D.O.E. FINAL REPORT:

A Summary of Geothermal Studies in Montana, 1980 through 1983

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DISCLAIMER

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INTRODUCTION

The geothermal resources of Montana can be divided into two general areas and categories. In the mountainous western portion of the state, all of the known resources are related to valley-bounding fault systems, commonly with cross-valley faulting evidenced on one or both sides of the mountain blocks. Water is heated by deep circulation and rises along boundary faults or the intersection of boundary and cross-valley faults. A moderate amount of seismic activity (small earthquakes) is believed necessary to keep the fracture and fault conduits through which the thermal waters ascend from plugging with mineral deposits.

East of the main mountain ranges, thermal waters are encountered in the deeper sedimentary rock units. Temperatures of these waters are related to how deeply an aquifer has been buried relative to the current land surface. The major production has been from Mississippian age limestones, usually the Madison Group. Water in the Madison loses its heat slowly as the elevation of the aquifer rises, provided that flow is from deeper to more shallow areas. A thermal gradient study (bottom hole temperature divided by depth of well) by Balster (1974) reflected the configuration of this rock unit at depth. Thus the ideal exploration target is over a dome or anticline (a feature similar to a buried ridge) where warm or hot waters are rising and the drilling depth is reduced.

The reader is referred to Montana Bureau of Mines and Geology Bulletin 110 (Rautio and Sonderegger, 1980) for an annotated bibliography of research published prior to early 1980. The major emphasis of this report is to summarize the results of investigations and provide references for recent work done in various areas. General references include Sonderegger and Schmidt (1981) and the state geothermal map and tables of Sonderegger and Bergantino (1981).

WESTERN MONTANA

Northwestern Area

This area is characterized by surficial exposures of Precambrian sedimentary ("Belt") rocks which were subjected to Laramide overthrust stresses. Water temperatures at land surface are normally $50^{o}C$ ($122^{o}F$) or less. As currently known, the thermal water area runs in a north-south band from the Camp Aqua area in the north to the Blue Joint springs in the south, with most occurrences in the Little Bitterroot and Bitterroot valleys as shown on the enclosed map (Sonderegger and Bergantino, 1981).

The Little Bitterroot geothermal system is believed to consist of thermal waters ascending valley-bounding faults on both sides of the valley, with a common source at depth having a maximum reservoir temperature of $77^{o}C$ (Donovan and others, 1980; Donovan and Sonderegger 1981a; Sonderegger and Donovan, 1981; Donovan, in manuscript). On the east side of the valley, the thermal water rises along fractures until encountering an areally-extensive gravel at the base of the Pleistocene deposits. It then flows laterally in the gravel deposit, presenting a much easier drilling target for development. As of December 1983, there are three wells which penetrate the gravel zone near the entry area of the thermal water. The oldest well of 6-inch diameter into the gravel supplies the Camp Aqua bath house. The intermediate well, drilled by the Montana

Bureau of Mines and Geology (MBMG) under a contract with the U.S. Department of Energy (DOE) as a 6-inch test hole, was cased through the gravel, has 980 feet of 2-inch liner pipe for geophysical probes, and receives water from fractured argillite and quartzite (Donovan and Sonderegger, 1981b). The latest well, drilled to a depth of 261 feet for Jackola Engineering in 1982, has a 10-inch casing perforated with a mills knife throughout the 10-foot gravel zone. The wells are artesian and flow rates depend upon completion and aquifer pressure, ranging from 200 to 1,000 gallons per minute (gpm).

The Green Springs warm pond was sampled in October of 1980; the sodium bicarbonate water is quite low in total dissolved solids (TDS = 182 milligrams per liter - mg/L). The interpretation of its setting is similar to that at Camas Hot Springs, with hot water rising in fractures associated with a valley- bounding fault and mixing slightly with cold meteoric water in the alluvium. The estimated reservoir temperature is 75°C at a depth of two to three kilometers.

The Quinns (Paradise) Hot Spring was dried up when the owners drilled for additional hot water. The higher silica content of this water suggests a hotter reservoir temperature (79°C) than previously estimated (Sonderegger and Bergantino, 1981). However, the association with the Perma Sills suggests that the warm water ascends along fractures associated with the sills. The well, drilled in 1980, is 145 feet (44m) deep and has a bottom hole temperature of 46.4°C (115.6°F); the yield from this 8-inch well was estimated at 50 to 100 gpm (3.15 to 6.31 liters/second - L/s) according to the owners.

The Lolo Hot Springs issue from a series of solution-widened fractures near the contact between the Idaho batholith and limestones of the Wallace Group. The low TDS and calcium content indicate limited contact time with the limestone unit. The combined discharge is approximately 180 gpm (11.4 L/s). The maximum measured temperature is 46.4°C (115.5°F). The thermal waters are believed to rise along fractures within the intrusive that are probably subparallel to the contact and the result of cooling and contraction, as the outer margin of the intrusive should have cooled more rapidly than the interior portions. Calculated reservoir temperatures (Fournier, 1981) are quite variable (Na-K-Ca geothermometer = 74.6°C; chalcedony geothermometer = 91.2°C; quartz (no steam loss) = 119.6°C) and a reasonable estimate of the depth to the reservoir cannot be made. The published estimate of the reservoir temperature (83°C, Sonderegger and Bergantino, 1981) is conservative.

The Florence (15°C, 59°F) test well shows that water at temperatures suitable for heat pump use is available at moderate depths (410 feet, 125 meters).

At Sleeping Child Hot Springs, the hot water issues from fractures in Precambrian granitic gneisses and quartzite(?) that have been intruded and hydrothermally "granitized" by the Idaho batholith. The 52°C (125.6°F) water issues from fractures at the base of a cliff north of the pool; a second spring which yields 43°C (109.4°F) water is located up the creek, northeast of the pool. Reported discharge values from the springs have varied widely. What appears to be the most reliable value for the useable combined flows is about 115 gpm (7.3 L/s) based upon information provided by the owners in 1964. The hotter spring contributes about 25 percent of the discharge. The estimated reservoir temperature published with the state geothermal map (Sonderegger and Bergantino, 1981) of 125°C is probably too high; the best value is in the range 85-90°C, which again suggests circulation to depths of 2 to 3 kilometers.

The Medicine Hot Springs appear to be controlled by fault-related fractures, possibly where the fault splayed (broke up into several faults with movement of the blocks of rock between the various smaller faults). The springs are located on the northwest side of the creek. They have been covered and their discharge is piped to the swimming pool and bath house. The 45°C (113°F) water is of low TDS; the chalcedony and sodium-potassium-calcium geothermometers agree closely for the estimated reservoir temperature of 82°C. This suggests 2 to 3 kilometer circulation depths, similar to the other springs in this group. The water issues from "granitic" rocks of the Idaho batholith. South of Laird Creek, aphanitic layers (sills?) were noted in a road cut along Highway 93, but it is not known if they also occur adjacent to the thermal springs.

The two Blue Joint spring areas are about one mile apart. They occur along the (sheared?) contact between the Idaho batholith and the Ravalli Quartzite (which in turn controls the location of the Blue Joint Creek in this immediate area) issuing from alluvial deposits adjacent to the quartzite contact. The chemistry gives widely ranging geothermometry reservoir temperatures for these low conductance (TDS values for no. 1 and no. 2 are 126 and 145 mg/L, respectively) waters. Circulation may be 2 kilometers or less as dilution by very pure shallow ground water is too difficult to evaluate. The low surface temperature (29°C, 84-85°F) limits the usefulness of these springs.

The Elkhorn Hot Springs are the easternmost springs included in the "northwestern" area. The springs issue from the Boulder batholith, but the water characteristics suggest a closer affinity with the other waters in this group than with the "southwestern" area. The springs produce 48-49^{o}C (118-120^{o}F) water with low dissolved solids (TDS = 179 mg/L). Reported discharge values have ranged widely ranging from 1 cubic foot per second (448 gpm, 28.3 L/s) reported to have been measured in 1938 down to 28 gpm (1.77 L/s) measured by the U.S. Geological Survey (USGS) in 1976. The observed temperature and calculated reservoir temperature (70-75^{o}C, 158-167^{o}F) suggest a two to three kilometer deep circulation system in relatively non-reactive rock type such as the Belt quartzites, as evidenced by the low TDS.

The Jackson Hot Spring area was recently studied by Geoff Black. His results (1984a, 1984b) suggest that listric faults control the movement of the thermal water (58^{o}C, 136^{o}F at land surface). Previous estimates of the reservoir temperature, using the uncorrected Na-K-Ca geothermometer were too high. The magnesium corrected Na-K-Ca, chalcedony, and oxygen 18 of sulfate and water geothermometers suggest a 70 to 75^{o}C reservoir temperature. The reason for the hotter surface temperature at Jackson is believed to be the greater insulating effect of the Tertiary sediments which cap the system. An alternate interpretation, preferred by Black, is that mixing or re-equilibration occursand that higher reservoir temperatures exist at greater depth. At Jackson and Sleeping Child, pre-existing U.S. Geological Survey (USGS) reservoir temperature estimates were used for the state geothermal map (Sonderegger and Bergantino, 1981); however, additional experience indicates that those values are probably too great unless substantial mixing has occurred. The discharge of 260 gpm (16.3 L/s) makes this a viable resource for direct use at the spring discharge temperature.

Southwestern Area

This area is characterized by Tertiary-age block-faulted valleys and mountain ranges which frequently cut features formed by earlier tectonic stresses. It is the author's personal belief many of the Tertiary features in this "block", bounded by the Montana Lineament on the north and the Snake River Valley zone of crustal melting to the south, have resulted from movement along pre-existing Precambrian basement fault zones.

The southwestern area contains the greatest variability of type for geothermal systems and is the only area with a remote chance of having a currently unrecognized igneous heat source due to the paucity of young igneous rocks elsewhere (Daniel and Berg, 1982). The Snake River Valley in eastern Idaho is a zone of thin continental crust, attributed by many to partial melting of the crust related to plate tectonics. The northeastern end of the valley has a sequence of volcanic rocks which become progressively younger as Yellowstone Park is approached. Within the Park, not too far from the Montana border, two domes are currently rising, and geophysical data show a non-solid condition--presumably molten magma--at depth. Areas on the western and northern edges of the Park have the potential for deep wells intersecting magmatically heated water, particularly along the Idaho boundary. This is the reason that a buffer zone of no geothermal devlopment was recommended by Don White (of the USGS) and others.

Establishing a widely accepted average geothermal gradient for southwestern Montana may be an unrealistic goal. However, such a value aids in comparisons of circulation depths. Data presented by Blackwell and Robertson (1973) for the Boulder batholith yield a calculated heat flow of 2.00 cal/cm^2 sec. and a measured average of 1.98 $\pm$ 0.06 cal/cm^2 sec. Using their figure D-2, the gradient fitted for the Butte area yields $\cong 30^{o}C/km$ for rock temperatures, which is slightly lower than their $31.9^{o}C/km$ interpretation (Table D-A). AMOCO's Hirschy number 1 well, located in the Big Hole Valley, Beaverhead County, was drilled to a total depth of 4.886 km (16,030 ft.) and had a bottom hole temperature of $183^{o}C$ ($362^{o}F$). This yields $36.6^{o}C/km$ as an average gradient; however, the temperature increase was greatest in the bottom 800 feet of the logged interval. An earlier Schlumberger run when the well was 13,374 feet (4.076 km) deep resulted in a $32.0^{o}C/km$ gradient. While recognizing that sedimentary basins normally have larger gradients than adjacent crystalline rocks (Rybach, 1981, p. 11), the depths and attained temperatures cited are such that the use of $30^{o}C/km$ as an average value is believed to be justified.

The southwestern Montana geothermal systems can be fit into three basic categories without too much difficulty. The first (type one) is similar to those previously discussed; fracture contolled circulation systems with a circulation depth of 2.5 kilometers (1.55 miles, 8,200 feet) or less, based upon calculated reservoir temperatures of $80^{o}C$ or less and an assumed regional gradient of $30^{o}C/km$. The second (type two) system is the same, with deep circulation (depth greater than 2 1/2 km) assumed, based upon higher calculated reservoir temperatures. The third type is a carbonate-related flow system (i.e., a permeable limestone) irrespective of depth and temperature although most of the thermal-spring systems are relatively shallow and do not contain high-temperature water.

This third type is typically a large-volume, low-temperature, system. Beaverhead and Madison counties have several systems of this type. Examples are the McMenomey Ranch, Brown's and Lovell's springs southwest of Dillon, the Apex and Beaverhead Rock springs north of Dillon, the Anderson's Pasture and Staudenmeyer springs in the Centennial Valley (Sonderegger and others, 1982), and the Trudau and Vigilante springs in the Ruby Valley (Sonderegger and Bergantino, 1981). Additional springs and wells of this type include Anderson's spring, the McLeod, Lucas and Ringling wells, the Bedford, Toston, and Plunket's Lake springs, the Bruce well, and the Carter's Bridge, Bridger Canyon, Garrison, Bearmouth, Nimrod, and Sun River springs. Wyatt (1984a, b) has studied the Radersburg basin area; however, most of these low-temperature systems have received very little study beyond discharge and temperature measurements, and selected water samples for chemical analysis.

There are a few, low-discharge, high-temperature carbonate system springs. Chico is a transitional sitution with a 320 gpm (20.17 L/s) discharge and a 45^{o}C (113^{o}F) temperature. The New Biltmore springs at 53^{o}C (127^{o}F) have a discharge of less than 100 gpm (6.3 L/s) with reported values ranging from 31 to 100 gpm (1.96 to 6.3 L/s). The reservoir temperature (Fournier, 1981) for New Biltmore calculated from chalcedony and Na-K-Ca geothermometers is 71^{o}C, more in line with what would be expected from a type one system. The higher temperature may be partly related to the lower thermal conductivity of the Tertiary sediments which overlie the carbonate bedrock.

The Corwin (LaDuke) hot spring discharges about 100 gpm (6.3 L/s) of 63^{o}C water which is believed (Struhsacker, 1976) to ascend along the intersection of the Mammoth and Gardiner fault zones. Alternate interpretations of chemical data yield circulation depths of 2 to 4 kilometers with reservoir temperatures of from 75^{o} to 130^{o}C (see Rautio and Sonderegger, 1980, p. 19-20). This system, including the Bear Creek Spring, because of its proximity to the Mammoth and Norris areas in Yellowstone National Park, could possibly have some magmatic heat contribution as suggested by Struhsacker (1976).

One of the enigmatic systems which may belong in this group occurs at Warm Springs State Hospital. The water chemistry is similar to that at Corwin, except somewhat lower in total dissolved solids. The travertine spring mound, which rises about 20 feet above the surrounding valley floor, may be a modern analogue of the extensive travertine terraces near Anaconda which were mined around the turn of the century (Weed, 1905). For this system, the surface spring temperature, the calculated reservoir temperature, and the temperature of water produced from a 1500 foot (457 meter) deep well are virtually identical ranging from 77 to 79^{o}C (171-174^{o}F), suggesting a relatively rapid upflow of the water. Discharge measurements of the spring and well yields probably give too low of an equilibrium discharge for the system because of leakage losses. Copious amounts of luke-warm water were encountered in a shallow gravel zone, at a depth of 15 to 18 feet (4.6-5.5 meters), when the MBMG test well to evaluate shallow aquifers was drilled southeast of the mound. Natural discharge from the system may be more in the 200 to 300 gpm (12.6-18.9 L/s) range. It has been suggested that the water quality at the Warm Springs site has been greatly modified by the Anaconda smelter operations and tailings. This could possibly been resolved by analyzing the sulfur isotope ratio ($^{34}S/^{32}S$) in the dissolved sulfate of the spring water. In hopes of sending a suite of samples from high sulfate springs, I kept waiting for the University of Utah sulfur isotope line to become functional and never did obtain these data. The reader is referred to Wideman, et. al. (1982) for a brief summary of geophysical studies in the Deer Lodge Valley.

The type two systems, because of their higher temperatures are probably of greatest interest. The major thermal systems in this category with calculated reservoir temperatures greater than 100°C are: Alhambra, Boulder, Bozeman, Broadwater, Ennis, Gregson, Norris, and Silver Star. All but Bozeman, Norris and Ennis are within or on the margin of the Boulder batholith.

Alhambra and Broadwater were studied in some detail by Robert Leonard of the USGS. The report on radioactivity by Leonard and Janzer (1978) includes a discussion of the geohydrologic setting at Alhambra. MBMG Open-File Report 98 by Dan Vice (1982) has sections on both Broadwater and Alhambra denoting anomalously warm ground at these sites. A test well drilled in 1981 by the Bureau on a cooperative basis with the Renewable Energy Division of the Department of Natural Resources and Conservation (DNR&C) and with DOE failed to find hot water at the Broadwater anomaly selected by DNR&C (Donovan and Sonderegger, 1982).

Galloway (1977) presented an interpretative cross section of the Alhambra system based upon geologic mapping and resistivity studies. Several different reservoir temperatures can be calculated for Alhambra; the most conservative, using the chalcedony geothermometer, yields a value of 87°C, requiring circulation to depths slightly greater than 2.5 kilometers. The measured temperatures at Alhambra range from 50 to 59.4°C, with most being in the vicinity of 55°C. In contrast, the Broadwater Hot Springs surface temperatures appear to range from 65 to 67°C (Leonard and others, 1978) and contain higher dissolved silica content. Using 98 mg/L dissolved SiO_2, the chalcedony geothermometer yields a calculated reservoir temperature of 109°C which requires circulation to a depth of nearly 3.5 kilometers. The high calcium and magnesium contents of these waters suggests that the chalcedony calculations are the most reliable and the low chloride content (<40 mg/L) makes mixing-model calculations highly questionable. The systems both appear to be controlled by fracture permeability associated with valley-margin block faulting. The results of a drilling and pump testing program by the owner at Broadwater have not been made public but are believed to indicate a stable yield in the vicinity of 500 gpm (31.5 L/s).

Attempts to study the Boulder Hot Springs system and outlying geophysical anomalies were essentially thwarted by the owner. A summary by Wideman (1981) was included in MBMG Open-File Report 94. Spring improvement and numerous plumbing modifications make discharge measurements nearly impossible; estimates from visual inspection range from 250 to 1,000 gpm (15.8 to 63.1 L/s) with 500 gpm (31.5 L/s) probably being a reasonable figure. The hottest measured temperature is 76°C. A previous owner, Willard Mack, stated that there were 40 springs ranging from hot to cool on the property. The early description of this site by Weed (1900) concentrates on the veins (which contain both quartz and chalcedony) and is one of the earliest studies undertaken in this country to understand precious metal deposits of geothermal origin. Calculations using the chalcedony geothermometer yield a reservoir temperature of 116°C, while the quartz and Na-Ca-K calculations yield 143 and 137°C, respectively. Assuming a reservoir temperature of 140°C and a thermal gradient of 30°C/km requires a circulation system 4.25 kilometers (2.6 miles or nearly 14,000 feet) deep. Weed's descriptions include calcite from veins southeast of the hotel which suggest that calcium may now be lost at depth and that the 116°C reservoir temperature may be more valid for the Boulder system.

The Bozeman Hot Springs are located at the KOA Campground, operated by Charles Page, six miles west of Bozeman on U.S. Highway 191. Drilling by Mr. Page during 1980 provided additional water samples which have altered the interpretation of the system's depth and equilibration (reservoir) temperatures. Previous estimates of the reservoir temperature, using data from Mariner and others (1976), which were the best available data when the manuscript was written, were too low (Sonderegger and Bergantino, 1981, Table 1; based upon quartz = 115°C, chalcedony = 86°C, and Na-K-Ca = 75°C). New samples, run in the Bureau laboratory, yield reservoir temperatures of 118, 90, and 122°C for quartz, chalcedony and Na-K-Ca geothermometers, respectively. This difference is attributed to shallow ground water diluting the samples collected by earlier workers. Our analyses are included in Appendix I; the major differences with respect to earlier samples are the lower calcium and magnesium concentrations, and the slightly higher silica content.

Use of the quartz rather than chalcedony temperature is rarely warranted where the observed temperature is so low (54°C, 129°F). The computer program WATEQF (Plummer and others, 1976) was used to evaluate potential solubility controls on the calcium content (the lower the Ca content, the higher the calculated temperature). Calcite and fluorite were calculated to be less than 32 percent of saturation, consequently, the Na-K-Ca temperature is believed to be valid and the calculated reservoir temperature should be about 120°C. This implies a system circulation depth of at least 3.7 kilometers, considerably greater than the 2.5 kilometer depth previously estimated.

Test-flow results for the 1980 well were remarkably promising, with 1500 gpm (95 L/s) initial flow rates, and a projected long-term sustained yield of 790 gpm (50 L/s) at 54°C (Donovan and others, 1982). The state is currently permitting this Bozeman Hot Springs well for 4.2×10^8 gallons per year (800 gpm daily average).

The gravity study, (Donovan and others, 1982) had alternate interpretations (bedrock high or siliceous cementing). Resistivity studies (Lupindu, 1983) failed to define the deep, hot water zones, presumably due to the masking effect of shallow, cold ground water. A seismic profile was attempted to aid in interpreting the gravity data, however, energy dissipation was so great that first arrivals from the bedrock were questionable. Reversed, high-resolution, reflection seismic profiles using explosives are needed to attain proper definition. However, permitting may be very difficult in this area, due to the high density of domestic dwellings (and wells) adjacent to the area.

A soil mercury survey was also attempted to aid in delineating the trend of the system. Soil mercury values were mostly less than 20 parts per billion (ppb). Three "high" values (45, 51, and 61 ppb) were all along roads, and impact from the local weed control program is suspected. Based upon these data, it is believed that the Bozeman Hot Springs system never was hot enough to have a significant vapor phase (Varekamp and Buseck, 1983, fig. 17; 1984).

The Ennis system will be the subject of a separate report (Sonderegger, 1984). The interpretation of the permeability in the gneiss being due to Laramide overthrusting (Sonderegger and Zaluski, 1983) was supported by geophysical data presented at the 1983 American Association of Petroleum Geologists regional meeting (Rasmussen and Fields, 1983). Only a "shallow" essentially horizontal reservoir encountered at depths of 500-1100 feet (152-335 meters) was evaluated with these wells. Stable production at 88°C from this zone appears to be limited to 500 gpm or less ($\leq$31.5 L/s) based upon a 24-hour pump test of a 1220-foot (366-meter) deep well (Sonderegger, 1983). Calculated reservoir temperatures vary considerably: (1) quartz = 141°C; (2) chalcedony = 115°C; (3) Na-K-Ca-Mg = 163°C; and (4) $\Delta^{18}O$ (SO_4-H_2O) of 92-95°C depending upon which value is used from Leonard and Wood (1980, p. 14). WATEQF (Plummer and others, 1976), a computer program to evaluate equilibrium of waters with mineral species, was run with the thermal water chemistry. Calculations show that the water is slightly (58 percent) supersaturated with respect to calcite; these results make the Na-K-Ca-Mg calculations suspect. The oxygen isotope temperatures are subject to contamination by meteoric water; the isotope values are from the spring, as the samples were collected prior to drilling, and the lack of a complete water analysis to go with the isotope data makes it suspect also. Assuming a minimum reservoir temperature of 115°C, the circulation system must be at least 3.5 kilometers deep using the regional gradient of 30°C/km.

The Gregson (Fairmont) area is being studied by David Brodahl (1984 a, b). Drilling during the summer of 1983 by the MBMG on the resistivity anomaly described by Wideman and others (1982) resulted in production at 300 gpm (18.9 L/s) from the 6-inch well during a two-hour development period at a temperature of 68°C (155°F). The shallow geothermal gradient is about 400°C/km, but becomes isothermal once the fractured granite is encountered (Wideman and Sonderegger, 1984). The test well, 1/3 of a mile south of the hot springs, has been turned over to the landowner but has not yet been put to use other than for observation purposes. Quartz and Na-K-Ca geothermometers yield reservoir temperatures of 128 and 124°C, respectively, while the chalcedony calculation yields 101°C. If the maximum temperature truly is 128°C, this requires a convection system 4 kilometers deep; while the minimum depth (based upon chalcedony) is slightly over 3 kilometers.

An initial study of the Norris area by Peterson (1983) will be followed in the near future by her M.S. thesis (at Montana Tech). The Norris site data yields a variety of geothermometer calculations (130°C, quartz; 103°C, chalcedony; 88°C, Na-K-Ca-Mg); the chalcedony value is a reasonable estimate and implies circulation to depths of about 3 km. The water is of good quality (TDS ≅ 640 mg/L) as are most hot springs which issue from pre-Belt, metamorphic rocks. The areas of anomalous resistivity appear to have fault controlled trends; Peterson notes about eight square miles of anomalous area, however, the Waterlode mine-water temperatures are not abnormal and the anomalous area should be reduced a bit. Measured temperatures range from 45 to 52.5°C; the temperature at the spring (rather than later discharge points) is believed to be 50 to 52.5°C (122-127°F).

The Silver Star (Barkell's Hot Springs) site has one of the highest calculated reservoir temperatures in the state. The quartz, Na-K-Ca, and $\Delta^{18}O$ (SO_4 - H_2O) geothermometers yield temperatures of 143, 139, an 135°C, respectively. In the past, debris-filled spring boxes and corroded pipes have caused discharge losses. During a site visit in 1978, the author measured 20 gpm (1.26 L/s) at the pool, estimated 45 to 50 gpm (2.84-3.15 L/s) being delivered to the spring boxes, and 75 gpm (4.73 L/s) as potential spring discharge if the springs were cleaned out. For yields in excess of 100 gpm (6.31 L/s) wells would be required. The water temperature is about 72°C (162°F) as measured at a grate below the upper spring boxes. The location of the springs appears to be controlled by the intersection of the western valley-margin fault and the Cherry Creek and Green Campbell faults. This area has had very little attention since Abdul-Malik's (1977) resistivity survey despite his recommendation for a test well at this site. Using the regional geothermal gradient, the calculated circulation depth is about 4.3 kilometers.

CENTRAL MONTANA

Two central Montana springs that have been of particular interest for development are Hunter's Hot Springs and White Sulphur Springs, which because of location or quantity of discharge are attractive for utilization, despite their lower calculated reservoir temperatures.

The Hunter's site was not investigated as part of the Bureau effort. Leonard's (Leonard and others, 1978) discharge values of about 750 gpm (47.3 L/s) are measured, while Mariner's (Mariner and others, 1976) value of less than 1320 gpm (<83.33 L/s) may include an estimate of non-measurable flow. Reported temperatures range from 54 to 60°C (129 to 140°F) (Leonard and others, 1978).

The state school sections adjacent to Hunter's Hot Springs were considered a detriment to development until leases for geothermal rights could be obtained. When these sections were put up for bid, there were no bidders in 1983 for the geothermal lease; this suggests that the group which was interested in trying to drill a deep well has abandoned the project. The proposed deep well was based upon the interpretation that the hot springs are fed by the rise of water along a west-dipping thrust fault, which is supported by Weed's (1905) description of gypsum "reefs" to the west of the hot spring area.

Calculated reservoir temperatures at Hunter's are: quartz, 115°C; chalcedony, 85.5°C; and Na-K-Ca, 85.3°C. The minimum circulation depth is believed to be 2.5 kilometers for this system based upon an 85°C reservoir equilibration temperature and assuming that the 30°C/km gradient is valid. The water chemistry used (Mariner and others, 1976) is so free of alkaline earth elements (Ca<1 mg/L, Mg<0.1 mg/L) that mixing is not believed to be significant despite the low fluoride (5.6 mg/L) and chloride (18 mg/L) contents. This alkaline water (pH = 9.1) is low in dissolved solids (calculated TDS = 390 mg/L) and the only drawbacks to its use should be its alkalinity and a tendency toward silica scaling. The calculated Eh of -0.439 volts (pe = -6.644), based upon the sulfide/sulfate ratio, is very reducing (i.e., the water is essentially devoid of oxygen) and supports the hypothesized unmixed water which in turn implies the lower reservoir temperature and relatively shallow circulation system.

At White Sulphur Springs, the situation is not nearly so clear cut. The spring location appears to be controlled by both thrust and normal faults, with substantial discharge into the valley alluvial fill (Gogas, 1984a, 1984b; Lipindu, 1983; Gierke, 1984). Chemical geothermometers yield quite variable results: quartz, 103°C; chalcedony 73°C; Na-K-Ca-Mg, 16°C; $\Delta^{18}O(SO_4 - H_2O)$, 52°C. The range of these temperatures shows that assumptions of equilibration at depth and a rapid ascent without mixing are not met in this case. Evaluation of Mariner's (1976) analysis using WATEQF indicates that the water is greatly supersaturated with respect to pyrite, supersaturated with respect to quartz, chalcedony and fluorite, and undersaturated with respect to calcite. If mixing during ascent has occurred, the Ralph Johnson well, drilled in Tertiary sediments and located about 3.5 miles east of White Sulphur Springs may represent a cooled thermal water with minor dilution. A copy of the laboratory analysis is included in Appendix I; the water is sodium dominant (99 percent) with bicarbonate plus carbonate (46.5 percent), sulfate (29.1 percent) and chloride (24.4 percent) as the anions.

Comparison of Mariners analysis of the springs to the analysis of the Johnson well yields ratios of 0.2176, 0.2254, and 0.2377 for Cl, Na, and SO_4, respectively, which permits the estimation that the spring water could be produced by mixing 23 percent geothermal water with 77 percent distilled water. The high chloride content suggests a thermal or oil-field brine origin, with a thermal origin the apparently more reasonable interpretation. A further discussion of the interpretation will be presented in the MBMG Memoir on geological and hydrogeochemical investigations (see Sonderegger, 1984). At this point in time, while previous reservoir temperature estimates are questioned and may need to be adjusted downward, there is still uncertainty as to how to treat these data.

EASTERN MONTANA

Madison Group Aquifer Units

In eastern Montana, the major potential geothermal resource is the Madison Group carbonate complex. Outside of the Little Rockies area, warm and hot water from these units can only be obtained by drilling wells. The first evaluation of the Madison Group for geothermal resource assessment was by Balster (1974). Since then, Richard Feltis with the U.S. Geological Survey has published a series of maps dealing with the Madison Group as MBMG Geologic Map Series numbers 9-12, 15-18, and 20-22, inclusive. These maps, at a scale of 1:125,000, permit reasonably accurate prediction of the depth that a well must be drilled to reach the top of the Madison Group at a specific site. When used in conjunction with Feltis' (1980l, 1980m) potentiometric and dissolved-solids maps, reasonable projections of aquifer pressure and ground-water quality can also be made for a site. Head and others (1978) have presented both temperature and structure contour data for the Madison Group in the Powder River Basin at a scale of 1:1,000,000. Downey (1982, p. 66) depicts temperatures for the eastern part of the state, however, this map is very large scale and generalized.

In the category of wells which incidentally encountered hot water, the best documented case is the Western Energy well at Colstrip. The well was drilled to a depth of 9200 feet (2800 m); the majority of the hot water is believed to have come from the Mission Canyon Limestone at a depth of 7700 feet (2350 m). Well tests by Van Voast (personal communication) yielded a transmissibility of 650 gpd/ft, and a storage coefficient of 2×10^{-4}; under test conditions, the well flowed 230 gpm of 97°C (207°F) water with a 16 psi confining pressure. A petroleum laboratory analysis of the water yielded a total dissolved solids content of about 1500 milligrams per liter. The pH value reported was 6.3, which is not very acidic, but, the water was sufficiently corrosive to cause casing leaks in a period of about five years. The well was cemented and abandoned seven years after being drilled.

Old petroleum test wells that produce warm or hot water frequently produce this water from the Madison Group. The Ringling and Lucas wells near White Sulphur Springs produce 800 and 100 gpm of 48°C (118°F) water from Mississippian age rocks (Leonard and others, 1978). The Saco well, now used by the Sleeping Buffalo Resort, produces a reported 290 gpm of 41.3°C (106°F) water from this same strata.

After several years of economic and engineering evaluation, it appears that hot-water producing (220-265°F, 104-129°C) wells in the Poplar area will finally be developed. The water quality of these brines has previously precluded their use.

SUMMARY

Development of geothermal resources is still occurring in Montana. The euphoric predictions of the early 1970's (e.g. Marysville) have passed and planning for development has become more realistic both in terms of the resource base and the costs of coming on-line with Montana's low- to intermediate-temperature resources.

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APPENDIX I

Water-Quality Information

MONTANA BUREAU OF MINES AND GEOLOGY — WATER QUALITY ANALYSIS
BUTTE, MONTANA 59701 (406)496-4101 — LAB NO. 80Q2828

STATE	MONTANA	COUNTY	GALLATIN
LATITUDE-LONGITUDE	45D39'38"N 111D11'10"W	SITE LOCATION	2S 4E 14 DAD 2
UTM COORDINATES	Z N E	MBMG SITE	
TOPOGRAPHIC MAP	BOZEMAN 15'	STATION ID	453938111111002
GEOLOGIC SOURCE	120SDMS* * *	SAMPLE SOURCE	SPRING
DRAINAGE BASIN	AH	LAND SURFACE ALTITUDE	4735. FT < 10
AGENCY + SAMPLER	MBMG*FAS	SUSTAINED YIELD	
BOTTLE NUMBER	BOZ-3	YIELD MEAS METHOD	
DATE SAMPLED	17-DEC-80	TOTAL DEPTH OF WELL	
TIME SAMPLED	14:00 HOURS	SWL ABOVE(-) OR BELOW GS	
LAB + ANALYST	MBMG*FNA	CASING DIAMETER	
DATE ANALYZED	14-JAN-81	CASING TYPE	
SAMPLE HANDLING	4120	COMPLETION TYPE	*
METHOD SAMPLED	GRAB	PERFORATION INTERVAL	
WATER USE	RECREATIONAL		

SAMPLING SITE BOZEMAN HOT SPRINGS * ORIGINAL SPRING
GEOLOGIC SOURCE SEDIMENTS (TERTIARY)

	MG/L	MEQ/L		MG/L	MEQ/L
CALCIUM (CA)	5.1	0.25	BICARBONATE (HCO3)	62.5	1.02
MAGNESIUM (MG)	.6	0.05	CARBONATE (CO3)	22.1	0.74
SODIUM (NA)	135.	5.87	CHLORIDE (CL)	49.7	1.40
POTASSIUM (K)	2.8	0.07	SULFATE (SO4)	130.	2.71
IRON (FE)	.028	0.00	NITRATE (AS N)	.093	0.01
MANGANESE (MN)	.001	0.00	FLUORIDE (F)	9.9	0.52
SILICA (SIO2)	69.3		PHOSPHATE TOT (AS P)		
TOTAL CATIONS		6.25	TOTAL ANIONS		6.40

STANDARD DEVIATION OF ANION-CATION BALANCE (SIGMA) 0.74

CALCULATED DISSOLVED SOLIDS	455.41	TOTAL HARDNESS AS CACO3	15.20
SUM OF DISS. CONSTITUENT	487.12	TOTAL ALKALINITY AS CACO3	88.12
FIELD CNDUCTVY, MICROMHOS	770.	FIELD ALKALINITY AS CACO3	86.0
LAB CNDUCTVY, MICROMHOS	711.9	RYZNAR STABILITY INDEX	8.40
FIELD PH	8.45	LANGLIER SATURATION INDEX	0.44
LABORATORY PH	9.29	SODIUM ADSORPTION RATIO	15.07

PARAMETER	VALUE	PARAMETER	VALUE
FIELD TEMP, WATER	54.0 C		
ALUMINUM, DISS (MG/L-AL)	<.03	STRONTIUM,DISS (MG/L-SR)	.099
SILVER,DISS (MG/L AS AG)	<.002	TITANIUM DIS(MG/L AS TI)	.002
BORON ,DISS (MG/L AS B)	.28	VANADIUM,DISS(MG/L AS V)	<.001
CADMIUM,DISS(MG/L AS CD)	.004	ZINC,DISS (MG/L AS ZN)	.004
CHROMIUM, DISS (MG/L-CR)	<.002	ZIRCONIUM DIS(MG/L AS ZR	.006
COPPER,DISS (MG/L AS CU)	<.002	LITHIUM,DISS(MG/L AS LI)	.037
MOLYBDENUM,DISS(MG/L-MO)	.03	NICKEL,DISS (MG/L AS NI)	<.01
LEAD,DISS (MG/L AS PB)	.06	ARSENIC,DISS(UG/L AS AS)	3.0
SULFIDE,TOTAL(MG/L AS S)	.11	DISSLVD SOLIDS(CALC MG/L	455.

REMARKS: ORIGINAL SPRING AT HOT SPRINGS SITE * BOTTOM HOLE TEMP 55.3 C *
(LEONARD, USGS, 1980) *

EXPLANATION: MG/L = MILLIGRAMS PER LITER, UG/L = MICROGRAMS PER LITER, MEQ/L = MILLIEQUIVELENTS PER LITER. FT = FEET, MT = METERS. (M) = MEASURED, (E) = ESTIMATED, (R) = REPORTED. TR = TOTAL RECOVERABLE. TOT = TOTAL. BIO = BIOLOGICALLY AVAILABLE.

QW WA S2 WI OW PW AT OTHER

OTHER AVAILABLE DATA
OTHER FILE NUMBERS:

PROJECT: — COST:
LAST EDIT DATE: 03-FEB-83 — BY: JKS*JKS
PROCESSING PROGRAM: F173OP V3 (09/1/83) — PRINTED: 01-MAR-84

PERCENT MEQ/L (FOR PIPER PLOT)

CA	MG	NA	K	CL	SO4	HCO3	CO3
4.1	0.8	94.0	1.2	23.9	46.1	17.5	12.5

NOTE: IN CORRESPONDENCE, PLEASE REFER TO LAB NUMBER: 80Q2828

MONTANA BUREAU OF MINES AND GEOLOGY
BUTTE,MONTANA 59701 (406)496-4101

WATER QUALITY ANALYSIS
LAB NO. 80Q2829

STATE	MONTANA	COUNTY	GALLATIN
LATITUDE-LONGITUDE	45D39'37"N 111D11'10"W	SITE LOCATION	2S 4E 14 DAD
UTM COORDINATES	Z N E	MBMG SITE	
TOPOGRAPHIC MAP	BOZEMAN 15'	STATION ID	
GEOLOGIC SOURCE	400PRBL* *	* SAMPLE SOURCE	WELL
DRAINAGE BASIN	AH	LAND SURFACE ALTITUDE	4735. FT < 50
AGENCY + SAMPLER	MBMG*FAS	SUSTAINED YIELD	30. GPM
BOTTLE NUMBER	BOZ-4	YIELD MEAS METHOD	BUCKET/STOPWATCH
DATE SAMPLED	16-DEC-80	TOTAL DEPTH OF WELL	540. FT
TIME SAMPLED	16:00 HOURS	SWL ABOVE(-) OR BELOW GS	FLOWING
LAB + ANALYST	MBMG*FNA	CASING DIAMETER	
DATE ANALYZED	20-JAN-81	CASING TYPE	
SAMPLE HANDLING	4120	COMPLETION TYPE	*
METHOD SAMPLED	GRAB	PERFORATION INTERVAL	
WATER USE	RESEARCH		

SAMPLING SITE BOZEMAN HOT SPRINGS * OWNER - CHARLES PAGE
GEOLOGIC SOURCE PRE-BELT

	MG/L	MEQ/L		MG/L	MEQ/L
CALCIUM (CA)	2.3	0.11	BICARBONATE (HCO3)	52.5	0.86
MAGNESIUM (MG)	.05	0.00	CARBONATE (CO3)	26.4	0.88
SODIUM (NA)	115.	5.00	CHLORIDE (CL)	50.	1.41
POTASSIUM (K)	2.4	0.06	SULFATE (SO4)	131.	2.73
IRON (FE)	.005	0.00	NITRATE (AS N)	.084	0.01
MANGANESE (MN)	.001	0.00	FLUORIDE (F)	10.1	0.53
SILICA (SIO2)	71.2		PHOSPHATE TOT (AS P)		
TOTAL CATIONS		5.18	TOTAL ANIONS		6.42

STANDARD DEVIATION OF ANION-CATION BALANCE (SIGMA) 6.46

CALCULATED DISSOLVED SOLIDS	434.40	TOTAL HARDNESS AS CACO3	5.95
SUM OF DISS. CONSTITUENT	461.04	TOTAL ALKALINITY AS CACO3	87.09
FIELD CNDUCTVY, MICROMHOS	734.	FIELD ALKALINITY AS CACO3	90.0
LAB CNDUCTVY, MICROMHOS	715.1	RYZNAR STABILITY INDEX	8.99
FIELD PH	8.60	LANGLIER SATURATION INDEX	0.21
LABORATORY PH	9.41	SODIUM ADSORPTION RATIO	20.52

PARAMETER	VALUE	PARAMETER	VALUE
FIELD TEMP, WATER	59.0 C		
ALUMINUM, DISS (MG/L-AL)	.05	STRONTIUM,DISS (MG/L-SR)	.056
SILVER,DISS (MG/L AS AG)	.007	TITANIUM DIS(MG/L AS TI)	.001
BORON ,DISS (MG/L AS B)	.26	VANADIUM,DISS(MG/L AS V)	.011
CADMIUM,DISS(MG/L AS CD)	.007	ZINC,DISS (MG/L AS ZN)	.011
CHROMIUM, DISS (MG/L-CR)	<.002	ZIRCONIUM DIS(MG/L AS ZR	.016
COPPER,DISS (MG/L AS CU)	.005	LITHIUM,DISS(MG/L AS LI)	.038
MOLYBDENUM,DISS(MG/L-MO)	.03	NICKEL,DISS (MG/L AS NI)	.02
LEAD,DISS (MG/L AS PB)	<.04	ARSENIC,DISS(UG/L AS AS)	5.0
SULFIDE,TOTAL(MG/L AS S)	.11		

REMARKS: SEEP EMITTING FROM MOUND AROUND NEW (1980) WELL *
MAY BE LEAKAGE AROUND CASING OR LEAK IN WELD *
LAB: FU NA OF 145 MG/L GIVES -.329 SIGMA *

EXPLANATION: MG/L = MILLIGRAMS PER LITER, UG/L = MICROGRAMS PER LITER, MEQ/L =
MILLIEQUIVELENTS PER LITER. FT = FEET, MT = METERS. (M) = MEASURED, (E) =
ESTIMATED, (R) = REPORTED. TR = TOTAL RECOVERABLE. TOT = TOTAL.
BIO = BIOLOGICALLY AVAILABLE.

QW WA S2 WI OW PW AT OTHER

OTHER AVAILABLE DATA
OTHER FILE NUMBERS:

PROJECT: COST:
LAST EDIT DATE: 06-APR-81 BY: TP *CLG
PROCESSING PROGRAM: F1730P V3 (09/1/83) PRINTED: 01-MAR-84

PERCENT MEQ/L (FOR PIPER PLOT)

CA	MG	NA	K	CL	SO4	HCO3	CO3
2.2	0.1	96.5	1.2	24.0	46.4	14.6	15.0

NOTE: IN CORRESPONDENCE, PLEASE REFER TO LAB NUMBER: 80Q2829

MONTANA BUREAU OF MINES AND GEOLOGY
BUTTE,MONTANA 59701 (406)496-4101

WATER QUALITY ANALYSIS
LAB NO. 80Q2830

STATE	MONTANA	COUNTY	GALLATIN
LATITUDE-LONGITUDE	45D39'37"N 111D11'10"W	SITE LOCATION	2S 4E 14 DAD
UTM COORDINATES	Z N E	MBMG SITE	
TOPOGRAPHIC MAP	BOZEMAN 15'	STATION ID	453937111111001
GEOLOGIC SOURCE	400PRBL* *	* SAMPLE SOURCE	WELL
DRAINAGE BASIN	AH	LAND SURFACE ALTITUDE	4735. FT < 50
AGENCY + SAMPLER	MBMG*FAS	SUSTAINED YIELD	
BOTTLE NUMBER	BOZ-2	YIELD MEAS METHOD	
DATE SAMPLED	17-DEC-80	TOTAL DEPTH OF WELL	460. FT (R)
TIME SAMPLED	13:00 HOURS	SWL ABOVE(-) OR BELOW GS	22.8 FT (R)
LAB + ANALYST	MBMG*FNA	CASING DIAMETER	
DATE ANALYZED	14-JAN-81	CASING TYPE	
SAMPLE HANDLING	4120	COMPLETION TYPE	*
METHOD SAMPLED	GRAB	PERFORATION INTERVAL	
WATER USE	RECREATIONAL		

SAMPLING SITE BOZEMAN HOT SPRINGS * OLD WELL
GEOLOGIC SOURCE PRE-BELT

	MG/L	MEQ/L		MG/L	MEQ/L
CALCIUM (CA)	1.3	0.06	BICARBONATE (HCO3)	53.7	0.88
MAGNESIUM (MG)	<.01		CARBONATE (CO3)	25.2	0.84
SODIUM (NA)	144.	6.26	CHLORIDE (CL)	50.	1.41
POTASSIUM (K)	2.8	0.07	SULFATE (SO4)	132.	2.75
IRON (FE)	.003	0.00	NITRATE (AS N)	.18	0.01
MANGANESE (MN)	<.001		FLUORIDE (F)	10.1	0.53
SILICA (SIO2)	70.3		PHOSPHATE TOT (AS P)		
TOTAL CATIONS		6.40	TOTAL ANIONS		6.42

STANDARD DEVIATION OF ANION-CATION BALANCE (SIGMA) 0.11

CALCULATED DISSOLVED SOLIDS	462.34	TOTAL HARDNESS AS CACO3	3.25
SUM OF DISS. CONSTITUENT	489.58	TOTAL ALKALINITY AS CACO3	86.07
FIELD CNDUCTVY, MICROMHOS	775.	FIELD ALKALINITY AS CACO3	92.0
LAB CNDUCTVY, MICROMHOS	713.9	RYZNAR STABILITY INDEX	9.47
FIELD PH	8.50	LANGLIER SATURATION INDEX	-0.02
LABORATORY PH	9.43	SODIUM ADSORPTION RATIO	

PARAMETER	VALUE	PARAMETER	VALUE
FIELD TEMP, WATER	54.0 C		
ALUMINUM, DISS (MG/L-AL)	<.04	STRONTIUM,DISS (MG/L-SR)	.065
SILVER,DISS (MG/L AS AG)	<.002	TITANIUM DIS(MG/L AS TI)	.001
BORON ,DISS (MG/L AS B)	.26	VANADIUM,DISS(MG/L AS V)	.003
CADMIUM,DISS(MG/L AS CD)	<.002	ZINC,DISS (MG/L AS ZN)	.004
CHROMIUM, DISS (MG/L-CR)	<.002	ZIRCONIUM DIS(MG/L AS ZR	.005
COPPER,DISS (MG/L AS CU)	<.002	LITHIUM,DISS(MG/L AS LI)	.038
MOLYBDENUM,DISS(MG/L-MO)	.03	NICKEL,DISS (MG/L AS NI)	<.01
LEAD,DISS (MG/L AS PB)	<.04	ARSENIC,DISS(UG/L AS AS)	5.4
SULFIDE,TOTAL(MG/L AS S)	.15		

REMARKS: OLD WELL AT HOT SPRINGS * NOT CASED INTO BEDROCK - HOLE SLOWLY CLOSING *

EXPLANATION: MG/L = MILLIGRAMS PER LITER, UG/L = MICROGRAMS PER LITER, MEQ/L MILLIEQUIVELENTS PER LITER. FT = FEET, MT = METERS. (M) = MEASURED, (E) = ESTIMATED, (R) = REPORTED. TR = TOTAL RECOVERABLE. TOT = TOTAL. BIO = BIOLOGICALLY AVAILABLE.

QW WA S2 WI OW PW AT OTHER
OTHER AVAILABLE DATA
OTHER FILE NUMBERS:

PROJECT: COST:
LAST EDIT DATE: 13-JUL-82 BY: TP *JKS
PROCESSING PROGRAM: F1730P V3 (09/1/83) PRINTED: 01-MAR-84

PERCENT MEQ/L (FOR PIPER PLOT)

CA	MG	NA	K	CL	SO4	HCO3	CO3
1.0	0.0	97.9	1.1	24.0	46.8	15.0	14.3

NOTE: IN CORRESPONDENCE, PLEASE REFER TO LAB NUMBER: 80Q2830

MONTANA BUREAU OF MINES AND GEOLOGY
BUTTE, MONTANA 59701 (406)496-4101

WATER QUALITY ANALYSIS
LAB NO. 80Q2831

STATE	MONTANA	COUNTY	GALLATIN
LATITUDE-LONGITUDE	45D39'37"N 111D11'10"W	SITE LOCATION	2S 4E 14 DAD
UTM COORDINATES	Z N E	MBMG SITE	
TOPOGRAPHIC MAP	BOZEMAN 15'	STATION ID	
GEOLOGIC SOURCE	400PRBL* *	* SAMPLE SOURCE	WELL
DRAINAGE BASIN	AH	LAND SURFACE ALTITUDE	4735. FT < 50
AGENCY + SAMPLER	MBMG*FAS	SUSTAINED YIELD	1000. GPM
BOTTLE NUMBER	BOZ-1	YIELD MEAS METHOD	ESTIMATED
DATE SAMPLED	17-DEC-80	TOTAL DEPTH OF WELL	540. FT (R)
TIME SAMPLED	12:00 HOURS	SWL ABOVE(-) OR BELOW GS	FLOWING
LAB + ANALYST	MBMG*FNA	CASING DIAMETER	
DATE ANALYZED	20-JAN-81	CASING TYPE	
SAMPLE HANDLING	4120	COMPLETION TYPE	*
METHOD SAMPLED	GRAB	PERFORATION INTERVAL	
WATER USE	RESEARCH		

SAMPLING SITE BOZEMAN HOT SPRINGS * OWNER - CHARLES PAGE
GEOLOGIC SOURCE PRE-BELT

	MG/L	MEQ/L		MG/L	MEQ/L
CALCIUM (CA)	2.68	0.13	BICARBONATE (HCO3)	55.1	0.90
MAGNESIUM (MG)	<.01		CARBONATE (CO3)	24.7	0.82
SODIUM (NA)	136.	5.92	CHLORIDE (CL)	50.3	1.42
POTASSIUM (K)	2.5	0.06	SULFATE (SO4)	133.	2.77
IRON (FE)	<.002		NITRATE (AS N)	.14	0.01
MANGANESE (MN)	<.001		FLUORIDE (F)	10.2	0.54
SILICA (SIO2)	70.2		PHOSPHATE TOT (AS P)		
TOTAL CATIONS		6.11	TOTAL ANIONS		6.46

STANDARD DEVIATION OF ANION-CATION BALANCE (SIGMA) 1.75

CALCULATED DISSOLVED SOLIDS	456.86	TOTAL HARDNESS AS CACO3	6.69
SUM OF DISS. CONSTITUENT	484.82	TOTAL ALKALINITY AS CACO3	86.39
FIELD CNDUCTVY, MICROMHOS	741.	FIELD ALKALINITY AS CACO3	72.0
LAB CNDUCTVY, MICROMHOS	716.8	RYZNAR STABILITY INDEX	8.86
FIELD PH	8.71	LANGLIER SATURATION INDEX	0.27
LABORATORY PH	9.41	SODIUM ADSORPTION RATIO	

PARAMETER	VALUE	PARAMETER	VALUE
FIELD TEMP. WATER	55.0 C		
ALUMINUM, DISS (MG/L-AL)	.04	STRONTIUM,DISS (MG/L-SR)	.067
SILVER,DISS (MG/L AS AG)	<.002	TITANIUM DIS(MG/L AS TI)	.001
BORON ,DISS (MG/L AS B)	.25	VANADIUM,DISS(MG/L AS V)	.003
CADMIUM,DISS(MG/L AS CD)	.003	ZINC,DISS (MG/L AS ZN)	<.003
CHROMIUM, DISS (MG/L-CR)	<.002	ZIRCONIUM DIS(MG/L AS ZR	.005
COPPER,DISS (MG/L AS CU)	<.002	LITHIUM,DISS(MG/L AS LI)	.038
MOLYBDENUM,DISS(MG/L-MO)	.02	NICKEL,DISS (MG/L AS NI)	<.01
LEAD,DISS (MG/L AS PB)	<.04	ARSENIC,DISS(UG/L AS AS)	5.0
SULFIDE,TOTAL(MG/L AS S)	.27	DISSLVD SOLIDS(CALC MG/L	457.

REMARKS: NEW WELL (1980) AT HOT SPRINGS SITE *
LAB: FU NA OF 144 MG/L GIVES -.010 SIGMA *

EXPLANATION: MG/L = MILLIGRAMS PER LITER, UG/L = MICROGRAMS PER LITER, MEQ/L = MILLIEQUIVELENTS PER LITER. FT = FEET, MT = METERS. (M) = MEASURED, (E) = ESTIMATED, (R) = REPORTED. TR = TOTAL RECOVERABLE. TOT = TOTAL. BIO = BIOLOGICALLY AVAILABLE.

QW WA S2 WI OW PW AT OTHER

OTHER AVAILABLE DATA
OTHER FILE NUMBERS:

PROJECT: COST:
BY: JKS*JKS
LAST EDIT DATE: 03-FEB-83
PROCESSING PROGRAM: F1730P V3 (09/1/83) PRINTED: 01-MAR-84

PERCENT MEQ/L (FOR PIPER PLOT)

CA	MG	NA	K	CL	SO4	HCO3	CO3
2.2	0.0	96.8	1.1	24.0	46.8	15.3	13.9

NOTE: IN CORRESPONDENCE, PLEASE REFER TO LAB NUMBER: 80Q2831

MONTANA BUREAU OF MINES AND GEOLOGY   WATER QUALITY ANALYSIS
BUTTE, MONTANA 59701 (406)496-4101   LAB NO. 82Q0862

STATE	MONTANA	COUNTY	MEAGHER
LATITUDE-LONGITUDE	46D32'40"N 110D54'22"W	SITE LOCATION	09N 06E 13 ADAA
UTM COORDINATES	Z N E	MBMG SITE	WSS026
TOPOGRAPHIC MAP	WHITE SULPHUR SPRINGS 7 1	STATION ID	463240110542201
GEOLOGIC SOURCE	120SDMS* * *	SAMPLE SOURCE	WELL
DRAINAGE BASIN	BC	LAND SURFACE ALTITUDE	5040. FT < 10
AGENCY + SAMPLER	MBMG*WGG	SUSTAINED YIELD	
BOTTLE NUMBER	WSS026	YIELD MEAS METHOD	
DATE SAMPLED		TOTAL DEPTH OF WELL	175. FT (R)
TIME SAMPLED	: HOURS	SWL ABOVE(-) OR BELOW GS	31.5 FT (M)
LAB + ANALYST	MBMG*FNA	CASING DIAMETER	6 IN
DATE ANALYZED	04-FEB-83	CASING TYPE	STEEL
SAMPLE HANDLING		COMPLETION TYPE	*
METHOD SAMPLED		PERFORATION INTERVAL	
WATER USE	IRRIGATION		

SAMPLING SITE RALPH JOHNSON, P.O.BOX 65, WHITE SULPHUR SPR
GEOLOGIC SOURCE SEDIMENTS (TERTIARY)

	MG/L	MEQ/L		MG/L	MEQ/L
CALCIUM (CA)	2.5	0.12	BICARBONATE (HCO3)	2533.	41.51
MAGNESIUM (MG)	3.4	0.28	CARBONATE (CO3)	86.4	2.88
SODIUM (NA)	2130.	92.65	CHLORIDE (CL)	827.	23.33
POTASSIUM (K)	19.	0.49	SULFATE (SO4)	1332.	27.73
IRON (FE)	.009	0.00	NITRATE (AS N)	.56	0.04
MANGANESE (MN)	.007	0.00	FLUORIDE (F)	7.7	0.41
SILICA (SIO2)	44.0		PHOSPHATE TOT (AS P)		
TOTAL CATIONS		93.55	TOTAL ANIONS		95.90

STANDARD DEVIATION OF ANION-CATION BALANCE (SIGMA) 1.59

CALCULATED DISSOLVED SOLIDS	5700.36	TOTAL HARDNESS AS CACO3	20.24
SUM OF DISS. CONSTITUENT	6985.58	TOTAL ALKALINITY AS CACO3	2221.60
FIELD CNDUCTVY, MICROMHOS		FIELD ALKALINITY AS CACO3	
LAB CNDUCTVY, MICROMHOS	7878.	RYZNAR STABILITY INDEX	6.88
FIELD PH		LANGLIER SATURATION INDEX	0.87
LABORATORY PH	8.63	SODIUM ADSORPTION RATIO	206.04

PARAMETER	VALUE	PARAMETER	VALUE
FIELD TEMP. AIR	68. F	FIELD TEMP. WATER	59.5 F
ALUMINUM, DISS (MG/L-AL)	.03	NICKEL, DISS (MG/L AS NI)	<.01
SILVER, DISS (MG/L AS AG)	<.002	LEAD, DISS (MG/L AS PB)	.10
BORON, DISS (MG/L AS B)	25.2	STRONTIUM, DISS (MG/L-SR)	.62
CADMIUM, DISS(MG/L AS CD)	<.002	TITANIUM DIS(MG/L AS TI)	.003
CHROMIUM, DISS (MG/L-CR)	<.002	VANADIUM, DISS(MG/L AS V)	.038
COPPER, DISS (MG/L AS CU)	<.002	ZINC, DISS (MG/L AS ZN)	<.004
LITHIUM, DISS(MG/L AS LI)	2.02	ZIRCONIUM DIS(MG/L AS ZR	.026
MOLYBDENUM, DISS(MG/L-MO)	.60	ARSENIC, DISS(UG/L AS AS)	11.8
DISSLVD SOLIDS(CALC MG/L	5700.		

REMARKS: WATER FOAMS WHEN AGITATED;SALTY;YELLOW;SUSPENDED CLAYS;DIRTY FILTER*
NO PRESSURE TANK, WELL HAS BEEN USED VERY LITTLE SINCE INSTALLATION IN
APRIL 1982*OWNER CLAIMS THE WATER IS KILLING HIS TREES*SUB PUMP 12 GPM
LAB: FU NA 2230 MG/L; GIVES 97.9 TOTAL CATION MEQVS AND BORON PRESENT AS
LAB: H3BO3 GIVES 98.2 TOTAL ANION MEQVS FOR .2 SIGMA*

EXPLANATION: MG/L = MILLIGRAMS PER LITER, UG/L = MICROGRAMS PER LITER, MEQ/L = MILLIEQUIVELENTS PER LITER. FT = FEET, MT = METERS. (M) = MEASURED, (E) = ESTIMATED, (R) = REPORTED. TR = TOTAL RECOVERABLE. TOT = TOTAL. BIO = BIOLOGICALLY AVAILABLE.

QW WA S2 WI OW PW AT OTHER
OTHER AVAILABLE DATA
OTHER FILE NUMBERS:

PROJECT: COST:
LAST EDIT DATE: 23-SEP-83   BY: TP *JKS
PROCESSING PROGRAM: F173OP V3 (09/1/83)   PRINTED: 28-FEB-84

PERCENT MEQ/L (FOR PIPER PLOT)

CA	MG	NA	K	CL	SO4	HCO3	CO3
0.1	0.3	99.0	0.5	24.4	29.1	43.5	3.0

NOTE: IN CORRESPONDENCE, PLEASE REFER TO LAB NUMBER: 82Q0862

NAME	LOCATION T	R	S	tract	TEMPERATURE °C	°F	FLOW l/min	gpm	cfs	TOPOGRAPHIC MAP	ALTITUDE meters	feet	APPARENT SOURCE OF WATER	SAMPLED BY agency	date	WATER CHEM sc @ 25°C	pH	DATA St. Anal
Vigilante	9S	3W	22	BDDD	23.5	(74)		(2200)	4.9	Varney 15′	1890	6200	Madison	MBMG	05-24-78	620	7.5	Yes
Warm Springs-State Hospital	5N	10W	24	A	77-78 (71)	(171-172) 160	600	(160) 60		Anaconda 15′	1470	4820	Boulder batholith(?), Madison(?)	USGS* MBMG	08-19-74 04-08-65	1510 TDS 1308	6.46 –	Yes No
Warm Springs (see Medicine Lodge)																		
Warm Springs (see Landusky Plunge)																		
Warner	5N	1E	22	DBBC	18.0	(64.4)		130		Radersburg 15′	1250	4100	alluvium; Tertiary sediments; Precambrian	MBMG	06-02-78	200	8.2	Yes
Weeping Child (see Sleeping Child)																		
West Fork Swimming Hole	12S	1E	18	CAD	25-28	(77-82)		(500)	1.1	Cliff Lake 15′	2040	6700	alluvium; Pleistocene volcanics(?)	MBMG*	09-29-77	322	8.30	Yes
White Sulphur Springs	9N	7E	18	BB	(35-52) 46	95-125? (115)	>1500	500 (>400)		White Sulphur Spgs. 7.5′	1530	5025	Tertiary sediments; Precambrian	MBMG USGS*	09-01-61 08-17-74	TDS 1450 2220	– 6.8	No Yes
Wolf Creek[2]	10S	1E	9	BBBA	54-66 68.0	(129-151) (154)		(310) 53	0.7	Cliff Lake 15′	1860	6100	Tertiary sediments; Precambrian	MBMG* USGS*	09-30-77 05-13-76	494 659	11.03 8.6	Yes Yes
Ziegler (see Apex or New Biltmore)																		

() Bracket indicates temperature or flow reported in other units and calculated value presented for purposes of comparison.

*Symbol after analysis indicates a preferred analysis, conducted for geothermal evaluation, with a field (rather than laboratory) pH measurement.

A standard analysis includes: Ca, Mg, Na, K, Fe, Mn, SiO_2, CO_3, HCO_3, SO_4, Cl, F, NO_3, pH, and specific conductance.

Flow values and chemistry for some springs may not agree because of multiple sampling; some questionable values have been included.

Abbreviations: Health—Montana State Board of Health
MBMG—Montana Bureau of Mines and Geology
USGS—United States Geological Survey
USFWS—United States Fish and Wildlife Service

Notes:

[1]The Potosi Spring area in sec. 6 was inventoried on 05-24-78. The lower spring area contained a spring and pool south of the road ($Q \cong 40$ gpm; T = 35.0°C; SC = 560 µmho/cm; pH = 8.45) and a spring north of the road (Q = 20 gpm; T = 26.1°C; SC = 415 µmho/cm; pH = 8.85). The upper spring ($Q \cong 20$ gpm; T = 37.1°C; SC = 464 µmho/cm; pH = 8.45) also had a lower temperature than previously reported (Leonard and others, 1978, U.S. Geological Survey Open-File Report 78-438); these differences are attributed to dilution by snowmelt.

[2]The Wolf Creek hot spring was disturbed by backhoe work at an adjacent warm spring late in 1976 or early 1977. By 09-29-78 the hot spring temperature had recovered to 65°C (149°F). The MBMG flow value was taken at the road and includes contributions from warm and cool springs and seeps.