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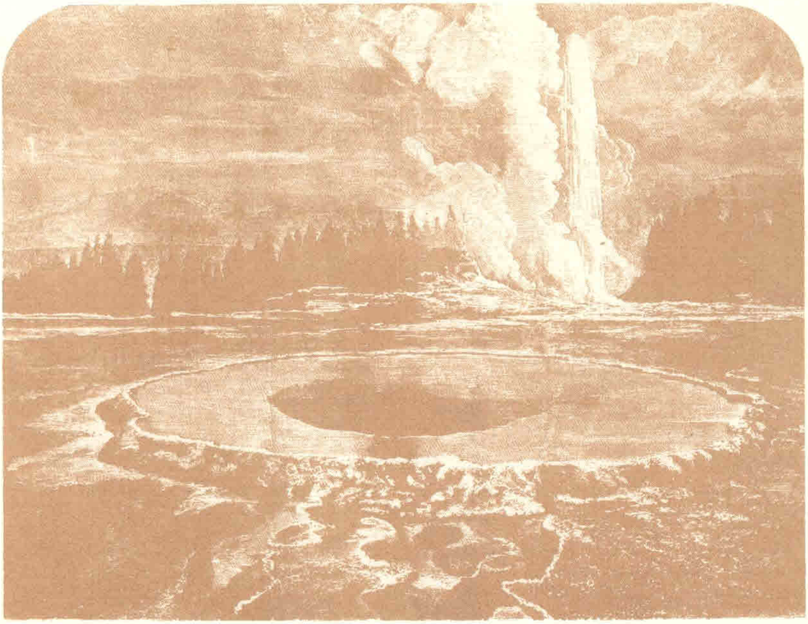
ANNOTATED BIBLIOGRAPHY OF THE GEOTHERMAL RESOURCES OF MONTANA

Compiled by
Sandra A. Rautio and John L. Sonderegger



From: Harper's Weekly, April 5, 1873.

Castle Geyser, Yellowstone National Park.

Bulletin 110 1980

Montana Bureau of Mines and Geology
A Department of
Montana College of Mineral Science and Technology

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About the cover . . . .
Castle Geyser, fronted by Crested Pool, was sketched from a William Henry Jackson photograph and appeared in Harper's Weekly on April 5, 1873. Jackson, who accompanied F. V. Hayden on the Yellowstone Expedition in 1871, wrote the following caption:

Hot Springs and Castle Geyser. The spring in the foreground is in all respects the most beautiful one in the National Park. The ornamental rim is nearly circular, being about twenty-two feet. The depth is unknown. When the rays of the sun fall nearly vertically on the almost unnaturally transparent waters, all the colors of the prism are produced. The temperature is about 180°. Just in the background is the Castle Geyser, which is so called from the form of its crater. It is really an old ruin. It seldom plays, but when in operation it is terrific power, shaking the ground for a considerable distance. It continues with great force for one to two hours.

The thermal features are located along the Firehole River in Upper Geyser Basin (approximately ½-mile walk from Old Faithful Visitor Center). [ed.]

Contents

Preface

Widespread interest in the direct use of geothermal resources is a relatively recent phenomenon, developing during the past decade as a result of shortages of more traditional energy sources. The authors' intent is to provide an annotated bibliography relating to geothermal research in Montana, representing work published as of January 1980.

Citations are listed alphabetically by the last name of the senior author. Indexing is then provided by methods of study, dominant geologic rock unit (type or age) and location. For example, a recent U.S. Geological Survey open-file report is described under the *principal author*, and is then cross indexed as a *telluric-method geophysical study*, involving *Tertiary valley fill* and *Precambrian metamorphic rock types*, and as being located near *Ennis, Montana* in *Madison County*.

The age of publications listed spans a period of 75 years, from 1905 to 1980. Items not included in the bibliography are Montana Bureau of Mines and Geology Open-File Reports 25 and 28, and Special Publication 65, which will be superseded by a forthcoming Bureau geothermal resource map of Montana, and by a future Bureau publication on the geothermal resource potential of the upper Madison and upper Centennial valleys.

If the reader is interested in an overview of the structural factors controlling the occurrence of hot springs in southwestern Montana, we strongly recommend Chadwick and Leonard (1979). For additional information concerning the geology of an area, the reader should consult other bibliographies of the geology of Montana, plus Bureau Special Publications 37, 70, 71 and 77, which are bibliographies for ground water, metallic minerals, coal and graduate theses, respectively.

Finally, we wish to thank the many researchers who provided copies of their work for our files, especially Robert Leonard, Robert Chadwick and Gerald Weinheimer, and Darrell Dunn for permission to make public his report on the drilling at White Sulphur Springs.

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Hydrogeologist
Montana Bureau of Mines and Geology

Butte
February 25, 1980

Annotated Bibliography

1 **Abdul-Malik, M. M.**, 1977, A geophysical investigation of the Silver Star area of Madison County, southwestern Montana [M.S. thesis]: Butte, Montana College of Mineral Science and Technology, 100 p.

The Silver Star area is in southwestern Montana in the southern half of sec. 1, T. 2 S., R. 6 W. Geophysical investigations also extended into sec. 6, T. 2 S., R. 5 W., sec. 12, T. 2 S., R. 6 W., and sec. 36, T. 1 S., R. 6 W. This area of approximately 3 square miles (7.8 sq. km) is included in the Jefferson River valley, which was downdropped during the Tertiary by block faulting. Several prominent faults are near the study area:

(A) The western boundary fault trends northeast through the study site and then swings northwest at the north edge of the site. The eastern part of the study site is downdropped and covered with valley-fill sediments of Tertiary and Quaternary age.

(B) The irregular Tobacco Root fault, at the west base of the Tobacco Root Mountains, forms the eastern edge of the Jefferson River valley east of the study area.

(C) The Cherry Creek fault trends northwest and intersects the western boundary fault approximately 2 miles (3 km) northwest of Silver Star. The northwest end of the Cherry Creek fault cuts Rader Creek granodiorite, a pluton of the Boulder batholith.

(D) South of the Cherry Creek fault, the Green Campbell fault strikes N. 30° W. and also intersects the western boundary fault about ¼ mile (0.4 km) southeast of Silver Star, at which point the Green Campbell fault is covered by valley sediments. The Green Campbell fault has brought Precambrian metamorphic rocks from the southwest into contact with the Rader Creek granodiorite to the northeast.

Northeast of the Green Campbell fault (within 2 miles [3 km] of the town of Silver Star), is an area in which limestone, possibly of the Madison Group (Mississippian), has been shattered by several faults. In former times, many hot springs were active in this limestone area. After activity subsided, slumping closed most of the holes and cracks. East of the contact between the limestone and Tertiary gravel is a group of active hot springs called Barkell's Hot Springs or the Silver Star Hot Springs. Barkell's Hot Springs is one of five major hot springs on a trend bearing about N. 17° E. and running 75 miles (121 km) roughly parallel to the eastern limit of the Boulder batholith.

Geophysical surveys were of two types. Galvanic resistivity soundings employing a Schlumberger array were taken at 13 stations. Instruments employed in the Schlumberger array included a DC power source, two current electrodes, two potential electrodes, a suitable receiver, meters, cable and reels. From these geoelectric data, the thickness and apparent resistivity of substrata to depths of 400 to 700 feet (122 to 213 m) were calculated and plotted on cross sections and an isopach map. Additional geophysical measurements were obtained at 37 gravity stations along two profiles, one trending east and the other northeast. Data from these stations were used to construct a hypothetical gravity map of the area.

The author suggested that the area west and northwest of the Jefferson River contains a low-resistivity layer (4 to 7 ohm-m), which is approximately 400 to 700 feet (122 to 213 m) thick near Barkell's Hot Springs, whereas the area east of the Jefferson River shows no evidence of a low-resistivity layer. Minimum measured resistivity in the eastern valley was 12 ohm-m and resistivity as great as 250 ohm-m is possible. The resistivity anomaly is supposed to extend from the hot springs area north to the Cherry Creek road, a distance of ¾ mile (1 km). Further, the resistivity anomaly seems to be related to the fracture pattern. A possible gravitational anomaly seems to be in good spatial agreement with the resistivity anomaly.

Abdul-Malik concluded that the resistivity anomaly is related to the nearby hot springs, which are near an apparent fault intersection. He further suggested that relatively hot fluids (between the measured surface temperature of 71°C and a maximum reservoir temperature of 112°C) may be available at a depth of 300 feet (90 m) or less. Study data reveal that the most likely test-well site would be near resistivity study station 11 (NW NE SW sec. 1, T. 2 S., R. 6 W.).

2 **Barger, K. E.**, 1978, Geology and thermal history of Mammoth Hot Springs, Yellowstone National Park, Wyoming: U.S. Geological Survey Bulletin 1444, 55 p., 1 pl.

Located 8 miles (13 km) south of the north entrance to Yellowstone Park, the Mammoth Hot Springs area represents a significant amount of geothermal activity. The Norris-Mammoth fault zone trends north through the area, and the collapsed Yellowstone caldera is situated to the south. Continuing hydrothermal activity in the vicinity of Mammoth Hot Springs is indicated by a myriad of travertine deposits produced by nearly 100 hot springs.

The author supplemented his study with brief descriptions of the regional geologic history and the chemical characteristics of local thermal water. Precipitation of travertine can result in several unusual formations. Among those discussed are cones, terracettes, collapse features, tension fractures, fissure ridges, solution caves, calcite "ice" and fossiliferous travertine. All thermal springs in the Mammoth area can be characterized as having extremely variable flow; an active spring may cease to flow during a period of a few days, new springs may begin abruptly and existing springs may alternate between active and inactive states. The author presented observations, including sources of water, discharges, activity histories, surface temperatures and travertine formations for 14 locations.

The author concluded that the thermal water derives its heat from partly molten magma in a fault zone beneath the Norris-Mammoth corridor. Calcium and bicarbonate absorption during circulation along the fault produces lightweight porous travertine deposits from rapid precipitation. Filling of pores in these early deposits with additional travertine is creating dense mounds of the mineral. Prolific algal growth lends colors to young travertine, whereas older deposits are white or gray. Weathering of travertine is developing soil capable of sustaining plant growth.

3 **Bowman, A. H., and Craighead, Barclay**, 1928, Montana resources and opportunities edition: State of Montana, v. 3, no. 2, p. 81-83.

Twenty-four commercially developed thermal springs were cataloged by county. The brief description of each spring includes information of historical interest, such as accessibility, accomodations and activities.

4 **Calderhead, J. H., and Holmes, O. M.**, 1900, Seventh report of agriculture, labor, and industry: State of Montana, p. 298.

This article described several developed hot springs areas that were known for their healing properties. Brief mention is made of undeveloped hot springs near the head of Sun River.

5 **Chadwick, R. A.**, 1978, Geochronology of post-Eocene rhyolitic and basaltic volcanism in southwestern Montana: Isochron/West, no. 22, p. 25-28.

This paper presented new K-Ar dates for post-Eocene volcanic rocks in southwestern Montana. Data are included on six sites of rhyolitic volcanism: the Helena volcanic field, Beaverhead field, Crater Mountain field (southwest of Drummond), northeastern Pioneer Range, Avon field and upper Madison field (1.9 to 2.0 m.y.). Basaltic volcanism at the Virginia City field, Volcano Butte (near White Sulphur Springs), Gravelly Range, Hepburn's Mesa (upper Yellowstone Valley), Sweetwater Canyon (southeast of Dillon, 4.2 to 3.8 m.y.), and the Gardiner area (1.2 ± 0.6 m.y.) is also incorporated in the study. A brief description of the extrusive body is included with the age date of the samples. Seven rock samples were dated by Geochron Laboratories, Incorporated, and two by R. L. Armstrong, University of British Columbia. A description of rock type and mineral constituents accompanies each specifically located sample.

Although both rhyolitic and basaltic volcanism reoccurred episodically in this area, the study showed no evidence that they occurred contemporaneously. The northwest-trending Montana lineament may represent a major crustal discontinuity and contains more than one episode of rhyolitic volcanism. Tensional tectonic forces that replaced earlier compressional forces may have caused rhyolitic and basaltic flows to cover older andesitic sequences. The author suggested that additional studies should explore the relationship of basaltic-rhyolitic volcanism to block faluting, and investigate the lineament as a center of post-Eocene basaltic and rhyolitic activity.

6 **Chadwick, R. A., and Leonard, R. B.**, 1977, Geothermal investigations in southwestern Montana: Status report [abs.]: *in* The Tobacco Root Geological Society 2d Annual Meeting program, Anaconda, Montana, p. 5.

Twenty-five hot springs in southwestern Montana were examined, with the cooperation and support of the U.S. Geological Survey, to improve understanding of thermal-water migration and to provide a preliminary assessment of the geothermal potential of the region. The study entailed geologic and structural mapping, hydrologic measurements, measurements of geothermal gradients in wells, chemical analyses of water, and shallow resistivity and seismic surveys.

Most springs issue from fractured igneous or metamorphic rocks or from valley-fill sediments within or marginal to fault-block valleys. Some springs are located at structural intersections such as faults or shears with open-joint systems (e.g., Potosi, Alhambra) or faults with subsidiary faults (e.g., La Duke, Chico, Renova, Wolf Creek). Other springs (Bozeman, Hunters, New Biltmore, Norris) are located along known or inferred faults, but any cross-structures are obscure. Resistivity lows are 33 to 131 feet (10 to 40 m) deep at Bozeman, Wolf Creek, Alhambra and White Sulphur Springs and may delineate fractures serving as conduits for the thermal water.

Calculations based on chemical geothermometers suggest that reservoir temperatures range from about 55° to 140°C. Observations from deep wells and mines, limited stable-isotope studies, and lack of post-Miocene igneous activity except near the southern border of the state, suggest that deep circulation of meteoric water is a major source of heat. If shallow reservoirs can be located and tapped, the thermal water may be utilized for space heating, greenhouse crop production or electric power generation using heat-exchange systems.

[Authors' abs.]

Note: This report was superseded by U.S.G.S. Open-File Report 79-1333.

7 **Chadwick, R. A., and Leonard, R. B.**, 1979, Structural controls of hot-spring systems in southwestern Montana: U.S. Geological Survey Open-File Report 79-1333, 25 p.

Twenty-five thermal springs with surface temperatures ranging from 38° to 83°C were discussed, with the major emphasis being upon the structural setting and lithologies involved. These data were conveniently summarized in a table listing spring name, location, surface-water temperature, lithology and structure(s). An introductory section summarized the regional structural setting, emphasizing the importance of the Montana lineament and the Bismark-Gardiner fault zone.

The authors believed that all of the springs included in their report result from deep circulation of ground water, predominantly in crystalline rock; suggested thermal gradients are 30°C/km for the crystalline rocks and 60°C/km for the valley sediments. The major regional controls are believed to be Cenozoic block faults, deep fractures within the crystalline rocks and major structural lineaments. The locations of the individual springs are related to (a) the intersection of faults [6 occurrences]; (b) the intersection of a fault and an anticlinal axis [3 occurrences]; (c) step faults or other intravalley faults [4 occurrences]; (d) the intersection of a fault and a sedimentary aquifer [4 occurrences]; and (e) minor faults and fracture zones in crystalline rock [8 occurrences].

The authors presented geologic sketch maps of nine hot-springs sites, the Jefferson Valley (showing four hot-springs locations), and southwestern Montana. Much of the site specific data are based upon Master's thesis work supervised by Chadwick, and discussion of these areas is emphasized. Because this timely paper brings together the work of many researchers and presents a lucid interpretation of factors controlling the locations of these springs, it is highly recommended for anyone interested in Montana's geothermal systems. Explorationists should be particularly interested in the step fault and intersection of fault and sedimentary aquifer categories.

8 **Chadwick, R. A., Weinheimer, G. J., Rose, C. C., and Boyer, C. I.,** 1978, Geophysical investigations and thermal water circulation at Hunters and Norris hot springs, Montana: Northwest Geology, v. 7, p. 26-33.

Hunters and Norris hot springs were the subjects of shallow geophysical investigations to define the geothermal potential of these systems and provide targets for drilling or additional surveys.

The authors described the methodology used in this study:

DC resistivity equipment was constructed by the Montana State University Electronics Research Laboratory using a Datel DM 2000AR potential meter and Simpson 260 current meter. Ground current is furnished by up to 22 6v rechargeable batteries, and chrome alloy stakes serve as electrodes. Using the Wenner array and the Barnes Layer method, the instrument is capable of "seeing" 100 m [328 ft.] deep. Arrays were kept parallel to power lines or other linear conductors in the vicinity. Electrode spacings were consistent with apparent depths of 20, 40, 60, 80 and 100 m [66, 131, 197, 262 and 328 ft.]. Stations were 50 m [164 ft.] apart where feasible.

The hammer seismic survey utilized a Bison Signal Enhancement Seismograph Model 1570B. A heavier hammer head (18 lb.) and extra cable permitted signal penetration to about 70 m [230 ft.] depth for the ground conditions encountered.

Hunters Hot Springs, located east of Livingston near the Yellowstone River, discharges from folded and faulted andesitic sandstone of the Livingston Group (Cretaceous). The axis of the northeast-trending Hunters anticline extends through the springs area. The authors suggested that the anticline represents a deep-seated shear zone. Norris Hot Springs, west of Bozeman and just beyond the Madison River, flows from alluvium underlain by Precambrian gneiss. Fractures in the gneiss probably provide the conduit. Although thermal water from both springs is high in sodium and bicarbonate and low in calcium, Hunters' methane content, 64 percent by volume, is unusually high for Montana spring water.

Geophysical data indicated that thermal water circulates to depths of 1.4 to 2.3 miles (2.2 to 3.7 km) at Hunters and 2 to 2.6 miles (3.2 to 4.2 km) at Norris. Conduits at both springs are provided by the intersection of major geologic structures. Estimated base temperatures for Hunters Hot Springs (surface temperature 60°C, flow 500 L/min) are 114°C (quartz), 67°C (chalcedony), and 78°C (cation). Estimated base temperatures for Norris Hot Springs (surface temperature 52.5°C, flow 400 L/min) are 130°C (quartz), 101°C (chalcedony), and 112°C (cation).

9 **Christopherson, K. R., Senterfit, R. M., Lewis, Vernon, and Dalati, Moutaz,** 1979, Telluric profiles and location map for the Broadwater Hot Springs area, Montana: U.S. Geological Survey Open-File Report 79-1670, 5 p.

A single E-field ratio telluric method profile 3.4 miles (5.5 km) in length was conducted in the vicinity of Broadwater Hot Springs, immediately west of Helena, Montana. Anomalies were found in the vicinity of the hot springs and 1 mile (1.6 km) further northeast along the traverse. These anomalies were interpreted to result from alteration and thermal waters along faults or fractures in the vicinity of the contacts (northeast and southwest) between a Tertiary quartz monzonite stock and Precambrian crystalline basement rock.

10 **Christopherson, K. R., Senterfit, R. M., Lewis, Vernon, and Dalati, Moutaz,** 1979, Telluric profiles and location map for the Ennis Hot Springs area, Montana: U.S. Geological Survey Open-File Report 79-1671, 5 p.

Two single E-field ratio telluric method profiles of 1.6 and 2.5 miles (2.5 and 4 km) in length were conducted in the vicinity of the Norris (Ennis) Hot Springs, 1.2 miles (2 km) north of Ennis, Montana. Despite noise problems, the interpretation of a thermal zone and a block fault was consistent with other data not yet published.

11 **Dunn, D. E.,** 1978, First National Bank of White Sulphur Springs thermal water well geologic report: Earth Sciences Services, Inc., Bozeman, Montana, 10 p., appendix (lithology log, pump test, temperature logs).

This report assessed the geothermal potential of a well drilled at White Sulphur Springs in central Montana. The well, drilled through the Greyson Shale (Precambrian), was 875 feet (267 m) deep and was developed to provide space heating for a local bank. A detailed description of the rocks drilled included an estimation of zones of maximum fracturing. A steep drawdown pump test was conducted. During the first 605 minutes the well was pumped at 42.8 gpm; the well was then pumped at 79.5 gpm for 400 minutes. Water-level recovery was monitored for 69 minutes. The "best" value for transmissivity (103,000 gpd/ft) was the lowest calculated value. Measurements of the temperature of thermal water discharged during pump testing indicated 119°F initially and 117°F after 136 minutes. The author regarded that decline as negligible. Water levels in three nearby locations were observed to decline a maximum of 0.11 foot during pump testing of the thermal well.

The author concluded that the well can provide approximately 50 gpm of hot water with a constant discharge temperature, as the well is probably drawing its water from a warmer source. The thermal water is most likely flowing from fractured sandstone layers between 150 and 250 feet (46 and 76 m) in depth. Temperature logs for four different dates all showed a maximum between 100 and 200 feet (30 and 61 m). Suggestions for further exploration included drilling shallow wells into the sandstone, measuring discharge temperatures and determining the approximate location of the conduit, if one exists, by additional drilling in the direction indicated by increasing well-water temperatures.

12 **Eaton, G. P., Christiansen, R. L., Iyer, H. M., Pitt, A. M., Mabey, D. R., Blank, H. R., Jr., Zietz, Isidore, and Gettings, M. E.,** 1975, Magma beneath Yellowstone National Park: Science, v. 51, no. 4190, p. 787-796.

The Yellowstone plateau volcanic field is less than 2 million years old, lies in a region of intense tectonic and hydrothermal activity, and probably has the potential for further volcanic activity. The youngest of three volcanic cycles in the field climaxed 600,000 years ago with a voluminous ash-flow eruption and the collapse of two contiguous cauldron blocks. Doming 150,000 years ago, followed by voluminous rhyolitic extrusions as recently as 70,000 years ago, and high convective heat flow at present indicate that the latest phase of volcanism may represent a new magmatic insurgence. These observations, coupled with (i) localized postglacial arcuate faulting beyond the northeast margin of the Yellowstone caldera, (ii) a major gravity low with steep bounding gradients and an amplitude regionally atypical for the elevation of the plateau, (iii) an aeromagnetic low reflecting extensive hydrothermal alteration and possibly indicating the presence of shallow material above its Curie temperature, (iv) only minor shallow seismicity within the caldera (in contrast to a high level of activity in some areas immediately outside), (v) attenuation and change of character of seismic waves crossing the caldera area, and (vi) a strong azimuthal pattern of teleseismic P-wave delays, strongly suggest that a body composed at least partly of magma underlies the region of the rhyolite plateau, including the Tertiary volcanics immediately to its northeast.

The Yellowstone field represents the active end of a system of similar volclanic foci that has migrated progressively northeastward for 15 million years along the trace of the eastern Snake River Plain (*8*). Regional aeromagnetic patterns suggest that this course was guided by the structure of the Precambrian basement. If, as suggested by several investigators (*24*), the Yellowstone magma body marks a contemporary deep mantle plume, this plume, in its motion relative to the North American plate, would appear to be "navigating" along a fundamental structure in the relatively shallow and brittle lithosphere overhead. The concept that a northeastward-propagating major crustal fracture controls the migration path of the major foci of volcanism is at least equally favored by existing data, as Smith *et al.* (*19*) noted.

[Authors' abs.]

13 **Field, M., Allen, E. T., Bartram, J. G., Bevan, Arthur, Blackwelder, Eliot, Bowie, William, Bucher, W. H., Chamberlin, R.T., Dorf, Erling, Emery, W. B., Fenneman, N. M., Jepsen, G. L. Sinclair, W. J., Thom, W. T., Jr.,** 1932, Yellowstone-Beartooth-Big Horn region: International Geological Congress 1933, 16th Session, Guidebook 24, Excursion C-2, 64 p.

The Yellowstone-Beartooth-Big Horn region is situated in south-central Montana and northwestern Wyoming between the Rocky Mountains to the west and the High Plains to the east. This guidebook contains a compilation of the geologic history, stratigraphy and structure of the entire region. Three appendices describe Paleocene and Eocene formations and faunas of the northern part of the Big Horn basin, petroleum development in the Big Horn basin, and a gravity map of the region.

Of special interest is a thorough description of the abundant hot springs within the Yellowstone Park area. Although most springs issue from rhyolitic flows in the central area of the park, a few springs are associated with limestone or with breccia of basalt and andesite fragments. It is believed that these thermal springs began flowing after the rhyolite flows were deposited (Pliocene) and previous to the last glaciation of the area. Volcanic gases, including steam, carbon dioxide, oxidized hydrogen sulfide, hydrochloric acid and hydrofluoric acid, bubble through the spring waters. E. T. Allen, author of this section, described three types of hot areas in the locale:

(A) Seventy-three percent of the Yellowstone hot water discharges from geyser basins located on the valley floors and in significant depressions that collect considerable volumes of ground water. These alkaline waters contain dissolved silica and sodium salts, small quantities of potassium, lithium and calcium salts, bicarbonate and chloride metal compounds, fluorides, borates, slight amounts of sulfates and traces of arsenates. Siliceous sinter deposits abound. Superheated steam vents are absent because of the large influx of ground water.

(B) One percent of the Yellowstone hot water flows from numerous sulfate springs on slopes, ravines and shallow depressions. These springs are characterized by dissolved metal sulfides, free sulfuric acid and traces of fluorides and chlorides. Superheated steam vents commonly occur near or within the sulfurous springs; residual quartz sand, kaolin and opal mud and precipitated sulfur surround the springs. The sulfate spring water is lower in temperature than that discharged by the alkali springs.

(C) Twenty-two percent of the Yellowstone hot water discharges from two or three springs that are depositing calcitic or aragonitic travertine. Volcanic gases are essential components at these springs.

The author concluded with brief but thorough descriptions of Mammoth Hot Springs, Roaring Mountain, Norris Basin (including description of on-site drilling by Carnegie Institution in 1930), Terrace Springs, Fountain Group, Excelsior or Midway Basin, Upper Basin and the West Thumb area along Yellowstone Lake.

14 **Galloway, M. J.,** 1977, Qualitative hydrogeologic model of thermal springs in fractured crystalline rock [M.S. thesis]: Bozeman, Montana State University, 197 p.

This paper discussed the development of a conceptual model of hydrothermal systems in crystalline rock. Because meteoric water must circulate to depths of 1.2 to 2.5 miles (2 to 4 km) to attain surface temperatures of at least 60°C and because the depth of graben-block basins in southwestern Montana is estimated at 1.2 miles (2 km) or less, Galloway suggested that thermal spring water must circulate within fractured or porous crystalline rock near or beneath the basins. This circulation model was based on extensive studies at Potosi, Boulder, Alhambra, Broadwater, Lolo, Sleeping Child and Elkhorn hot springs and the Marysville geothermal area. Each investigation encompassed regional geology; regional and site hydrology; spring discharge, temperature and piezometric pressure; geochemistry and geothermometry.

The proposed hydrothermal circulation model of southwestern Montana thermal springs includes:

(A) Recharging meteoric water percolates down through faults, fractures and weathered bedrock. Most permeable fracture zones exist below 984 feet (300 m) and remain open because of tectonic activity.

(B) Water is warmed during descent as the country rock temperature increases. Convecting systems develop along permeable fracture zones, linear fault zones and internal fracture systems of intrusive bodies.

(C) Rock expansion and subsequent failure increase permeability. Lower fluid viscosity and density upon heating contribute to increased flow. Surface expressions of hydrothermal systems may result from erosion uncovering the convection cell.

(D) Intersections of competent rock and structures such as faults or joint systems, provide conduits for ascending thermal water, which moves in response to local hydrology. Cooler ground water probably combines with thermal water.

Based upon this model, Galloway concluded that the economic potential of geothermal systems in Montana is limited by low temperatures and lack of reservoirs that have adequate permeability. The most appropriate uses for the thermal water may be local space heating and agriculture.

It should be noted that the geothermal gradient in central and western Montana averages about 1.8°F (1.0°C) per 100 feet (30 m). Hence a 55°C increase in temperature could be achieved at a depth of less than 1.2 miles (2 km). The areas studied by Galloway, however, are all believed to involve fractured bedrock reservoir systems.

15 **Gilbert, F. C.**, 1932, Mining properties near Radersburg: Mining Truth, v. 17, no. 10, p. 5.

This article describes the stratigraphy and ore zones of three mining districts north of Radersburg in southwestern Montana. The gold-producing Beaver, Indian Creek and Radersburg mining districts are situated in Broadwater County at T. 8 N., R. 1 W.; T. 7 N., R. 1 W.; and T. 5 and 6 N., R. 1 and 2 W., respectively. The author briefly described gold-bearing calcite veins deposited by hot springs in the "loose clays" of Tertiary lake beds in the southeast corner of the Radersburg district. Those veins may represent the upper part of fissure veins in the underlying andesite (Cretaceous or early Tertiary) and the final stages of incipient mineralization. Gilbert suggested that hot springs deposits of chalcedony (T. 9 N., R. 2 W.) may be similarly related to the gold deposits of the Helena district.

16 **Halvorson, J. W., and Wideman, C. J.**, 1980, A geophysical investigation of the Warm Springs, Montana, area: Montana Bureau of Mines and Geology Open-File Report 37, 11 p.

This paper contains interpretive cross sections and contoured plan map presentation of gravity and resistivity values for a study conducted at Warm Springs State Hospital. Cross sections constructed from the data suggest that a very low density for the valley-fill materials (2.0 grams per cubic centimeter) provides the most reasonable interpretation of the fault-block structures. Near-surface density distributions suggest that cementing of the valley-fill materials by the thermal water has occurred. This is supported by the deflection of resistivity contours in the vicinity of the residual gravity high.

17 **Hawe, R. G.**, 1974, A telluric current survey over two known geothermal areas [M.S. thesis]: Missoula, University of Montana, 45 p.

Geophysical resistivity surveys are commonly used in geothermal prospecting and assessments. Because probing to depths of one to three kilometers (0.6 to 1.9 mi.) can require large quantities of electrical energy, this study employed natural earth currents (telluric currents) for resistivity probes in lieu of generated electricity. Telluric currents were measured at frequencies of 8 Hz, 70 Hz and 7,000 Hz. A relative measuring device composed of two electrodes with separation of 25 to 200 feet (7.6 to 61 m) was used. Data generated by this method were compared to previous geophysical data available on the Camas Hot Springs and Marysville areas, both regarded as promising geothermal sites.

Camas Hot Springs is situated southwest of Flathead Lake in northwestern Montana. The thermal water issues approximately from the contact of the diverse Ravalli Group (Precambrian) with glacial lake deposits (Quaternary). A north-trending swarm of dominantly mafic dikes and sills (Precambrian) penetrates the country rock. Camas Hot Springs lies adjacent to the edge of one of these intrusive bodies. This study site was mapped at 70 Hz because of the low resistivity of the lake sediments. A high-resistivity anomaly coincided with a magnetic anomaly. The author interpreted his results across this anomaly to be a water-saturated clay and silt unit, which overlies normal Belt rocks; however, there exists a high-resistivity zone from depths of 1,000 to 6,000 feet (300 to 1,800 m), and a low-resistivity zone underlies it. A possible interpretation presented by Hawe is that a vapor-dominated system could exist from depths of 1,000 to 6,000 feet, and an intrusive might be beneath that zone.

Measurement of telluric currents near Marysville, northwest of Helena, constituted the second part of the research. (For a discussion of Marysville geology, see abstract of Mazzella [1973].) This area was mapped at 70 Hz and 7,000 Hz. Resistivity data input into two multiple-frequency profiles suggested two small intrusive bodies buried at a depth of approximately 2,500 feet (762 m). (Later drilling encountered only hot water at depth.)

The author concluded that the technique of using telluric currents in resistivity surveys is promising. He noted that the method is especially well suited to deep probes because it may be used at reasonable expense and requires the least time and effort.

18 **Kaczmarek, M. B.**, 1974, Geothermometry of selected Montana hot springs [M.S. thesis]: Bozeman, Montana State University, 141 p.

This thesis presented an extensive discussion on estimation of subsurface temperatures of geothermal prospects by geochemical methods. The author then applied those tools to evaluate six Montana hot springs and one Idaho hot spring.

The author located the thermal springs as follows:

Specifically, Alhambra, Boulder, and Helena Hot Springs discharge from Late Cretaceous quartz monzonite rock of the Boulder batholith; Pullers Hot Springs discharges from Quaternary and Tertiary sediments in the intermontane Ruby River Valley; Hunters Hot Springs issues from Late Cretaceous sediments on the extreme southwestern flank of the Crazy Mountains Basin; and Big Spring near Toston discharges from deformed and faulted Amsden carbonates along the margin of an intermontane basin comprising the Townsend Valley. Salmon Hot Springs in Idaho issues from Tertiary age Challis Volcanics extruded through Tertiary sediments at the southern end of the intermontane Salmon Basin.

The investigation included two segments: (1) geologic field mapping and (2) field analysis for dissolved silica and laboratory analysis of sodium, potassium, calcium, magnesium and chlorine concentrations. The author began his discussion of theory with the physical characteristics of hot springs. Included in this section are proposed sources of heat, economic potential of the system as a function of reservoir temperature, effect of geologic setting of the system and fluid phases found in geothermal systems. A thorough discussion of the chemical characteristics of hot springs details sources of dissolved solids in hydrothermal systems, equilibrium of water with wall rock in contact with the system, and finally hydrologic effects of moving water upon dissolved constituents. Dissolved silica and Na-K-Ca hydrogeothermometers were then applied to geochemical data to estimate the reservoir temperature of the hydrothermal system. The author explained the use of those methods in extensive detail.

This investigation clarified the geothermal potential of seven prospects:

(A) Alhambra Hot Springs thermal water seems to circulate in an unconfined fractured area in the Cretaceous Boulder batholith. [Surface temperature 54°C, flow 500+ gpm, reservoir temperature estimated at 103°C (SiO_2) and 162°C (Na-K-Ca).]

(B) Boulder Hot Springs thermal water, which probably circulates in an unconfined reservoir, utilizes a joint system in the Boulder batholith to ascend to the surface. [Surface temperature 75°C, flow 1,000+ gpm, reservoir temperature estimated at 111°C (SiO_2) and 81°C (Na-K-Ca).]

(C) Helena Hot Springs water discharges from a joint system in a quartz monzonite intrusive mass overlain by Quaternary alluvium. [Surface temperature 63°C, flow 30 gpm, reservoir temperature estimated at 108°C (SiO_2) and 92°C (Na-K-Ca).]

(D) Pullers Hot Springs thermal water may be circulating in fractured basement rocks underlying the Ruby River valley graben block and rising to the surface through a fault, which is supposed to cut both basement rocks and Tertiary valley fill. [Surface temperature 43°C, flow 150 gpm, reservoir temperature estimated at 60°C (SiO_2) and 173°C (Na-K-Ca).]

(E) Hunters Hot Springs includes nine main springs and ten smaller springs, which flow from the Livingston Formation (Upper Cretaceous). The author suggested that the geothermal water circulates in a confined aquifer between 5,700 and 6,800 feet (1,737 and 2,073 m) below the surface. Four possible host formations are the Lakota Sandstone, Swift Formation, Quadrant Formation and the Madison Group. [Surface temperature 60°C, flow 1,500 gpm, reservoir temperature estimated at 104°C (SiO_2) and 41°C (Na-K-Ca).]

(F) Big Spring thermal water issues from the upper carbonate member of the Amsden Formation (Mississippian) and probably circulates within the Amsden Formation on the west-dipping flank of a north-trending anticline. [Surface temperature 15.5°C, flow 29,000 gpm, reservoir temperature estimated at 15.5°C (SiO_2) and 18°C (Na-K-Ca).]

(G) Located in Idaho, Salmon Hot Springs flows from an unconfined reservoir in fractured volcanic rocks. [Surface temperature 45°C, flow 145 gpm, reservoir temperature estimated at 79°C (SiO_2) and 204°C (Na-K-Ca).]

The author concluded that the silica hydrogeothermometer provided the best estimate of reservoir temperatures because silica is not being precipitated or assimilated by the thermal water. Cold-water dilution, which limits the reliability of the silica hydrogeothermometer, must be considered in the evaluation of data from these springs. Base temperatures calculated for the reservoirs suggest the division of Montana hot springs into two groups: (1) lower base temperatures, which are 8° to 10°C above local mean annual temperatures, and (2) higher base temperatures between 100° and 120°C. The author believed the source of energy for these thermal systems to be the geothermal gradient and presented data on heat flow in the Boulder batholith area.

The reader should be aware that the author used the quartz version of the silica geothermometer and that at higher silica concentrations, the author's silica values were significantly lower than those of other researchers. Consequently, the reader is referred to U.S.G.S. Open-File Report 78-438 for additional chemical analyses and discharge measurements, and to U.S.G.S. Circular 726 for alternate calculations of reservoir temperatures.

19 **Lawrence, Stan**, 1978, A gravity investigation of the Gregson Hot Springs of Silver Bow County, southwestern Montana: Department of Physics and Geophysical Engineering, Montana College of Mineral Science and Technology, Butte, 16 p.

This study, undertaken as an exercise in geophysical prospecting, yielded information that may shed light on the occurrence of Gregson Hot Springs, an interesting geothermal prospect in southwestern Montana.

The study area is located in the southern end of the Deer Lodge valley. The valley results from a north-trending graben structure and contains Quaternary alluvium and Tertiary sediments to depths as great as 5,000 feet (1,524 m). To the east and south of the valley is the Boulder batholith (Late Cretaceous) and its associated Elkhorn Mountains volcanics. West of the study area is the Flint Creek mountain range, composed of various formations including Precambrian, Paleozoic and Mesozoic sedimentary units, which have been intruded by Tertiary igneous bodies.

The initial phase of the investigation involved leveling of the 73 gravity stations. Gravity measurements were made with a Worden Gravity Meter (sensitivity 0.4017 mgal/division and dial range of 321.4 mgal). Reductions applied to gravity data included drift corrections, latitude corrections, free-air corrections, Bouguer corrections, terrain corrections and removal of the effects of the Boulder batholith's deep roots. A residual gravity map was constructed from the data.

The author concluded that the anomalous gravity high found in the Gregson area may be produced by precipitation of solids from rising thermal water. This may be compared to a gravity low associated with the structural basement of the Deer Lodge valley. The author suggested that a fracture system would allow water to circulate to great depths where it is warmed. Recharge water probably flows from higher units farther south.

[Gregson Hot Springs: surface temperature 68° to 70°C, flow 10 to 69 gpm.]

20 **Lawson, D. C., and Sonderegger, J. L.**, 1978, Geothermal data-base study: Mine-water temperatures: Montana Bureau of Mines and Geology Special Publication 79, 38 p.

Investigation of about 1,600 mines and prospects for perennial discharge resulted in the measurement of temperature, pH, specific conductance and discharge at 80 sites, to provide information for a geothermal data base. Measurements were made in the fall, winter and late spring or early summer to provide information about seasonal variability. None of the temperatures measured exceeded the mean annual air temperature by 15°F, but three areas were noted where discharges were anomalously warm, based upon high temperatures, slight temperature variation and quantity of discharge.

The most promising area, at the Gold Bug mine in the Little Rockies, discharges water averaging 7.3°C (12.1°F) above the mean annual air temperature. The discharge may represent water heated during circulation within the syenite intrusive body. If the syenite is enriched with uranium and thorium, an abnormal amount of heat would be produced by radioactive decay. Alternatively, the water may move through deep permeable sedimentary strata, such as the Madison Group, and be discharged to the surface through fractures in the pluton.

[Authors' abs.]

21 **Leonard, R. B., Broston, T. M., and Midtlyng, N. A.**, 1978, Selected data from thermal-spring areas, southwestern Montana: U.S. Geological Survey Open-File Report 78-438, 71 p.

This report consists of data collected at 24 thermal springs and three deep wells where water temperatures exceeded 38°C. Collection sites were located in the Bitterroot River basin, Clark Fork River basin, Big Hole River basin, Beaverhead River basin, Ruby River basin, Jefferson River basin, Madison River basin, Gallatin River basin, upper Missouri River basin, Smith River basin, Yellowstone River basin, the abandoned Ringling oil test well (flowing), the abandoned Lucas oil test well (flowing), and the Marysville geothermal test well.

Each of the first 27 tables contains detailed chemical characteristics of the thermal water at one research site. The next table consists of composition of gases escaping from thermal springs and wells. Oxygen plus argon, nitrogen, methane, carbon dioxide and ethane quantities are included in this analysis. Hydrogen and oxygen isotope ratios and gross alpha and gross beta activity of selected thermal and cool waters are reported in tabular form. Finally, a supplementary table contains subsurface temperatures of selected water wells near thermal spring sites.

This open-file report is part of an assessment of geothermal resources of southwestern Montana. The user should be cautioned that both air and water temperatures are included in the last table, and a check of the water level is advised.

22 **Leonard, R. B., and Janzer, V. J.**, 1978, Natural radioactivity in geothermal waters, Alhambra Hot Springs and nearby areas, Jefferson County, Montana: U.S. Geological Survey Journal of Research, v. 6, no. 4, p. 529-539.

Located about 10 miles (16 km) south of Helena in southwestern Montana, Alhambra Hot Springs issues from the jointed, faulted perimeter of the Boulder batholith. The investigators studied the anomalously high radioactivity of thermal water from three hot-springs groups, several seepage zones, a flowing hot-water well in the Alhambra area, and at Broadwater Hot Springs west of Helena.

Thermal water samples were analyzed for dissolved uranium, radium-226, radon-222, potassium-40, gross alpha and gross beta concentrations, specific conductance, sum of dissolved solids and sodium-adsorption ratios.

The authors concluded that:

(A) High levels of radioactivity occur at Alhambra Hot Springs in the discharges from springs and flowing wells, in calcareous incrustations around the springs and in silicified zones and chalcedony veins in associated crystalline intrusive rock. High levels of radioactivity are not characteristic of hot springs that issue from fractured crystalline rock in Montana.

(B) The thorium and uranium concentrations of the type of acid igneous rocks exposed near the hot springs are higher than the average for the Boulder batholith. The predominance of thorium suggests that a toxic beta-emitting daughter, radium-228, is present in the thermal water.

(C) Gross alpha and beta activities and the concentrations of radium-226 in thermal water from springs and flowing wells exceed recommended maximum permissible levels of the U.S. Environmental Protection Agency (1976) for drinking water. High concentrations of radon are dissolved in the water and mixed with other gases at several sites.

(D) In general, gross alpha and gross beta activities determined by the Survey exceeded the values reported for corresponding samples by the Montana Department of Health and Environmental Sciences. Both laboratories verified anomalously high levels of radioactivity at the same sites, and the results were normally proportional. The discrepancies may be attributable to differences in calibration-isotope solutions and analytical procedures.

(E) Fractures associated with the Alhambra fault seem to act as conduits for ascending thermal water that was heated by deep circulation along a thermal gradient of about 21°C/km.

(F) The chemical composition of the water ranges from the calcium-bicarbonate type in surface and shallow ground water to more highly radioactive thermal water of the sodium-bicarbonate type with increases in temperature, concentrations of dissolved solids and silica and sodium-adsorption ratio.

(G) Under atmospheric conditions, some of the thermal water is supersaturated with respect to calcium carbonate and carbon dioxide gas. Reactions of dissolved carbon dioxide with rocks in the subsurface probably have released the sodium and calcium ions and produced bicarbonate ion in the water.

(H) Loss of carbon dioxide by ascending thermal water caused deposition of radioactive travertine at the surface and probably in the subsurface.

(I) Radium-226 is the source of radon-222 that is dissolved in the thermal water and discharged with other gases from several springs and wells. The radium-226 probably formed as a decay product of thorium-230 sorbed on fracture surfaces and coprecipitated with calcium carbonate.

(J) Dissolution of radioactive chalcedony at depth probably accounts for most of the radioactivity and part of the dissolved silica in the thermal water.

(K) The reservoir temperature probably is less than 110°C, but could be as high as 160°C.

23 **Leonard, R. B., Shields, R. R., and Midtlyng, N. A.**, 1978, Water-quality investigation near the Chico and Hunters geothermal lease-application areas, Park and Sweet Grass counties, Montana: U.S. Geological Survey Open-File Report 78-199, 23 p.

Water quality in and adjacent to the Chico and Hunters geothermal lease-application areas was investigated during two surveys, in October 1976 and April 1977, periods when high to low base flow of the Yellowstone River and its tributaries was representative of natural baseline conditions. The percentage composition of the sampled water at each site remained relatively constant from survey to survey, although the concentrations of dissolved solids and rates of streamflow differed.

The discharges of Chico Hot Springs, the Yellowstone River and tributaries in the Chico area are generally suitable for drinking water and irrigation with respect to inorganic constituents. With the exception of fluoride and hydrogen sulfide, the major and trace chemical constituents in samples from Hunters Hot Springs and Hunters Creek do not exceed maximum contaminant levels specified for drinking water by the U.S. Environmental Protection Agency. The discharge of Hunters Hot Springs presents very high sodium and medium salinity hazards for irrigation.

The effects of the hot springs and of individual tributaries that drain the proposed lease areas on streamflow and chemical discharge of the Yellowstone River during the surveys, were negligible and less than the accepted error of the measurements. Larger volumes of more concentrated thermal water can be expected to accompany testing and development of the geothermal resource. The potential effect of releases of geothermal water on the receiving streams can be estimated from preliminary test data by using the methods described in this report to compare then-existing conditions with the baseline conditions described herein.

[Authors' summary]

24 **Lewis, R. J. G.**, 1970, Magnetotelluric studies in Montana and Wyoming [Ph.D. dissertation]: Princeton, New Jersey, Princeton University, 91 p.

Part I

In late summer and fall of 1968, magnetotelluric observations were made at nine sites along a 124-mile (200-km) traverse extending north from the southern boundary of Yellowstone Park. In all cases records of three components of the magnetic field were obtained on digital magnetic tape.

Magnetic-field fluctuations were observed with induction coils and electric fields measured on an L-shaped electrode array with 1,640-foot (500-m) sides.

Data in the period range from 13 to 1000 seconds, have been analyzed for five sites with the higher frequency analysis to be performed. These sites include one in a geyser basin and one outside the obviously active thermal areas. The analysis includes the computation of scalar and tensor impedances, actual and predicted coherences, tensor skewness estimates and the derivation of principal axes and apparent resistivities.

With the exception of the site in the geyser basin, the tensor skewnesses are high, being typically of the order of 0.3; predicted E coherences are in general low, 0.5 being typical with some notable values exceeding 0.9. In addition, coherence between orthogonal H components is generally high, frequently reaching 0.6. These characteristics indicate that the data quality is generally low as far as two-dimensional analysis is concerned.

The observed apparent resistivities span a wide range. The apparent resistivities invariably fall with increasing period. At 13-second periods, the range is 4,000 to 20 ohm meter; at 100-second periods the range is 10 to 0.1 ohm meter. The two principal apparent resistivities differ by up to three orders of magnitude for sites outside the geyser basins. Results from within a geyser basin indicate isotropic conductivity. This is attributed to a joint or fracture pattern filled with highly conductive fluids. The isotropy in the geyser basin is attributed to the ubiquitous presence of such fluids. The principal axes of the resistivity tensors within the thermal area have a consistent orientation with one axis on about N. 30° W. (magnetic). The site outside the thermal area in the Gallatin Range has the corresponding principal axis on magnetic north.

The results indicate that the active thermal areas are characterized by isotropy, while the less active areas yield results largely controlled by fracture patterns. The observed apparent resistivities cover the ranges of other observations further to the north and south, but also include substantially lower values, which may be associated with thermal activity. In terms of defining resistivity anomalies caused by thermal effects, the data are inconclusive.

Part II

An operating digital field system for magnetotellurics is described, together with a system for later processing and editing of the data so obtained.

The field system is a general-purpose instrument whose operation is controlled by a small computer (PDP-8/S), so that different experiments may be conducted by merely changing the control program. It provides great flexibility in gathering and editing of large quantities of high-quality data in a form amenable to automatic analysis. Typical field-data rates are 30 samples/channel/second with a passband of 0.0003 to 10.0 Hz and about 150,000,000 bits of data per field site written on IBM compatible digital tape.

Data reduction is carried out on a large-scale system (IBM 360/91). A comprehensive set of programs for transcription, editing and simple analysis has been developed for this machine. The editing facilities include interactive graphics methods using a CRT terminal. Before analysis, the data are filtered and decimated to reduce the quantity to manageable proportions. Analysis includes the computation of cross spectra, tensor impedances, Cagniard scalar impedances and various figures of merit based on interchannel coherence and the trace of the impedance tensor.

[Author's abs.]

25 **Long, C. L., and Senterfit, R. M.**, 1979, Audio-magnetotelluric data log and station-location map for the Ennis Hot Springs area, Montana: U.S. Geological Survey Open-File Report 79-1308, 7 p.

This is a basic-data report. The authors' brief text is as follows:

Four days were spent collecting 20 audio-magnetotelluric (AMT) soundings in the area of the Ennis Hot Springs, Mont. (fig. 1). These soundings were made to assist in a regional evaluation of the geothermal potential of the Ennis Hot Springs area.

Scalar resistivities from the data log (table 1) are indicative of thermal water altering the Quaternary alluvium to the southeast. The alteration extends over an area of 1.5 by 4 km [1 by 2.5 mi.]. The geothermal system is probably along a north-south range fault between the Precambrian gneiss and the Tertiary gravels. The scalar resistivities also indicate a northwest trend that may be an intersecting fault. Therefore any geothermal potential would probably be in the area near the existing hot spring, with a possible extent to the northwest of 1 km [0.6 mi.] and to the southeast some 3 km [1.9 mi.].

26 **Long, C. L., and Senterfit, R. M.**, 1979, Audio-magnetotelluric data log and station-location map for the Silver Star Hot Springs area, Montana: U.S. Geological Survey Open-File Report 79-1307, 8 p.

This is a basic-data report. The authors' brief text is as follows:

During a period of 3 days, 22 audio-magnetotelluric (AMT) soundings were made in the area of the Silver Star Hot Springs, Mont. (fig. 1). These soundings were made to assess the geothermal potential along a northern trend of hot springs from New Biltmore Hot Springs north to Broadwater Hot Springs, Mont.

Scalar resistivities from the data log (table 1) show that thermal waters have probably altered the Cenozoic basin fill to the northeast for at least 4 to 5 km [2.5 to 3 mi.]. Leakage of the geothermal system to the surface is probably taking place along a range-front fault at the contacts between the Precambrian metamorphics on the west and the Cenozoic basin fill on the east. Any potential geothermal system would probably be in the area near the existing hot springs or within a few kilometers to the north or northeast.

27 **Mariner, R. H., Presser, T. S., and Evans, W. C.**, 1976, Chemical characteristics of the major thermal springs of Montana: U.S. Geological Survey Open-File Report 76-480, 31 p.

Fourteen of the 21 sampled springs are apparently associated with low-temperature thermal systems (≤100°C). In these low-temperature systems (Lolo, Sleeping Child, Medicine, New Biltmore, Pipestone, Elkhorn, Potosi, Bozeman, Chico, Warm Springs, Camas, Hunters, Broadwater and La Duke hot springs), the silica concentration may be controlled by the solubility of chalcedony rather than quartz. Jardine and White Sulphur hot springs have several characteristics typical of mixed waters: they issue at temperatures below boiling; they have reservoir-temperature estimates, based on quartz, that are less than the accompanying cation geothermometer; and the cation geothermometer indicates a temperature markedly above the spring temperature. Boulder, Silver Star, Norris, Alhambra and Gregson hot springs could issue mixed waters or conductively cooled water from low-temperature reservoirs. The apparent agreement between the silica (chalcedony) and cation geothermometers, along with the nitrogen gas discharging at most of these hot springs, could indicate that they are associated with low-temperature systems. Even if equilibrium with quartz rather than chalcedony is controlling the silica concentrations, the springs are still associated with low-temperature aquifers (110° to 150°C). The apparent equilibrium of the more concentrated waters with fluorite may indicate that only Jardine has been appreciably diluted.

Based on this limited sampling, the hot springs of Montana do not appear to have potential for power generation. Additional work is desirable at Jardine and White Sulphur hot springs, and perhaps Boulder, Silver Star, Norris, Alhambra and Gregson hot springs.

28 **Mazzella, F. E.**, 1973, A thermal and gravity model of a geothermal anomaly near Marysville, Montana [M.S. thesis]: Dallas, Texas, Southern Methodist University, 35 p.

Extremely high geothermal gradients have been noted in the area of Marysville, Montana. The author of this thesis tested the hypothesis that the source for the excess heat is a recently emplaced magma chamber.

Marysville, located approximately 19 miles (30 km) northwest of Helena, occupies a section of the Montana lineament. In this area, the Marysville stock, a granodiorite of Cretaceous age, is surrounded by rocks of the Belt Supergroup (Precambrian). Several outcrops of Tertiary volcanic rocks are scattered through the study area, and Paleozoic and Mesozoic sedimentary units overlap the Belt Supergroup a few kilometers southwest of Marysville. The geothermal area is dissected by many faults; four of the more prominent faults trend northwest, while the others trend northeast.

The investigation employed two methods: (1) a gravity survey and (2) computer construction of thermal and gravity models. The gravity survey included 210 stations.

Data were used to construct maps of the complete Bouguer anomaly and the residual anomaly. The author made use of available geothermal gradient measurements (Blackwell) to define the thermal anomaly. The maximum measured geothermal gradient coincides with the residual gravity low. Computer modeling on these data produced a final body having an initial temperature of 800° ± 40°C and minimum depth of emplacement of 0.9 ± 0.03 mile (1.45 ± 0.05 km). The intrusive body is probably granitic and has a density of 2.55 ± 0.02 gm/cm^3 and volume of 124 cubic miles (200 km^3). Time since emplacement was estimated at 14,500 ± 300 years.

The results of later drilling, which encountered hot water rather than the hot dry rock used in the modeling calculations, severely limit the value of the interpretive portion of this thesis.

29 **McKay, Harold**, 1977, Hot springs and spas in the United States and Canada: McKay and Associates, Las Vegas, Nevada, 72 p.

This publication is a guidebook of resort and camping facilities associated with warm and hot springs.

30 **McSpadden, W. R.**, 1975, The Marysville, Montana, geothermal project final report: U.S. Energy Research and Development Administration, issued by Battelle Pacific Northwest Laboratories, Richland, Washington, 337 p.

This report summarized two years of intensive geothermal exploration conducted near Marysville, Montana. Anomalous heat-flow values ranging from 3.1 to 19.5 heat-flow units were recorded in an elliptical region 3 miles (4.8 km) long by 1.5 miles (2.4 km) wide. Exploration methods utilized during drilling to a depth of 6,790 feet (2,070 m) included coring, logging of hole dimensions, formation resistivity, formation density and porosity, hydrogen concentration, cement bonding, natural radioactivity, fracture patterns, hole deviation from vertical, temperature and water flow. The study also made use of thermodynamic computer simulation of drilling, an infrared study, geological mapping and geophysical surveys.

Although the researchers hoped to encounter hot dry rock, temperatures did not exceed 204°F. Water flow in the hole reached 250 gpm before casing was installed. The geothermal system probably consists of meteoric water circulating deep within the fractured Empire stock. The authors concluded that the geothermal anomaly may be associated with a zone of seismic activity extending southeast toward Helena.

31 **Muffler, L. J. P.**, 1979, Assessment of geothermal resources of the United States—1978: U.S. Geological Survey Circular 790, 163 p.

This circular evaluated geothermal energy potential on the basis of information that was not available when the earlier U.S. Geological Survey Circular 726 was published. The five discussions include conduction-dominated regimes, igneous-related systems, high- and intermediate-temperature convection systems, low-temperature systems and geopressured-geothermal energy (thermal energy and energy from dissolved methane). Several Montana hydrothermal areas are included in a tabular collection of hot-water convection systems. Location, estimated mean reservoir temperature, mean reservoir volume and mean reservoir thermal-energy data complete the table. Fourteen Montana sites are proposed as areas favorable for geothermal research and development. The statistical assessment of these sites includes number, depth and temperature of thermal wells considered for development; number and temperature of thermal springs on the site; thermal gradients; equilibration temperature; dissolved solids; constraints on circulation; and additional comments.

32 **O'Haire, D. P.**, 1977, Geology and hydrology of hot springs in the Jefferson valley, Montana [M.S. thesis]: Bozeman, Montana State University, 100 p.

This thesis described geophysical and geological investigations in the Jefferson valley of southwest Montana at four hot springs sites—Silver Star, Renova, Pipestone and New Biltmore. The Jefferson valley, a broad block-faulted basin filled with as much as 6,560 feet (2,000 m) of Cenozoic sediments, trends northeast. The irregular Tobacco Root fault forms the valley's eastern contact with the Tobacco Root Mountains. Faulted Paleozoic and Mesozoic sedimentary deposits and intensely deformed Precambrian gneiss and schist surround the Tobacco Root batholith. Renova Hot Springs is near the northwest extremity of the Tobacco Root complex. Those geothermal springs issue from the Meagher Limestone and flow directly into the Jefferson River. They are close to the intersection of the Tobacco Root fault and a west-trending fault that cuts through a series of radiating thrusts in the strata north of the Tobacco Root batholith. Pipestone Hot Springs, approximately 9 miles (14 km) northwest of Renova, is on the valley's northwestern perimeter east of the outcrop of the Boulder batholith. In that location, Tertiary sand, gravel and ash surround the hot springs area, and Tertiary volcanic extrusive rocks cover the nearby batholith. A valley-margin fault is thought to follow the Boulder batholith-Jefferson valley contact. Silver Star Hot Springs occupies an intensely fractured area about 13.5 miles (22 km) south of Pipestone. [Geology of the Silver Star area is discussed in the abstract of Abdul-Malik (1977).] Nineteen miles (30 km) southwest of Silver Star, New Biltmore Hot Springs issues from the southern edge of a small outcrop of Paleozoic sedimentary rocks, which are surrounded by Cenozoic sand, gravel and ash and Quaternary alluvium.

O'Haire presented extensive investigations in the Silver Star area, including detailed geologic mapping of the area. Geochemical data include surface temperature, 72°C; pH, 7.6; specific conductance, 917 micromhos/cm; discharge, 160 L/min; estimated thermal aquifer temperature based on chalcedony, quartz and Na-K-Ca geothermometers, 109° to 143°C; analyses for silica, calcium, magnesium, sodium, potassium, lithium, alkalinity, sulfate, chloride, fluoride and boron. O'Haire discussed earlier geophysical work, including a regional gravity survey and a soil-temperature survey. A hammer-seismograph survey used a Bison signal-enhancement hammer seismograph and an 18-lb. hammer. Data were combined into four profiles. Resistivity surveys utilized chrome-steel stakes in a Wenner configuration, dry-cell batteries and a DC resistivity meter. The author postulated two circulation models based on geophysical results and the geochemistry of the water.

The geology of the Renova study site was remapped by O'Haire. Included are several geologic cross sections and a degree-of-alteration overlay map. Geochemical data include surface temperature, 50°C; pH, 7.5; specific conductance, 1,100 micromhos/cm; discharge, 150 L/min; estimated thermal aquifer temperature based on chalcedony, quartz and Na-K-Ca geothermometers, 58° to 92°C; chemical analyses for silica, calcium, magnesium, sodium, potassium, lithium, alkalinity, sulfate, chloride, fluoride and boron. Geophysical studies include hammer-seismograph and resistivity-profile surveys. O'Haire suggested three possible routes for water circulation.

Pipestone Hot Springs (surface temperature, 57°C; reservoir temperature estimated 72° to 115°C) and New Biltmore Hot Springs (surface temperature, 53°C; reservoir temperature estimated 70° to 178°C) are analyzed in a manner similar to the previous discussions. Brief reconnaissance geology was done in those two areas.

O'Haire concluded (1) these four thermal springs almost certainly do not share the same reservoir but are related by numerous faults, which may provide conduits for circulation of water; (2) the use of hot water for space heating and bathing is the most appropriate use at the present time; (3) although thermal reservoirs in igneous rock are probably not economical exploration choices, O'Haire suggested that with technological advances, Tertiary basin fill may present promising geothermal prospects. Additionally, Silver Star and New Biltmore were considered for commercial greenhouse operations during 1978.

33 **Petefish, D. M.**, 1975, Metamorphism of the Marysville geothermal area, Marysville, Montana [M.S. thesis]: Dallas, Texas, Southern Methodist University, 46 p.

Epizonal stocks intrude Precambrian formations, creating contact-metamorphic aureoles in the vicinity of Marysville. The Marysville district has been designated as a KGRA—Known Geothermal Resource Area. Dates of intrusion for the Marysville, Bald Butte, Silver City and Empire stocks are 79, 48, 43 and 40 m.y., respectively. Maximum temperatures and pressures during metamorphism are calculated to be Marysville, 550°C, 1,000 bars; Bald Butte, 450°C, 700 bars; Silver City, 500°C, 1,000 bars; Empire, 475°C, 700 bars.

Maximum geothermal gradients developed were calculated to be at least 125°C/km over the Marysville and Silver City stocks, and greater than 200°C/km over the Bald Butte and Empire stocks. Uranium, thorium and potassium determinations were made on 36 samples from stocks, dikes and volcanic rocks, and heat-generation values were calculated and plotted. Emphasis was on the Silver City stock (average heat generation 3.2 cal x cm^{-3} x sec^{-1}), related dikes and similar intrusions.

34 **Robertson, E. C., Fournier, R. O., and Strong, C. P.**, 1976, Hydrothermal activity in southwestern Montana: *in* Proceedings—Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, p. 553-561.

Temperature measurements of 14 hot springs were made yearly from 1966 to 1974; since 1970, measurements have had a precision of 0.01°C. Temperatures range from 45° to 78°C; monthly measurements for 1½ years showed no seasonal fluctuations. Six nearly constant temperature springs varied only ± 0.4°C from 1970 to 1974; six other springs changed by an average of 1.1°C. Estimated discharges ranged from 0.6 to 60 L/sec; no seasonal effect was found. Chemical compositions of the spring waters remained nearly constant between 1967 and 1974. Silica temperatures obtained from dissolved quartz afford minimum temperature estimates of subterranean water; they range from 59° to 161° C; the changes in silica temperature from 1967 to 1974 ranged from −2.4° to +1.8°C; chalcedony and Na-K-Ca temperatures give similar results. A linear relation was found between surface and quartz temperatures: $T_S = 0.52\ T_Q$; this relation is useful in evaluating the deep hydrology of hot springs.

A 198-mile (320-km) alignment at N. 79° E. and a 74-mile (120-km) alignment at N. 17° E. of hot springs are along inferred fault zones; a poorly defined northwest-trending zone of hot springs is roughly along a seismically active zone. Circulation in the breccia of the faults is estimated to reach depths of 2 to 3 miles (3 to 5 km).

[Authors' abs.]

35 **Senterfit, R. M.**, 1980, Principal facts for a gravity survey of the Ennis, Montana, geothermal area: U.S. Geological Survey Open-File Report 80-98, 8 p.

This report presented, in a tabular format, the basic gravity data collected at Ennis, Montana. Information provided includes:

1. Station identification number
2. Latitude
3. Longitude
4. Elevation
5. Observed gravity reading, in milligals
6. Theoretical gravity reading, in milligals
7. Terrain correction, in milligals
8. Bouguer correction, in milligals
9. Curvature correction, in milligals
10. Free-air anomaly, in milligals
11. Bouguer anomaly, in milligals

There is also a station location map (scale 1:62,500). The density values used in the calculation procedures are not clear. One of the two columns for item (11) was calculated using a density of 2.67 gm/cm^3. The second column in the computer printout (table 1), however, uses 2.45 gm/cm^3, while the text claims that a value of 2.50 gm/cm^3 was used.

36 **Sobotka, Harry, and Reiner, Miriam**, 1941, Chemical composition of a lithia spring near McLeod, Montana: American Journal of Science, v. 239, no. 5, p. 383-385.

Sobotka and Reiner reported a temperature of 70°F and a discharge of 45 gallons per minute (gpm). This report provided an early chemical analysis of the calcium bicarbonate-magnesium sulfate spring water, which contained a considerable amount of lithia. The report contained a tabular arrangement of chemical data and a list of nine additional springs that showed significant lithium content.

Recent investigations by the Montana Bureau of Mines and Geology identified the Madison Group (Mississippian limestone) as the source of the water, with a temperature of 77°F and a discharge of 75 gpm.

37 **Stearns, N. D., Stearns, H. T., and Waring, G. A.**, 1937, Thermal springs in the United States: U.S. Geological Survey Water-Supply Paper 679-B, p. 59-191, pl. 7-14.

This paper contained a tabular listing of locations, geology, temperature and approximate discharges of 1,060 thermal springs. An annotated bibliography arranged by states supplemented the data. The authors preceded the data with a comprehensive discussion of the theory of hydrothermal systems, including water and heat sources, relation to geologic structure and approximate age of thermal springs.

The springs, located within the continental United States, were grouped according to eight physiographic regions. Of special interest are the northern Rocky Mountain province, Wyoming basin province and southern Rocky Mountain province. Geology, structure and geography supplemented the discussion of selected major hot-springs groups in these regions. Four maps of spring distributions and one cross section through hot springs at Thermopolis, Wyoming, were included.

38 **Struhsacker, E. M.**, 1976, Geothermal systems of the Corwin Springs-Gardiner area, Montana: Possible structural and lithologic controls [M.S. thesis]: Bozeman, Montana State University, 93 p.

The Corwin Springs-Gardiner area of southwestern Montana lies just beyond the northwest corner of Yellowstone Park. Significant hydrogeothermal activity, although less than that in the neighboring park, has been observed in the Corwin Springs-Gardiner area. This study attempted to explain the structural and lithologic controls on the hydrothermal system through geologic considerations.

Metamorphosed pre-Belt formations (Precambrian) crop out extensively north and west of Gardiner. The northwest-trending northeast-dipping Gardiner reverse fault has elevated these pre-Belt formations to the surface, requiring the erosion of nearly 10,000 feet (3,048 m) of Paleozoic and Mesozoic strata. Several normal faults cut these strata and form a north-trending horst-graben system. One fault, the Reese

Creek fracture zone, intersects the Gardiner fault near La Duke Hot Springs. Bear Creek Springs issues from the intersection of the Mammoth normal fault and the Gardiner reverse fault. The sedimentary rocks have also been folded into the Gallatin anticline, which trends northwest. Widespread dacitic and andesitic volcanic rocks blanketed the area during Eocene time. These were later buried by a series of basalt flows (Quaternary).

This study was based on detailed geologic mapping of the La Duke Hot Springs area, and reconnaissance work in three areas—the Gardiner fault zone, Cinnabar Mountain (northwest of Gardiner), and the northwest corner of Yellowstone Park. Black and white aerial photographs (scale 1:20,200) and regional ERTS photos expedited the mapping.

The author concluded that the Corwin Springs-Gardiner thermal water rises along the northwest-trending Gardiner fault zone in conduits created by fault intersections. The water probably derives its heat from circulation at depth, and a small amount of additional heat supplied by the Yellowstone magma body 25 miles (40 km) south of Gardiner. The two likely sources of recharge are (1) ground water percolating downward through the joint system in the hanging wall of the Gardiner fault, and (2) a larger amount of water, which may flow down the northeast flank of the Gallatin anticline within the Mission Canyon Limestone (Late Mississippian) paleokarst zone. The author suggested that the hydrothermal system is centered at a depth of 10,000 feet (3,048 m) in the Mission Canyon Limestone. La Duke Hot Springs surface temperature was 65° to 68°C; flow was 130 to 500 gpm; reservoir temperature was estimated by silica geothermometer at 81°C (summer) and 130°C (winter). The author placed greater reliance on the winter temperature because there is less ground-water dilution at that time.

Calculations by the Montana Bureau of Mines and Geology, using the U.S. Geological Survey data from the July 2, 1975, samples (U.S.G.S. Open-File Report 78-438), yielded an Na-K-Ca geothermometry reservoir temperature of 74.5°C, a quartz geothermometry reservoir temperature of 101°C, and a chalcedony geothermometry reservoir temperature of 71°C. The similarity of water chemistry for discharge rates of 132 and 220 gpm (temperatures 65.0° and 67.5°C, respectively) precluded the use of mixing models, and suggested a reservoir temperature of about 75°C and conductive cooling during the thermal water's ascent to the land surface.

39 **Umpleby, J. B.**, 1909, Drainage history of Warm Spring Creek, central Montana [M.S. thesis]: Chicago, Illinois, University of Chicago, 37 p.

The area discussed is in Fergus County and includes the area of Brooks Warm Spring. Umpleby reported the spring discharge as greater than 1,000 miner's inches (greater than 11,000 gpm), at a temperature of 70°F. He estimated that 75 percent of the discharge came from the east side of the basin, passing through a synclinal structure to a depth of about 1,800 feet (549 m) below land surface. The total discharge represented a geothermal gradient of 1°F per 90 feet (27 m), and he thought that if cooler water were mixed, the gradient was too great not to be influenced by "hot igneous rock".

The geologic map showed travertine deposits on the southern edge of the North Moccasin Mountains, covering an area of roughly 150 square miles (388 sq. km), northwest of the current spring. The author did not speculate, however, about a possible relationship of the spring and its feeder system with the travertine deposits.

40 **Weed, W.H.**, 1905, Economic value of hot springs and hot-spring deposits: Contributions to Economic Geology, U.S. Geological Survey Bulletin 260, p. 598-604.

This report discussed economic ore deposits within spring deposits at Anaconda Hot Springs, three miles from Anaconda, Montana, and economic and scientific considerations at Hunters Hot Springs, north of the Yellowstone River, 20 miles (32 km) east of Livingston, Montana. In the Anaconda area, thermal water with a high iron content was replacing earlier travertine deposits with low-silica gold-bearing limonite. Those deposits aroused economic interest because they provided a source of flux for the nearby copper smelter, and recoverable gold as a byproduct of the smelting process. The numerous vents of Hunters Hot Springs were connected with reeflike veins of gypsum containing minor amounts of stilbite and calcite. The springs' economic value was chiefly in the resorts built nearby.

41 **Weinheimer, G. J.**, 1979, The geology and geothermal potential of the upper Madison valley [M.S. thesis]: Bozeman, Montana State University, 107 p., 1 pl.

Five thermal springs located in the upper Madison valley of southwest Montana were investigated with respect to geologic controls on water circulation and reservoir potential. The upper Madison valley is a north-trending graben valley south of Ennis, Montana. The study area is bounded by the Gravelly Range to the west and the Madison Range to the east. Inferred range-front faults separate the Precambrian metamorphic rocks of these ranges from the Tertiary and Quaternary valley fill. Twelve valley-fill sedimentary units include basalt; rhyolite tuffs; glacial till, moraines and outwash; alluvial fan deposits; landslide and slump deposits; and recent alluvial deposits. Numerous northwest-trending cross-valley faults offset these units and show Holocene movement. The Wall Canyon cross fault provides significant displacement of basement gneisses.

Weinheimer employed several exploration methods to evaluate the geothermal potential of Wolf Creek Hot Springs, Wall Canyon Warm Spring, Curlew Creek Warm Spring, West Fork Swimming Hole Warm Spring and Sloan Cow Camp Spring. Geologic mapping of the study area from field reconnaissance, air photos and topographic maps was supplemented with a shallow resistivity survey and a seismic survey near Wolf Creek Hot Springs. Detailed geochemical analyses of about 30 samples of warm and cold spring waters completed the research.

The author concluded that thermal water is heated during deep circulation and rises to the surface in conduits formed by cross-valley faults where they intersect other faults or zones of weakness. Reservoir temperatures were estimated by silica, Na-K-Ca and chloride carbonate geothermometers, from 50° to 110°C. The five springs probably do not have interconnected reservoirs as evidenced by chemical data. The geothermal potential of the upper Madison is probably limited to low-temperature applications for space heating and agriculture.

42 **White, D. E., Fournier, R. O., Muffler, L. J. P., and Tuesdell, A. H.**, 1975, Physical results of research drilling in thermal areas of Yellowstone National Park, Wyoming: U.S. Geological Survey Professional Paper 892, 70 p.

Yellowstone National Park, located in northwestern Wyoming, abounds with geothermal activity. During 1967-1968, 13 research holes were drilled by the U.S. Geological Survey in areas of abundant thermal activity. The drill sites included Upper Basin, Upper Firehole River, Lower Basin, Midway Basin, Norris Basin, Mammoth Hot Springs and the Mud Volcano area.

The Mammoth Terrace exploration hole, drilled to 370 feet (111 m), revealed what may be a low-temperature convection system that is depositing travertine. Temperature of the water probably does not exceed 73°C in the system. Exsolution of dissolved gases, principally carbon dioxide, which is 97.1 to 99.5 volume percent of total gases, produced gas partial pressures of at least 5.8 atmospheres. The authors suggested that first exsolution may occur at depths of 170 feet (51 m), where hydrostatic pressure is less than that required to dissolve gases in liquids. Subsurface pH of less than 6.5 is controlled by dissolved carbon dioxide. Newly deposited travertine is porous; older deposits are dense because of later deposition of calcite in earlier pore spaces.

43 **White, D. E., and Williams, D. L.**, 1975, Assessment of geothermal resources of the United States—1975: U.S. Geological Survey Circular 726, 155 p.

This circular attempted to evaluate the economics of geothermal reserves within the United States. Extensive discussions of geothermal theory examined hydrothermal convection systems, igneous-related geothermal systems, temperatures and heat contents based on conductive heat transport, geothermal resources in hydrothermal convection systems and conduction-dominated areas, energy recoverability from molten igneous systems, and geopressured resources in the northern Gulf of Mexico basin.

Nine major hot springs in Montana are included in a tabular collection of hot-water convection systems. Subsurface- and surface-temperature data; silica and Na-K-Ca geothermometer calculations; and thickness, volume, heat content and subsurface area of the thermal reservoir are provided for each spring.

44 **Williams, T. R.**, 1975, Geothermal potential in the Bearmouth area, Montana [M.S. thesis]: Missoula, University of Montana, 81 p.

Located near Drummond in western Montana, the Bearmouth area is within the northwest-trending Montana lineament north of the Boulder batholith (Cretaceous). The research site contains Paleozoic and Mesozoic sedimentary rocks folded into an overturned thrust-faulted syncline. The area's attractiveness as a geothermal prospect is enhanced by several warm springs and seeps and extensive basalt-andesite-rhyolite flows, which may be as young as Pleistocene.

This study employed geochemical sampling, age dating, microearthquake monitoring, gravity surveying and magnetic surveying to evaluate the area's geothermal energy production potential. Silica geothermometers, Na-K-Ca geothermometers and magnesium concentration analysis were utilized during geochemical studies of five main thermal springs in the study area. Data revealed high magnesium concentrations and indicated that subsurface reservoir temperatures may range from 50° to 55°C. Potassium-argon age dating (accurate to about 2 percent) of three samples of volcanic rocks, by Richard Armstrong of the University of British Columbia, yielded mid-Eocene ages; consequently these rocks were discounted as possible heat sources. Microearthquake activity, an almost continuous phenomenon in active geothermal areas, was monitored during two separate periods. Four Sprengnether MEQ-800 portable high-gain recorders with 1 Hz vertical-component seismometers revealed a very low level of seismicity, which suggested the absence of geothermal reservoirs in the area. A ground magnetic survey, incorporating 279 stations, was conducted with a portable proton magnetometer. That survey showed no evidence of a subsurface body of igneous rock. A gravity survey of 171 stations, with a portable gravimeter, seemed to indicate a relationship between the thermal springs and a significant structural zone in the area.

The author concluded that a subsurface magma chamber was probably not the source of heat for the thermal springs, but rather attributed it to deep circulation of meteoric waters within fault zones.

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