems and consequently the geothermal potential is limited.

Thermal Springs in Basin Fill

A number of Montana hot springs discharge from gently tilted basin fill. Some springs issue from within a valley, while others

discharge along the valley margins. Wolf Creek, Pipestone, Warm Springs and Bozeman hot springs are examples of the first type. Renova and Silver Star are examples of the second type.

The basin fill from which the springs issue is underlain at depth by crystalline or sedimentary rock, where the water may reside before rising through the basin fill along recently active faults.

The basin fill is anisotropic to the flow of water. It is composed of coarse and fine layers which differ in their permeability. The more coarse or permeable layers have great permeability but the fine and relatively impermeable layers limit vertical permeability. The stratification works to limit the occurrence of hot springs in basin fill to zones where faults have created vertical permeability.

Unfortunately, the geothermal gradient is not well known for the basin fill due to a lack of deep wells for measurement and to perturbations of the geothermal gradient caused by the lateral flow of ground water. If the geothermal gradient were known more precisely then one could calculate on the basis of the gradient the expected temperature of water at the bottom of basin fill 2 km deep. Measurements in granitic rock of the Boulder batholith give a value of 30°C/km. The gradient in basin fill should be higher because thermal conductivities are lower (Blackwell and Robertson, 1973; see discussion on "Source of Heat"). The basin fill is in many

places 1 or 2 km deep and should be saturated with warm or hot water at those depths.

Reservoir storage capacity should be relatively large. Lenses and layers of coarse material confined and insulated by interbedded finer sediment might collectively comprise a geothermal reservoir.

Thermal Springs in Sedimentary Rock

A number of Montana thermal springs issue from folded sedimentary rocks. Some of these are lukewarm and probably represent circulation to a depth of perhaps 300 to 500 m within the carbonate aquifer. Water recharges in nearby highlands, then flows down-gradient, under head along the flank of the structure and emerges when it intersects the surface. Included in this category are Garrison, Lewistown, Big Warm, Little Rockies, Plunket and Bridger Canyon warm springs (Chadwick and Kaczmarek, 1975). These waters usually have a relatively high calcium content and are neutral to slightly acid, compared to springs in crystalline rock, which are neutral to slightly alkaline and which contain less dissolved calcium and magnesium. The low pH of the springs is probably related to a high sulphate content.

Calculated base temperatures of the thermal springs in this category are generally lower but also more variable than for hot springs in crystalline rock.

Water from Hunters Hot Springs is thought to circulate in permeable sandstone formations at a depth of 1500 to 2500 m (Chadwick and Kaczmarek, 1975). The springs occur along calcite-stilbite veins where they intersect the axis of the Hunters anticline. The water rises along the fracture zone under head after circulating at depth in the permeable sandstones where they are affected by the geothermal gradient and warmed.

Thermal springs in the Bearmouth area issue from carbonate rocks after circulating in a major fold on the flank of a mountain. Meteoric ground waters infiltrate the carbonate aquifer in high recharge areas, then percolate down along the flank of the fold until encountering the permeable fault zone of the Bearmouth thrust. There they rise to the surface under thermo-artesian head (Williams, 1975).

Struhsacker (1976) described the Corwin Springs-Gardiner (La Duke) hot spring system which is located immediately north of Yellowstone National Park. He speculated that hot water rises along the Gardiner fault zone after residing at 10,000 ft (3,000 m) depth in the Mission Canyon Formation. Water probably recharges in the limestone at the crest of the Gallatin anticline, 10-15 km to the southwest. Struhsacker speculated that some water may recharge where the fault zone intersects the surface, possibly water from the Yellowstone River.

CHAPTER 4

GEOLOGIC SETTING OF SOUTHWEST MONTANA

Precambrian, Paleozoic and Mesozoic sedimentary rocks were deposited upon Precambrian metamorphic rocks. During the Cretaceous Laramide orogeny, these sedimentary rocks were deformed. Deformation was accompanied by the intrusion of granitic batholiths and volcanism. In the Cenozoic, block faulting was accompanied by the accumulation of a great thickness of basin fill. Distribution of major geologic units is shown in Fig. 3.

Sedimentary and Volcanic Rocks

Precambrian, Paleozoic and Mesozoic Rocks

The oldest rocks exposed in the study area are gneisses and schists of the Precambrian metamorphic complex. They are overlain in places by sedimentary rocks of the Precambrian Belt Series. Belt strata attain an overall thickness of up to 1500 m and include a coarse grained clastic sequence and a shale unit. Belt strata do not crop out in Montana south of a line passing 30 km south of Three Forks and 16 km south of Whitehall (Berg, 1959).

South of this line, Cambrian strata directly overlie the metamorphic rocks and include marine sandstone, shale, and limestone.

The Flathead Sandstone forms the base of the Cambrian sequence and lies on the Precambrian Belt rocks. The Flathead is a well

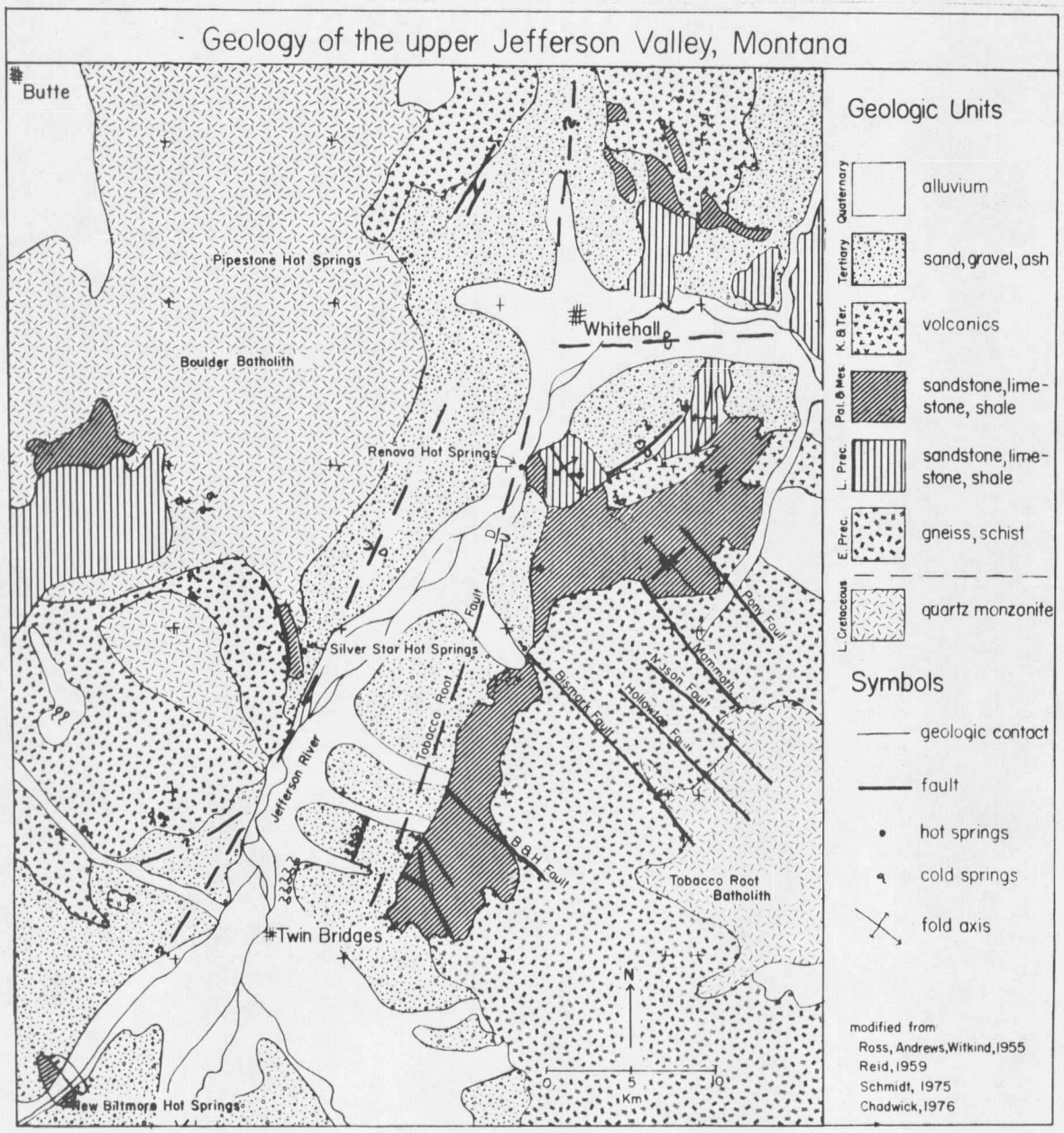


Figure 3. Geologic Map of the Upper Jefferson Valley, Montana.

cemented quartz sandstone. It weathers by breaking into blocks along joint planes. The Flathead forms a conspicuous ridge and is a convenient marker. The Wolsey Shale overlies the Flathead and forms a swale so that normally outcrops are poor. The Meagher Limestone overlies the Wolsey and forms two prominent ridges. The rock unit is about 200 m thick and may be recognized by its thickness and characteristic blue and gold mottling. Fossils are rare. The limestone is massive at the top and bottom but highly jointed and thin-bedded in the middle of the section. The massive portions form ridges and stand higher than the thin-bedded and more easily weathered middle section. Solution channels are plentiful in the Meagher Limestone. Some are aligned along joints. Calcite has been deposited in some of the joints and solution voids. If the solution features persist at depth, then the Meagher Limestone probably has sufficient permeability to serve as an aquifer. The Park Shale conformably overlies the Meagher Limestone and is "an olive green fissile shale with intercalated lenses of silty limestone and dolomite" (Berg, 1959). This formation is about 40 m thick in the area around Renova Hot Springs.

The Pilgrim Formation stratigraphically overlies the Park Shale and is a "light to dark gray, mottled dolomitic limestone." The Pilgrim Formation is about 140 m thick and forms a prominent ridge. The Red Lion Formation stratigraphically overlies the Pilgrim

Formation and is a "light to dark brown, thin-bedded, shaly sandstone with intercalated beds of dolomite and limestone." This unit is about 20 m thick and forms a swale. It corresponds to the Dry Creek Formation (Berg, 1959).

Devonian sedimentary rocks lie unconformably upon the Cambrian strata. They are exposed on both sides of the upper Jefferson Valley. The Devonian Jefferson Formation consists of limestone and dolostone and forms rounded ridges and knolls. The formation is a "light tan to brown to black, thin-bedded to massive, coarsely crystalline dolomitic limestone with minor amounts of chert," which averages about 600 m thick (Berg, 1959).

The Devonian Three Forks Formation is about 70 m thick and consists of limestone and purple and green shale. The weathered shale is brown and fragmented.

Mississippian and Pennsylvanian strata include marine limestone, sandstone and shale. The Mississippian Madison Group contains two limestone formations, the lower, thin-bedded Lodgepole Formation and the upper, massive Mission Canyon Formation. Each formation is over 200 m thick.

The Pennsylvanian Amsden Formation and Quadrant Formation overlie the Madison and consist of shale and quartz arenite, respectively.

The name "Elkhorn Mountain Volcanics" was first used by Klepper, Weeks and Ruppel (1957) to describe the thick sequence of volcanic

and sedimentary rocks in the Elkhorn Mountains. The formation is divided into lower, middle and upper members, each conformably overlying its predecessors; collectively they comprise as much as 2,000 m thickness. The Elkhorn Mountain Volcanics are late Cretaceous in age. They extend from the Elkhorn Mountains to the Boulder batholith on the west (Fig. 3).

Tertiary Basin Fill

Through the Paleozoic Era and into the Mesozoic, southwest Montana was characterized by low relief. Uplift during the late Cretaceous Laramide orogeny increased the relief as previously deposited sediments were folded. This episode of folding was followed by one of block faulting which persisted through the Tertiary and continues into the present. The accumulation of great quantities of sediment in the valleys accompanied the block faulting. The sediment consists of clay, silt, sand and gravel; in places volcanic ash is abundant.

The Tertiary basin fill has been assigned the name "Bozeman Group" which includes the Sixmile Creek Formation and the overlying Renova Formation. In the upper Jefferson Valley, these strata collectively are as much as 2000 m thick and tilt gently to the east (Kuenzi and Fields, 1971).

The Sixmile Creek Formation is composed of coarse grained material deposited by relatively high energy streams. The formation is a conglomerate near the basin margin, and in the more central parts of the basin it is commonly a pebbly arkose, volcanic arenite, or conglomerate. Total thickness ranges from 0 to 1000 m (Kuenzi and Fields, 1971).

The Renova Formation is primarily Oligocene and includes in upward order the Dunbar Creek, Bone Basin and Climbing Arrow members. The relatively fine grained strata of the Renova Formation were deposited in a low-energy floodplain. The strata range in thickness from 0 to 1000 m and pinch out at the basin's margin (Kuenzi and Fields, 1971).

The strata of the Bozeman Group have been displaced along the Tobacco Root fault. North of Renova, a displacement of 2000 m is suggested (Kuenzi and Fields, 1971).

The most recent sediments in the upper Jefferson Valley are Quaternary alluvium. They overlie and are derived from older strata and sediments upstream. Most of the deposits are near the present river course.

A prominent negative gravity anomaly is associated with the Upper Jefferson Basin. Interpretations of gravity data show an asymmetric pre-basin fill configuration for the valley. The fill is about 1.6 km thick on the eastern side and thins gradually to the west (Burfeind,

1967). According to Burfeind, thickness of the basin fill between Silver Star and Twin Bridges ranges from 1500 to 1700 m. This value is consistent with the findings of Kuenzi and Fields (1971). The basin fill is interpreted to thin slightly to 1300 m near Whitehall and to thicken to more than 2000 m near Twin Bridges.

These values are supported in part by seismic data and drill-hole information. Seismic depth soundings east of Silver Star show a minimum depth of 300 m for the basin fill (Wilson, 1962). A little further south near Twin Bridges, a well (Sec 19, T3S R5W) encountered only Tertiary material to a depth of 780 m. These observations place a minimum value upon the thickness of the basin fill.

The presence of steep gravity gradients on the east side of the basin suggests a fault. The gradients, as large as 24 milligals per kilometer, are linear and closely parallel the mountain front (Burfeind, 1967).

The Tobacco Root range front fault may lie as much as 1.5 km west of the mountain front (Burfeind, 1967). Wilson (1962) indicated the presence of a shallow bedrock surface beneath the alluvium near the mountain front. It appears that deposition and erosion from the sides have widened the valley somewhat from the configuration produced by block faulting. A Tertiary pediment may underlie the gravels near the mountain front at a relatively shallow depth, extending west to where it is truncated by the Tobacco Root range front fault.

Intrusive Igneous Rocks

Intrusive igneous rocks form two major bodies in the study area, the Boulder and Tobacco Root batholiths (Fig. 3). These rocks are principally quartz monzonite and are described in the following sections.

Boulder Batholith

The shape of the Boulder batholith is controversial. Lawson (1914) suggested that the Boulder "batholith" was a laccolith. This idea was later refuted by Knopf (1914) and by Billingsly (1916). Grout and Balk (1934) similarly concluded that there was no evidence for a laccolithic form and that the body is "a batholith in almost every sense of the word." Cloos (1923) first suggested that the batholith had the shape of the number "7," with the shallow flat limb extending to the west. On the basis of a regional gravity survey, Burfeind (1967) described the batholith as "a tabular mass that dips gently northwest." Burfeind also suggested that the Boulder batholith is connected to the Tobacco Root batholith beneath the upper Jefferson Valley. Hamilton and Myers (1967) suggested a maximum thickness of 5 km for the batholith. However, Klepper, Robinson and Smedes (1971) concluded that it has steep contacts on all sides and is at least 15 km thick.

Tilling, Klepper and Obradovich (1968) reported on the basis of K-Ar dates that emplacement occurred between 78 and 68 million years ago during the late Cretaceous.

The batholith contains at least 15 separate plutons, but 75 to 80 percent of the exposed area consists of a single large pluton, mostly of quartz monzonite or granodiorite composition. The units become progressively more felsic with time. Late stage felsic dikes crosscut the main body of quartz monzonite.

Tobacco Root Batholith

The Tobacco Root batholith is a large body of quartz monzonite exposed over 300 square km in the central part of the Tobacco Root Mountains (Tansley, Schafer and Hart, 1933). It is elongated in a northwest direction with several small outliers distributed around it (Fig. 3).

The Tobacco Root batholith is probably derived from the same parent magma as the Boulder batholith. Quartz monzonite outliers in Bear Gulch are only about 10 km from the eastern margin of the Boulder batholith. Furthermore, quartz monzonite from the two batholiths is petrographically similar, and age dating demonstrates that the two intrusives were emplaced contemporaneously in late Cretaceous time, about 75 million years ago (Gilletti, 1966).

If both batholiths are derived from the same parent magma, then it is possible that granitic rock underlies the upper Jefferson Valley at a comparatively shallow depth. This hypothesis is supported by the conclusions of Burfeind (1967, p. 29):

> The southeastern portion of the Boulder batholith is interpreted to extend at a shallow depth southeastward for several kilometers beyond its exposed contact with the Jefferson Basin. This southeastern extension of the batholith terminates beneath the northern end of the Tobacco Root Mountains.

Tectonic History

Three major episodes of tectonic activity are recognized in the study area. These are (1) Precambrian, (2) Late Cretaceous (Laramide) orogenies and (3) Tertiary block faulting. Northwest trending high angle faults are prominent in the Tobacco Root Mountains (Fig. 3). These faults first moved during the Precambrian and continued to be active during the late Cretaceous Laramide Orogeny. During the Cenozoic, there has been uplift along north-south high angle faults at the valley margin.

Northwest Trending Faults

A swarm of northwest trending faults transects Precambrian metamorphic and Belt sedimentary rocks and younger granitic and sedimentary rocks in the Tobacco Root Mountains. Included are the B&H, Bismark, Mammoth, Pony, Elk Mountain, Hollowtop and Potosi faults

(Reid, 1957; Fig. 3, p. 23). These faults probably originated in Precambrian time and were reactivated during the Laramide orogeny. Perhaps the most compelling evidence for Precambrian movement is the apparent 7000 m offset of the Pony-Cherry Creek contact between the Bismark and Mammoth faults (Schmidt, 1975). Younger rocks appear to have lesser displacement. This observation assumes the validity of the questionable Pony-Cherry Creek distinction in the metamorphic rocks.

The Mammoth fault (Fig. 3) is named for the Mammoth Mine and is best exposed in the north valley wall of upper Mill Creek. The fault strikes N40° to 50°W and is believed to dip 70°S (Reid, 1957). Movement on the fault has raised the north block relative to the south block, and placed Precambrian metamorphic rocks in contact with the Cambrian Meagher Limestone.

The Bismark fault is named for the Bismark Mine and is well exposed near the Strawn Mine in lower Beall Creek. The fault is aligned with the Spanish Peaks fault which offsets rocks in the Madison Range to the southeast, and possibly extends to the Gardiner fault system near Yellowstone, a total distance of 160 km (Reid, 1957). The Bismark fault strikes N40° to 50°W and is believed to dip about 70°S. Movement along the fault has placed Precambrian metamorphic rocks in contact with the Cambrian Meagher Limestone. The fault can be traced

through the higher Tobacco Root Mountains as a rust colored zone about 200 m wide.

Emplacement of the Tobacco Root batholith was controlled at least in part by the faults. Tongues of magma followed the Mammoth and Bismark faults, but in other places the batholith appears to have intruded without regard to existing faults. Shear zones in the vicinity of Potosi Hot Springs suggest post-intrusion faulting of the batholith (Galloway, 1977).

Laramide Orogeny

Sedimentary rocks which had accumulated during the Paleozoic and Mesozoic were folded intensely during the Laramide orogeny in late Cretaceous time. The Tobacco Root Mountains today are flanked by sedimentary rocks which were folded during the Laramide orogeny into a broad symmetrical dome which has been called the "Tobacco Root anticlinorium." Schmidt (1975) described it as "the northernmost of a series of arches and depressions in the craton of southwest Montana." The structure has also been described as a "broad asymmetrical dome" or "doubly plunging anticline" (Tansley, Schafer and Hart, 1933, p. 19). The structure plunges northwest and passes from near Whitehall south to the crest of the Gravelly Range. Erosion has removed the top of the structure so that only portions of the limbs remain on the northern and western slopes of the range.

Superimposed on the Tobacco Root anticlinorium is a series of large northwest plunging folds in the Paleozoic and Mesozoic rocks (Schmidt, 1975). These folds apparently developed in response to the same Laramide compressional forces which shaped the Tobacco Root anticlinorium.

The Highland Mountains to the west are similarly flanked by Paleozoic and Mesozoic sedimentary rocks in the form of a dome, which has been eroded until only in the southeast and southwest do the limbs remain. A block of sedimentary rocks remains at Silver Star and is protected by the hanging wall of the Green Campbell fault. The strata were intensely folded and metamorphosed by heat from the batholith which borders on the northwest and northeast.

Cenozoic Block Faulting

Mountain ranges in southwest Montana are characterized by straight and abruptly rising fronts. These and other features, such as fault scarps and faceted spurs indicate block faulting. The faulting responsible for these features began in early Tertiary time, but was most intense during the Miocene. Minor faulting has continued to the present (Pardee, 1950).

The Tobacco Root range front fault is typical of the range front faults of southwest Montana. The Tobacco Root Mountains were uplifted on the east while the Jefferson Valley was dropped on the west.

Alluvial fans hide the fault from view but features attesting to its presence include a "regular base line, a steep and abruptly rising slope, and faceted spurs, the bases of which are aligned" (Pardee, 1950). The preservation of these features suggests that there has been significant fault movement in Pleistocene or Holocene time.

A range front fault has been postulated for the western margin of the upper Jefferson Valley, but no such fault has been positively located. Burfeind's gravity contours steepen at the margin, and suggest a fault, as do small and isolated outcrops of sheared and altered rock along the margin (SE1/4, Sec16, T4S, R7W; NW1/4, Sec24, T3S, R7W; SE1/4, Sec11, T2S, R6W).

CHAPTER 5

HOT SPRINGS IN THE UPPER JEFFERSON VALLEY

Silver Star, Renova, Pipestone and New Biltmore hot springs are located within the confines of the upper Jefferson Valley of southwest Montana. These springs are described in detail in this chapter.

Silver Star Hot Springs

Location and Appearance

Silver Star Hot Springs is located in a cow pasture about 300 m west of Barkell's Plunge near the town of Silver Star, Montana (N45°41'07", W112°17'42"). The springs discharge from gravels in a slight topographic depression. The spring is about 50 m above the Jefferson River, which lies about a km to the east. Nearby shallow wells tap the hot water and collect it in an underground tank. From the tank, the hot water is piped underground to the swimming pool in Silver Star.

Geology

The oldest rocks exposed at Silver Star Hot Springs are Precambrian gneiss, schist and amphibolite. Cambrian strata, which are prominently exposed elsewhere in southwest Montana, are not present (see geologic column in Fig. 4). Paleozoic and Mesozoic

strata have been folded, faulted and altered by heat from the Boulder batholith.

Sedimentary Rocks

The oldest sedimentary rock unit present is the Devonian Jefferson Formation. This carbonate unit is usually dolomitic. At Silver Star it is mostly limestone. The rock is coarsely crystalline and weathers to a yellow, sandy appearance. Fractures are abundant and are commonly filled with limonite and calcite.

A sequence of Paleozoic and Mesozoic sedimentary rocks overlies the Jefferson Formation and is listed in Fig. 4. These units are described in Chapter 4.

Slightly consolidated Tertiary alluvium is the youngest stratigraphic unit present near the hot springs. The unit is a few meters thick near the springs but thickens to a kilometer and more in the valley to the east. Collectively called the Bozeman Group, the beds are locally derived conglomerate with layers of sand, silt and ash.

A section of the Tertiary basin fill about 300 m north of the hot springs is impregnated with calcite and silica. Tunnels have been dug in the gravel in a search for opal and geodes. The silica and calcite may have been deposited by the hot water of a new extinct hot spring. The Galena fault in nearby carbonate rocks could have

served as a conduit for the water and the carbonate rock as a source for the dissolved solids (see Fig. 4).

For a discussion of the possible range front fault near Silver Star, see the section "Cenozoic Block Faulting."

Structure

The Paleozoic and Mesozoic sedimentary rocks at Silver Star are arranged in an asymmetrical overturned syncline adjacent anticline whose axes trend NE. The rocks form a NW-elongated block which averages 1500 m long and 500 m wide. Almost all of the exposed beds are on the same limb of the syncline. They dip about 30-40° to the south or southwest, with the exception of the beds on the overturned portion of the limb (Figs. 4 and 5). The overturned beds are exposed in the northwest corner of the structure. Here the Jefferson Formation, Three Forks Shale and a portion of the Lodgepole Limestone have been overturned by intense folding. Inverted sedimentary structures are present in the Lodgepole Limestone (oral communication, Donald Smith, 1976). It is uncertain whether the syncline portion of the fold extends to the southeast corner of the sedimentary block or if the overturned limb is a drag fold produced by the Green Campbell thrust fault (Fig. 4).

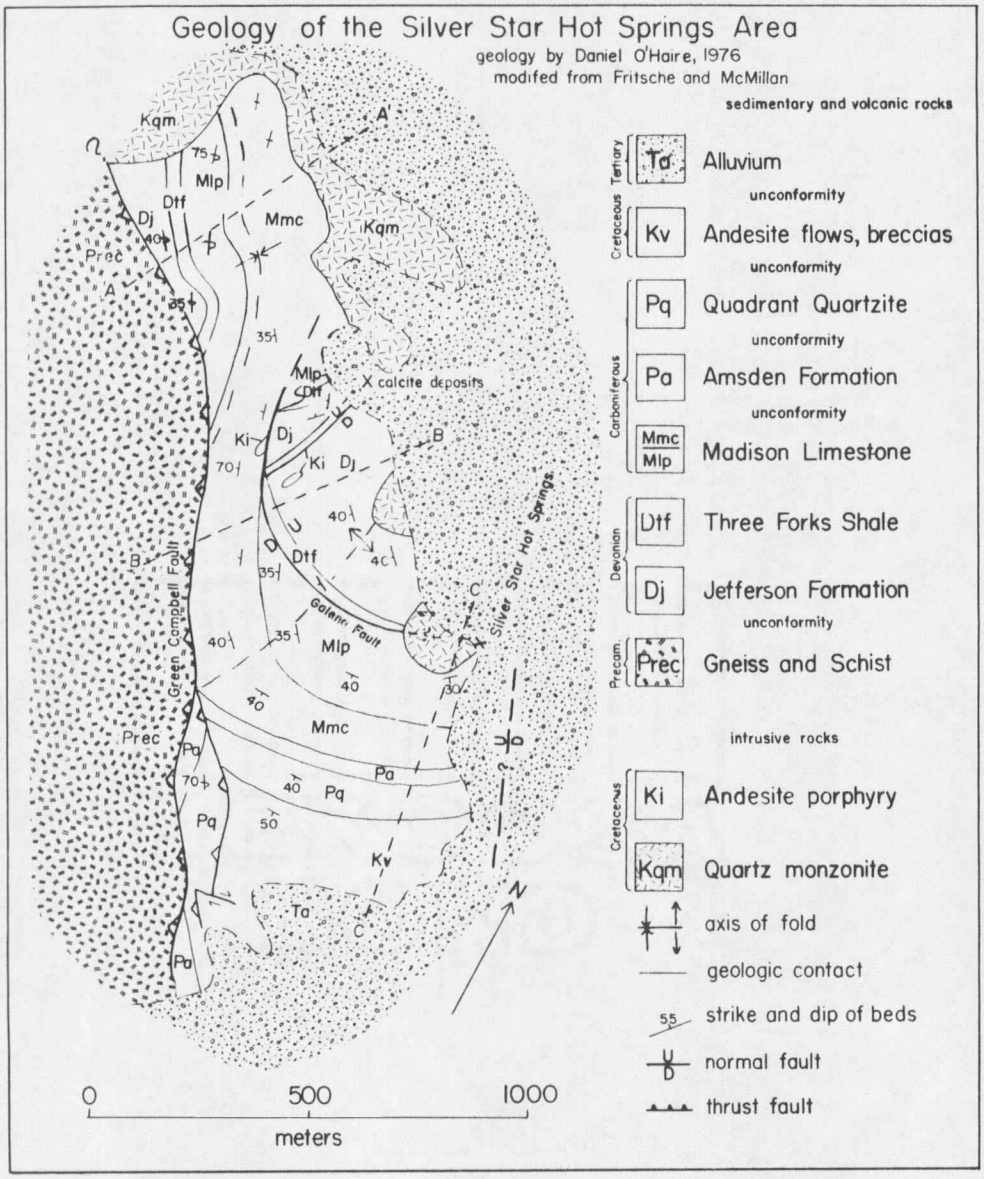


Figure 4. Geologic Map of the Silver Star Hot Springs Area.

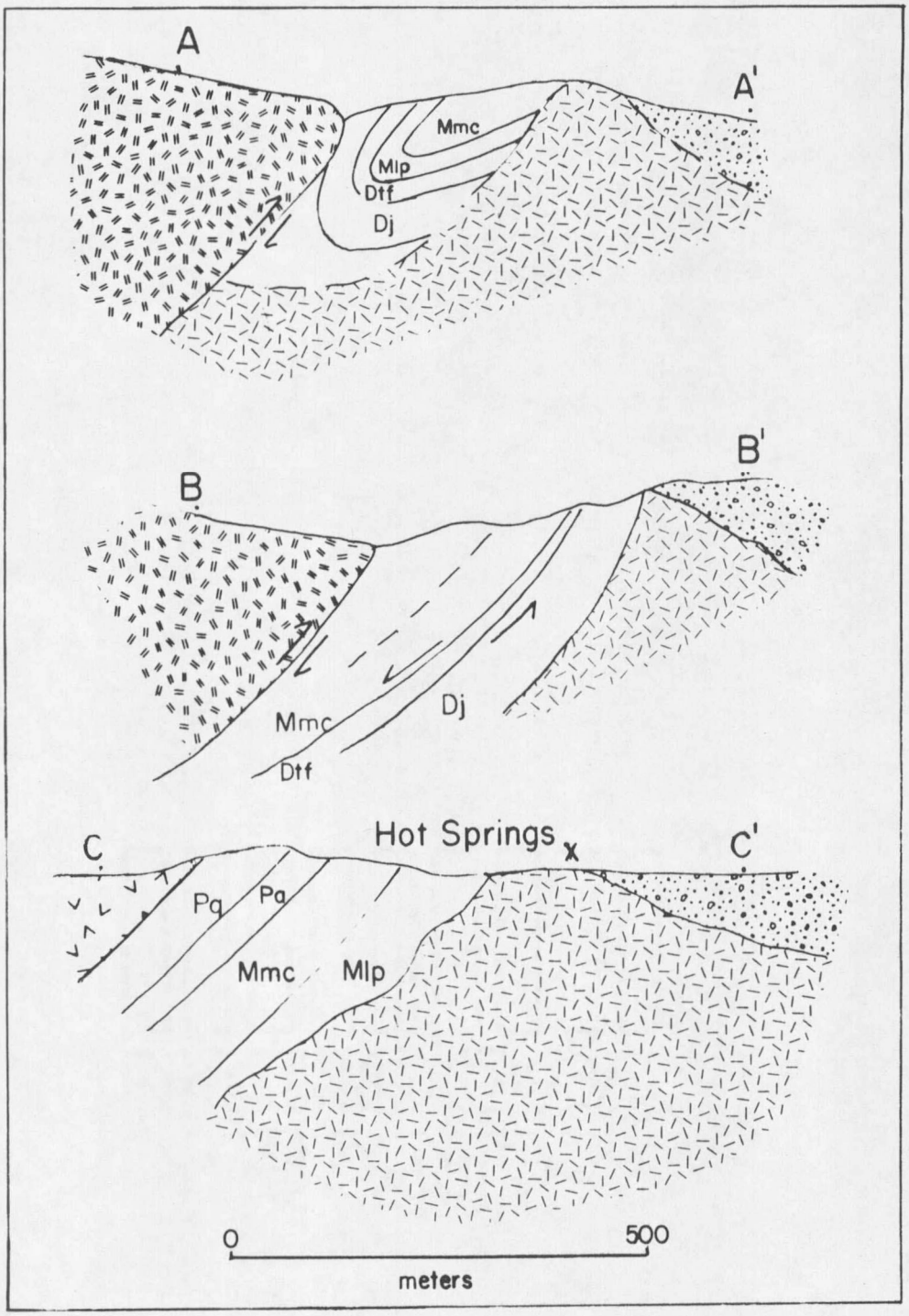


Figure 5. Geologic Cross Sections of the Silver Star Hot Springs Area. Refer to Fig. 4 for location of cross sections.

Minor folding on a scale too small to be shown in Fig. 4 is common. In many places, however, it is difficult to observe the bedding because alteration has obscured the bedding planes.

Boulder Batholith

Quartz monzonite of the Boulder batholith surrounds the sedimentary block on the north and east. Fingers and lobes of the quartz monzonite intrude the sedimentary rocks (Fig. 4). In places, a chilled border zone of more mafic composition is present. An alteration aureole surrounds the intrusion.

A lobe of the quartz monzonite is in contact with limestone of the Madison Group near Silver Star Hot Springs. The contact may extend beneath the springs site. Because of the gravel, it is not known if the nearby Galena fault cuts the quartz monzonite at the springs site.

Alteration

The carbonate rocks have been recrystallized and have a sugary texture. Elsewhere in Montana, the Jefferson Formation has a distinct "fetid" odor, especially when struck with a hammer. This property is absent at Silver Star, perhaps due to volatilization of organic matter at the time of intrustion of the Boulder batholith. Minor sedimentary features or fossils are rarely observed.

Lenticular and patchy zones of epidote are scattered through the carbonate rocks. In these zones, the carbonate is coarsely crystalline; concentrations of hematite and silica are present also. Magmatic fluids probably penetrated to these zones and caused the alterations.

The carbonate rocks are riddled with solution voids and cross-cutting breccia. The breccia is in some places related to faulting but in other places may be caused by solution. These features make the carbonate quite permeable. The Madison is one of the most important aquifers in Montana; the waters of several thermal springs issue from this unit.

Faulting

The relatively incompetent Three Forks Shale was intensely fractured as the Madison and Jefferson blocks slid past one another along the shale (Fig. 4). The fault is termed here the Galena fault because for much of its length the fault follows Galena Gulch, along the Three Forks Shale. Where the Three Forks Shale pinches out and the fault intersects the Madison, an extensive breccia zone was created. On the east, the fault trends toward Silver Star Hot Springs but cannot be traced closer than about 100 m from the springs.

The Green Campbell thrust fault has placed Precambrian metamorphic rocks in contact with the sedimentary rocks (Fig. 4). This fault strikes approximately N30°W. Where it abuts the Madison, it was

observed to dip 45° to the southwest. The thrust fault cannot be traced north of the sedimentary block. The trend of the fault appears to follow the contact of quartz monzonite of the Boulder batholith and gneiss of the metamorphic complex. The age relationship of faulting to intrusion of the batholith is uncertain. Speculation at the Green Campbell Mine suggests that the fault existed prior to intrusion of the quartz monzonite.

Geochemistry and Hydrology

Water from Silver Star Hot Springs issues at the surface with a temperature of 71.5°C and an estimated discharge of 160 1/min. The principal dissolved cations are sodium, calcium and potassium. The principal dissolved anions are sulphate, chloride and fluoride. Silica is also dissolved in the water (Mariner, Presser and Evans, 1976; Table 1). The pH is 8.2 and the specific conductance is 808 micromhos/cm. Dissolved trace elements and dissolved gases are within bounds typical of ground water, except for fluorine which is notably high. The estimated base temperature of the geothermal system based on the chemical composition of the water is 110°C for chalcedony, 143°C for quartz and 109°C for Na-K-Ca (Mariner, Presser and Evans, 1976).

Water sampled from nearby cold springs, a cold well and the Jefferson River (Leonard, personal communication, 1977) differs

Table 1. Geochemical Data for Silver Star Hot Springs and Nearby Surface Waters*

	Jefferson River	Cold Spring No. 1	Cold Spring No. 2	Cold Well	Silver Star Hot Springs
Surface temperature	14.5°C	10.0	12.0	---	72°C
pH (field)	8.8	8.3	8.3	---	7.6
Specific conductance (Micromhos/cm)	741	574	365	931	917
Discharge	---	---	---	---	160 l.p.m.
Estimated thermal aquifer temperature based on chemical composition					
chalcedony					110°C
quartz					143
Na-K-1/3Ca					139
Na-K-4/3Ca					109
Composition (mg/1)					
silica (SiO2)	19	25	21	--	110
calcium (Ca)	52	82	40	48	9.5
magnesium (Mg)	19	20	13	11	0.3
sodium (Na)	20	31	13	140	170
potassium (K)	9.4	3.2	7.0	10	6.7
lithium (Li)	.01	0	0	--	0.38
alkalinity (as CaCO3)	174	192	138	--	144
sulfate (SO4)	68	64	48	220	190
chloride (Cl)	11	19	8.2	22	29
fluoride (F)	0.4	0.8	0.5	7.0	8.9
boron (B)	.05	.06	.03	--	.26
hardness total	210	290	150	170	26

*U.S.G.S. Water Quality Analysis, unpublished records, samples collected by Bob Leonard, 1976; estimated thermal aquifer temp by Mariner, Presser & Evans

chemically from the hot water. Bicarbonate and sulphate are not significantly different but chloride is somewhat lower and sodium and silica are significantly lower. Calcium and magnesium are significantly higher (Table 1).

The overall chemical composition of the Silver Star water is similar to that of other hot springs issuing from fractured, crystalline rock, such as Broadwater, Boulder, Alhambra and Potosi hot springs, which issue from the Boulder or the Tobacco Root batholith. In each case, the water contains sodium bicarbonate with lesser amounts of the other common constituents of ground water. The chemistry of these waters reflects the chemistry of the rocks they have been circulating in, which are rich in sodium and potassium but poor in magnesium and calcium. In conclusion, geochemical data indicate that thermal water from Silver Star Hot Springs circulates at depth within silicic crystalline rock.

Geophysical Investigations

Regional Gravity Survey, 1967

Burfeind (1967), in a regional gravity survey, mapped a steepening of the gravity contours at the valley margin near Silver Star. He said, "In every section except Silver Star, the eastern basin wall is steeper than the western wall." In addition, he

reported, the basin near Silver Star bottoms at approximately -800 feet (-240 m), while to the north and south the basin bottoms at around sea level. This indicates that the floor of the basin dropped and by implication, that a range front fault exists near Silver Star. At Silver Star, the thickness of the basin fill, according to Burfeind's calculations, is about 1.7 km.

Soil Temperature Survey, 1975

A soil temperature map of Silver Star Hot Springs was prepared from data gathered during the summer of 1975 by John Goering and Michael Galloway of Montana State University (Fig. 6). The survey demonstrates that soil temperature increases toward the main orifice. The isotherms crowd close to the hot springs on the west or uphill side and are more widely spaced on the east or downhill side. The waters may spread out under the gravels on the east side as they flow down gradient. From the soil temperature map it appears that the subsurface thermal waters reach the surface via a cylindrical conduit.

Seismic Surveys, 1976 and 1977

Hammer seismograph surveys were conducted at Silver Star (1976 and 1977) in an effort to delineate structural features and thermal water circulation paths. The 1976 work was conducted by the author with assistance from others. In 1977, the instrument was modified, and Weinheimer and other MSU personnel conducted a deeper survey.

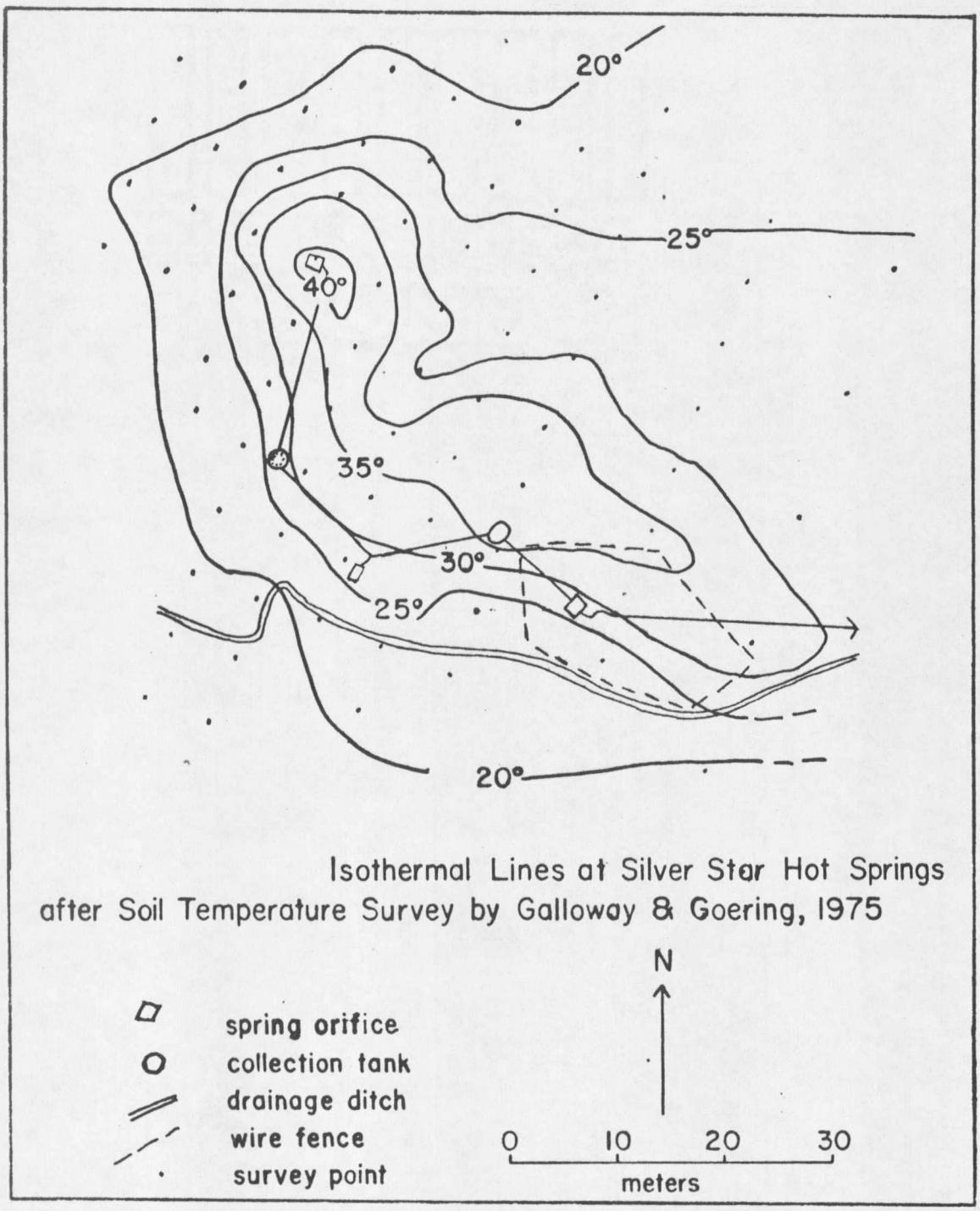


Figure 6. Soil Temperature Map of Silver Star Hot Springs.

The seismograph surveys were conducted using a Bison signal enhancement hammer seismograph.

For the 1976 study, readings were taken at spacings from 2 m up to 30 m and combined into profile A-A' of Fig. 7. A separation between geophone and hammer of 60 m was attempted at both Silver Star and Renova, but results were unsatisfactory. In 1977, the 8-lb. hammer was replaced by an 18-lb. hammer to provide greater depth of penetration, and the cable was lengthened to 200 m to provide about 60 m depth penetration. Results are shown in seismic profiles B-B' through D-D' of Fig. 8.

Hammer seismograph soundings along line A-A' locate a seismic discontinuity at a depth of 3 to 5 m immediately beneath the hot springs. The seismic discontinuity coincides roughly with a sharp drop in resistivity with depth. Seismic velocities in the upper layer averaged 740 m/sec, while seismic velocities in the lower layer averaged 1620 m/sec. This may represent the local water table, a permeable layer in the gravel or the surface of altered bedrock.

In the 1977 study, two types of bedrock were encountered having different seismic velocities. These types were interpreted as silicified limestone and skarn (average 4560 m/sec) and quartz monzonite (average 2240 m/sec). These units are overlain by sand and gravel from 3 to 18 m thick consisting of two units with velocities of 400 m/sec (loose gravel) and 1200 m/sec (compacted sand and gravel).

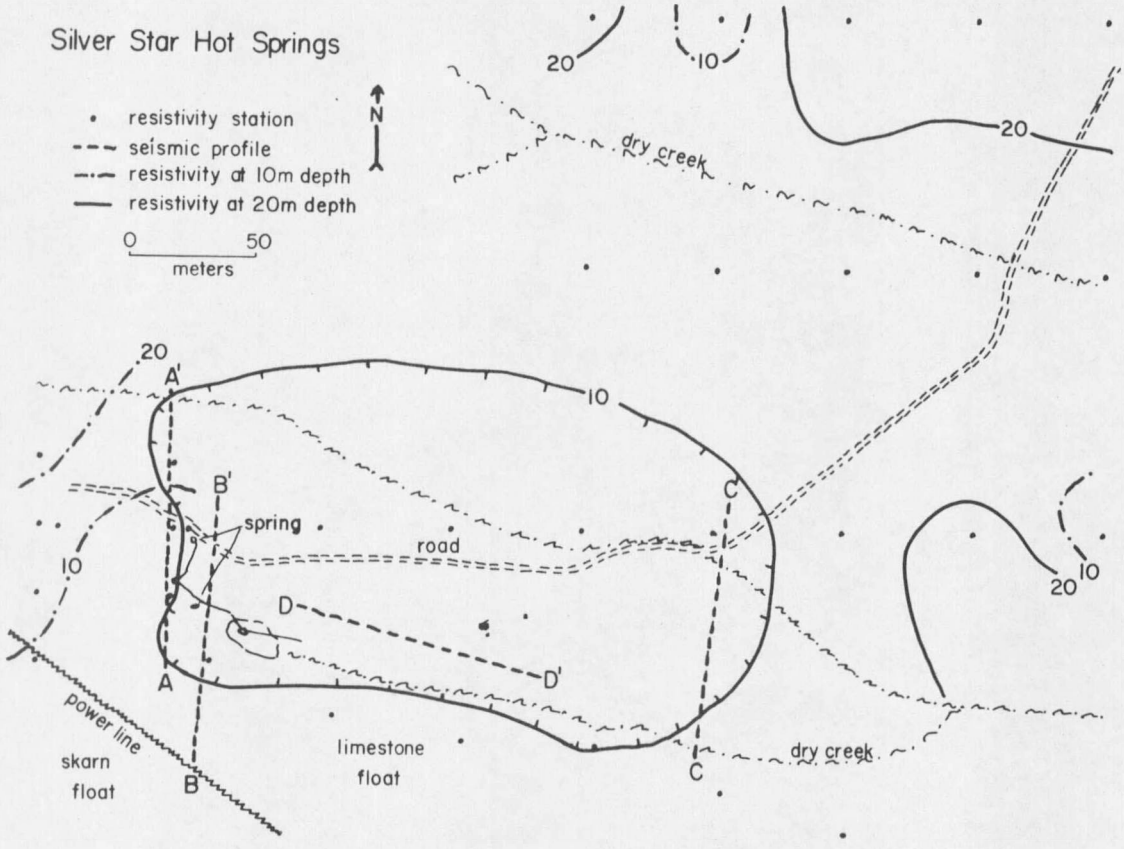


Figure 7. Base Map of Silver Star Hot Springs with Resistivity in ohm-m at 10 and 20 m depth (Weinheimer et al., 1977) and Location of Seismic Profiles.

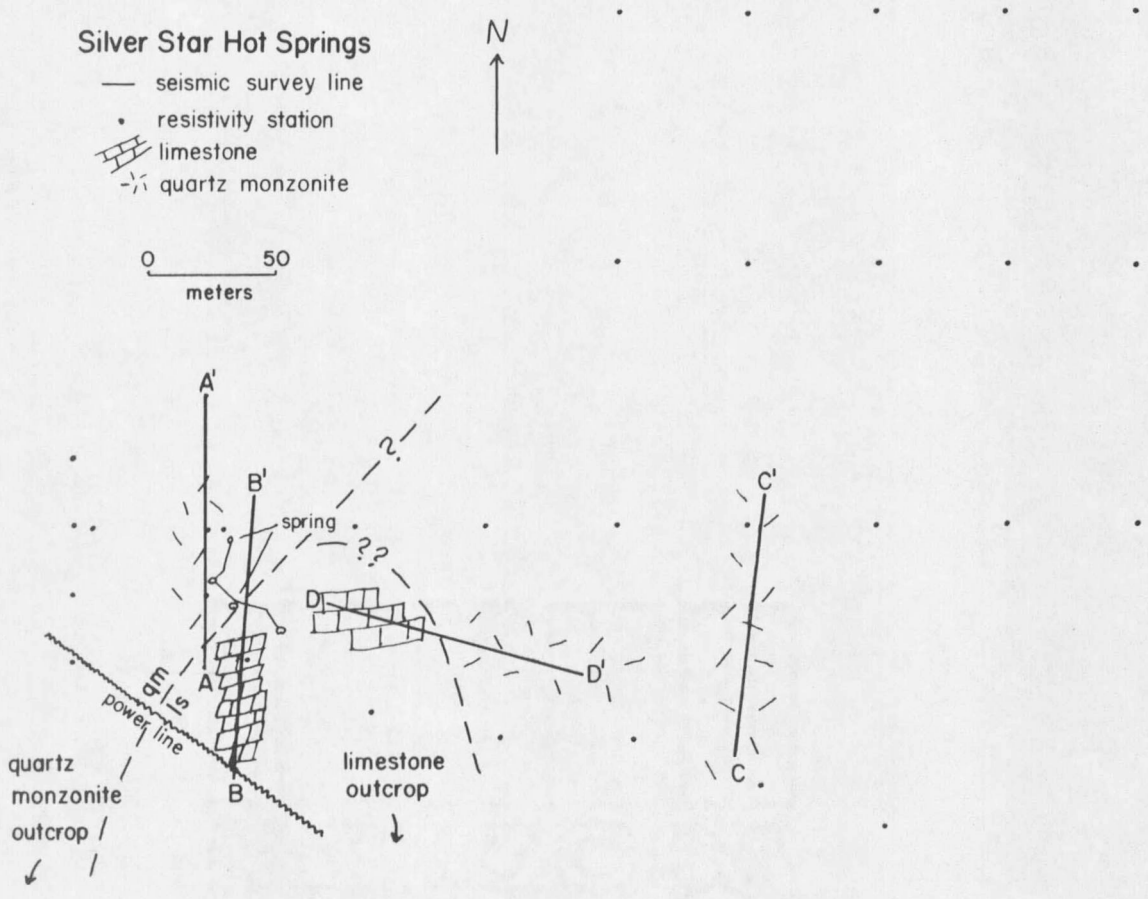


Figure 8. Seismic Interpretation Map of Silver Star Hot Springs at 20 m depth. Seismic velocities averaging 4560 m/sec are interpreted to represent silicified limestone and skarn; velocities averaging 2240 m/sec are interpreted to represent quartz monzonite survey by Weinheimer et al., 1977.

Figure 8 is an interpretation of the subsurface at about 20 m depth based on the seismic data (Chadwick, unpublished report to the United States Geological Survey, 1977). A skarn-quartz monzonite contact passes beneath the springs. The contact may be faulted or highly fractured and is interpreted to transect section B-B' at strike of about N40°E and dip of moderate to gentle northwest. This transection is also marked by a local deepening of the alluvium to about 18 m. The contact zone may curve around to the southeast to intersect seismic profile D-D' (dashed line). Alternatively, the contact may continue to the northeast and parallel another northeast trending, southeast dipping contact through D-D'. Between these two contacts would be a recumbent or up-faulted block of skarn. For either of these two interpretations, a contact zone, probably fractured, trends northeast and may plunge in that direction (Chadwick, unpublished report, 1977).

Resistivity Surveys, 1976 and 1977

Resistivity surveys in 1976 were conducted by the writer with assistance from other MSU personnel using a direct current resistivity meter powered by a bank of two to ten (1.5) volt dry cell batteries. Chrome steel stakes were driven into the ground in a Wenner configuration. Measurements were taken using both forward and reverse polarity and then averaged in order to eliminate the influence of random

currents in the earth. In order to minimize the influence of a nearby power line on resistivity readings, the arrays at Silver Star were arranged parallel to the power line. Resistivity stations were arranged along two N-S lines 50 m apart forming a grid pattern (Fig. 7). Apparent resistivity values were obtained for depths of 2, 4, 10, 15, 20, 25, and 30 meters.

Apparent resistivity contour maps (Figs. 9a and 9b) in the vicinity of Silver Star Hot Springs reveal a resistivity low immediately surrounding the springs. Isoresistivity lines trend west or southwest. Resistivity increases away from the hot springs, to the north and west.

The data (Figs. 9a and 9b) show a zone of relatively high resistivity near the surface at the north ends of the cross sections. This may be a high in the quartz monzonite which is inferred to continue north beneath the springs.

Lower resistivity values at a greater depth (10 to 30 m) may represent water saturated gravel or the bedrock surface which is in this depth range in seismic profile B-B'. If the low represents bedrock, it is probably highly altered.

In 1977, a wider survey was conducted. Resistivity readings were taken at stations 50 m apart in a grid consisting of four generally E-W lines (Fig. 7). Up to 22 6v batteries were used to

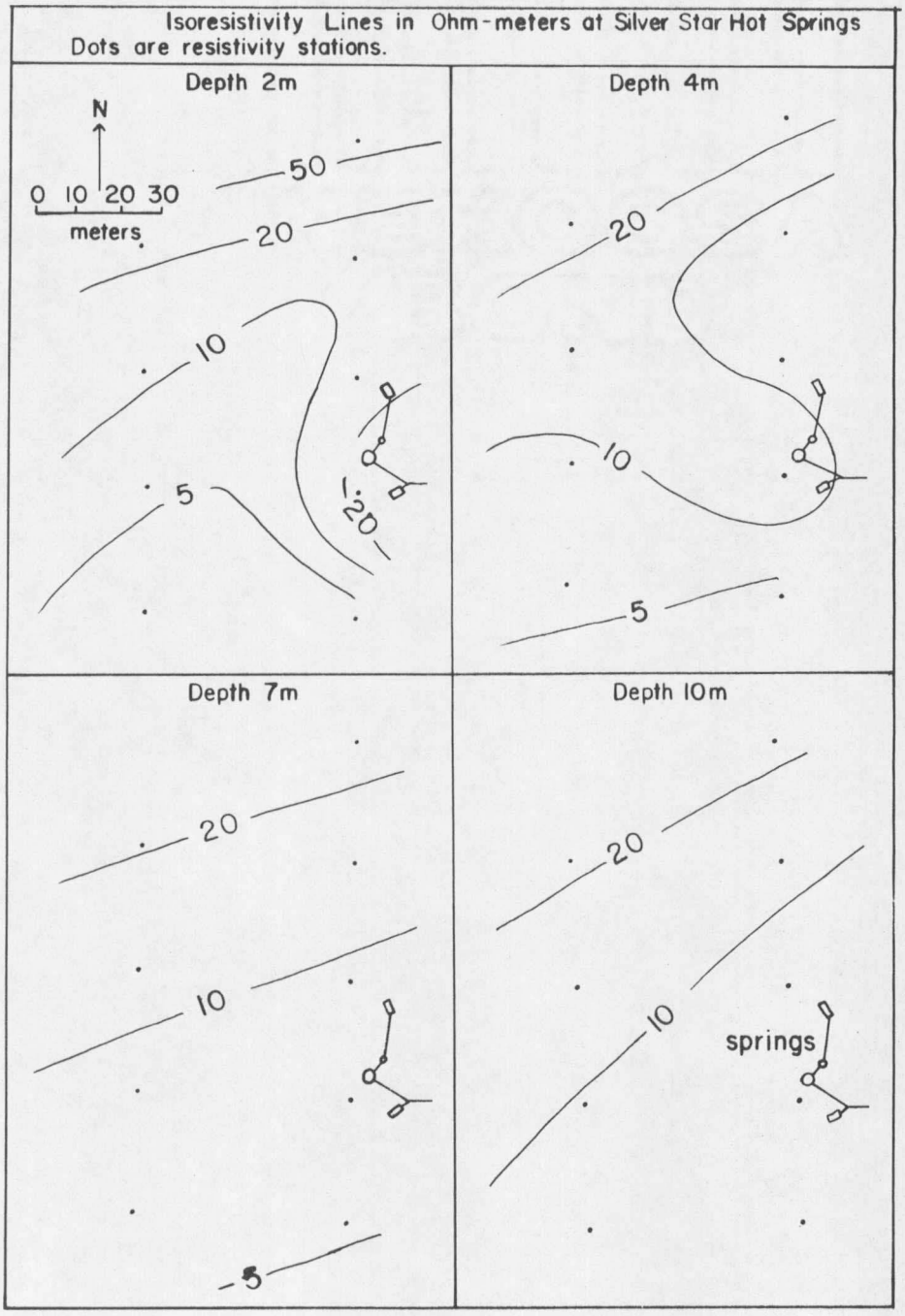


Figure 9a. Isoresistivity Lines in ohm-m at Silver Star Hot Springs. Dots are resistivity stations.

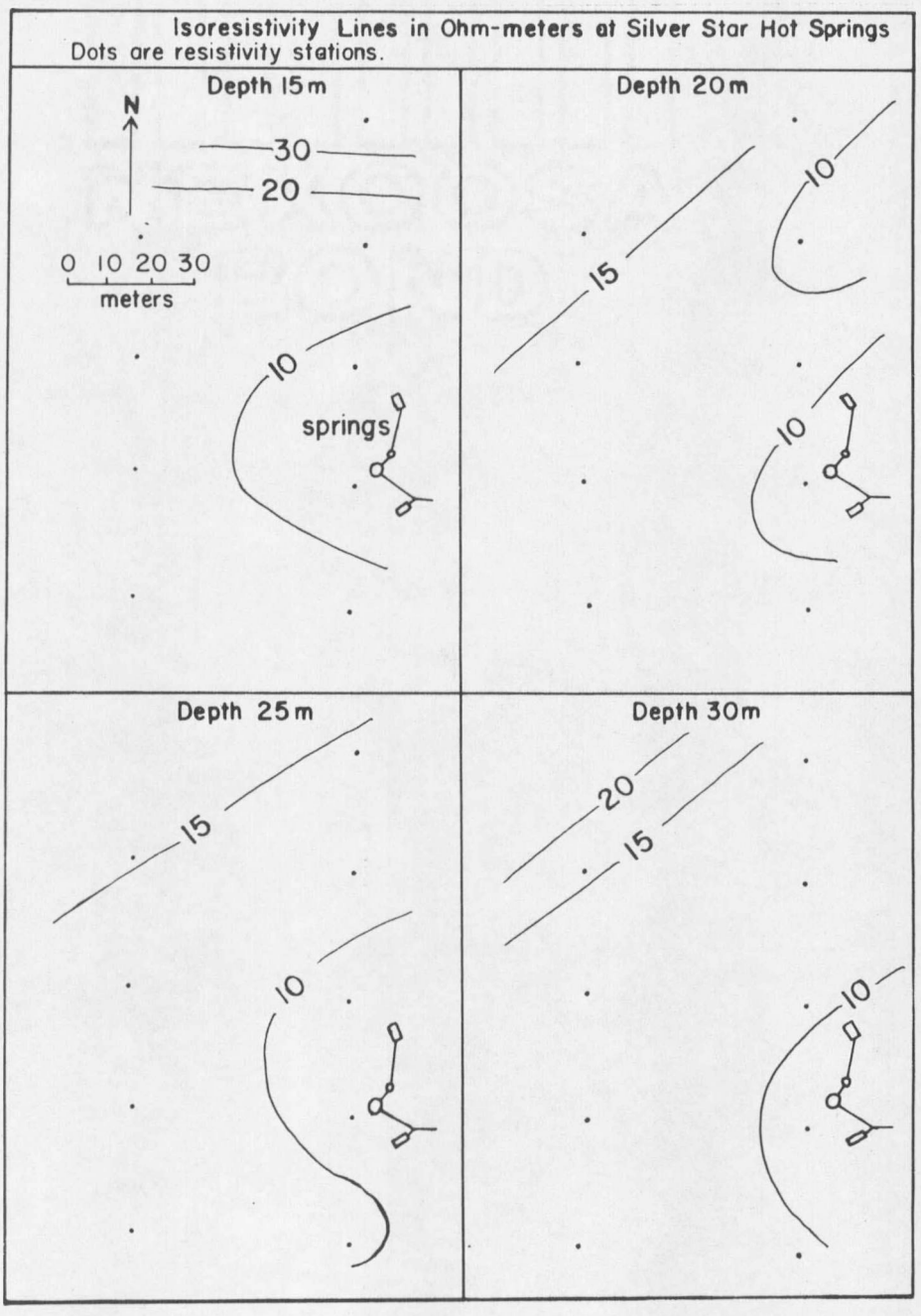


Figure 9b. Isoresistivity Lines in ohm-m at Silver Star Hot Springs. Dots are resistivity stations.

provide greater depth of penetration. Calculated depths for readings were 20, 40, 60, 80, and 100 m.

The surveys delineated a broad diffuse low less than 10 ohm-m, at 20 m depth which extends eastward for about 250 m (Fig. 7). At 100 m depth, the low is centered about 200 m N60°E of the hot spring (Fig. 10). The low is interpreted as being well down in the bedrock and may represent a thermally altered zone plunging northeast along the structures delineated by the seismic survey (Chadwick, unpublished report, 1977). If this interpretation is correct, thermal waters may have migrated or be migrating upward toward the hot springs from the northeast.

Neither the soil temperature nor the resistivity data suggest the continuation of the Galena fault into the hot springs site from the west, or the migration of thermal water from this direction.

Regional Gravity and Resistivity Survey, 1977

Malik (1977) conducted a broad gravity and resistivity survey across an area of about 10 km^2 principally east and north from the hot springs. The survey extended across the Jefferson River.

The survey reveals an ill defined resistivity low (4 to 7 ohm-m) extending about 2 km northeastward from the springs. The low resistivity unit is interpreted as a layer thickening from zero at the hot springs to 150 m at about 350 m northeast of the springs. The

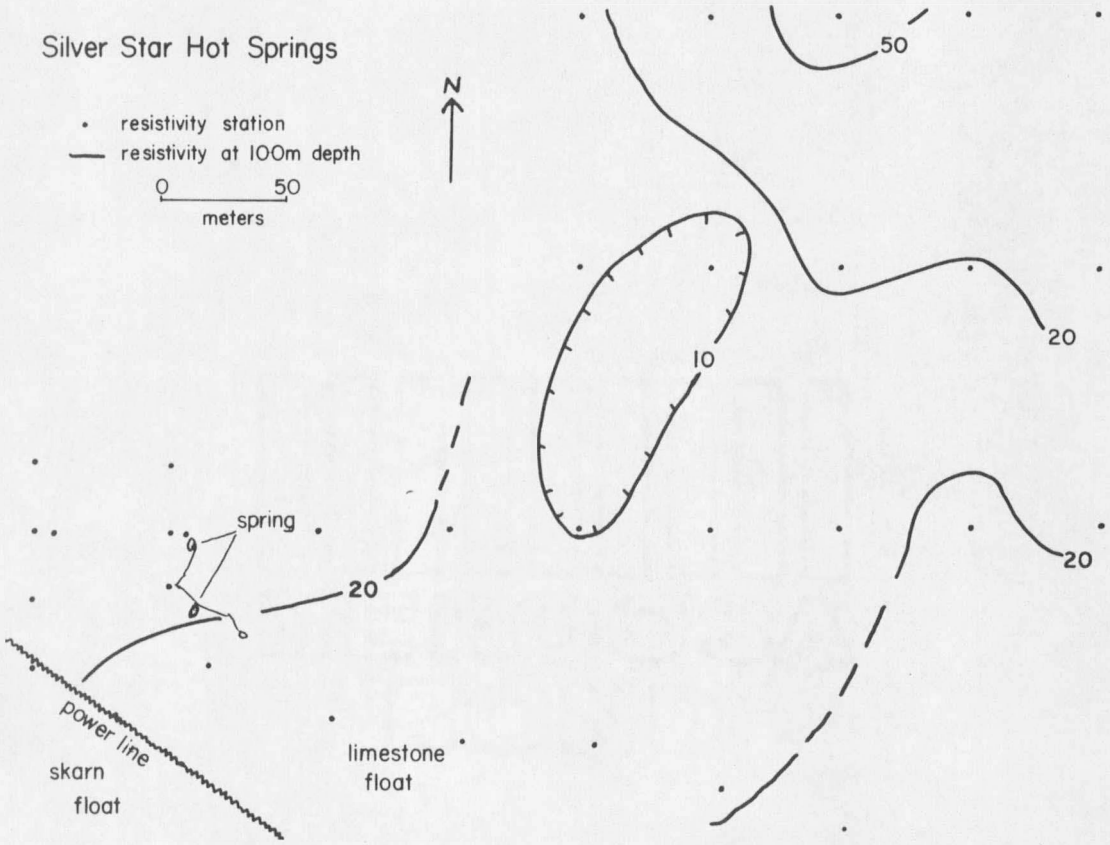


Figure 10. Resistivity Contours in ohm-m at Silver Star Hot Springs at 100 m depth. A low is centered about 200 meters northeast of the springs and may represent rising thermal water.

upper surface of the unit dips eastward from near the surface at the hot springs site to 120 m depth at 400 m east of the springs. In general, this pattern confirms the more local resistivity patterns previously described. The Malik survey was limited by a small number of data points and lack of subsurface drilling information.

The gravity survey delineates a northeast-trending gravity low centered approximately along Highway 287, 500-600 m east of the hot springs. The gravity low parallels and partly overlaps the resistivity low.

Malik suggested that the water of Silver Star Hot Springs rises along a conduit formed by the intersection of a northeast trending range-front fault and one of the swarm of NW-trending faults exposed in the Tobacco Root Mountains. However, the existence of these two faults has not been positively demonstrated.

Possible Water Circulation Patterns

The data are consistent with at least two basic conceptual models. In the first model, 1 of Fig. 11, the thermal waters may circulate at depth within fractured quartz monzonite or gneiss and rise to the surface within the quartz monzonite, possibly utilizing the Green Campbell or Galena faults for part of the distance. Source at depth would be to the west of the hot springs. In the second model, 2 of Fig. 11, the thermal waters may ascend through a great thickness of

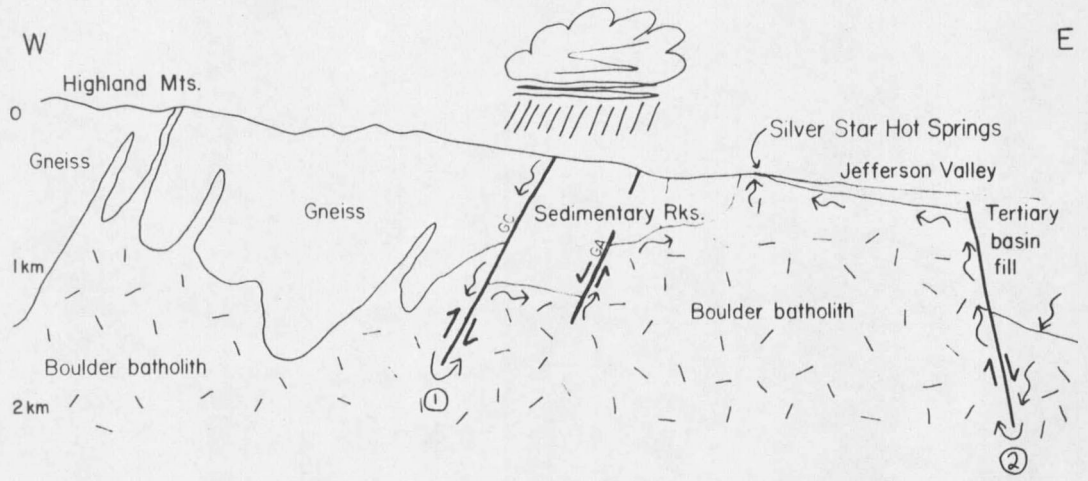


Figure 11. Possible Water Circulation Paths at Silver Star Hot Springs. GC = Green Campbell Fault. GA = Galena Fault. See discussion beginning on previous page for details of water circulation paths.

basin fill, or along a fault bounding the basin fill, after having resided at depth either in the fill or underlying crystalline or sedimentary rock. The course at depth would be generally to the east. These models are evaluated below, in terms of both structures and lithologies involved in thermal water circulation.

Model 1: Circulation From the West

Model 1 envisions thermal water traveling through batholith rock, Precambrian metamorphics and/or Paleozoic sedimentary rocks.

Quartz monzonite of the Boulder batholith crops out several meters from the springs and probably can be found at several meters depth beneath the springs site. Gneiss crops out about 500 m west of the springs on the upthrown side of the Green Campbell fault.

Because of the proximity of the batholith rock to the springs it seems possible that the thermal waters may be ascending through fractures in the quartz monzonite. If so, then Silver Star Hot Springs overlies geology similar to that at several other hot springs along the eastern margin of the Boulder batholith. Boulder and Alhambra hot springs both issue directly from fractured rock in the batholith (Galloway, 1977), while Pipestone issues from a thin sedimentary cover overlying the batholith or adjacent Elkhorn Mountain Volcanics. Analogy with the geology at these other hot springs supports the suggestion that Silver Star waters reside at depth in batholith rock.

Geophysical data do not directly confirm or deny this hypothesis since the surveys did not extend to great depth; however, seismic evidence suggests that the batholith-skarn contact lies beneath the springs.

The water chemistry, while not conclusive, is consistent with thermal water circulation in batholith rock or gneiss. The dilute sodium bicarbonate water (with lesser amounts of Ca, K, SO4 and others) is typical of water issuing from fractured crystalline rock. This is difficult to distinguish, however, from the chemistry of water circulating in sedimentary rocks such as sandstone. A relatively low calcium and magnesium content suggests that the water has not circulated in carbonate rock, while a relatively high fluorine content is typical of many crystalline rock hot springs (Mariner, Presser and Evans, 1976).

The Galena Fault displaces Paleozoic sedimentary rocks near the hot springs. The fault trends southeast for much of its length and curves to the east as it approaches the hot springs, but it disappears beneath an alluvial cover and cannot be traced to the springs site. If the relationship of faulting to intrusion were known, then it would also be known if the quartz monzonite is cut by the fault. Faulting is necessary to maintain permeability of the crystalline rock at depth by the creation of fracture systems (Galloway, 1977).

Soil temperature evidence (Fig. 6, p. 47) does not support the extension of the fault to the springs site.

Gneiss has been thrust over sedimentary rocks along the Green Campbell fault. The fault could serve as a conduit for the hot water. Because granitic gneiss and quartz monzonite are similar chemically, waters circulating in these rocks are similar chemically.

If movement along the Green Campbell fault post-dated the batholith intrusion, it could serve as a conduit. However, if the batholith intruded across the fault zone, the fault would be destroyed as a conduit unless it were reactivated later.

The question of whether the water passed through or was in substantial contact with the sedimentary rocks located between the gneiss and the batholith must be evaluated. The block of sedimentary rocks attains a width of perhaps 0.5 km and the beds dip from 30 to 70° west and southwest toward the thrust fault. It is uncertain how deep the structure extends.

It may be argued that hot water residing deep in crystalline rock could originate there and later enter sedimentary rocks at a shallow depth before final passage to the surface. Brecciation, solution and faulting in the limestones at Silver Star have created sufficient permeability to allow passage of the thermal waters. Other Paleozoic units such as shales and quartzite are probably of low permeability. However, a hypothesis employing the limestone as an aquifer would

fail to take into account the relatively low calcium and magnesium content of the water. Therefore, it seems unlikely that waters passed through the Paleozoic sedimentary sequence. If the Green Campbell fault served as a conduit, waters must have entered the batholith without traveling through the sedimentary block.

Calcite and silica have been deposited in the alluvium about 500 m north of the hot springs, or about 50 m along the projection of a fault in the limestone. They suggest that at some time in the past, water flowed through the limestone and during final passage to the surface deposited minerals in the alluvium which had been dissolved from the limestone. The batholith underlies the limestone here and it is possible that the water originated from fractures in the batholith and then rose up through the limestone and finally the alluvium.

Model 2: Circulation From the East

Water circulating in accordance with Model 2 (Fig. 11) might be in contact with basin fill, batholith rock and possibly Paleozoic sedimentary rocks if they extend beneath the Jefferson Valley.

The question of whether the water has passed through or was in substantial contact with the Tertiary basin fill as much as 2 km deep must be evaluated. The basin fill is unusually deep near Silver Star and might be the geothermal aquifer. Evidence regarding the

thickness of the basin fill and the possible existence of a range-front fault has been discussed in the sections "Cenozoic Block Faulting" and "Geophysical Investigations."

It is difficult to distinguish chemically between water from the basin fill and water from siliceous igneous or sedimentary rocks. One possible clue is the amount of fluoride in the water. Several springs which issue from the Boulder batholith have relatively large quantities of fluoride in their water. Broadwater Hot Springs has 9.4 mg/1; Alhambra, 8.4; Boulder, 11.0 and Pipestone, whose water may circulate in the batholith at depth, 5.3 mg/1 (Mariner, Presser and Evans, 1976). The quantity of fluoride in springs which issue from sedimentary rocks or the basin fill is less. Renova and New Biltmore Hot Springs both probably circulate within Paleozoic sedimentary rocks and have 3.0 and 3.3 mg/1 fluoride, respectively. Warm Springs issues from the basin fill and contains 3.9 mg/1 fluoride. The value of 8.7 mg/1 fluoride for Silver Star would seem to place it within the group of hot springs issuing from the batholith and argue against the possibility of extensive circulation within the basin fill.

The recognition of the Silver Star system as one with a reservoir at depth in the Tertiary basin fill would place it in a category containing few of Montana hot springs. Ennis, Wolf Creek, Warm Springs and Bozeman may be in this category, while about half of 25 hot

springs in the state are known to issue directly from crystalline rock or from thin alluvial cover overlying crystalline rock.

Evidence favors, but does not prove, that circulation takes place in fractured batholith rock as opposed to basin fill. Circulation in Paleozoic sedimentary rocks, if they exist beneath the valley, is unlikely for reasons previously discussed. The model must assume that the batholith extends at depth eastward from the hot springs and is cut by a range front fault.

Resistivity data previously cited suggest that thermal water is rising toward the springs from the northeast and may have risen from depth along one or more range front faults. Such water may reside at depth either in the basin fill or in crystalline rock beneath the valley floor or adjacent to the valley margin. The deepening of the basin near Silver Star (Burfeind, 1967) implies a deep reservoir in the fill and also a fault which could serve as a conduit for rising hot water. It may be significant that the basin fill is interpreted as up to 2 km deep 1 km east of Silver Star, and the depth of origin suggested by geochemical thermometers (110-140°C) and a geothermal gradient of 60°C/km for valley fill is in the range of 1.7 to 2.2 km. Thermal water might reside at the base of the fill or slightly below it.

The resistivity low about 200 m northeast of the springs beneath the alluvium (Fig. 10) may or may not actually represent hot water

beneath the surface. If the low is indeed caused by hot water, there may be undiscovered seeps or conduits in the thermal water circulation system at this location beneath the alluvium. The source of this water must be the same as that of the springs.

Summary

In summary, two major water circulation systems can be postulated for Silver Star Hot Springs, a western and an eastern circulation. Water chemistry and analogy to other springs favors an origin in crystalline rock, though a valley fill reservoir cannot be ruled out. A sedimentary carbonate reservoir seems unlikely.

Geophysical evidence supports a source to the northeast or east and does not favor a source to the west. Waters may be rising along a range front fault after residing at depth in fractured batholith rock or possibly the basal portion of the Tertiary sediments in the Jefferson Valley. However, the possibility that the Green Campbell fault serves as a channel for rising water cannot be ruled out. Such water would be derived largely from recharge in mountains to the west.

The author favors the hypothesis that thermal water is circulating from fractures in the Boulder batholith.

Renova Hot Springs

Location and Physical Appearance

Renova Hot Springs lies near the Point of Rocks where the Jefferson River cuts around the northwest corner of the Tobacco Root Mountains as it flows north through the upper Jefferson Valley (N45°47'30", W112°07'35" or Sec32T1NR4W).

The springs are located at the river's edge. The thermal water issues from numerous joints in the limestone or from river gravel cover. Several vents are located along the waterline. More vents can be seen underwater on the river bed, where luxuriant growth of algae and rising bubbles attest to the presence of rising hot water. Significant mixing of the river and thermal waters probably occurs, even with the water issuing from vents above the waterline.

Someone, in an effort to channel the flow, has constructed a crude stone wall about 5 m from shore. It channels the hot water into a pool which serves as a swimming hole. A bed of green algae covers the gravelly bottom.

Geology

Sedimentary Rocks

Precambrian, Paleozoic and Cenozoic sedimentary rocks are all found within a short distance of Renova Hot Springs. These units

are listed in Fig. 12, and described in Chapter 4. They include the Precambrian Belt Supergroup (1500 m), the Cambrian Flathead Formation (40 m), Wolsey Formation (50-80 m), Meagher Formation (150 m), Park Formation (50 m), Pilgrim Formation (100 m) and the Red Lion Formation (20 m). The Devonian Jefferson Formation (150 m) and the Tertiary Bozeman Group (0 to 2000 m) are also included.

The Wolsey Formation near Renova Hot Springs contains an andesite (?) porphyry sill. The sill is in the upper portion of the unit and appears to have been intruded prior to folding and faulting of the sedimentary rocks.

The Meagher Formation near Renova Hot Springs consists of upper and lower massive members and a middle thin-bedded member. The spring issues from the upper part of the thin bedded member.

Faults

The older rocks in the vicinity of Renova Hot Springs are cut by a group of Laramide (?) radiating faults (Figs. 12 and 13). The faults radiate from a center about 200 m south of the hot spring. When deformation exceeded the plastic limit of the relatively brittle rock, adjustment to the stress of folding occurred through movement along the faults.

Another group of faults cuts the sedimentary rocks and is oriented approximately E-W. The faults are most prominent in the

southern portion of the mapped area (Fig. 12). One E-W fault located on line with Renova Hot Springs has caused the Wolsey and Meagher formations to repeat in outcrop.

The Tobacco Root range front fault (Chapter 4) lies an undetermined distance west of the mountain front and is obscured by alluvium. Cenozoic movement along this fault may be as great as 2000 m.

Alteration

The rocks are altered, especially in the zones of most intense faulting. Alteration includes brecciation, hematization and silicification.

A map of the alteration was prepared (Fig. 14). Alteration was categorized on a scale of 0 to 4. "0" corresponds to no noticeable alteration. "1" corresponds to slight alteration, including a sugary texture in the carbonate, local hematite staining and/or limited brecciation. Limestones effervesce vigorously upon application of dilute HCl. "2" corresponds to moderate alteration, including widespread hematite staining, a coarse sugary texture in the carbonates and slight silicification. "3" corresponds to extensive silicification, hematization and brecciation, and weak reaction to dilute HCl, indicating destruction of most of the carbonate. "4" corresponds to total removal of carbonates as evidenced by lack of reaction with

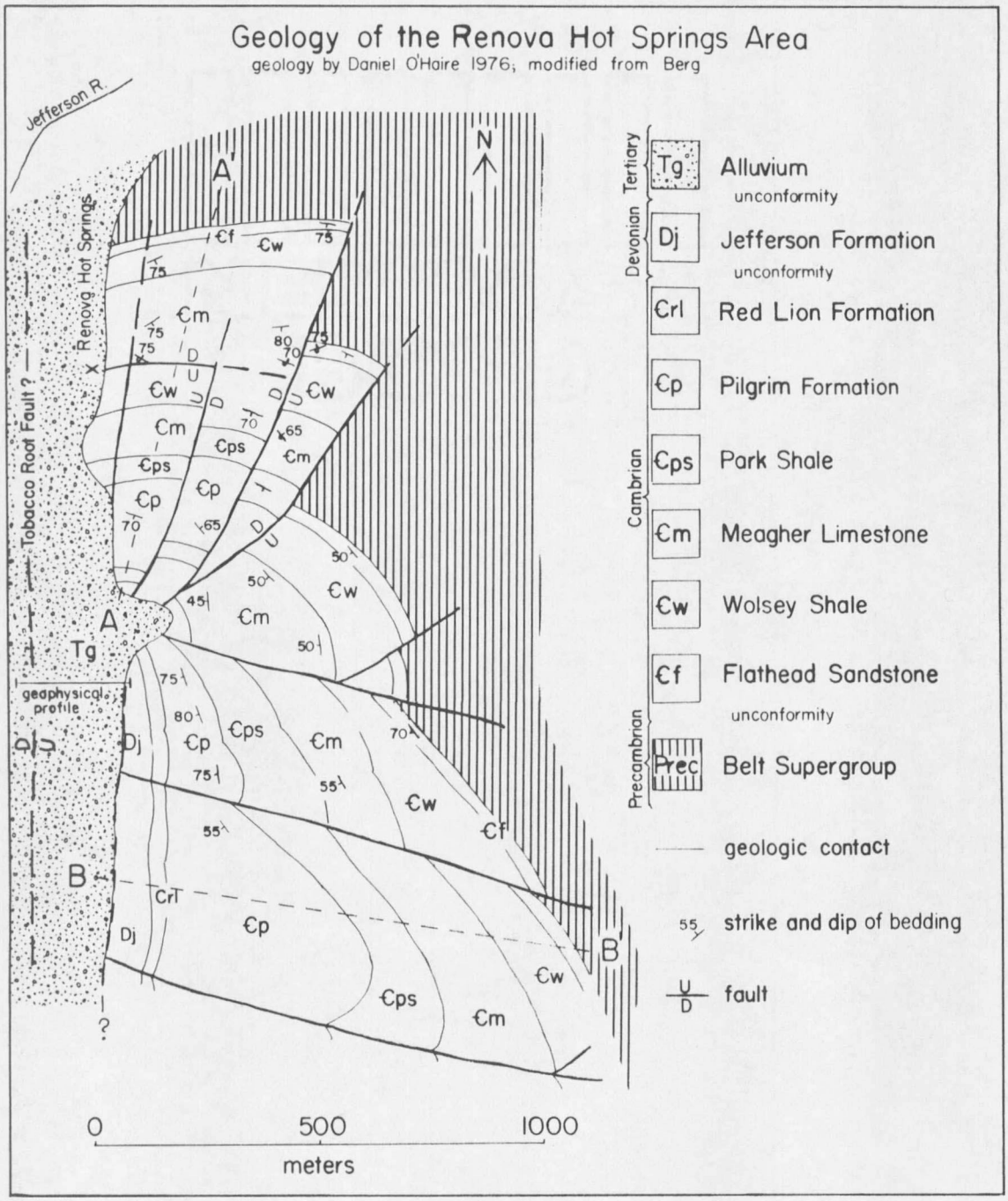


Figure 12. Geologic Map of the Renova Hot Springs Area.

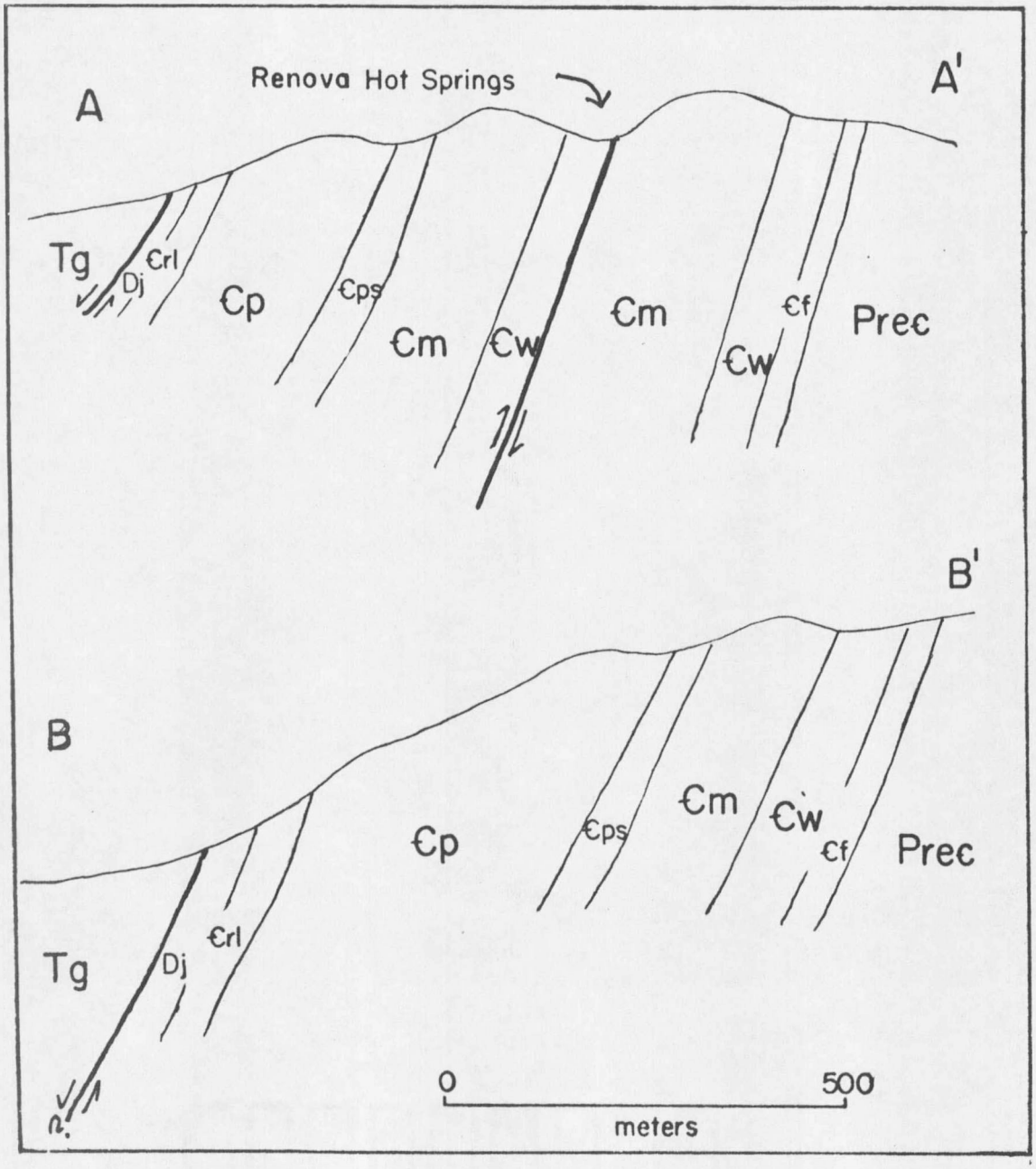


Figure 13. Geologic Cross Sections of the Renova Hot Springs Area. See Fig. 12 for location of cross sections.

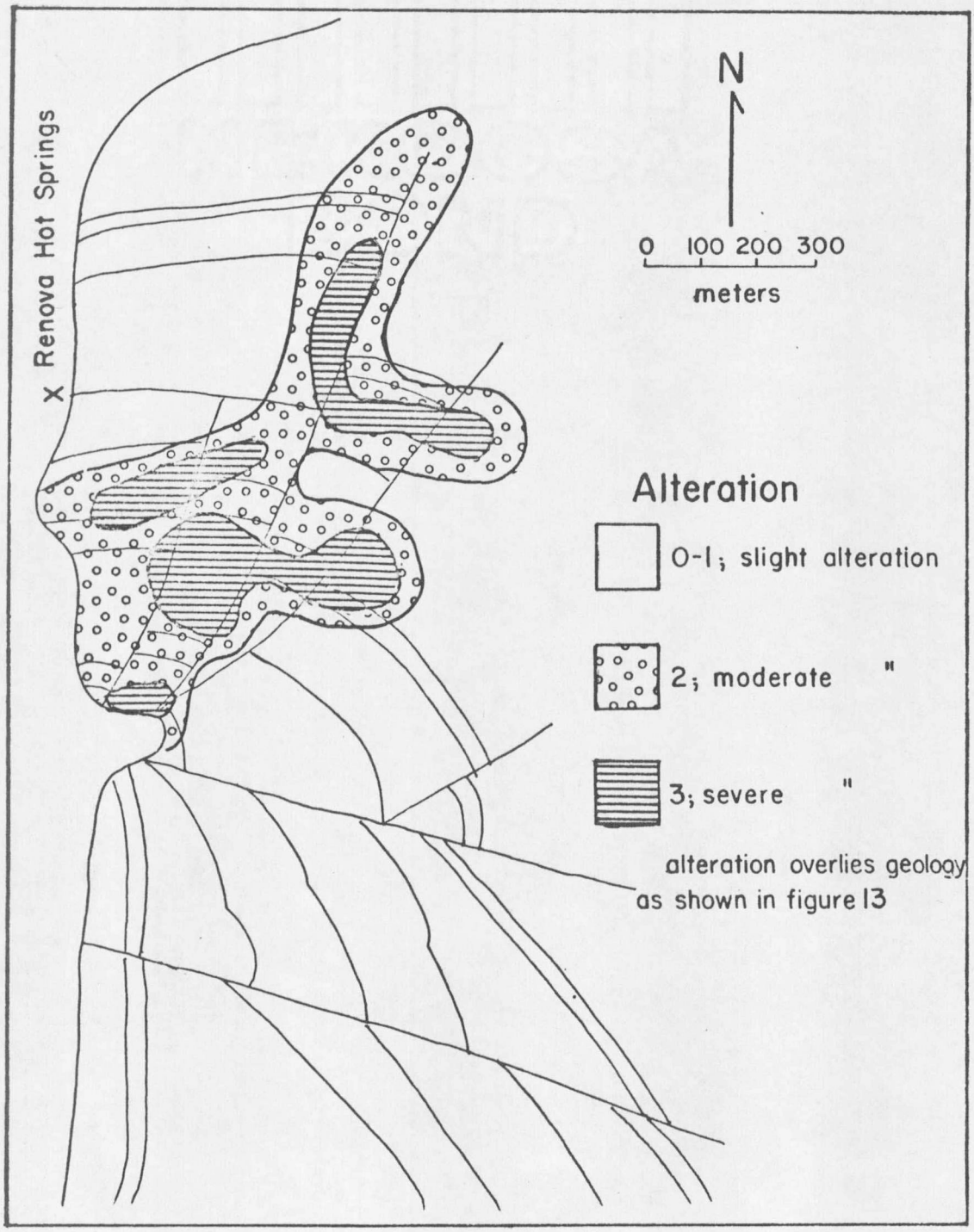


Figure 14. Alteration Map of Renova Hot Springs. See text for description of alteration categories.

dilute HCl; the rock is completely silicified or hematized and severely brecciated.

Alteration was found to coincide with the faults, and the most intense brecciation and alteration were found near the center of the radiating fault system. The zone extends SE from 50 to 200 m away from the hot springs. The proximity of the fault zone to the hot springs suggests a relationship. If the fluids which accomplished the alteration used the fault zone as a conduit, then perhaps the fault zone could serve as a conduit for the waters of the present hot springs.

Geochemistry and Hydrology

Thermal waters from Renova Hot Springs issue with a surface temperature of 50°C and an estimated discharge of 150 l/min. The principal dissolved cations are sodium, calcium, magnesium and potassium. The principal dissolved anions are sulphate, chloride, fluoride and bicarbonate (Table 2).

The pH is 7.5 and the specific conductance is 1100 micromhos/cm. Composition of dissolved trace elements and dissolved gases is typical of Montana hot spring waters.

Estimations of aquifer temperature based on the chemical composition of the water indicate a low temperature system. Estimated base

Table 2. Renova Hot Springs Geochemical Data*

surface temperature	50°C
pH (field)	7.5
specific conductance (Micromhos/cm)	1100
discharge	150 l/min
Estimated thermal aquifer temperature based on composition	
chalcedony	58°C
quartz	88°C
Na-K-nCa	92°C
Major and trace element composition	**PPM**
silica (SiO2)	37
calcium (Ca)	51
magnesium (Mg)	13
sodium (Na)	150
potassium (K)	13
lithium (Li)	.13
alkalinity (as CaCO3)	254
sulfate (SO4)	200
chloride (Cl)	34
fluoride (F)	3
boron (B)	.48
hardness total	180

*U.S.G.S. Water Quality Analysis, unpublished records

temperatures are 58°C for chalcedony, 88°C for quartz and 92°C for Na-K-Ca.

Water chemistry differs in several respects from that of the nearby Jefferson River, which flows by the springs. Bicarbonate and sulphate are significantly higher. Silica, sulphate and chloride are also significantly higher. Calcium and magnesium are somewhat lower (Table 2). Overall, the chemistry of the hot water is typical of subsurface water which circulates in sedimentary rocks.

Geophysical Investigations

Hammer seismograph and resistivity profile surveys were conducted in the vicinity of Renova Hot Springs in an effort to locate a fault or other feature which might exercise structural control on the circulation of the water (Fig. 15). The profile was at right angles to the mountain front and on the gently sloping grassy alluvium which drapes the foot of the mountain. The profile was located to intercept a shear zone parallel to the mountain front near the hot springs. It is not known whether the sedimentary rocks which dip westward under the alluvium are unbroken or whether they are displaced by faulting beneath the alluvial cover.

An interpretation of the resistivity data is presented in graphic form in Fig. 15. Resistivity values increase markedly toward the east or uphill end of the profile. This increase is interpreted to

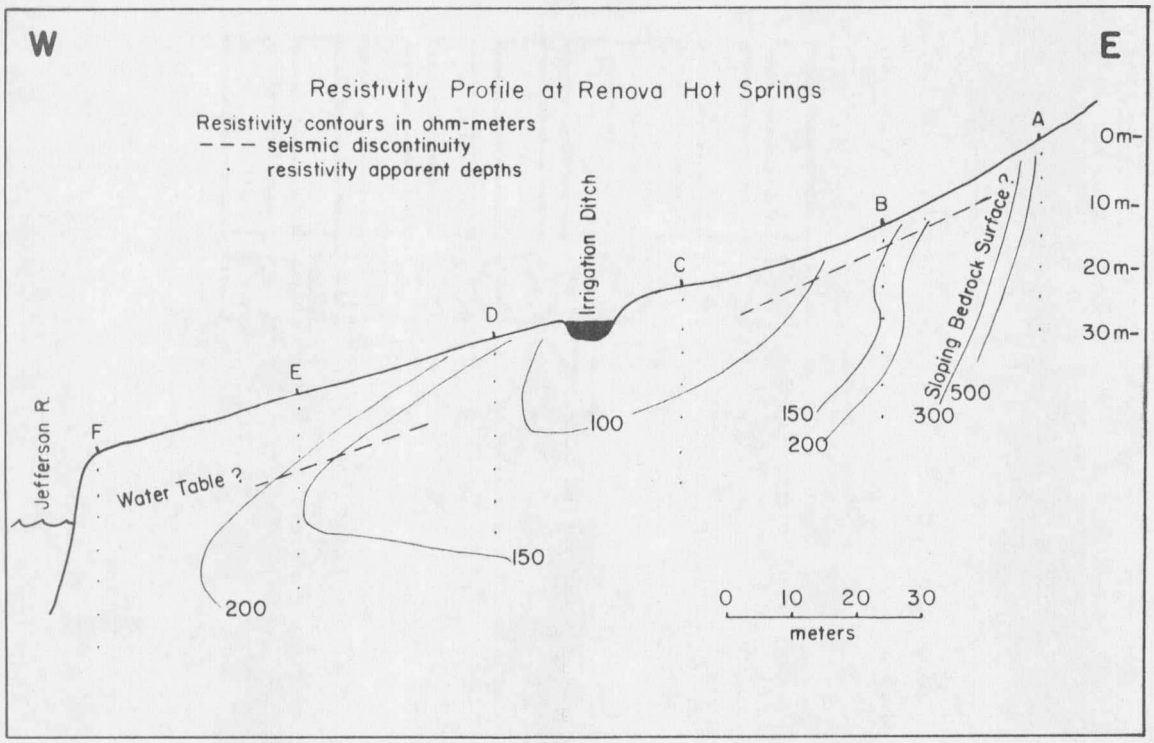


Figure 15. Resistivity and Seismic Profile at Renova Hot Springs.

represent the approach to the surface of the west-sloping contact of the high-resistivity bedrock and the overlying alluvial cover.

In the middle of the profile a resistivity low extends beneath and downhill from an irrigation ditch. The upper surface of the low is interpreted to represent the water table as water flows from the irrigation ditch downhill through the alluvium to the nearby Jefferson River. A seismic discontinuity coincides with this surface.

A seismic discontinuity was also revealed at the east or uphill end of the profile. Seismic velocities increase markedly at a depth of approximately 4 m. The discontinuity may represent some layering in the alluvium or possibly, the contact of the soil and underlying less weathered alluvium. No seismic discontinuity is apparent on the west end of the profile to a depth of 30 m.

Possible Water Circulation Patterns

Water from Renova Hot Springs issues from joints in the Cambrian Meagher Limestone. The water may circulate in the limestone only during final passage to the surface; the water circulation path at depth is uncertain. Three possibilities exist (Fig. 16): thermal water may circulate 1) within dipping Paleozoic sedimentary rocks on the flank of the Tobacco Root Anticlinorium, 2) within metamorphic or batholithic rock beneath the sedimentary sequence or 3) within Tertiary basin fill of the upper Jefferson Valley. Water may

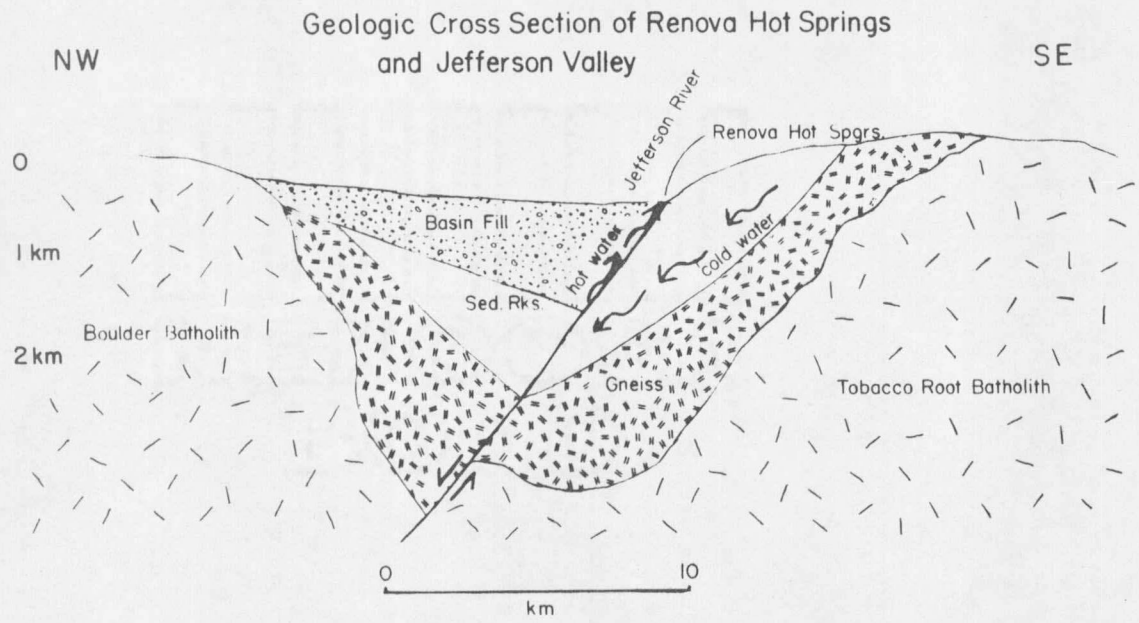


Figure 16. Diagrammatic Cross Section of Renova Hot Springs and the Jefferson Valley Showing Possible Hot Water Circulation Paths.

circulate across more than one of these units. Fig. 16 follows Burfeind's (1967) interpretation that the Boulder and Tobacco Root batholiths are connected at depth.

If the local geothermal gradient were known, one could calculate the depth of circulation necessary to obtain the temperature of the Renova water. The only value available is a thermal gradient measurement taken in the northwest part of the Silver Star mining district about 4 km northwest of Silver Star Hot Springs. A gradient of 30.1°C km was measured in a drill hole in the Rader Creek pluton of the Boulder batholith (Blackwell and Robertson, 1973).

Assuming a mean annual temperature of 7°C for the Renova area and a geothermal gradient of 30°C/km, circulation to a depth of 2 to 3 km would agree with the estimated base temperature of about 90°C.

Since basin fill is estimated as about 1 km thick based on Burfeind's 1967 gravity data, water probably circulates below the basin fill into sedimentary or crystalline rock. It is likely that the thermal water is diluted because of the location of the springs along the banks of the Jefferson River. Interpretation of the geochemical data is difficult because of mixing with the river water. For example, dilution would lower the silica content and give silica base temperatures which are too low. If the base temperature was actually higher than 90°C, water would probably have to circulate still deeper.

The water may circulate in carbonate rocks along the flank of the Tobacco Root Anticlinorium. Water might recharge in the Tobacco Root Mountains and infiltrate sedimentary or even metamorphic or igneous rocks, then percolate down along permeable formations and fault zones to depths of 2 km and more, finally rising under thermal-artesian head within the Tobacco Root range front fault zone or within carbonate aquifers along the fault zone.

This interpretation is favored by the high elevation of the recharge area relative to the springs. The thickness and configuration of the Tobacco Root Anticlinorium make this interpretation seem reasonable because water would recharge at a higher elevation than it discharges. The presence of numerous high angle faults within the Tobacco Root Mountains also lends credence to this interpretation. The faults could serve as conduits for the descending cold water. Widespread minor faulting in the immediate vicinity of the hot springs probably serves to allow the passage of rising hot water.

Although it appears that thermal water circulates deeper than the basin fill, it might travel through the fill as it rises, perhaps along intra-valley faults or along the Tobacco Root fault. Some thermal water might be stored in the permeable layers of basin fill. The Tobacco Root fault could serve as a conduit for rapid passage of the hot water to the surface. Because of the presence of the river

it is difficult to investigate this possibility without deep geophysical studies.

In conclusion, thermal water from Renova Hot Springs emerges at the surface after circulating within folded sedimentary rocks on the flanks of the Tobacco Root Mountains, and perhaps in crystalline rocks below. The water recharges in the Tobacco Root Mountains, flows downhill within the limb of the Tobacco Root Anticlinorium, and rises to the surface when it intersects the Tobacco Root range front fault. An alternate hypothesis favoring recharge from the Jefferson River and circulation along the Tobacco Root range front fault within the Tertiary basin fill or underlying crystalline rock is not favored.

Pipestone Hot Springs

Pipestone Hot Springs (Sec.28, T2N, R5E) is located in a topographic low where Pipestone Creek cuts through Tertiary basin fill in the upper Jefferson Valley. There is an indoor swimming pool and resort stand at the springs site, but they are presently inactive. Pipestone Hot Springs may be approached by dirt road leading from the Pipestone Springs exist of I-90, approximately 300 m north of the springs.

The water has a surface temperature of 57°C and an estimated discharge of 300 1/min. The springs have some small artesian pressure but it has not been measured. There are several orifices including

an open well from which hot water shoots upward into the air a few centimeters. The pH is 8.7 and the specific conductance is 455 micromhos/cm (Mariner, Presser and Evans, 1976).

The principal dissolved anions are sulphate and bicarbonate (Table 3). The principal dissolved cation is sodium. Other constituents include silica and fluoride. Hydrogen sulphide at a concentration of 2 mg/l probably is derived from bacterial reduction of organic sulphur contained in the basin fill. The calculated base temperature of the water is between 70 and 90°C (Table 3). If the thermal gradient were 30°C/km, water would circulate to about 2 to 2.5 km depth.

The springs issue from alluvium in a swampy depression about 100 m across. At this point, Pipestone Creek has cut down into the Tertiary basin fill. Bedrock does not crop out near the springs site, but granodiorite of the nearby Boulder batholith is found 2 km to the west and may exist at depth beneath the springs. The Elkhorn Mountain Volcanics may overlie the batholith beneath the basin fill at the springs site. The volcanics are exposed on the surface about 2 km to the north but cannot be traced beneath the alluvial cover. They are cut by two normal faults, SE side down, which trend southwest toward Pipestone Hot Springs. Recent movement is indicated by the displacement of Quaternary alluvium and by the change in character of Whitetail Creek as it crosses the faults (Prostka, 1966). The

Table 3. Pipestone Hot Springs Geochemical Data*

Surface temperature	57°C
pH	8.72
Specific conductance (Micromhos/cm)	455
Discharge	300 l/min

Estimated thermal aquifer temperature based on chemical composition	
chalcedony	72°C(87)
quartz	115°C(115)
Na-K-1/3Ca	113°C----
Na-K-4/3Ca	89°C(89)

Major and trace element composition	milligrams per liter
silica (SiO2)	66
calcium (Ca)	2.6
Magnesium (Mg)	less than 0.1
sodium (Na)	98
potassium (K)	1.9
lithium (Li)	0.09
alkalinity (as HCO3)	108
sulfate (SO4)	94
chloride (Cl)	20
fluoride (F)	5.3
boron (B)	.28
dissolved constituents	396
hydrogen sulfide (H2S)	2.3
aluminum (Al)	.015
rubidium (Rb)	.02
ammonia (as N)	less than .1
manganese (Mn)	less than .02
zinc (Zn)	less than .01

*from Mariner, Presser and Evans, 1976
values in parentheses: Leonard, 1977, personal communication

faults may extend to the springs site and provide a conduit for ascension of the thermal water which probably rises to the surface from a depth of about 2 km in the underlying batholith or volcanic rocks (Fig. 17).

New Biltmore Hot Springs

New Biltmore Hot Springs (Sec28, T4S, R7W) is located along the lower Big Hole River about 10 km southwest of Twin Bridges, Montana. Shallow wells tap the thermal water; it is collected in covered concrete tanks and used to fill a swimming pool.

Hot water issues from river gravel overlying the Meagher Limestone, and probably circulates at depth in Paleozoic sedimentary rocks. A syncline whose axis plunges south toward the hot springs may allow circulation at a depth sufficient for the geothermal gradient to warm the water to the temperature observed. The Madison Limestone and Meagher Limestone are both sufficiently permeable to serve as aquifers, and they form part of the syncline. A probable NE-trending fault displaces rocks near the springs site and may be the conduit for final passage to the surface (Robert Chadwick, personal communication). A stretch of the Big Hole River at the springs may be controlled by this fault.

Water may recharge in the hills south of McCarthy Mountain at the southern extreme of the Highland Mountains. Here, water could

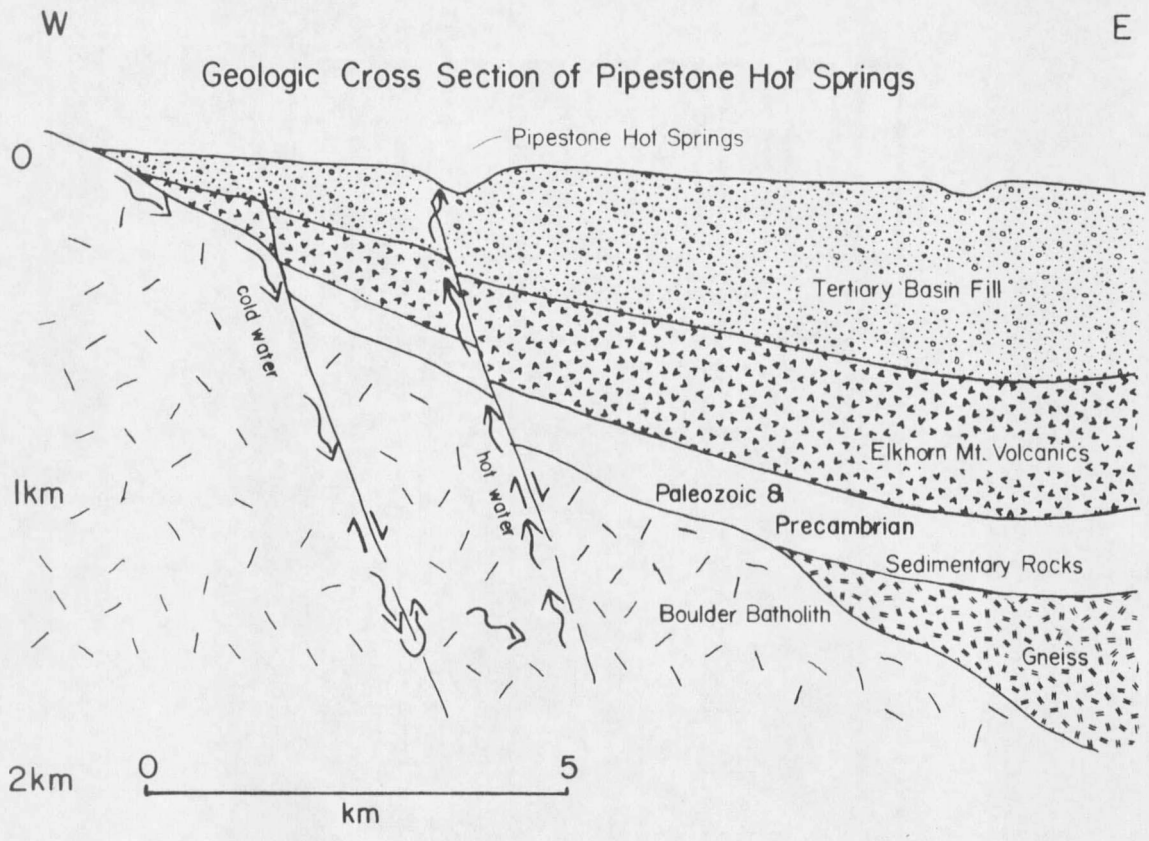


Figure 17. Diagrammatic Cross Section of Pipestone Hot Springs Showing Possible Water Circulation Paths.

percolate down the plunge of the syncline, to resurface near the river at the springs site.

Water from New Biltmore Hot Springs issues at the surface with a temperature of 53°C and an estimated discharge of more than 100 l/min. The pH is 6.8 and specific conductance is 2,160 micromhos/cm (Mariner, Presser and Evans, 1976). The water from this spring is among the most saline of any thermal waters in Montana (Table 4). Sulphate is more abundant than chloride, and calcium is more abundant than sodium. Silica, magnesium and potassium are present in lesser amounts (Mariner, Presser and Evans, 1976). In addition to the major dissolved constituents, the water also contains higher than average concentrations of minor elements, including nickel, rubidium, manganese and zinc.

The K/Na ratio is higher than average for Montana hot springs, 0.09. The NCa/Na is also higher than average, 12. The high ratios may be due to interaction of the hot water with calcareous sediments such as the Paleozoic carbonates or possibly, mafic volcanic rocks within the syncline.

The estimated thermal aquifer temperature based on the chemical composition of the water ranges from 66 to 98°C (Table 4). A low temperature reservoir is indicated.

If we assume an average annual ground water temperature of 7°C, a reservoir temperature of 75°C and a geothermal gradient of 30°C/km,

Table 4. New Biltmore Hot Springs Geochemical Data*

surface temperature	53°C
pH (field)	6.76
specific conductance (micromhos/cm)	2160
discharge	100 l/min
Estimated thermal aquifer temperature	
chalcedony	70(66)°C
quartz	98(96)°C
Na-K-1/3Ca	178(96)°C
Na-K-4/3Ca	75(96)°C
Major and trace element composition	**milligrams per liter**
silica (SiO2)	46
calcium (Ca)	290
magnesium (Mg)	73
sodium (Na)	160
potassium (K)	24
lithium (Li)	.18
alkalinity (as HCO3)	226
sulfate (SO4)	1,100
chloride (Cl)	46
fluoride (F)	3.3
boron (B)	.92
dissolved constituents	1,969
hydrogen sulfide (H2S)	1.1
aluminum (Al)	.002
rubidium (Rb)	.08
ammonia (as N)	.2
manganese (Mu)	.03
zinc (Zn)	.08

*from Mariner, Presser and Evans, 1976

then water must circulate to a depth of at least 2 km. This depth agrees roughly with the estimated depth of the plunge of the synclinal axis in the Cambrian beds beneath the springs. It seems likely, therefore, that water circulates within carbonate rock of the syncline.

CHAPTER 6

SUMMARY AND SYNTHESIS

The hot springs studied in this investigation almost certainly do not share a common reservoir. They are related by a tectonic setting in which faults are numerous and can serve as conduits for rising hot water or sinking cold water, and by being located in an area of above average crustal heat flow. The waters are of meteoric origin and are warmed by heat associated with the regional geothermal gradient.

Thermal water circulation patterns at Silver Star Hot Springs most likely utilize fractures in the Boulder batholith, though circulation in the basal portion of the basin fill sediments is not ruled out. Evidence is based on water chemistry and on analogy with other hot springs in the region. Geophysical evidence suggests that a range front fault may serve as a principal conduit for ascending thermal water, though faults west of the springs cannot be ruled out as conduits. Water would probably recharge either from the Jefferson River, or from precipitation in the Highland Mountains.

Thermal water from Renova Hot Springs emerges at the surface after circulating within folded sedimentary rocks on the flanks of the Tobacco Root Mountains. Recharge is probably from the Tobacco Root Mountains. Thermal water may circulate within the Tertiary basin fill along the Tobacco Root range front fault, but base temperature

and thermal gradient data indicate that circulation must extend deeper than the basin fill.

Pipestone Hot Springs is located in the Tertiary basin fill but water probably circulates at depth in underlying volcanics or rocks of the Boulder batholith. High angle faults on trend with the hot springs may provide a conduit for rapid ascension of the thermal water.

Hot water from New Biltmore Hot Springs probably circulates at depth in Paleozoic sedimentary rocks, descends down along the plunge of a syncline and resurfaces along a fault at the spring site.

Hot springs are relatively numerous in the upper Jefferson Valley as compared to other parts of Montana because of the deep, narrow, block faulted nature of the valley and the numerous additional faults which fracture the mountain blocks adjacent to the valley. The Mammoth-Bismark series of major northwest faults (Fig. 3, p. 23) may provide additional deep tectonic intersections in the Silver Star-Renova part of the valley. Higher thermal gradient favors hot spring development in this portion of Montana as compared to the eastern part of the state.

CHAPTER 7

ASSESSMENT OF THE GEOTHERMAL RESOURCE

The United States Geological Survey has divided hot water convection systems into three categories (Renner, White and Williams, 1975, p. 7)

1) above 150°C; these systems may be considered for generation of electricity
2) from 90°C to 150°C; these systems are attractive for space and process heating
3) below 90°C; these systems are likely to be utilized for heat only in locally favorable circumstances in the United States.

One of the springs in the study area, Silver Star Hot Springs, falls into the second category with an estimated base temperature of about 110 to 140°C (Leonard, 1977). However, the water emerges at the surface with a temperature of only 72°C and a drilling program would be necessary to tap the hotter water at depth.

As previously discussed, the water of Silver Star Hot Springs may circulate at depth within fractured crystalline rock. The reservoir storage capacity of this type of aquifer is generally considered to be quite small. It would be uneconomical to attempt to drill into the crystalline aquifer at depth because output of the system would probably not be significantly increased. However, if the thermal water resides at depth within the Tertiary basin fill, then a larger volume reservoir may be present. Proper evaluation of the geothermal potential rests upon a solution to this question.

Present usage and plans for the thermal waters are appropriate. Presently, the waters are piped downhill to a swimming pool, Barkell's Plunge. If base temperature and reservoir capacity of this geothermal system are both so low as believed, then perhaps the best use of the hot water has already been discovered . . . heating for a swimming pool or greenhouse.

The other hot springs in the study area, New Biltmore, Pipestone and Renova, have slightly lower surface temperatures in the range of 50 to 57°C. Base temperatures estimated by chalcedony quartz conductive, and Na-K-4/3Ca equilibrium geochemistry are between 58 and 115°C for New Biltmore, Pipestone and Renova. These are all low-temperature systems and appear to have only limited geothermal potential.

In order for a low temperature system to be attractive as a drilling target, it must either be near the surface or else possess a very large reservoir capacity.

Shallow cased wells to tap ascending hot water may be advised to prevent mixing with surface waters, and to insure a constant and uncontaminated supply. This has been done at Pipestone, Silver Star and New Biltmore hot springs, but Renova remains undeveloped.

The possibility of a large capacity, though low temperature geothermal reservoir at depth retains some allure as a geothermal

prospect. Present data are inadequate to direct a drilling program except on a hit-or-miss basis, but speculation on the subject may be in order.

The possibility of drilling to intercept hot water at depth in limestone may be attractive for hot springs issuing from that type of aquifer, such as Renova or New Biltmore. However, the costs involved in deep drilling are prohibitive. A detailed knowledge of water circulation and subsurface structure would be required. Water supplies in cavernous limestones are notoriously erratic. Drilling deep into a limestone aquifer to intercept hot water at depth would probably yield higher temperature water but might not significantly increase the volume of flow.

The Tertiary basin fill is an attractive geothermal prospect. As discussed earlier, the fill near Silver Star may be up to 2 km thick with base temperatures of 100°C and more. Large volume reservoirs may exist in the permeable sand or gravel layers. They constitute an attractive geothermal prospect but drilling costs may be prohibitively high. If the market value of hot water rises sufficiently, or if drilling and extraction become economical, then the hot water may be exploited some day.

CHAPTER 8

SUGGESTIONS FOR FUTURE INVESTIGATIONS

Geologic Mapping

Detailed geologic mapping in the vicinity of New Biltmore Hot Springs would help to reveal subsurface structure and water circulation patterns. This is prerequisite to further investigation of the spring system.

Geochemical Sampling

Isotope and trace element determinations of thermal and surface waters may outline recharge areas for geothermal systems. It may be possible to distinguish on this basis between recharge from the Jefferson River and recharge from precipitation in nearby uplands. Cleary (1976) was able to use sulphur isotope ratios to trace recharge of a geothermal system to volcanic rocks in nearby uplands.

Seismicity

Passive seismic monitoring of the spring areas would determine the seismicity of faults controlling the local thermal system. Microearthquake activity is generally associated with vigorous geothermal systems (Comb and Muffler, 1973), and it is believed that recurrent tectonic activity is needed to prevent sealing of conduits in fault zones by deposition of carbonate and silica. In the case of Silver Star Hot Springs, microearthquate monitoring might indicate

the presence of a range front fault which could serve as a conduit for rising thermal water.

Resistivity and Seismic

It would be interesting to search for a range front fault at Silver Star. Deep resistivity and seismic arrays stretching east from the hot springs might be able to locate a discontinuity in the bedrock configuration.

Heat Flow Holes

A knowledge of local heat flow values would provide data for a more thorough understanding of geothermal systems. A survey of heat flow values might be used to discover hidden geothermal systems. On a regional scale, heat flow might shed light on the nature of underlying basement rock.

Exploratory Drilling

In the end, drilling is the only way to find out what is actually beneath the surface. Drilling at any of the hot springs discussed in this text would provide additional information, but Silver Star Hot Springs may be the most attractive target. Drill holes to depths of 100 m at the springs site and within the resistivity low located by the Weinheiner survey would provide additional information.

Drilling to depths of perhaps 2000 m would be necessary to evaluate the possibility of a large volume reservoir of hot water at depth within the Tertiary basin fill. One might drill where the basin deepens near Silver Star, or along the range front fault at Renova or Twin Bridges. Such exploratory drilling should be preceded by deep geophysical surveys to help locate attractive targets.

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