# Borehole Temperature Analysis and Interpretation of the Marysville Montana Geothermal Area

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***Keywords***

*Marysville, Montana, Empire Creek, heat flow, isotopic analysis, blind system*

## ABSTRACT

The Marysville Geothermal Area in western Montana is a unique geothermal study region due to its history of high-precision temperature-depth data dating back to the 1970s and the unusual characteristics of the geothermal system: lack of known surface manifestations, shallow depth, and the location in a structural and topographic high with no evidence of recent volcanism, hot springs, or fumaroles. Previous NSF/ERDA sponsored exploration of the anomaly comprises a variety of detailed geological, geophysical, and geochemical studies. These are briefly summarized and updated here. Since the Marysville anomaly is, as far as is presently known, a blind system, a detailed stream and spring $\delta^{18}O$ and $\delta^{2}H$ isotopic analysis of the area was carried out to provide insight into any possible surface manifestations which are common in other shallow geothermal areas and might be so subtle as to have been unrecognized in the past. This study provides a denser coverage of stream and spring sampling focusing on probable outflow regions based on analysis of previous geophysical results. A review of the gravity and magnetics surveys with the addition of new temperature-depth and surface water geochemical data is presented. The conclusion is that the Marysville Geothermal Area as a blind system with the circulating geothermal fluids having no identified surface discharge.

## Introduction

The geothermal anomaly near Marysville, Montana is a unique geothermal system in that it is a "blind" geothermal system, meaning it appears to be contained wholly within basement rocks, and thus have no surface manifestations. The shallow depth of the anomaly is also of interest because it occurs in a structural and topographic high (the anomaly extends on both sides of the Continental Divide) with no evidence of recent volcanism, hot springs, or fumaroles. The geothermal anomaly was discovered in 1965 while performing a regional heat flow study using wells drilled for mineral exploration (Blackwell and Baag, 1973). The geothermal anomaly lies approximately 30 km northwest of Helena, Montana and less than 5 km from the historic gold mining camp of Marysville, Montana (Figure 1). The geophysical setting is also at the north end of the Intermountain Seismic Belt which to the south extends to the southern boundary between the Colorado Plateau and the Basin and Range in Utah (Smith and Sbar, 1974;

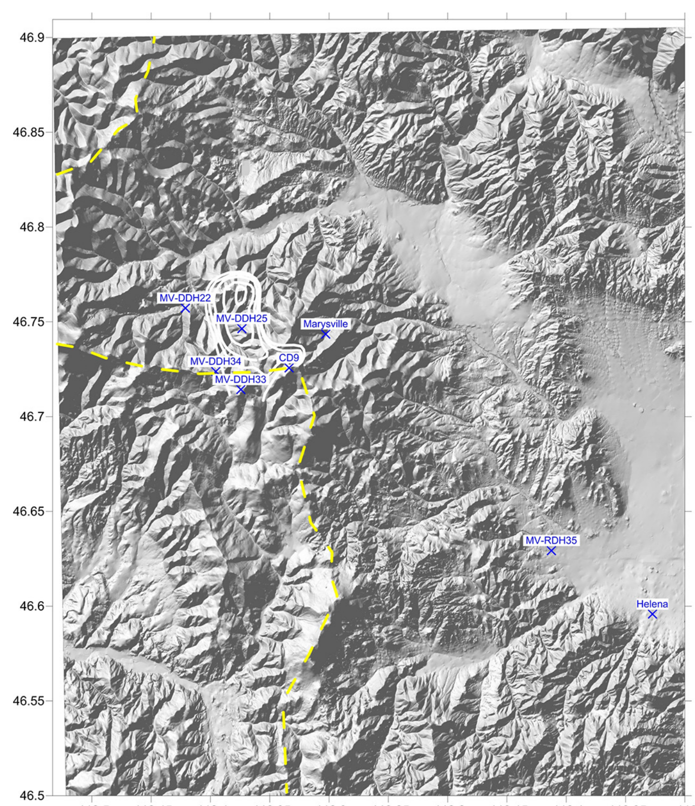


**Figure 1.** Digital Elevation Model (DEM) map view of the Marysville Geothermal Area with 2013-logged well locations indicated with blue 'X's. The Continental Divide in this area is represented by a yellow dashed line.

Freidline et al., 1976). The measured heat flow values associated with the anomaly are several times higher than the regional heat flow for western Montana, a region already above the global stable continental average and in fact typical of Basin and Range heat flow values (Blackwell and Baag, 1973; Blackwell et al., 1975; McSpadden et al., 1975).

## *Study Location*

The Marysville Geothermal Area is located in western Montana, almost directly on the Continental Divide, 30 km northwest of Helena, Montana. In this study, new temperature-depth data were collected and analyzed from six well sites in the National Geothermal Data System (http://geothermal.smu.edu). Five sites are located near Marysville, Montana (CD9, MV-DDH22, MV-DDH25, MV-DDH33, and MV-DDH34) and a sixth (MV-RDH35) is located within Fort William H. Harrison, northwest of Helena, Montana and approximately 11 kilometers east of the Continental Divide (Figure 1). All six sites were also part of the geothermal exploration well data set collected between 1966 and 1974. Each well has high precision temperature-depth data dating back to the 1970s as part of the NSF sponsored study of the area. The long time span, coupled with highly detailed geologic descriptions of the area and its relation to heat flow (Blackwell et al., 1975), makes these sites unique settings for temperature-depth analysis and surface temperature change analysis. The fact that the Marysville Geothermal Area is considered a blind system also makes its surrounding streams and springs interesting candidates for stable isotope analysis.

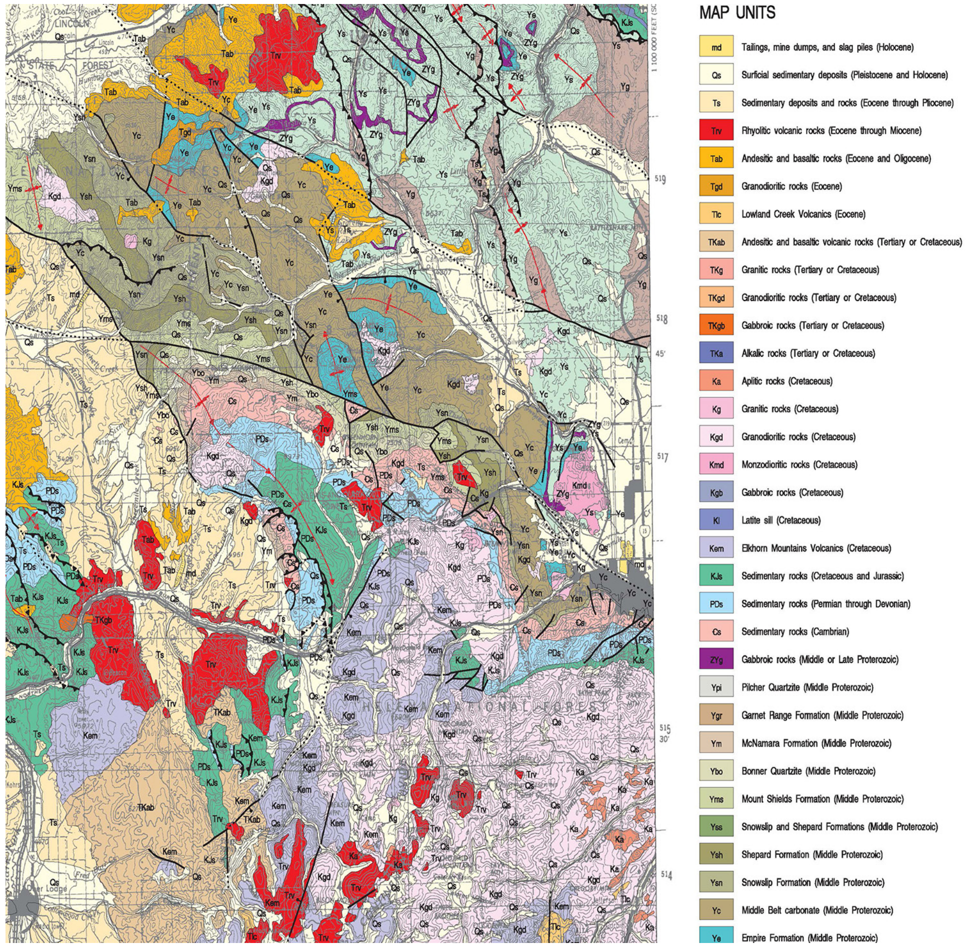


**Figure 2.** Portion of the Butte 1:250,000 quadrangle geologic map showing Boulder Batholith type intrusives (Kgd) as a dominant regional surface geology feature (Lewis, 1998). The Marysville stock is also represented as Kgd.

## *Geologic Setting*

The Marysville Geothermal Area is dominated topographically by the Rocky Mountains. A detailed geologic description of the Marysville stock and the entire mining area was first published by Barrell (1907). The Marysville Geothermal Area is part of the North American Cordilleran Orogen and has undergone episodes of volcanism, folding, thrusting and normal faulting since the Cretaceous (Tammemagi et al., 1986).

The bedrock in the area consists of Precambrian Belt Series sedimentary units, primarily the Empire Shale and Helena Limestone (Ross, 1963). The sedimentary rocks are cut by a series of intrusions, the largest in outcrop being the Marysville stock. Figures 2 and 3 show a map view of the major igneous intrusions and a generally north-northwest trending cross-section covering the entirety of the geothermal anomaly, respectively. The Marysville granodiorite stock was dated at 78 Ma and is considered a satellite intrusion of the much larger magnitude Boulder batholith emplacement event (Baadsgaard et al., 1961). The Empire Creek granite stock has been dated at 40 Ma and is probably the intrusive equivalent of the rhyolitic composition Hope Creek volcanics (37 Ma) located to the southwest. Much of the limestone in the area has been transformed into calcsilicate hornfels and everywhere in the map area the two formations have undergone some degree of contact metamorphism (Petefish, 1975). Pressures associated with metamorphism were measured to be ~1 kb, indicating a depth of metamorphism around 4 km (Blackwell and Baag, 1973). The structural and topographic high in the area, a doubly plunging anticline (Figures 2 and 3), coincides with the extent of contact

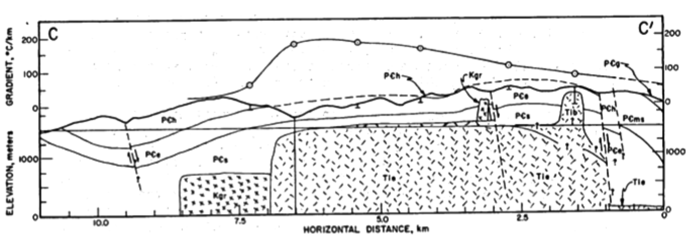


**Figure 3.** Northwest to Southeast geologic cross section of the Marysville Geothermal Area and the Empire Creek Stock (Tertiary Intrusive stock, TIs) along section C-C′ from Blackwell et al. (1975). The terrain corrected gradients for six wells from the NSF study that fall along C-C′ (open circles) are displayed above the cross section.

metamorphosed Empire Shale and is likely caused by emplacement of the Marysville and Empire Creek stocks. The extent of the heat flow anomaly also appears to be bounded to the west and south by faults shown in Figure 2, pointing to structural boundaries in the area playing a role in defining the generally linear nature of the anomaly.

### *Empire Creek Stock*

The Empire Creek Stock, apparent host to the geothermal fluid convection system discovered through the drilling and geophysical surveys, is porphyritic at its top grading to equigranular granite at depth. It consists of relatively equal amounts of quartz and alkali feldspar with smaller amounts of plagioclase feldspar and biotite. The igneous rocks in the area have long been of interest for gold and molybdenum mineralization. Alteration mineralogy, vein mineralization, and fluid inclusions are important characteristics in geothermal systems, showing the extent and relative temperatures of hydrothermal interaction (Tammemagi et al., 1986). The feldspar and quartz alteration evidenced in the cores taken from the Empire Creek stock suggest a post-magmatic hydrothermal system, which coincides with the extensive contemporary fluid movement and high degree of meteoric water input found in the deep borehole (Blackwell et al., 1975). Fluid in the present day geothermal system may be responsible for some degree of feldspar alteration and fracture silicification, but even the deepest sections indicate that temperatures over the past one million years have remained below the K-Ar blocking temperature (Tammemagi et al., 1986).

## Geophysical Review

### *Geophysical Exploration*

A total of 24 holes were used in the original heat flow study of the area. Analysis of heat flow obtained from the 15 relatively shallow holes from previous mineral exploration alongside 9 holes drilled specifically for geothermal purposes led to the development of a detailed heat flow map of the area (Blackwell et al., 1975). Fitting a least-squares straight line to the temperature-depth data, using mean harmonic average conductivities from the rocks encountered in the drill holes, and applying terrain corrections, local geothermal gradient and heat flow values were obtained (Blackwell and Baag, 1973; McSpadden et al., 1975). The pre-1974 heat flow, together with borehole logging, gravity, magnetic, electrical resistivity, magnetotellurics, microseismic, and ground noise surveys were used in determining the location for a deep drill hole (just over 2 km) to explore the full extent of the zone believed to be responsible for the geothermal anomaly (Figure 1).

Surface geophysical surveys undertaken during the exploration of the Marysville geothermal area were of great use in constraining the extent of the anomaly. A magnetics survey made available by AMAX Inc. and referenced in the 1975 Marysville Final Report (McSpadden et al., 1975) revealed a large magnetic anomaly over the Marysville stock, which allowed the shape of the stock to be mapped in some detail as shown in Figures 3 and 4. The magnetic anomaly ended at the contact between the relatively unfractured Marysville stock and the unexposed Empire Creek stock discovered to the west. These particular surveys highlight the differences between the two similar rock types that contrast greatly in geothermal (fracture) and physical (density and magnetic susceptibility) characteristics. Another important geophysical study is the electrical resistivity survey that showed high resistivity in both plutons. This result is of interest because it does not logically fit with the dynamic hydrothermal system in the unexposed Empire Creek stock discovered in later drilling (Tammemagi et al., 1986).

A 1973 field survey documented that the generally N-S trending Intermountain Seismic Belt trend, which passes through

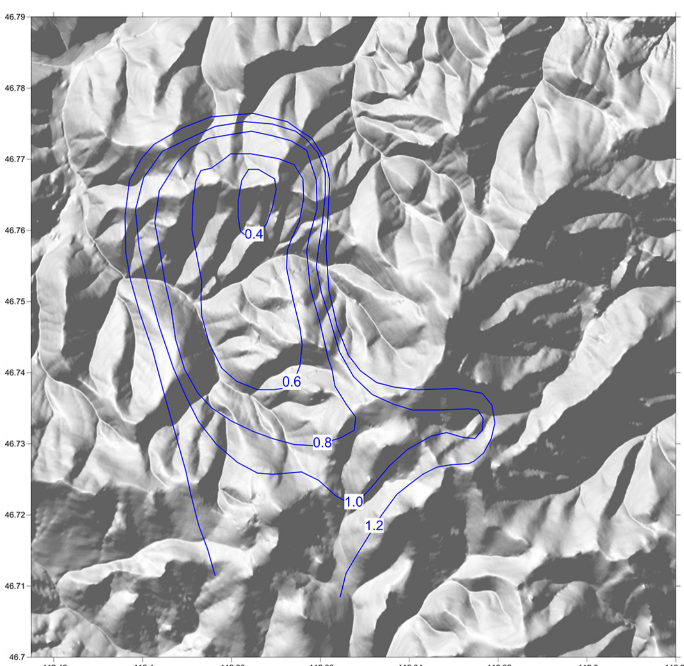


**Figure 4.** Depth in kilometers to the geothermal reservoir (in blue) after Brott et al. (1981).

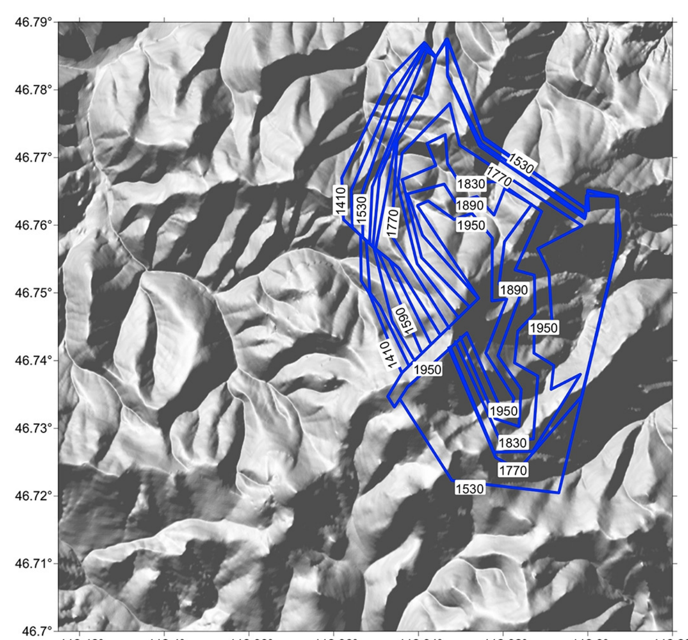


**Figure 5.** Marysville granodiorite stock magnetic anomaly. Blue contours represent the elevation of the magnetic anomaly (meters) (Blackwell et al., 1975). Dike apophasis shown as blacked dashed line.

Helena, dies out to the north of the Marysville heat flow anomaly (Freidline et al., 1976). Extended seismic monitoring in the past few years has located continuing diffuse seismicity in the area (Stickney, 2013, personal communication). Also, the lack of seismic ground noise in the NSF studies in the immediate area of the thermal anomaly was thought to be evidence against a hot water system, as most geothermal systems were proposed to have high seismic ground noise levels (Clacy, 1968).

### Magnetic Anomaly

An AMAX magnetic survey of the general area revealed a large magnetic anomaly over the Marysville stock, but no anomaly over the Empire Creek stock, source of the geothermal anomaly. The interpreted magnetic model (Figure 5) is considered a close approximation of the shape of the Marysville stock (Blackwell et al., 1975). The contact between the relatively less fractured Marysville stock and the pervasively fractured Empire Creek stock is seen as the western boundary and southwestern faulted boundary of the magnetic anomaly (Figure 5). These boundaries are extremely important in defining the geothermal system as a whole because they may represent an impermeable surface preventing the flow of geothermal fluids to the northeast of the source. A dike apophasis associated with the Marysville Stock and its accompanying faults are represented in Figure 5 as the contour in the center of the magnetic anomaly striking southwest towards the Empire Creek stock. This dike apophasis-fault feature is important because it is one of the possible pathways for discharging fluids from the geothermal system (Figure 7).

### Gravity Anomaly

Over a broad regional area, there is a strong northeast-southwest gravity gradient from more positive values in the Great Plains to more negative values in the Boulder batholith (Blackwell et al., 1974). This regional variation reflects crustal thickness changes in the transition from the Great Plains to the Rocky Mountains. The Marysville Geothermal Area itself is characterized by a negative gravity anomaly due to the Cenozoic Empire Creek stock (2.54 g/cm$^3$) being emplaced into Precambrian Belt Series sedimentary rocks (2.69 – 2.89 g/cm$^3$) (Mazzella, 1974) (Figure 6). Directly to the west, the older Cretaceous Marysville stock has a much less pronounced gravity anomaly as it does not have the significant fracture network and subsequent alteration of the Empire Creek stock. For these reasons, this gravity survey is the best geophysical representation of the Empire Creek stock, interpreted to coincide with the Marysville geothermal anomaly (Blackwell et al., 1975). The -10 milligal contour line (Figure 6) is a good approximation of the shape of the peak of the geothermal anomaly, however the gravity anomaly does not match the closure of the heat flow contours defining the southern portion of the anomaly as shown in Figure 7.

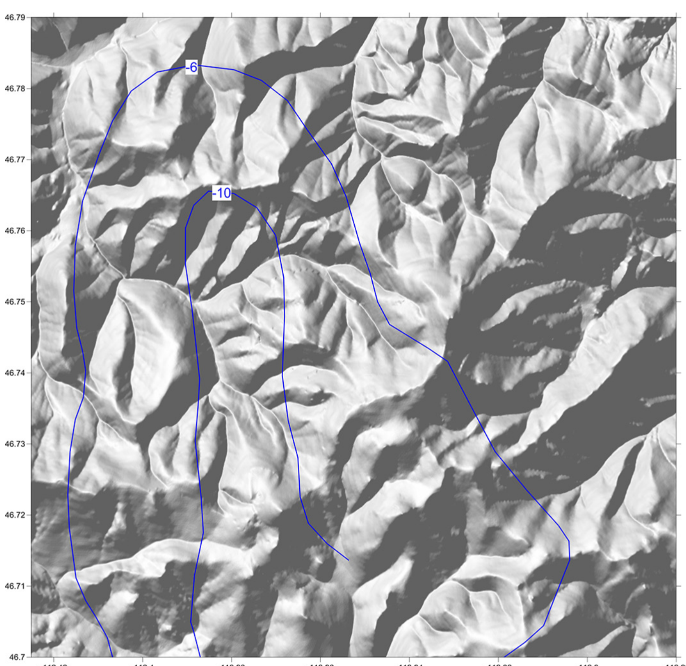


**Figure 6.** Gravity anomaly of the Empire Creek stock emplaced in Precambrian sediments. Gravity anomaly contours from Mazzella, 1974 (blue) are in milligals.

### Heat Flow and Heat Loss

The Marysville Geothermal Area is highly unusual because of the extremely high geothermal gradients (as high as 181°C/km terrain corrected gradient), the shallow nature of the system (as shallow as 400 m below surface) and the lack of surface evidence in the mountainous terrain along the Continental Divide. For these reasons, defining the heat flow of the geothermal systems compared to the regional background is of great importance for understanding the shape, boundaries, and recharge of the geothermal reservoir. Heat flow (Q) for the area is calculated by combining geothermal gradient ($\delta T/\delta z$) data from well logs along with thermal conductivity measurements (k) obtained from rotary drill cuttings or core.

In all the wells used to create the heat flow model in Figure 7, terrain corrected geothermal gradients are used (McSpadden et al., 1975). The heat flow over the system provides the most accurate

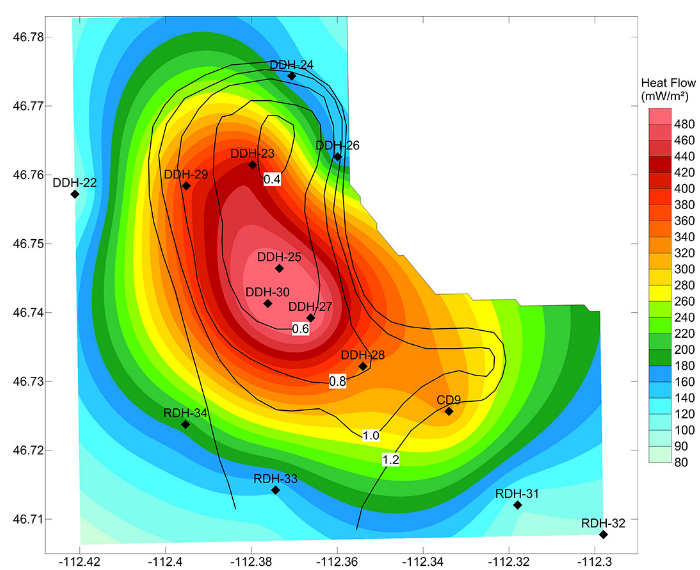


**Figure 7.** Heat flow map of the Marysville Geothermal Area (contours in mW/m$^2$) with the depth to the geothermal reservoir (black lines) after Brott et al., (1981). Blanked area in upper right corner is in the area of background heat flow levels in Marysville stock.

geothermal reservoir representation and prediction of fluid flow in the Marysville Geothermal Area (Figure 7).

Heat loss, the total thermal output of the geothermal system, was calculated for the Marysville Geothermal Area using the contour map in Figure 7. This value is determined by taking the anomalous heat flow of the system (Figure 7) and subtracting the background heat flow of the region. A background heat flow of 80 mW/m$^2$ was used, as it represents a typical cutoff of geothermal systems in the Basin and Range equivalent provinces in the western United States (Wisian et al., 1999). The blanked area to the northeast of the heat flow anomaly is not used in the heat loss calculation because it represents the extent of the impermeable Marysville stock. Since the Marysville stock is dated at 78 Ma, it should currently be cooled to background heat flow levels. As it may serve as an impermeable boundary, any heat flow between the Empire Creek stock and the Marysville stock would diffuse over a short lateral area. The total heat loss for the thermal anomaly as shown in Figure 7 was calculated to be 10.2 MW.

The depth to the geothermal reservoir based on the results of the deep well was determined to coincide with the depth to the 95°C isotherm. The temperatures were found to be isothermal at 95°C below the 500 m conductive cap over a drilled depth of about 1.5 km in the deep well, MGE #1, (McSpadden et al., 1975) so the 95°C isotherm is assumed to be the best representation of the shape of the fracture system in the Empire Creek stock (Figure 8). The shape of the gravity anomaly associated with the stock also closely mimics the shape of the heat flow anomaly as shown in Figures 7 and 8. To further validate the shape of the geothermal reservoir, 3-D extrapolations of temperature-depth curves from the wells in the area were made to define the shape of the 95°C isotherm. Figure 8 shows model results from this extrapolation, employing the 3-D topography of the area and extrapolating the temperature gradient of each well to depth. The model from this study appears to be an accurate representation of the elongated north-south shape of the Empire Creek stock, based on the gravity anomaly interpretation from Mazzella, (1974), with elevated temperatures on an east-west salient possibly attributed to fluid flow from the system along the dike apophasis/fault feature from Blackwell et al., (1975) (Figure 8).

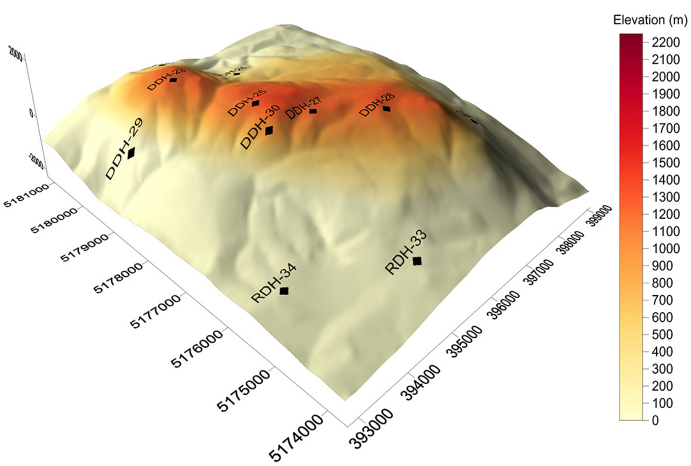


**Figure 8.** Shape of the upper surface of the Empire Creek stock interpreted by the depth to the 95°C isotherm from the area wells (black diamonds). Displayed on a UTM Zone 12N grid.

## Surface Water Geochemistry

### *Stable Isotope Geochemistry*

The Marysville Geothermal Area's lack of any recognized surface manifestations commonly associated with geothermal systems, and its position straddling the Continental Divide, make it an unusual and valuable case to study to better understand geothermal circulation systems in general. $\delta^{18}O$ analysis of water samples from the deep borehole after drilling did not indicate a statistically significant shift from meteoric water in the region (McSpadden et al., 1975). This result, along with the temperatures calculated by the $SiO_2$ and Na-K-Ca geothermometer methods suggests circulating waters of geologically recent meteoric origin and reservoir temperatures of 110°C to 180°C (Tammemagi et al., 1986). Eleven samples collected in 2013 during the course of the study similarly underwent $\delta^{18}O$ and $\delta^2H$ isotopic analysis in hopes of improving the understanding of the relationship and history of hydrothermal fluids from the Empire Creek stock and the surrounding area (Figure 9). These results were compared to the local meteoric water line, LMWL, to identify any geothermal input directly or after mixing with surface waters (Figure 10). Plotting $\delta^{18}O$ vs $\delta^2H$ and comparing sample values to meteoric water trend lines for the region will show any shifts due to water-rock interaction and help to confine possible reservoir temperatures and discharge locations.

### *$\delta^{18}O$ Analysis*

The oxygen isotope composition for the water at each sample location is determined using a method after Epstein

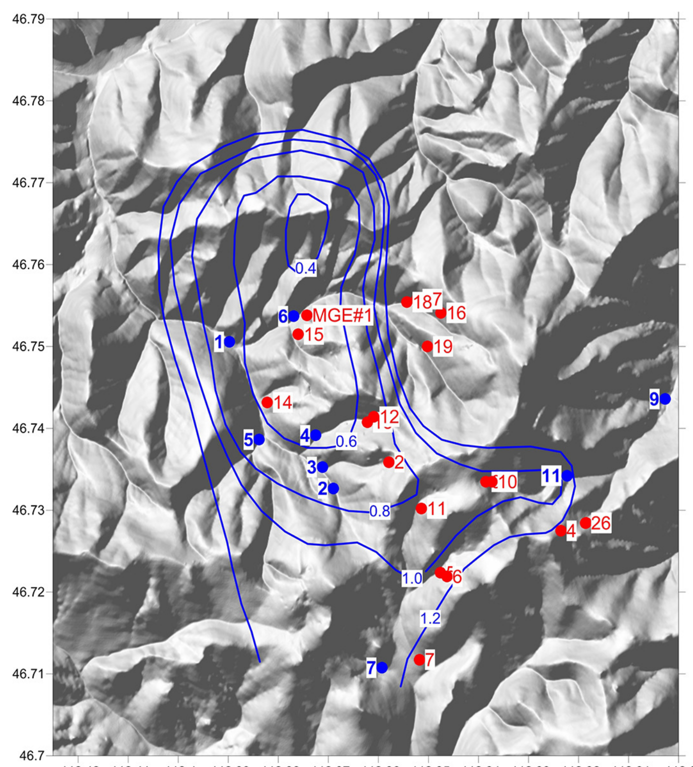


**Figure 9.** Stable isotope sample location site numbers from 2013 in blue and from 1975 in red plotted with the depth (in km) of the geothermal reservoir (blue contour lines) after Brott et al. (1981).

and Mayeda (1953) where the isotopic composition (in ppm) is calculated by the equation:

$$\delta^{18}O_{sa} = (R_{sa}/R_{std} - 1) \times 1000 \quad (2)$$

where R is the ratio of $^{18}O/^{16}O$ of the water sample and standard (Figure 10). Any positive shift in isotopic signature in a stream or spring water source at a given location would suggest outflow of circulating hydrothermal fluid. Such a change could prove useful in constraining flow directions and possibly hint at the ultimate ending location of the geothermal fluids.

### *δ²H Analysis*

The hydrogen isotope composition for the water at each sample location is determined using a method after Bigeleisen (1952) where the isotopic composition is calculated by the equation:

$$\delta^{2}H_{sa} = (R_{sa}/R_{std} - 1) \times 1000 \quad (3)$$

where R is the ratio of $^{2}H/^{1}H$ (Figure 10). Any shift in isotopic signature from a given sample location on a $\delta^{18}O$ vs $\delta^{2}H$ plot compared to the LMWL would suggest outflow of hydrothermal circulating fluid. $\delta^{18}O$ (x axis) vs $\delta^{2}H$ (y axis) for each of the 11 samples from August 2013, along with national and local meteoric water lines, are plotted in Figure 10 to show any deviation from meteoric waters representative of possible geothermal interaction with surface waters. According to Gammons et al. (2006), the substantial deviation in the sample data from Kendall and Coplen's (2001) Montana MWL can be attributed to modification of isotopic composition of stream waters by non-equilibrium evaporation. Gammons et al. (2006) performed an isotopic composition analysis on rain and snow samples, deriving a LMWL based solely on precipitation for Butte, Montana. All the samples collected in this study fall closer to the National MWL or the Butte MWL than the Montana MWL from Kendall and Coplen (2001) for this reason. Overall, the results show no significant deviation from the LMWL. These results could not be compared to previous isotopic samples from AMAX Inc. (Figure 9) because those were collected in the spring months and were therefore likely to be affected by spring snowmelt, driving their data to more negative oxygen isotope values.

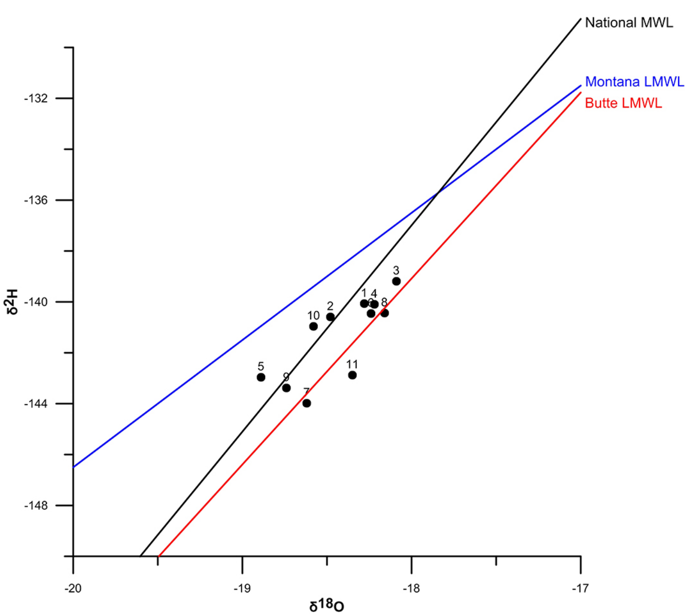


**Figure 10.** $\delta^{2}H$ - $\delta^{18}O$ Plot versus MWL of Marysville area stable isotope samples with 1-sigma error bars (black circles) plotted with nearby meteoric water lines (MWL). Shown are the 'national' MWL (black) $\delta^{2}H=8.11\delta^{18}O + 8.99$ and Montana MWL (blue) $\delta^{2}H=5.0\delta^{18}O - 46.5$ from Kendall and Coplen (2001) and the Butte LMWL (red) $\delta^{2}H=7.31\delta^{18}O - 7.5$ from Gammons et al. (2006).

## Summary and Conclusions

The range of geophysical surveys undertaken at the Marysville Geothermal Area coupled with the detailed sampling and isotopic analysis of nearby streams and springs make the area a prime candidate for understanding a well-defined but unusual geothermal system. Even with its shallow depth and its placement in a structural and topographic high, geothermal discharge (mixing with meteoric surface waters) cannot be proven. With no outflow of geothermal fluids in the area, the circulation of the system cannot be clearly defined. Petrographic analysis of the MGE #1 drill core in combination with evidence from the magnetic, heat flow and gravity surveys suggest a system of isothermal deep convection with silicified fracture zones in the geothermal host rock serving as an upper boundary to the system. Fluid is likely moving in or out of the system along the southern edge of the Marysville stock through the dike apophasis/fault feature caused by the emplacement of the Marysville stock. These fluids, whose isotopic signature may not be significantly different than regional meteoric waters, are likely being diluted through mixing with normal meteoric waters to the point that no high-temperature water-rock interaction signature is left when they discharge into surface waters. The system appears to be a paleohydrothermal mineralization system possibly reactivated by contemporary seismic activity and driven by buoyancy forces operating in a most unusual topographic setting. The system is of significant size (heat loss) and approaches quite near the surface. Thus in the climatic setting of western Montana, it could be commercially exploited using binary technology.

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