

Utah State University

DigitalCommons@USU

All Graduate Theses and Dissertations, Spring
1920 to Summer 2023

Graduate Studies

5-2013

Evaluation of the Geothermal Potential of the Snake River Plain, Idaho, Based on Three Exploration Holes

Thomas G. Freeman
Utah State University

Follow this and additional works at: <https://digitalcommons.usu.edu/etd>

 Part of the [Geology Commons](#)

Recommended Citation

Freeman, Thomas G., "Evaluation of the Geothermal Potential of the Snake River Plain, Idaho, Based on Three Exploration Holes" (2013). *All Graduate Theses and Dissertations, Spring 1920 to Summer 2023*. 2020.

<https://digitalcommons.usu.edu/etd/2020>

This Thesis is brought to you for free and open access by the Graduate Studies at DigitalCommons@USU. It has been accepted for inclusion in All Graduate Theses and Dissertations, Spring 1920 to Summer 2023 by an authorized administrator of DigitalCommons@USU. For more information, please contact digitalcommons@usu.edu.



EVALUATION OF THE GEOTHERMAL POTENTIAL OF THE SNAKE RIVER
PLAIN, IDAHO, BASED ON THREE EXPLORATION HOLES

by

Thomas G. Freeman

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

of

MASTER OF SCIENCE

in

Geology

Approved:

Thomas E. Lachmar
Major Professor

John W. Shervais
Committee Member

James P. Evans
Committee Member

Mark R. McLellan
Vice President for Research and
Dean of the School of Graduate
Studies

UTAH STATE UNIVERSITY
Logan, Utah

2013

Copyright © Thomas Freeman

All Rights Reserved

ABSTRACT

Evaluation of the Geothermal Potential of
the Snake River Plain, Idaho, Based on
Three Exploration Wells

by

Thomas G. Freeman, Master of Science

Utah State University, 2012

Major Professor: Dr. Thomas E. Lachmar
Department: Geology

Over the period of September 2010 to January 2012 three exploratory wells were drilled on the Snake River Plain in Idaho as part of the Snake River Plain Geothermal Drilling Project (Project Hotspot). These wells were intended to help document the existence of geothermal potential in the Snake River Plain area; specifically, along the axis of the eastern Snake River Plain, along the margin of the plain, and in the western Snake River Plain.

I examined five water samples that were collected from the three wells (one each from Kimama and Mountain Home, and three from Kimberly) and analyzed for 24 ion concentrations. The Kimama waters are Na-chloride, Kimberly waters are Na-bicarbonate, and Mountain Home waters are Na-sulfate. These chemical results were used in seven solute geothermometers to estimate reservoir temperatures at depth. Three

of the water samples were also analyzed for the stable isotopes ^2H , ^{13}C , and ^{18}O .

Temperature logs were used to calculate geothermal gradients in the wells.

The Mountain Home well had the highest recorded water temperature (140 °C), the highest geothermometer results, and highest geothermal gradient for the entire well (73 °C/km). Mountain Home isotopic properties indicate it is not meteoric water.

Kimama had a maximum recorded temperature of 59.3 °C, and geothermometer results only slightly lower than at Mountain Home. The Snake River Plain aquifer suppresses the geothermal gradient in the upper portion (0-960 m) of the Kimama well to 5.5 °C/km, while below a depth of 960 m the gradient increased to 88.9 °C/km. Kimama isotopic properties indicate that it is meteoric water. Kimberly had a maximum recorded temperature of 57.3 °C, the lowest geothermometer results of 112.9 °C, and a geothermal gradient of 15.1 °C/km. The gradient from 800-1,953 m is only 5 °C/km. Mountain Home and Kimama had the strongest indicators of future geothermal potential with high temperatures, high geothermometer results, and high geothermal gradients.

(102 pages)

PUBLIC ABSTRACT

Evaluation of the Geothermal Potential of the Snake River Plain, Idaho, Based on Three Exploration Wells

The work in this thesis was based on analyzing water samples collected from three exploratory boreholes drilled during Project Hotspot. The water samples were analyzed for their chemical properties. The chemical properties of the water samples were used as a basis for further analysis.

Geophysical logs, mainly temperature logs, were also analyzed for this project. Temperature logs measure temperature in relation to depth within a borehole.

All the analyses were made in order to estimate the geothermal potential of the project areas. The exploratory boreholes were all drilled in different areas and each had unique characteristics. The Mountain Home borehole provided the most promising evidence for future geothermal potential. Geothermal energy is a form of renewable energy and potential production areas are difficult and expensive to locate.

Thomas G. Freeman

ACKNOWLEDGMENTS

Thank you to all of my family and friends. Without all of you I would not be the person I am today. Most of all my parents and future wife, Whitney. Whitney packed up and moved across the country with me and supported me throughout my studies.

Next, I want to thank my advisor, Tom Lachmar, for the opportunity to be a graduate student at Utah State University. Tom not only helped me learn and be a good student, but also taught me about being a good person and making decisions in life. Many conversations we had were over a warm bowl of soup and a hearty piece of bread at “Soup Night.”

John Shervais and Jim Evans comprised the rest of my committee and provided valuable thoughts and input throughout the process. John was the lead scientist on Project Hotspot and was instrumental in many decisions that helped me as a graduate student.

My gratitude is also extended to my fellow students, especially those that were involved with Project Hotspot. There were many days that I will never forget moving boxes of core and those that were there will also remember.

Marsha Hunt and Jean Daddow were the Geology Department secretaries and made my life infinitely easier. Also, Nina Glaittli was involved with Project Hotspot and provided me support for dealing with the project.

I would like to thank the Department of Energy for providing funding for Project Hotspot, which my thesis work revolved around.

To Kit and Brent thank you for being the great friends that you are. You guys always helped me and Whitney adjust to life in Utah and even helped teach me new things like skiing and hockey.

Special thanks go to my parents, Uncle Bub, and Aunt Sissy for helping Whitney and me move across the country not once, but twice.

Thomas G. Freeman

CONTENTS

	Page
ABSTRACT.....	iii
PUBLIC ABSTRACT	v
ACKNOWLEDGMENTS.....	vi
LIST OF TABLES	x
LIST OF FIGURES.....	xi
INTRODUCTION.....	1
BACKGROUND.....	4
Geologic and Hydrologic Setting.....	4
Geothermal Energy.....	8
METHODS.....	12
Well Completion Information.....	12
Logging.....	17
Core and Lithologic.....	17
Temperature	21
Geophysical Logs.....	22
Sampling.....	23
Kimama.....	23
Kimberly.....	26
Mountain Home.....	28
Analyses.....	30

	ix
RESULTS	33
Hydrochemical Properties.....	33
Isotopic Compositions.....	39
Geothermal Gradients	41
Kimama.....	42
Kimberly.....	47
Mountain Home.....	47
DISCUSSION	51
Geothermometry.....	51
Kimama.....	54
Kimberly.....	56
Mountain Home.....	57
Graphic Techniques	57
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS	61
Summary	61
Kimama.....	61
Kimberly.....	62
Mountain Home.....	63
Conclusions.....	64
Recommendations.....	65
REFERENCES CITED.....	67
APPENDICES.....	72
Appendix A. Chemical Results.....	73
Appendix B. Core Photos	76
Appendix C. Geothermometer Calculations.....	82

LIST OF TABLES

Table	Page
1	Geophysical logs summary..... 22
2	Chemical analyses of Project Hotspot samples (all units in mg/L unless otherwise noted)..... 34
3	Chemical analyses of McLing (2002) (all values in mg/L)..... 37
4	Isotopic analyses of Project Hotspot samples..... 40
5	DOSECC temperature tool measurements (Neilson et. al., 2012)..... 43
6	Geothermometer equations..... 52
7	Geothermometer calculations (all results in °C)..... 56
A.1	USUAL chemical results (all values in mg/L)..... 74
A.2	ThermoChem and UVDL chemical results (all values in mg/L)..... 75
C.1	Geothermometer calculations for KA-1..... 83
C.2	Geothermometer calculations for KB-38..... 84
C.3	Geothermometer calculations for KB-52..... 85
C.4	Geothermometer calculations for KB-63..... 86
C.5	Geothermometer calculations for MH-5,726 (USUAL)..... 87
C.6	Geothermometer calculations for MH-5,726 (ThermoChem)..... 88
C.7	Geothermometer calculations for MH-5,726 (UVDL)..... 89

LIST OF FIGURES

Figure		Page
1	Location map of SRGDP wells.....	2
2	Extent of SRPA (Whitehead, 1994).....	5
3	Heat flow map of the United States (Blackwell and Richards, 2004). The SRP is circled.....	9
4	Atlas-Copco CS4002.....	13
5	Eaton Drilling & Pump Service setting surface conductor casing.....	14
6	Generalized lithologic log for Kimama well (Shervais et al., 2012, 2013).....	18
7	Generalized lithologic log for Kimberly well (Shervais et al., 2012, 2013)....	19
8	Generalized lithologic log for Mountain Home well (Shervais et al., 2012, 2013).....	20
9	Foerst mechanical sampler.....	24
10	SMU logging rig.....	25
11	Artesian flow out of Mountain Home well.....	30
12	Field analytical equipment.....	31
13	Piper (1944) plot of geothermal waters from Project Hotspot.....	36
14	McLing et al. (2002) sample location map.....	38
15	Piper (1944) plot of select samples from McLing et al. (2002).....	39
16	Piper (1944) plot of waters from all Project Hotspot samples and select McLing et al. (2002) samples.....	40
17	Plot of deuterium (^2H) and oxygen-18 (^{18}O) in comparison to GMWL.....	41
18	Kimama temperature log (DOSECC).....	44

		xii
19	Kimama temperature log (OSG).....	45
20	Kimama temperature log (SMU).....	46
21	Kimberly temperature log (OSG).....	48
22	Mountain Home temperature log (OSG).....	49
23	Project Hotspot samples plotted on Giggenbach triangular plot (Giggenbach, 1988).....	59
24	Project Hotspot samples plotted on Cl, SO ₄ , and HCO ₃ triangular plot (Giggenbach, 1988).....	60
B.1	Kimama core (1,070.5 - 1,073.3 m).....	77
B.2	Kimberly core (1,157.8 - 1,161.7 m).....	78
B.3	Kimberly core (1,581.5 - 1,585.0 m).....	79
B.4	Kimberly core (1,917.8 - 1,921.4 m).....	80
B.5	Mountain Home core (1,743.5 - 1,748.6 m).....	81
C.1	Giggenbach diagram for MH-5,726 (ThermoChem and UVDL) (Giggenbach, 1988).....	90
C.2	MH-5,726 (ThermoChem) plotted on Cl, SO ₄ , and HCO ₃ triangular plot (Giggenbach, 1988).....	90

INTRODUCTION

The Snake River Geothermal Drilling Project (SRGDP) is an attempt to explore for new geothermal resources in the Snake River Plain (SRP) area of southern Idaho (Shervais et al., 2012, 2013). The SRP is a prime target for geothermal exploration due to residual heat from the passage of the North American plate over the Yellowstone Hotspot, which lies to the northeast of the SRP. High geothermal gradients have been documented in the area (Blackwell, 1989).

Phase 1 of the project included field studies, establishment of a geophysical framework, and seismic profiles. Phase 2 consisted of the drilling of three deep (1,821.5-1,953 m) cored slimholes. Two holes were located in the Twin Falls area, and one on the Mountain Home Air Force Base (Figure 1). The Kimama well was located approximately 30 km north of Burley, ID on the axis of the eastern SRP. The Kimberly well was located 10 km east of Twin Falls, ID on the edge of the SRP. The Mountain Home well was located on the Mountain Home Air Force Base which is 15 km southwest of Mountain Home, ID in the western SRP. After completion of the wells borehole logging, core analysis, water sampling, and vertical seismic profiles took place.

The majority of funding came from the United States Department of Energy (DOE) and was supplied through the American Recovery and Reinvestment Act of 2009 (ARRA) (U.S. DOE EERE-0002848, 2011).

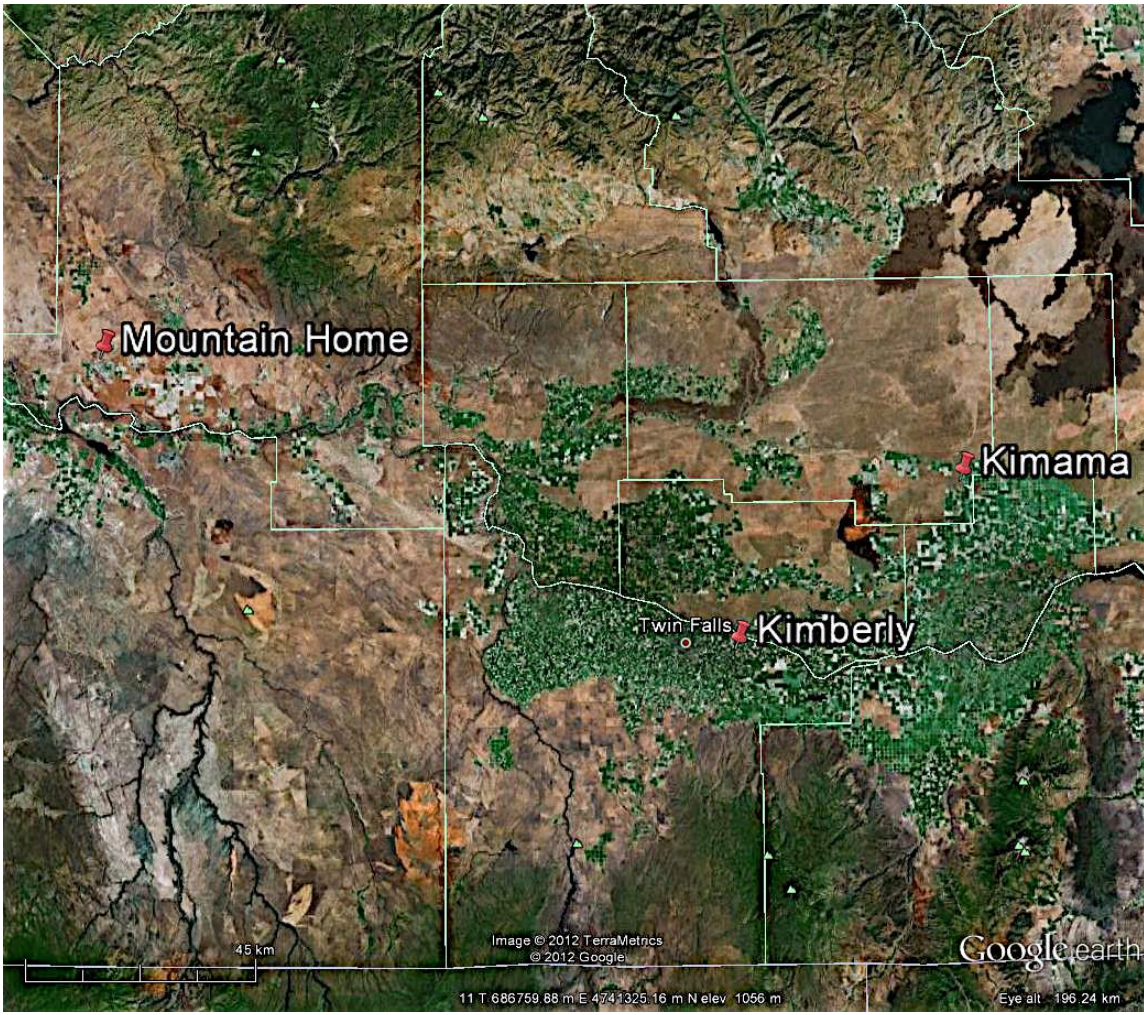


Figure 1. Location map of SRGDP wells.

The purpose of this study is to evaluate the physical and chemical properties of the water sampled in three boreholes of the SRGDP in order to assess the feasibility of developing future geothermal resources in the SRP area. This was accomplished by examining the results of logging, hydraulic testing, and sampling.

Logging consists of core, temperature and geophysical logs that provide indications of areas with high temperatures and other desirable properties. The results from the temperature logs are integral to the evaluation of the boreholes, in relation to

their geothermal potential. Temperature logs provide data that show where higher temperatures occur in the boreholes.

Hydraulic testing was set to include injection testing, but due to budget limitations this was not possible. Injection tests provide data that can be used to estimate the hydraulic properties of the boreholes. A shut-in test could have been conducted on the Mountain Home hole after it started flowing, but the decision was made to plug the zone and keep drilling.

Sampling results include water samples and core samples, both of which have been analyzed chemically to allow characterization of the water and core. Results from the water samples are used for geothermometry and also compared to other wells' chemistry. Geothermometers are temperature indicators that use temperature dependent geochemical and/or isotopic compositions of geothermal waters (Gupta and Roy, 2007).

The results from all of the tests have been correlated with each other to determine the hydrogeologic characteristics of the boreholes. Information about the physical and chemical properties of the three boreholes will provide insight into whether or not the locations targeted can be productive geothermal resources.

BACKGROUND

Geologic and Hydrologic Setting

The eastern Snake River Plain (ESRP) in southeastern Idaho, stretches from the Yellowstone Plateau in the east to the Twin Falls area on the western end. It is a topographic low and is surrounded by mountain ranges. It covers an area of ~28,000 km² (Morse and McCurry, 2002).

The ESRP owes its existence to a unique sequence of processes that are associated with the migration of the North American tectonic plate southwestward over the Yellowstone Hotspot (Smith and Braile, 1994). The Yellowstone Hotspot developed from a mantle plume interacting with the North American plate as it moved over top it (Smith et al., 2009). During recent geologic time the North American plate has been moving in a southwestern direction and about 16 or 17 million years ago (m.a.) the area that is now the western part of the ESRP was over the Yellowstone hotspot. Eruptions occurred about 16 or 17 m.a., which started the generation of the ESRP. The hotspot was stationary as the plate moved over it at a rate of about 2.5 cm/year (Smith and Braile, 1994).

Volcanic processes played the dominant role in the creation of the ESRP. Silicic volcanic rocks (rhyolites) that are analogous to those at the surface in the Yellowstone area today underlie basaltic lavas in the ESRP (Morgan et al., 1984; Hackett and Morgan, 1988; Hackett and Smith, 1992). These rhyolites record the early formation of the ESRP when the hotspot was directly beneath it.

Rhyolitic eruptions in the SRP were large caldera-forming events. As the plate progressed over the hotspot the rhyolite transitioned to persistent basaltic volcanism which filled in the ESRP. The basaltic volcanism resulted from the continual expansion of the ESRP which allowed magma bodies to make their way to the surface while they were still small resulting in numerous small eruptions (Smith, 2004). Consequently Quaternary volcanic landforms dominate the landscape of the ESRP (Hughes et al., 1999).

About 4 m.a. the ESRP was no longer over the hotspot and thus it began to cool and subside which it has been doing to the present day. During the time of subsidence and basaltic volcanism the surrounding mountains were eroding and providing sediments that affected the ESRP. These erosional forces were supplying alluvial and lacustrine sediments to form sedimentary interbeds in the basalt flows.

The ESRP is home to the Snake River Plain aquifer (SRPA) (Figure 2). The

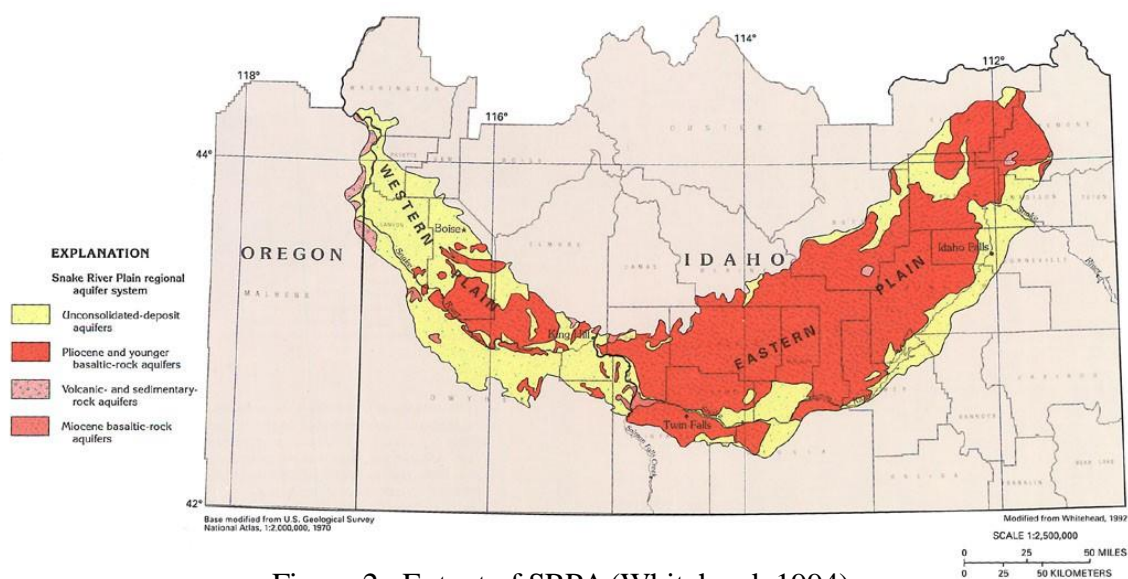


Figure 2. Extent of SRPA (Whitehead, 1994).

aquifer is hosted predominately in basalt (Welhan et al., 2002a, 2002b). The US Environmental Protection Agency (EPA) designated the SRPA a sole source aquifer in 1991. The EPA defines a sole or principal source aquifer as “an aquifer that supplies at least 50 percent of the drinking water consumed in the area overlying the aquifer. These areas may have no alternative drinking water source(s) that could physically, legally and economically supply all those who depend on the aquifer for drinking water” (U.S. EPA, 2011). Groundwater supplies over 92% of drinking water in the state of Idaho and the SRPA is a large source for both drinking and irrigation water.

The SRPA is one of the most productive aquifers in the United States (U.S. Geological Survey, 1985). Water budget and isotopic analyses of SRPA waters indicate that most of the water in the aquifer is local meteoric in origin (Wood and Low, 1986). Recharge to the aquifer occurs mainly in the north and east of the SRPA and comes from irrigation water, streams, and drainage from the mountains to the north of the SRPA. Discharge from the aquifer is predominately from irrigation pumping and flow from springs (Mann and Knobel, 1990).

The SRPA, along with the Snake River, supplies the majority of the fresh water needed for agricultural operations in the region (Whitehead, 1994). The area of Idaho that the SRPA underlies is arid and without the SRPA it would be difficult to support the current level of agriculture.

The SRPA and its vadose zone are composed of numerous basalt lava fields (Welhan et al., 2002a, 2002b). The fields each contain many lava flows that vary in thickness. The style of these basaltic eruptions tends to make a porous and permeable

host rock for the SRPA. Many of the individual lava flows tend to have a characteristic distribution of layers that affects the permeability and porosity of the aquifer (Smith, 2004). The bottom of the flows are typically rubble zones. The middle of the flows are massive and are not as porous or permeable as the top or bottom. The tops are commonly vesicular due to gases that were trapped in the basalt. At deeper levels of the aquifer the porosity and permeability tend to decrease due to secondary mineralization (Smith, 2004; Sant, 2012).

McLing et al. (2002) examined shallow groundwater, deep thermal wells, and thermal springs in the SRPA area. The chemical characteristics showed that deep thermal waters and shallow groundwater were mixing. The water chemistry of the upper SRPA is dominated by Ca-Mg-HCO₃, whereas the deeper thermal aquifer consists of Na-K-HCO₃ waters. A majority of the data came from the Idaho National Laboratory (INL) area (McLing et al., 2002). Two wells that reach depths similar to those in the SRGDP were examined by McLing et al. (2002), the Sturm well and the INEL-1 well. The INEL-1 well was drilled to assess geothermal potential in the INL area and it reached a depth of 3,159 m. This well shows the progression from Ca-Mg-HCO₃ dominated water at shallow depths to Na-K-HCO₃ dominated water at deeper depths (Mann, 1986). The Sturm well is near Ashton, Idaho, in the northern SRPA and is 1,000 m deep.

The INL is on the northern edge of the ESRP. The INL began its history by being the testing grounds for nuclear reactors. Many other projects have taken place there which involve hazardous chemicals. Before recent times some of these chemicals were not disposed of properly so the INL has done extensive testing of the groundwater in that

general area. Many wells have been drilled in and near the INL and provide an abundance of data for the aquifer in that area. The general flow direction for the aquifer is to the southwest, but due to the heterogeneity of the basalt flows there are many smaller scale differences in flow direction (Smith, 2004). Tension-cracks and eruptive fissure systems have implications on the movement of groundwater in the SRPA at the INL (Welhan et al., 2002a, 2002b).

Geothermal Energy

Geothermal energy is thermal energy produced by and stored in the earth that can be extracted and used economically. Natural hot springs are the most obvious manifestation of geothermal heat. Hot springs were the original use of geothermal energy and have been used for balneological purposes for centuries.

Geothermal energy can also be used for space heating. Space heating is a use of direct geothermal heat to heat buildings, greenhouses, and aquaculture. Ground source heat pumps only require the heat that is stored in the ground close to the surface. Below 3 m the ground generally has a constant temperature and ground source heat pumps take advantage of that. In the winter when the ground is warmer than the air outside, heat is pulled into the buildings by a heat pump. In summer when the ground is cooler, the process works the other way. Space heating is an efficient way to use geothermal energy, but it does not provide enough energy to generate electricity.

In reality heat from the earth is essentially everywhere, but the difficulty is finding some way to tap into and use that heat for our purposes. In areas where the heat

is concentrated by the flow of hot water and is closer to the surface it becomes easier to access and use the heat. An efficient way to tap into this resource is in areas where a hot water geothermal system has formed. The general components that need to be present for a hot water geothermal system to be formed are heat, water, and permeability.

Heat for a system generally comes from a magma body, but there are other known sources of heat. There are five broad categories of geothermal systems: (1) vapor-dominated, (2) hot water, (3) geopressured, (4) hot dry rock, and (5) magma (Gupta and Roy, 2007). The high heat flow below the SRPA is related to the intrusion of mafic magmas in the mid-crustal sill complex (Blackwell, 1989). It has been shown that the ESRP has an above average heat flow (Figure 3).

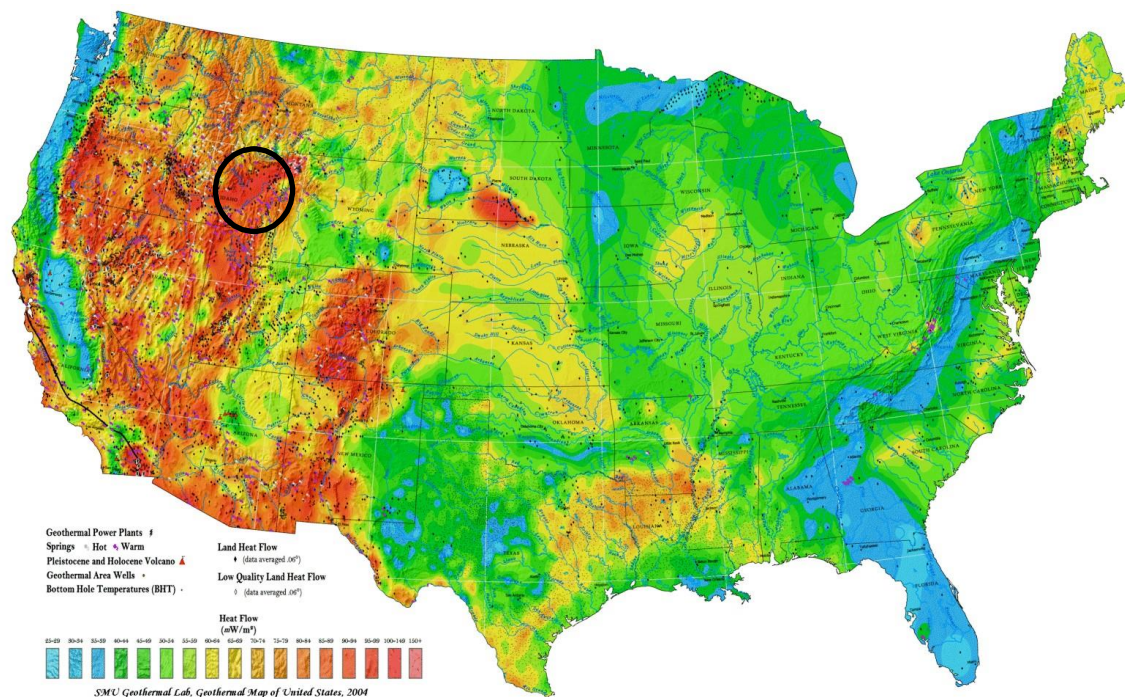


Figure 3. Heat flow map of the United States (Blackwell and Richards, 2004). The SRP is circled.

Permeability is the ability of a material to transmit fluid. Sufficient permeability is required due to the need to extract sufficient heat from water or steam to generate power. The temperature of the water is increased by the heat in the system and needs to be trapped in order to be a viable resource. Temperatures of 60-100° C are required to provide enough heat for a reservoir to be economical, if permeability and fluid flux are sufficiently high. Temperatures above 180 °C are required for conventional power production (flashing of water to steam during compression), but lower temperatures can be used with binary fluids (Fridleifsson et al., 2008). An impermeable barrier must be above the area where hot water is located in order to stop, or at least slow, the transfer of heat out of the reservoir. Below this barrier must be a porous and permeable formation where the hot water can gather and form a geothermal reservoir.

Surficial manifestations of geothermal energy, such as hot springs, are easy to find, but it is considerably more difficult to locate geothermal reservoirs that are viable sites for energy production. Surficial manifestations are not always indicators of potential geothermal energy, as the conditions at depth may not be reflected by the surface conditions (McNitt, 1973).

Below the SRPA there is significant heat flow (Blackwell and Richards, 2004). This heat flow of up to 100 mWm⁻² is closer to the surface on the margins of the ESRP. Many surface manifestations, such as hot springs, are present along the margins. The center of the ESRP has a lower thermal gradient than the margins due to the SRPA, but the heat flow is higher below the SRPA on its axis (Blackwell, 1989). The thickness of the SRPA has a cooling effect on the geothermal waters below it (Blackwell, 1989). Due

to the effect of the SRPA on geothermal gradients it is difficult to target an area of high geothermal potential.

METHODS

Well Completion Information

All three wells for the SRGDP (Project Hotspot) were slimholes, which are < 10 cm in diameter and typically are 5 cm or less at the total depth reached by many wells. Slimholes offer many advantages versus drilling conventional boreholes. Slimholes are generally core drilled, which is how the Project Hotspot wells were drilled. Core drilling is especially efficient in geothermal exploration as many geothermal areas have lithology that tends to have large lost-circulation zones. In a conventional borehole lost-circulation zones are expensive to deal with and sometimes can even cause boreholes to be abandoned. With core drilling lost-circulation zones are simply drilled through. The drill rods used in a core drilling operation are designed to fit inside one another so if problems are encountered smaller rods are dropped down the bigger rods and drilling continues.

The drilling was done by Drilling, Observation, and Sampling of Earth's Continental Crust (DOSECC), which is a non-profit organization that works in concert with the International Continental Drilling Program (ICDP) to work on scientific drilling projects such as these. DOSECC has over 30 years of geothermal and scientific drilling experience. DOSECC drilled the boreholes with an Atlas-Copco CS4002 drill rig set up for core drilling slimholes (Figure 4).

Initial site preparations for the Kimama borehole were made in the summer and early fall of 2010, with the beginning of core drilling taking place on 27 September 2010. Prior to the beginning of core drilling a local water well company, Eaton Drilling &



Figure 4. Atlas-Copco CS4002.

Pump Service, installed a 7-5/8 inch diameter surface conductor casing to a depth of 12 m (Figure 5). This company had an Ingersoll-Rand T3W air rotary drill rig that is better suited to drilling the larger hole required for the surface casing, which made it quicker and cheaper, rather than DOSECC drilling it with the coring rig (Delahunty et al., 2012). This protocol would follow on all other wells. Eaton also drilled a water supply well due to the remoteness of the Kimama well site. It would have been unnecessarily expensive to drive water trucks out to this site everyday to provide enough water to drill the well.

Drilling continued until 10 October 2010 when problems were encountered and a



Figure 5. Eaton Drilling & Pump Service setting surface conductor casing.

portion of drill pipe twisted off in the bottom of the hole. Many attempts were made to fish out (i.e., retrieve) the section, but they were not successful. The twisted off section was in a portion of the hole that had deviated significantly, and the decision was made to bypass this portion. Essentially this amounted to re-drilling a small portion of the hole, but it was quicker than having to mill out the lost section. This section of the hole was named Kimama B, with the first portion of the hole being Kimama A. The drilling of Kimama B took place from 10 October 2010 through 27 January 2011. At this point Kimama B had reached a total depth (TD) of 1,912.5 m. The well started out as HQ (96 mm outside diameter (O.D.)) to a depth of 303.6 m. At this point the hole was reamed with a 6-1/2 inch hole opener to a depth of 272.8 m. Then the 4-1/2 inch HWT casing was set to 272.8 m. This was required due to Idaho Department of Water Resources rules regarding geothermal exploration well casing requirements. Drilling continued with HQ rods to a depth of 1,184.8 m, when it was decided to step down to NQ (77 mm O.D.) to increase penetration rates (Delahunty et al., 2012). NQ rods were then used to TD.

The Kimberly well was begun on 5 February 2011, after also having a surface conductor casing set to a depth of 12 m, followed by an 8-inch diameter hole for the 4-1/2 inch HWT casing to 214 m (703 ft) by Eaton Drilling & Pump Service. Rotary drilling the upper cased part of the hole was less expensive and faster than coring and reaming, as was done on the Kimama well (Delahunty et al., 2012). Drilling continued until 20 June 2011, with many setbacks occurring along the way. On 12 March 2011 the top head drive on the drilling rig had to be taken off and transported to Salt Lake City, UT to be completely rebuilt as it suffered an irreparable breakdown on site. Drilling resumed on

19 April 2011. HQ rods were used to a depth of 1,130.5 m and then stepped down to NQ for the rest of the well. On 13 June 2011 a total depth of 1,953.0 m was reached in this well.

Project Hotspot then progressed to the final site on the Mountain Home Air Force Base in Mountain Home, ID. The drilling there began on 10 July 2011. As with most drilling projects and as seen with other Project Hotspot wells the drilling did not go as planned. The Mountain Home well offered a different set of drilling conditions for about 650 m, as this first portion of the well is mainly old lake sediments. This required a different coring setup to properly retrieve the sediments. A plastic sleeve was inserted inside of the core barrel, which can be taken out after retrieval and the sediments are preserved intact with minimal effort. This is termed HQ3. This sediment layer turned out to be thicker than previously thought.

Drilling continued in the sediments until the drill rods became stuck in the bottom of the hole at a depth of 599.5 m. Many attempts were made to fish the rods, but, once again, they were not successful. The decision was made to abandon this first hole, designated Mountain Home A. The next hole was designated Mountain Home B, located 7 m east of Mountain Home A. This hole was quickly rotary drilled through previously cored depths to slightly below where Mountain Home A was abandoned to a depth of 618.7 m. At this point HQ sized rods were used until a depth of 1,143.9 m. The hole was logged at this time. After logging the rods were stepped down to NQ size which was used until TD.

A flowing zone was encountered at 5,726 ft (1,745.3 m) on 26 January, 2012.

Operations were ceased for a few days until it was decided that drilling would continue.

On 3 February 2012 the hole was completed to a TD of 1,821.5 m.

Logging

Core and Lithologic

The Kimama hole was cored from 12 m to TD, Kimberly from 214 m to TD, and Mountain Home from 162 m to TD. The three SRGDP holes drilled a total of 5,687 m and produced 5,299 m of core. As drilling progresses more drill rods are added to increase the depth that drilling reaches. Each drill rod is 10 ft (3.05 m) long. Before a new drill rod is added to the drill string a wireline tool goes to the bottom of the drill string to retrieve the core barrel to the surface. The core barrel holds the core that was drilled through. Field logging took place when the core reached the surface. Field logging consisted of: washing, measuring, writing a physical description of the core, photographing, and boxing the core. Once boxed the core was transported to off site labs and/or storage locations.

By using the physical descriptions of all the core from the wells, generalized lithologies can be made for all three (Figures 6-8). The Kimama hole drilled through basalt with a small amount of clay and sediment. At least 550 basalt flow units were identified in the Kimama core (Potter et al., 2011). The Kimberly hole encountered basalt for the first 104.8 m and then transitioned to rhyolite to a depth of ~235 m. The hole alternated between basalt and sediment layers until a depth of ~427 m, where it encountered rhyolites until TD. The Mountain Home hole encountered lacustrine

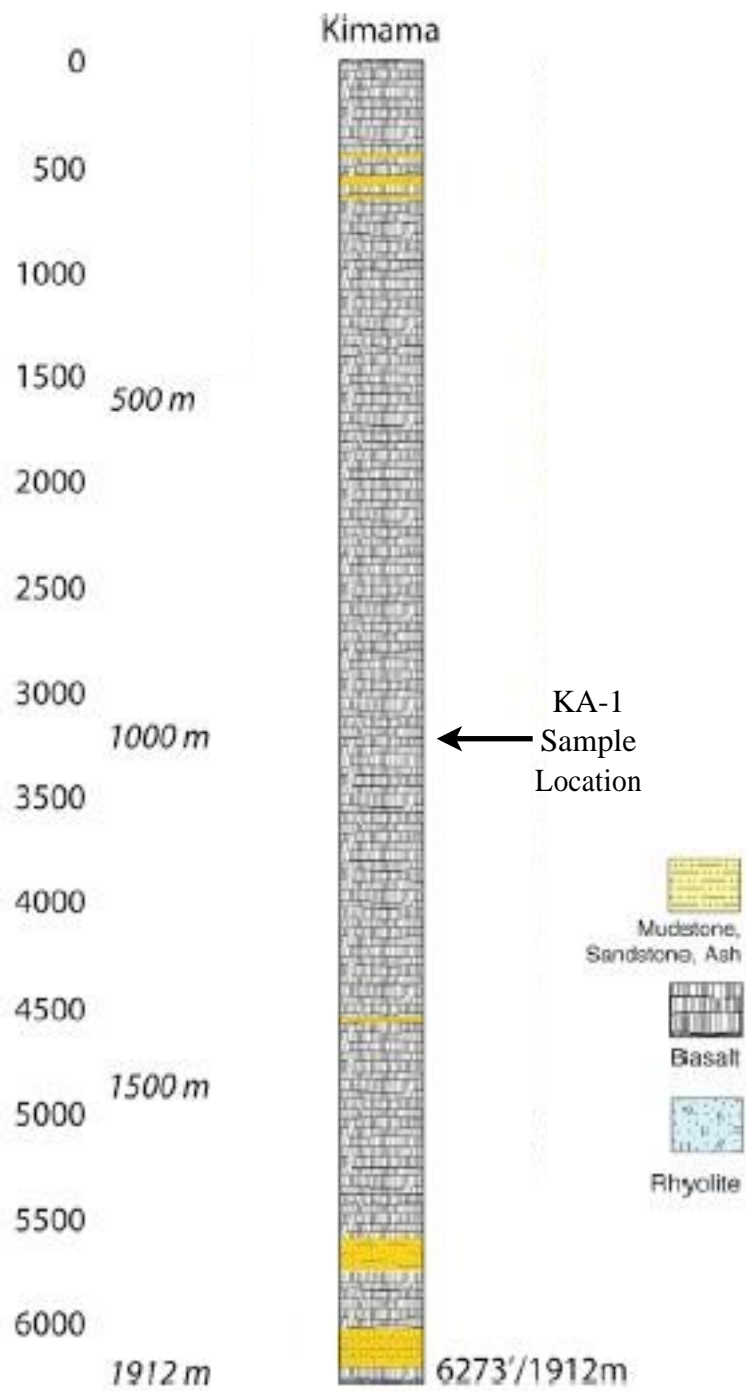


Figure 6. Generalized lithologic log for Kimama well (Shervais et al., 2012, 2013).

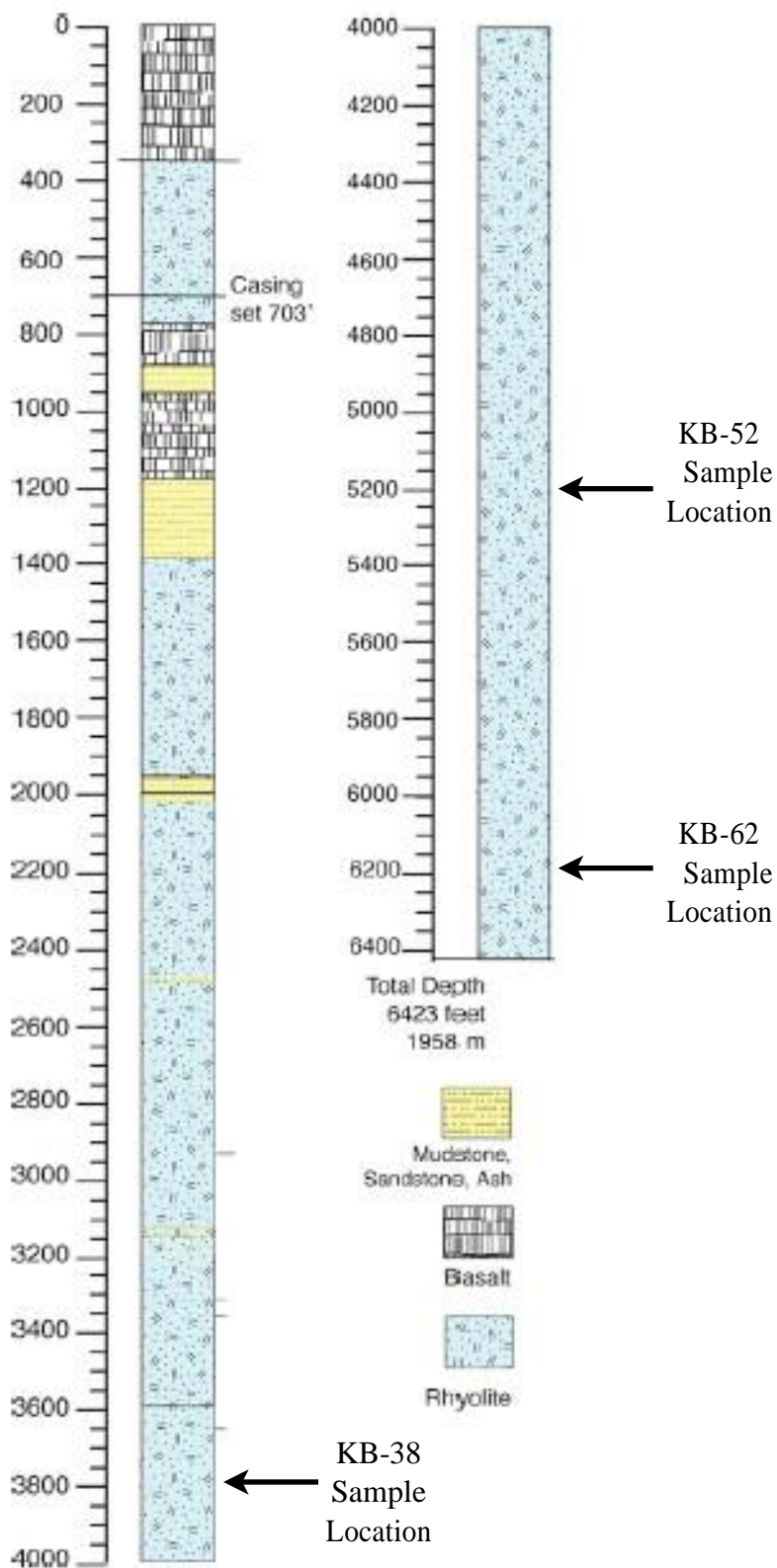


Figure 7. Generalized lithologic log for Kimberly well (Shervais et al., 2012, 2013).

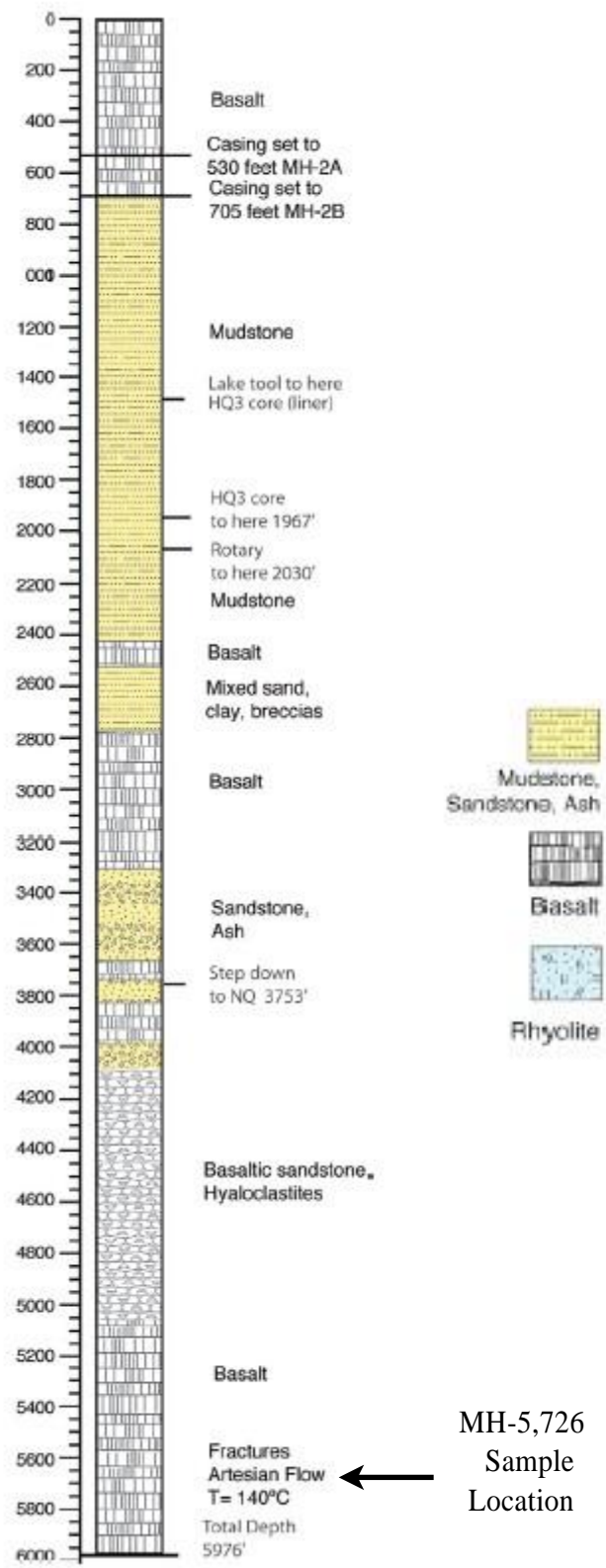


Figure 8. Generalized lithologic log for Mountain Home well (Shervais et al., 2012, 2013).

sediments to a depth of about 850 m where it transitioned to basalt and basaltic sediments until TD.

Temperature

Temperature logs are a crucial part of the SRGDP (Nielson et al., 2012). All wells had several different temperature logs run in them. The first temperature log was run as drilling was taking place. DOSECC designed a temperature tool that was stored in the top of the core barrel. This temperature tool recorded temperatures during drilling and was recovered along with the core samples. Drilling was halted for about 30 minutes in order for the tool to equilibrate on the bottom of the hole. While the tool was on bottom there was no circulation of drilling fluids to minimize disturbances in the hole (Nielson et al., 2012).

The Operational Support Group (OSG) from Geo Forschungs Zentrum (GFZ), German Research Centre for Geosciences, also ran temperature logs in all of the wells, and Southern Methodist University (SMU) sent a logging tool that ran temperature logs for the SRGDP. The OSG and SMU logging operations had wireline temperature tools that were used to record temperatures in the wells. OSG logged temperature while pulling the tool out of the well and SMU logged temperature while running their tool into the well. Temperature measurements between the two were similar. The OSG temperature tool gave live readings while logging, while SMU's tool had to upload the data to a computer once it was retrieved from the well.

Geophysical Logs

Borehole geophysical logs of the drill holes (Schmitt et al., 2012; Shervais et al., 2013) were run by several different entities and are summarized in Table 1. Gamma ray logs measure the amount of natural gamma radiation. This information is used to differentiate clay layers from hard rock layers and also used to determine the depth of the water table. Gamma ray logs were used to correlate lithologic layers. Neutron logs directly measure the presence and abundance of hydrogen and are used to estimate porosity. Resistivity logs measure how strongly the formations oppose the flow of electric current. Sonic logs use sound waves to estimate the porosity of the formation. Dip logs measure the dip of the formations. The acoustic televiewer logs create an image of the borehole based on acoustic impedance, which is used to map fractures and

Table 1. Geophysical logs summary.

Company	Logs	Well	Dates
Century	Neutron, Gamma	Kimama	6/15/11
Colog	Neutron, Gamma	Kimberly	7/8/11
OSG	Dip, Sonic, Resistivity, Gamma, Magnetic Susceptibility, Acoustic Televiewer, Temperature	Kimama Kimberly Mountain Home	6/29/11-7/4/11 6/17/11-6/24/11 1/17/12-1/21/12
SMU	Gamma, Temperature	Kimama Kimberly	5/4/11 5/5/11
DOSECC	Temperature	Kimama Kimberly Mountain Home	9/10-2/12

plot the strike and dip of formations. Dip logs also measure the dip of formations through physical means. Magnetic susceptibility measures the magnetic field in the formations and is used to differentiate between formations.

Sampling

Five water samples were taken from the three boreholes (one each from Kimama and Mountain Home, and three from Kimberly) in order to determine the chemical characteristics of the waters in the boreholes. Most water samples were taken with a Foerst Kemmerer-type mechanical sampler that was donated by Roy Bartholomay of the U.S. Geological Survey (Figure 9). It holds about one liter of water, which is an ample amount to provide for all of the analyses that were run in this study. It is lowered down the hole on a wire to the desired depth at which time a messenger weight that is kept at ground level, also on the wire, is dropped down the hole. When the messenger weight reaches the sampler it triggers the mechanism and the sampler shuts enclosing the water at that depth. The sampler is designed to be open on both ends so that the water flows through while it is lowered down the hole. This design feature makes it possible to get a representative sample of the water at the depth at which the sampler is closed. The sampler is all mechanical and simple to operate. The sampler was attached to the slickline of SMU's logging rig (Figure 10).

Kimama

The Kimama well was the second well sampled. Water samples were collected at Kimama on 3 July 2011, shortly after samples were taken at Kimberly. The Kimama well



Figure 9. Foerst mechanical sampler.

had been completed for several months and the borehole had time to naturally clean itself out. In between geophysical logging operations at Kimberly and Kimama, OSG was able to bring in its water sampler. We did not use the SMU logging rig and Foerst mechanical sampler at the Kimama well. OSG's logging setup is significantly more sophisticated than the simple mechanical sampler that we had previously used, but it was also much more complicated and difficult to operate. This was due to the water sampler, which also



Figure 10. SMU logging rig.

captured gas samples, having only one person on the OSG team that could operate it.

Due to a blockage in the Kimama hole no logging tools were able to get past approximately 1,220 m in the well. Several attempts to retrieve water samples were made, but the sampler was not working properly and not all the samples were retrieved. One of the samples from 1,070 m was retrieved and had enough water to do field analysis and further tests. Unfortunately OSG's water sampler turned out to be irreparable and one sample was all that was retrieved from the Kimama well. Future attempts to get samples from the Kimama well were planned, but the well was plugged and abandoned before they could happen.

We also collected a sample from the nearby water supply well drilled by Eaton to compare the chemistry of the SRPA water with the water in the Kimama well. The supply well was drilled to a TD of about 90 m into the extremely productive SRPA, which has been discussed previously. There was an electric submersible pump in this well and a sample was taken directly from the spigot.

Kimberly

The Kimberly well was the first one to be sampled. The first opportunity to get samples from the Kimberly well was immediately following the geophysical logging operations carried out by OSG. Geophysical logging took place immediately after the well was finished being drilled and reached final total depth (TD) on 13 June 2011.

The timing of the sampling did not allow sufficient time for the borehole to naturally flush itself out. There was not an option to pump the well either due to its small diameter. This resulted in water samples that were not thought to be entirely formation waters.

During the drilling operation the drill rods are greased at each joint where they are joined. Heavy application of grease in the joints causes grease to spill onto the outside of the drill rods, and therefore into the borehole. Also, drilling mud was still present in the borehole. This is not a desirable situation for gathering water samples. However, it was thought this might be the only available time to obtain a water sample so sampling took place.

Four water samples were taken from the Kimberly hole on 21 and 22 June of

2011. Only three of the samples were retrieved as one of the samples was spilled while being transferred from the Foerst sampler to a bucket. This caused a significant amount of time to be added to the sampling operation, but the desired number of samples were retrieved.

The first sample was taken directly below the casing at 3,800 ft (1,160 m). This sample was expected to give a representative sample of the deeper geothermal waters and provide a comparison to deeper samples to see if there was a change in chemistry throughout the lower portion of the borehole. Another sample was collected at 5,200 ft (1,585 m). The third sample was from the bottom of the well, at a depth of 6,300 ft (1,920 m).

All of the samples retrieved with the Foerst mechanical sampler were oily-looking, but we were able to analyze them in the field for basic water parameters. Filtering of these samples was not possible at the time and the samples were filtered later of the dark oily substance. This allowed further tests to occur.

The total amount of time taken for this sampling operation was approximately 14 hours, which included setup and breakdown of the SMU logging rig. Each sample took approximately two hours to collect, one hour for the sampler to reach depth and one hour to retrieve the sample. Several tens of minutes were also given for the messenger weight to reach the Foerst sampler and trigger its mechanism to close. The first round of water sampling operations at Kimberly were a success despite the dropped sample and a few problems with the depth counter on the SMU logging rig.

There were several more attempts to get water samples from the Kimberly well,

but on each attempt a new problem presented itself that prevented samples from being taken. On 16 October 2011 operations were going smoothly when the depth counter on the SMU logging rig abruptly stopped working. Several attempts were made in the field to fix the counter, but to no avail. The counter was taken off the rig for repairs. After a lengthy wait for the counter to be repaired another attempt was made to retrieve samples on 23 November 2011. On this third attempt the sampler was not able to advance past a depth of approximately 210 m. The reason for this was never determined and the Kimberly well was eventually plugged and abandoned before any more attempts could take place.

Mountain Home

The first attempt to retrieve samples from the Mountain Home well took place on 21 January 2012. This attempt was a hurried one due to an unexpected stoppage in drilling which led to an opportunity to sample.

The round of sampling on 21 January 2012 did not go as smoothly as the operations at Kimberly. Setup of the SMU logging rig was easy. The first sample was set for a target of 1,100 m, which would put it below the casing into the open hole, similar to Kimberly. The sampler was run down, the messenger weight sent, and sampler retrieved. But when the sampler was retrieved and opened there was no fluid in it. Upon inspection of the Foerst sampler it seemed that the messenger weight had not fully triggered the sampler to close. More weight was added and the sampler was sent back down. On this second attempt there was no doubt that the messenger weight had triggered the closure of

the sampler, but when it was opened there was no fluid in it. Knowing that closure of the sampler was not the problem another inspection was made on the Foerst sampler. On this inspection it was noted that the drain valve on the bottom of the sampler had loosened and allowed all the fluid to leak out as the sampler was being pulled up the well.

Tightening the valve was not an option, but we used silicone to plug the valve. However another problem cropped up as the sampler was being lowered down on this, the third, attempt. The depth counter on the SMU logging rig had stopped working once again.

The sampler was retrieved to the surface while repairs were being attempted on the depth counter. Without a functioning depth counter sampling is essentially useless as one does not know where the sample is coming from. Estimates can be made on the rate at which the sampler is being lowered, but they are inaccurate. However, we simply ran the sampler to the TD of the Mountain Home well (1,675 m). It was the only sample from this well at this point in time.

After this first round of sampling funding was secured from the US Air Force and drilling resumed. About a week later the hole encountered a large fracture zone at a depth of 5,726 ft (1,745.3 m). This large fracture zone produced artesian flow of geothermal waters out of the wellhead (Figure 11). Drilling was stopped and the well was shut in until Dr. Tom Lachmar collected a sample from the wellhead on 26 January 2012. This was the last sample collected from the Mountain Home well. The flowing zone was mudded up and no further attempts were made to retrieve samples from the Mountain Home well.



Figure 11. Artesian flow out of Mountain Home well.

Analyses

All of the water samples were analyzed in the field for basic parameters that included temperature, electrical conductivity, salinity, pH and alkalinity (Figure 12). A Yellow Springs Instruments Model YSI 30 was used to measure temperature, electrical conductivity (EC), and salinity. Temperatures were measured in degrees Celsius, EC in



Figure 12. Field analytical equipment.

microSiemens (μS), and salinity in parts per thousand (‰). An Orion Model 230A was used to measure pH. Alkalinity measurements were made using a Hach-Alkalinity Test Kit, Model AL-AP MG-L in milligrams per liter (mg/L).

The water samples were analyzed for major and minor ions and trace elements at the Utah State University analytical laboratory (USUAL). Samples were analyzed for Al, As, B, Ba, Ca, Cd, Cl, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Se, Si, Sr, and Zn. The results for the samples were reported in mg/L. The samples were stored in

plastic 60 mL containers after filtering. They were stored in a refrigerator until sent to the laboratory.

In addition to the USUAL analyses the MH-5,726 sample was analyzed by two more laboratories, ThermoChem and the Utah Veterinary Diagnostic Laboratory (UVDL). The results of these analyses can be found in Appendix A (Table A.2).

Deuterium and oxygen-18 samples were also collected, and were analyzed by the Stable Isotope Ratio Facility for Environmental Research (SIRFER) at the University of Utah. Stable isotope compositions are reported as delta (δ) values in parts per thousand (‰ or per mil) enrichments or depletions relative to a standard known composition, and values are calculated by:

$$(\text{in } \text{‰}) = (R_{\text{sample}}/R_{\text{standard}} - 1) 1000 \quad (1)$$

where R is the ratio of the heavy to light isotope in the sample or standard (Kendall and McDonnell, 1998). All samples were compared to two primary laboratory reference materials (PLRM) and a secondary laboratory reference material (SLRM).

Carbon-13 samples were analyzed by Geochron Laboratories, a division of Krueger Enterprises, located in Billerica, MA. Carbon-13 results were also reported in per mil notation and were calculated as follows:

$$\delta^{13}\text{C}_{\text{sample}} \text{‰} = [({}^{13}\text{C}/{}^{12}\text{C}_{\text{sample}})/({}^{13}\text{C}/{}^{12}\text{C}_{\text{standard}}) - 1] \times 1000 \quad (2)$$

where ${}^{13}\text{C}/{}^{12}\text{C}$ standard is PDB (Pee Dee Belemnite), and ${}^{13}\text{C}/{}^{12}\text{C}_{\text{standard}} = 0.011237$.

RESULTS

Hydrochemical Properties

Select results of the chemical and field analyses of the sampled waters for Project Hotspot are given in Table 2. Complete results of the chemical analyses are provided in Appendix A and core photos from sample depths are provided in Appendix B. Samples are indicated by the abbreviations used to designate them in the field. KA-W is the sample from the water supply well at the Kimama site. This supply well taps into the SRPA and was taken to compare to deeper thermal waters. KA-1 is the sample from Kimama 1-B from a depth of 1,070 m. The core at this depth is lightly vesiculated basalt with a few fractures (Figure B.1). There does not appear to be any significant pore space and the recovery for these runs was 100%.

Samples KB-38, KB-52, and KB-63 are from the Kimberly well and the numbers following the KB correlate to hundreds of feet at which the sample was taken. For example KB-38 was taken at a depth of 3,800 ft (1,160 m). Three samples were taken at different depths to determine if there was variation in chemistry throughout the well. There was little variation between the three Kimberly samples. The core for KB-38 is rhyolite (Figure B.2). Some of the core in the vicinity of KB-38 is rubbly and some is solid. Large pore spaces are not visible. KB-52 is rhyolite (Figure B.3). It has a low percentage of vesicles (< 10%) and very few fractures (< 1 m). KB-63 is rhyolite (Figure B.4). It is similar to KB-52 except it is more broken up. Distinguishing between core that is naturally broken and/or fractured from core that was broken and/or fractured from

Table 2. Chemical analyses of Project Hotspot samples (all units in mg/L unless otherwise noted)

Sample	T (°C)	EC (µS)	pH (units)	Alkalinity	Ca	Mg	Na	K	Cl	SO ₄	SiO ₂
KA-W	15.8	336	7.71	160	25.0	12.7	16.5	3.60	13.1	22.1	60.9
KA-1	28.8	1,060	8.17	120	21.1	3.21	284	10.3	315	306	158
KB-38	23.3	2,970	7.60	1,100	24.7	10.1	562	17.9	204	7.29	94.5
KB-52	15.6	1,765	7.72	950	15.4	5.43	363	9.38	128	14.1	71.6
KB-63	17.7	2,568	7.83	850	23.8	9.33	541	13.2	189	13.8	76.7
MH- 5,726	31.3	870	9.59	100	8.71	0.16	288	9.02	74.8	477	196

drilling activities is difficult.

Sample MH-5,726 was taken from the Mountain Home well when it was flowing. It is assumed that the flowing sample came from a depth of 5,726 ft (1,745.3 m), which was the depth at which the well began to flow. The core at this depth is basalt (Figure B. 5). Core recovery at this depth was low (< 50%), which suggests significant porosity. Note in the core photo that the box covers a length of 5 m. The boxes hold approximately 3 m of core. This supports the idea that there is a fracture zone or a zone of higher porosity at this depth.

Field water chemical analyses are reported in Table 2. All of the temperature values, except the KA-W sample, are not representative of the actual temperatures where the samples came from. This is due to the amount of time between when the sample is captured downhole to when it is actually measured for temperature at the surface. For this reason, the temperature logs that were taken downhole will be used to analyze the temperature of the waters in the wells. All of the water pH values indicate the waters are alkaline, with the Mountain Home sample being much more so than the others. The Mountain Home sample had a pH of 9.59 while the other samples range from 7.60 to 8.17. Electrical conductivity varied throughout all of the samples. The KA-W sample is from a shallower source and the chemistry is definitely distinct from all of the other samples. The EC value for KA-W is 336 μS while the lowest from the rest of the samples is 870 μS for MH-5,726. The EC value for KA-1 was 1,060 μS , and the values for the three Kimberly samples ranged from 1,765 μS for KB-52 to 2,970 μS for KB-38.

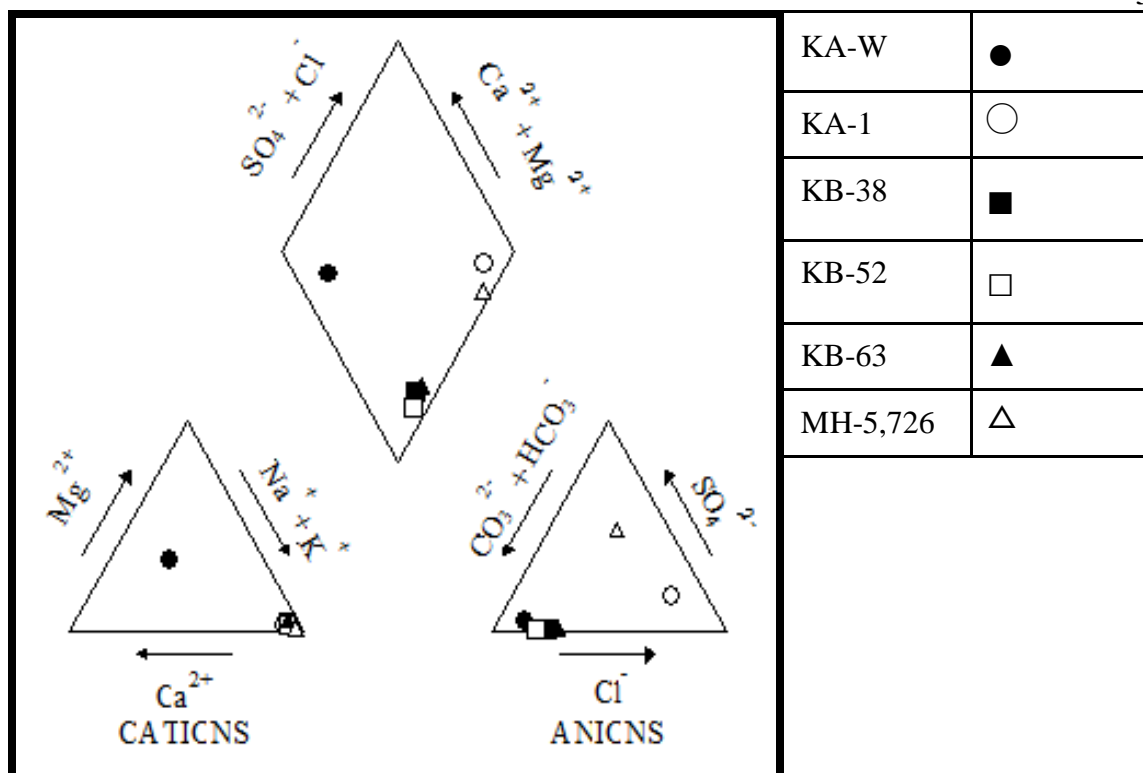


Figure 13. Piper (1944) plot of geothermal waters from Project Hotspot.

The water samples were characterized by plotting them on a Piper (1944) trilinear diagram (Figure 13). Analytical values for the major cations and anions were input into GW Chart (Winston, 2000), which automatically created the plots. The KA-W sample is Ca-Mg-bicarbonate water and is distinct from the others. The dominant cation for all of the other samples is Na. However, the dominant anion is different for all three wells. The KA-1 sample is Na-chloride water. The KB samples are Na-bicarbonate waters. The MH sample had similar values to the KA-1 sample, but it had lower chloride levels. The MH sample is Na-sulfate water.

The water samples reported in McLing et al. (2002) include several deep wells, hot springs, and rivers that are located in the Snake River Plain area (Table 3 and Figure

Table 3. Chemical analyses of McLing (2002) (all values in mg/L).

Sample	Ca	Mg	Na	K	HCO ₃	Cl	SO ₄
Sturm	3.8	0.02	32.13	0.84	74	3	4.54
INEL-1 460-670 ft	8.2	2	92	10	210	17	32
INEL-1 >1,460 m	7	0.5	385	7.3	740	12	99
Condie HS	61.30	11.5	58	18.00	362	14	27
Liddy HS	88	16	27	15	174	6.7	200
Big Lost River	37.5	9.9	5.8	1.4	200	4.8	18

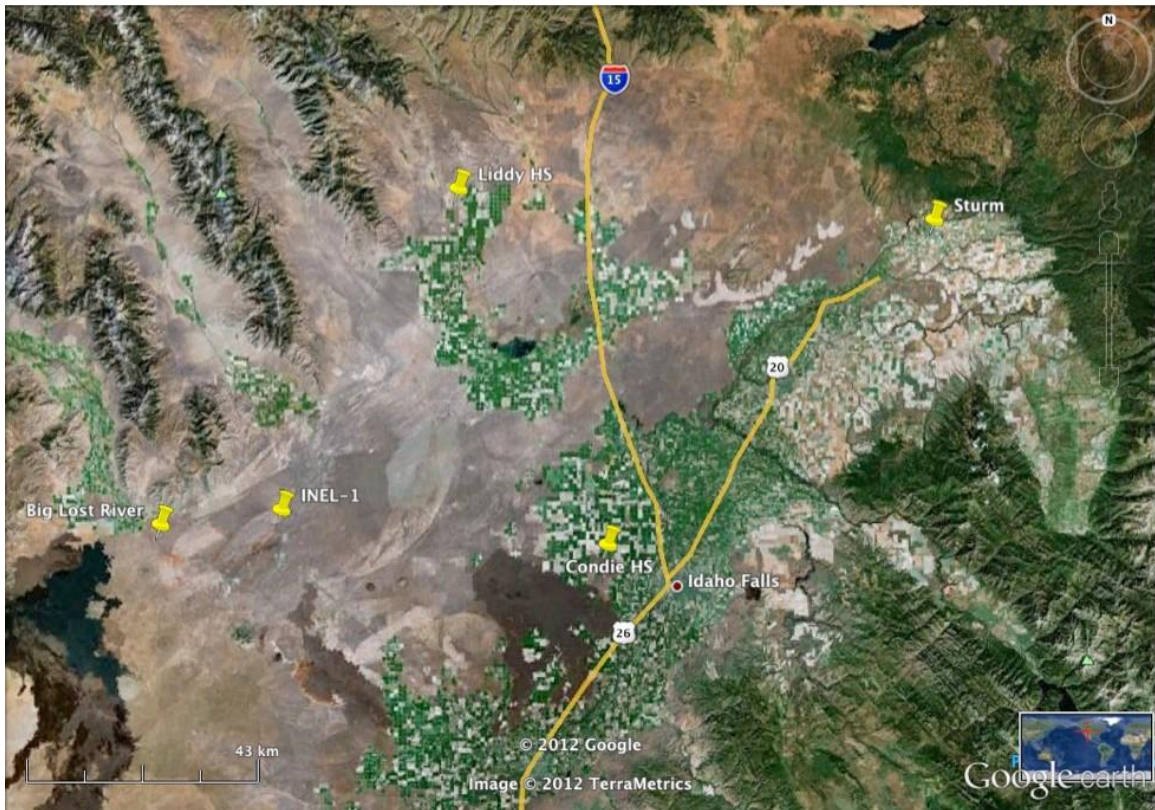


Figure 14. McLing et al. (2002) sample location map.

14). These samples are from two depths in INEL-1, the Sturm well, Condie and Liddy hot springs and the Big Lost river, and are plotted on a Piper (1944) trilinear diagram in Figure 15. The INEL-1 well was an exploration well drilled in order to assess geothermal potential in that area (Mann, 1986). The KB samples are similar to INEL-1 and Sturm, which are 3,159 m and 1,000 m deep, respectively. When the Project Hotspot and McLing et al. (2002) samples are plotted together it is easy to see that the KA-1 and MH samples are distinct from all other local geothermal waters (Figure 16). Sodium is the dominant cation, but their dominant anions are different from any other wells in Project Hotspot and the McLing et al. (2002) data, which all have bicarbonate as the dominant anion. For the McLing et al. (2002) data Liddy hot springs has bicarbonate and sulfate as

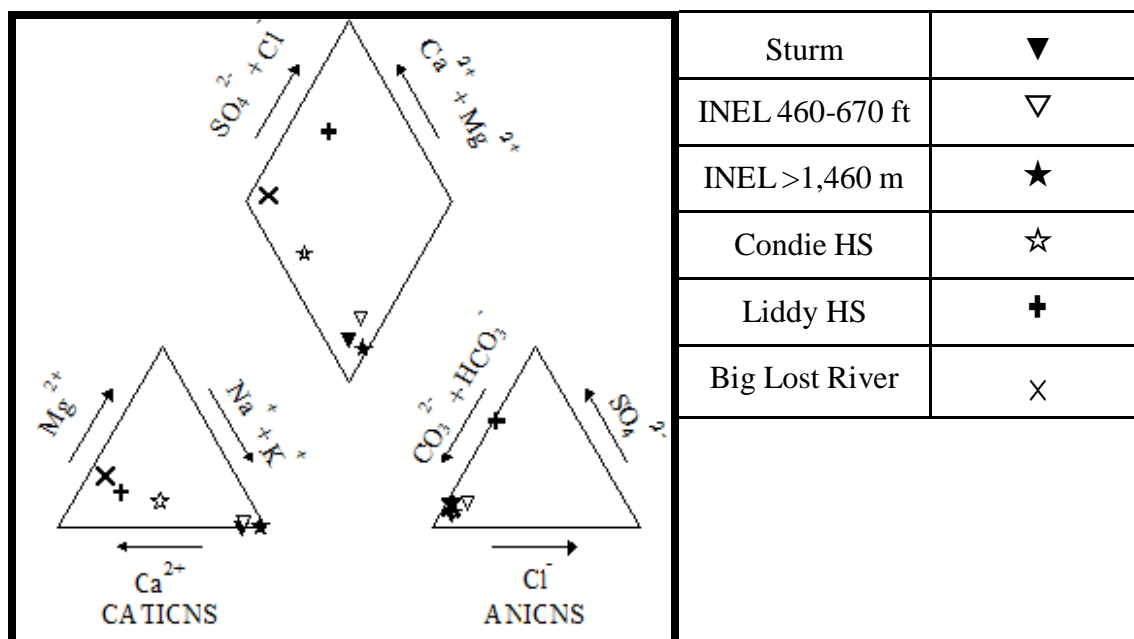


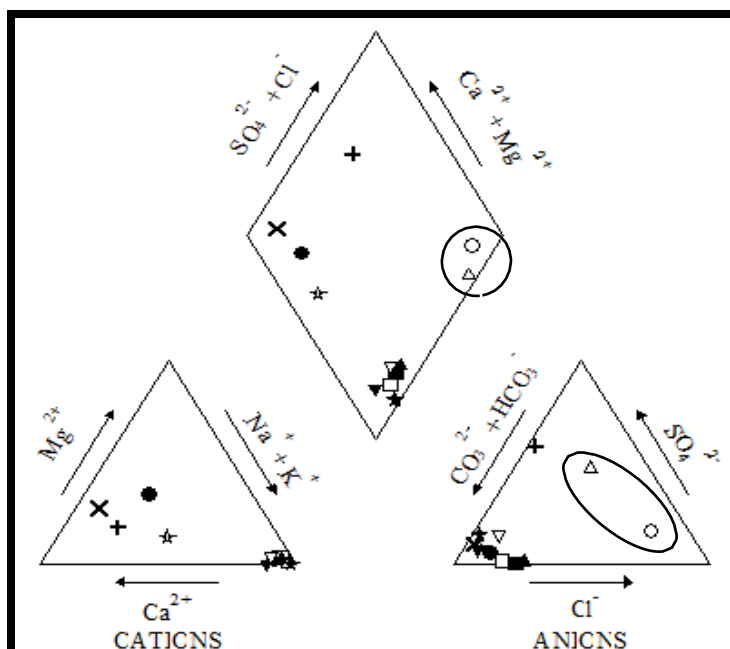
Figure 15. Piper (1944) plot of select samples from McLing et al. (2002).

dominant anions. Calcium and sodium are the dominant cations for Condie hot springs.

Calcium is the dominant cation for the Big Lost River.

Isotopic Compositions

Results of the isotopic analyses for deuterium and oxygen-18 are displayed in Table 4. Isotopic analyses were not made for all of the samples that were retrieved due to costs. Comparison to the global meteoric water line (GMWL) ($\delta^2\text{H}=8 \delta^{18}\text{O}+10$; Craig, 1961) shows that all three samples plot below the GMWL (Figure 17). The Mountain Home sample is heavier (i.e., less negative) than both Kimama samples. The KA-W sample is meteoric. The KA-1 sample is also meteoric water. The MH-5,726 sample is not meteoric water as it plots away from the GMWL. Differences in the isotopes supports the idea that the lower geothermal waters are different than the upper aquifer waters.



KA-W	●	Sturm	▼
KA-1	○	INEL 460-670 ft	▽
KB-38	■	INEL >1,460 m	★
KB-52	□	Condie HS	☆
KB-63	▲	Liddy HS	+
MH-5,726	△	Big Lost River	×

Figure 16. Piper (1944) plot of waters from all Project Hotspot samples and select McLing et al. (2002) samples (KA-1 and MH-5,726 circled).

Table 4. Isotopic analyses of Project Hotspot samples.

Sample	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	$\delta^{13}\text{C}$ (‰)
KA-W	-18.2	-139	N/A
KA-1	-17.0	-141	-10.5
KB-38	N/A	N/A	N/A
KB-52	N/A	N/A	-10.2
KB-63	N/A	N/A	N/A
MH- 5,726	-3.2	-88	N/A

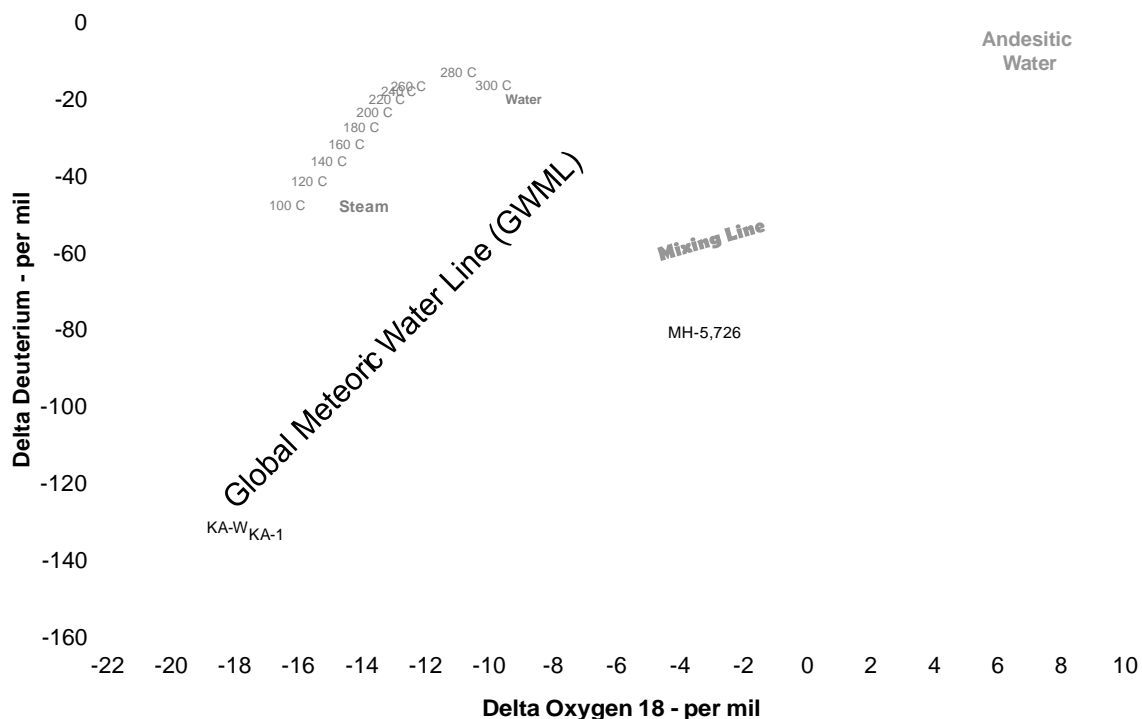


Figure 17. Plot of deuterium (^2H) and oxygen-18 (^{18}O) in comparison to GMWL.

The KA-1 and KB-52 samples were analyzed for $\delta^{13}\text{C}$ (Table 4). Both of the samples were depleted in ^{13}C and had negative $\delta^{13}\text{C}$ values. The KB-52 sample was highly contaminated with drilling grease, as well as drilling mud, which probably provided the carbon.

Geothermal Gradients

A geothermal gradient is a measure of the amount of temperature change over a specific depth (usually a km). An average of 25-30 $^{\circ}\text{C}/\text{km}$ is typical (Fridleifsson et al., 2008). Geothermal gradients can be used to postulate what temperatures might be at greater depths by using temperature data from the wells (Nielson et al., 2012). Due to the

proximity of the SRP to the Yellowstone hotspot and recent volcanic activity in the area, higher than average geothermal gradients were expected. Geophysical logs other than temperature were run on all the wells for Project Hotspot, but are not used in this report.

Kimama

The Kimama temperature log was acquired from the DOSECC temperature tool. This tool lies in the core barrel and thus does not continuously log and was instead used throughout the drilling operations. This was necessary because the IDWR requires a blow out prevention device if the temperature of the well exceeded 100 °C (Delahunty et al., 2012). There were 25 data points for the Kimama well starting with a measurement at 520 m and ending at 1,824 m (Table 5). The inflection point that marks the bottom of the SRPA is below 1,000 m for the DOSECC log (Figure 18). The gradient over the measured depths (520 m to 1,824 m) is 34.7 °C/km, which is likely elevated due to the lack of data for the first 520 m of the well.

The OSG log records a low gradient in the upper 960 m and then it increases to a higher gradient below that depth (Figure 19). For the upper 960 m the gradient is 0.2 °C/km. Unfortunately the temperature log only reached a depth of 1,131 m, where the well reached a temperature of 34.7 °C. The gradient from 960-1,131 m is extremely high at 100 °C/km. The inflection point at 960 m is thought to be caused by the transition from the upper SRPA to the lower geothermal aquifer (Sant and Shervais, 2011).

SMU also logged temperatures in the Kimama well. The SMU log reached a depth of 1,440 m and displayed a similar profile to the other logs (Figure 20). The SMU

Table 5. DOSECC temperature tool measurements (Nielson et al., 2012).

Depth (m)	Temp °C
520	14.03
660	15.02
700	16.01
731	16.35
937	16.70
1014	17.35
1035	21.50
1059	23.90
1084	23.65
1120	34.20
1139	27.00
1169	29.55
1185	33.95
1221	28.85
1282	36.55
1322	37.30
1364	39.50
1397	41.65
1443	46.60
1492	40.10
1538	50.10
1556	54.95
1586	49.45
1610	50.95
1824	59.30

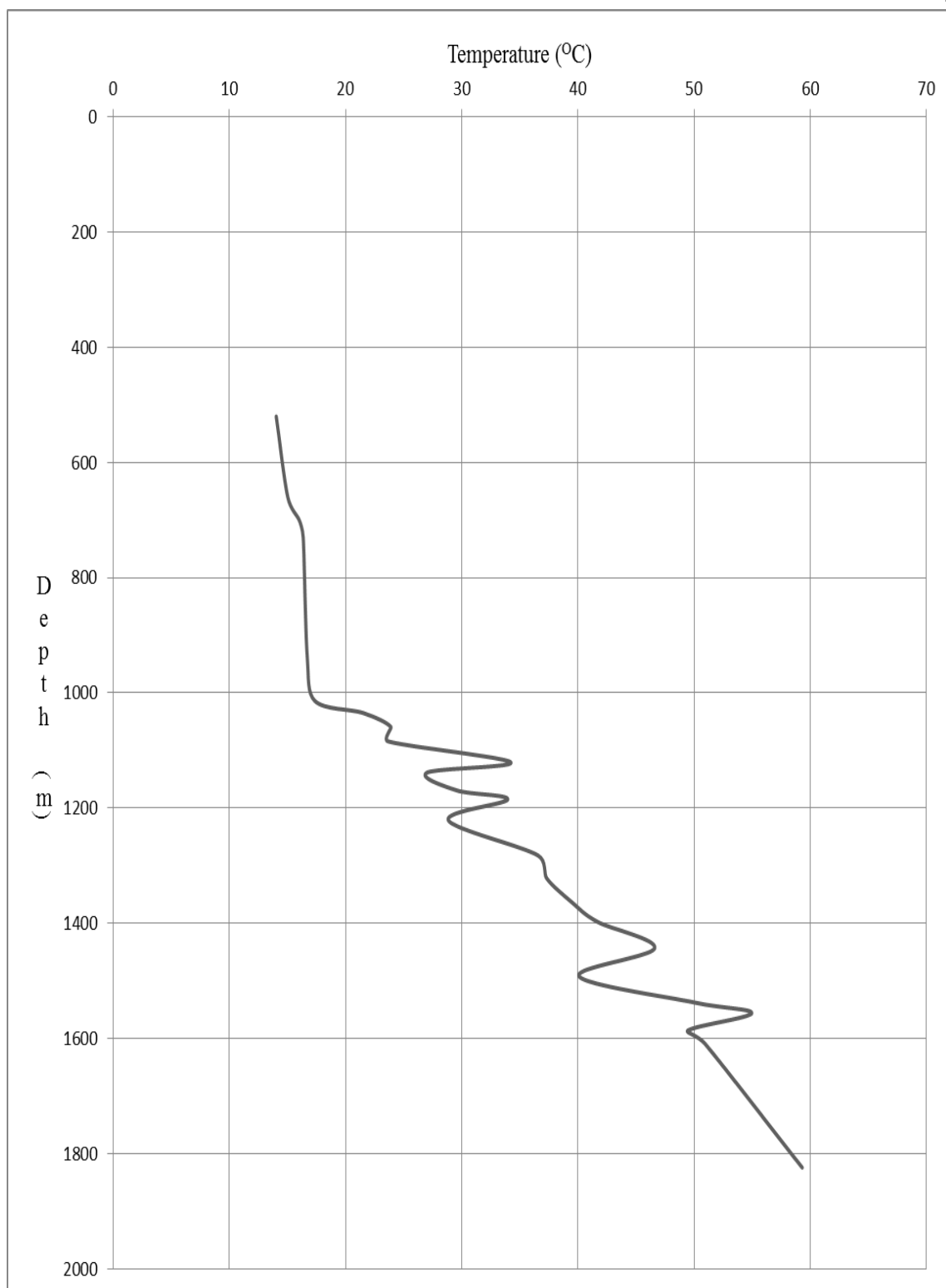


Figure 18. Kimama temperature log (DOSECC).

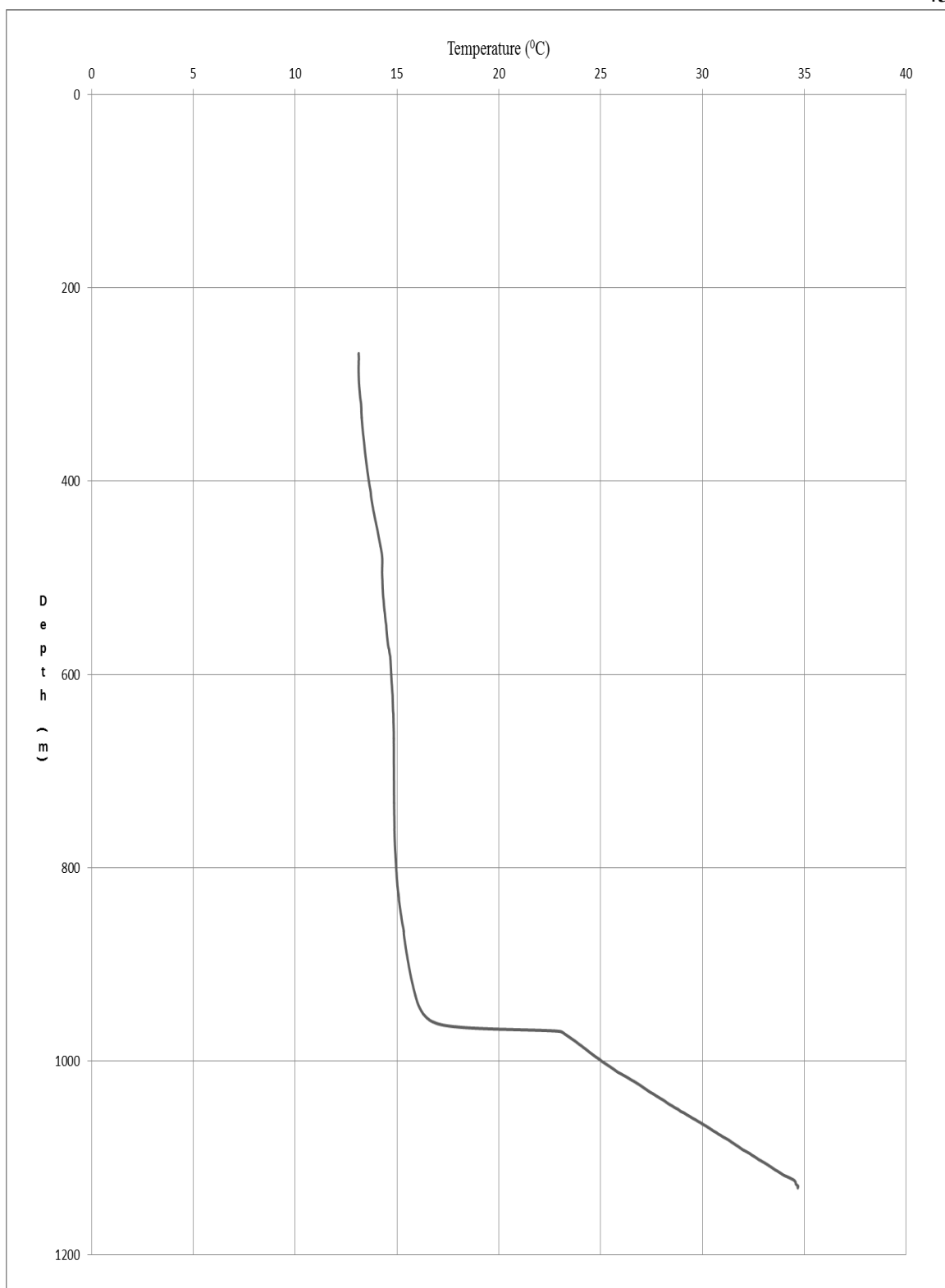


Figure 19. Kimama temperature log (OSG).

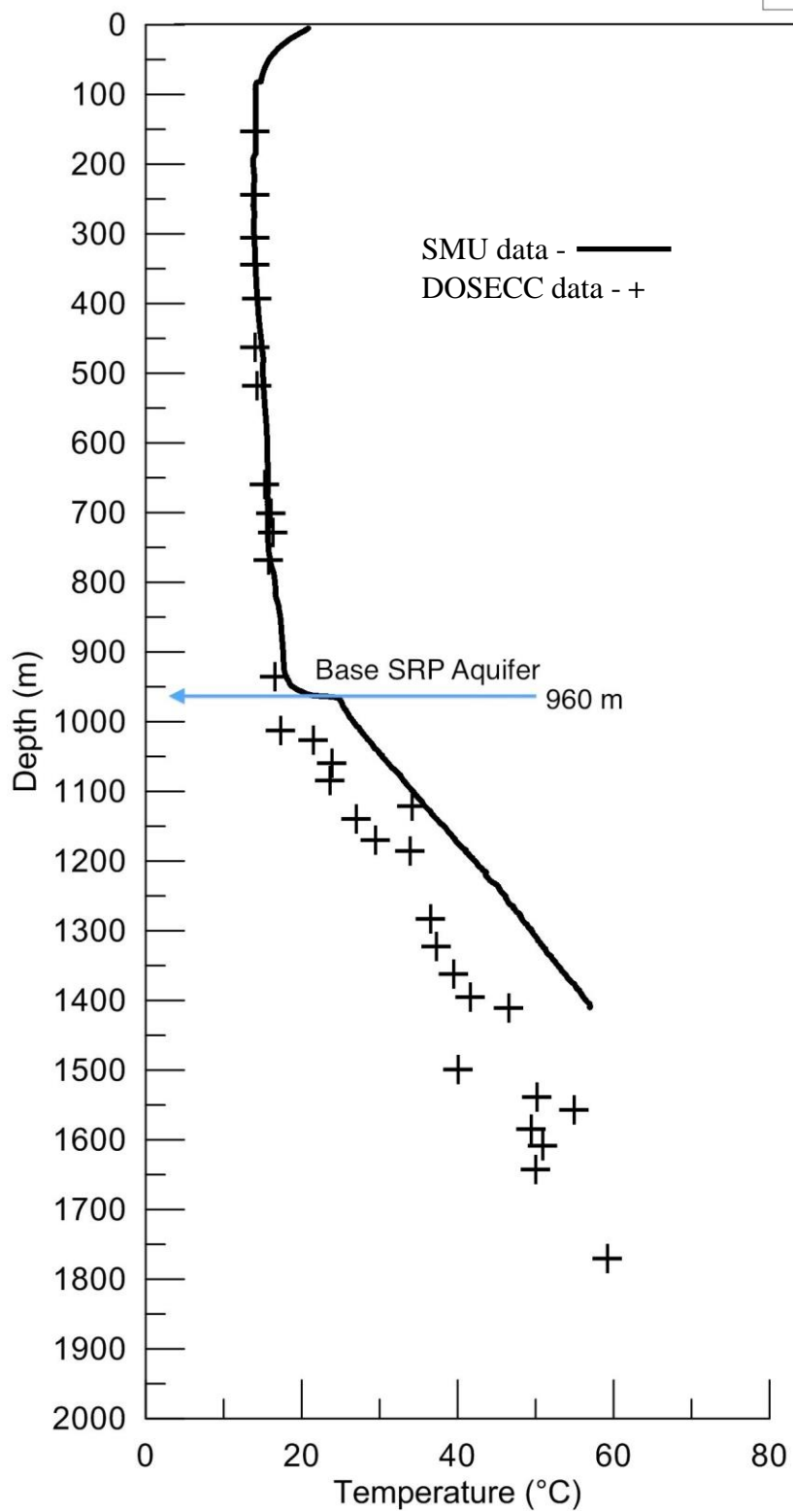


Figure 20. Kimama temperature log (SMU).

log had a gradient of 88.9 °C/km below the inflection point at 960 m. The projected temperature at TD, extrapolated from the SMU gradient, would be approximately 110 °C.

The DOSECC temperature log is suppressed due to drilling activities while the measurements were being made and it also has a low resolution of data points over a great depth. The highest temperature recorded in the Kimama well was 59.3 °C at a depth of 1,824 m by the DOSECC tool. The DOSECC tool was made to monitor the temperature while drilling.

Kimberly

The gradient for the entire Kimberly well is 15.1 °C/km (Figure 21). There are several dips in the temperature log. In the Kimberly well the temperature cools immediately from the surface to a depth of 143 m where it begins rising. There is a gradient of 85.2 °C/km from 143 m to 490 m where the temperature spikes at 47.98 °C. The temperature begins dropping at 490 m until 548 m where it drops to 44.85 °C. There is a gradient of 27.6 °C/km from 548 m to 800 m where the temperature reaches 51.8 °C and then flattens out. From 800 m to 1,900 m the gradient is 5 °C/km. The highest temperature recorded in the Kimberly well is 57.29 °C, which is reached at TD.

Mountain Home

The Mountain Home well has a gradient of 73 °C/km for the entire well, from 3 m to 1,675 m (Figure 22). That is the highest of all the Project Hotspot wells. There is not much variation in the well as the gradient is close to linear for the entire well except at two depths, one at about 900 m and one just below 1,000 m. The dips are probably



Figure 21. Kimberly temperature log (OSG).

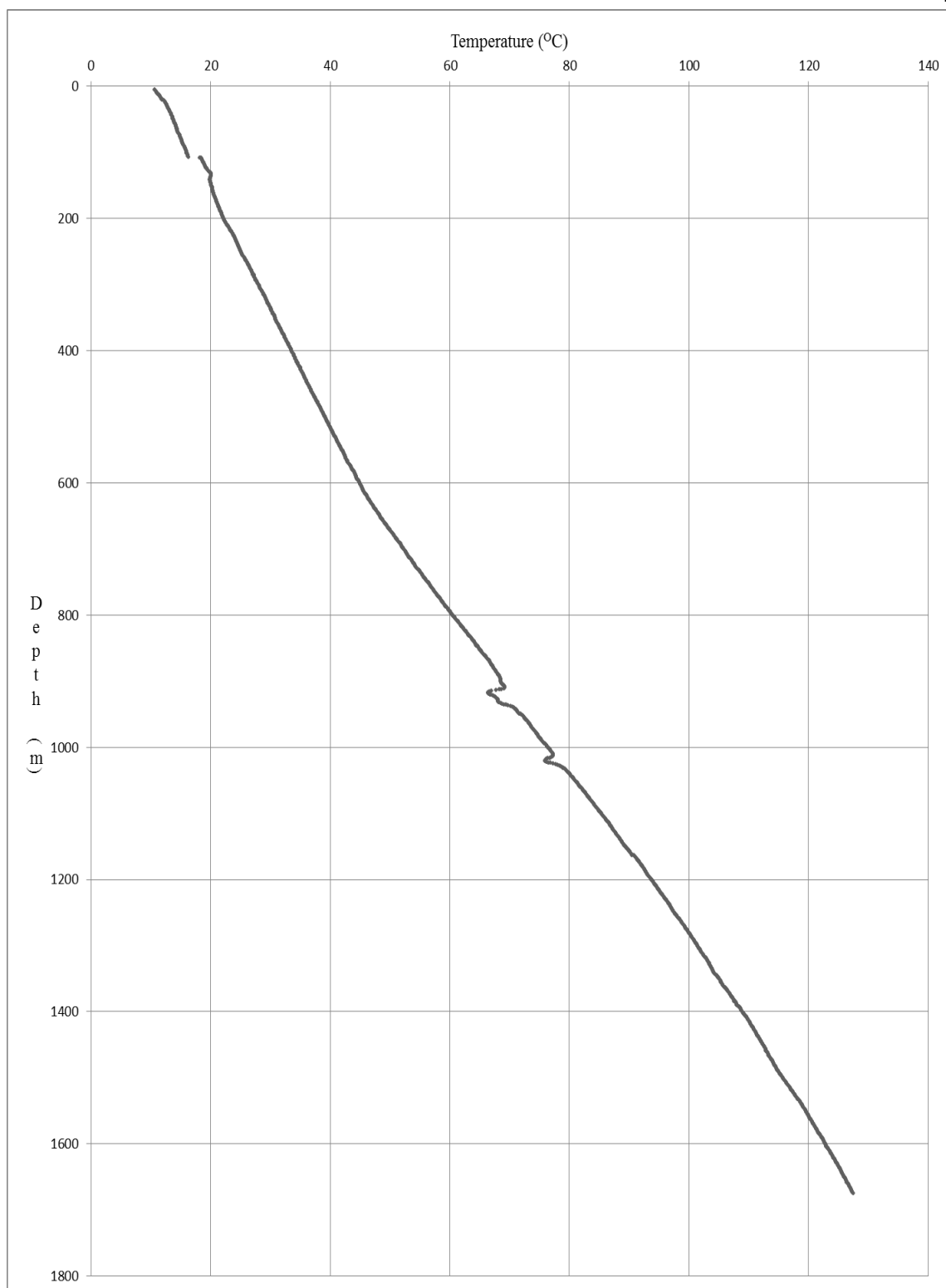


Figure 22. Mountain Home temperature log (OSG).

caused by the input of cold water from a producing formation. Despite these two dips the gradient picks back up and resumes at the same rate that it had prior to the temperature dips. The highest temperature recorded in the Mountain Home well was ~140 °C, which is the highest for all Project Hotspot wells. It is more than two times the highest recorded temperature of the Kimama and Kimberly wells. It is 30 °C higher than the projected temperature at the TD of Kimama using the SMU data, which is 110 °C.

DISCUSSION

Geothermometry

Geothermometers are temperature indicators using temperature dependent geochemical and/or isotopic compositions of geothermal waters (Gupta and Roy, 2007). Some chemical relationships have been observed and the temperature is predictable for certain parameters and ratios of these parameters. All geothermometers have limitations.

The following assumptions are made when using geothermometers: (1) the relevant hydrothermal minerals in the reservoir are in equilibrium with the geothermal liquid; (2) the pore-fluid pressure in the reservoir is fixed by coexistence of liquid and steam; (3) the geothermal liquid cools either conductively or adiabatically, through steam separation at 100 °C; (4) the geothermal liquid does not mix with cold, shallow waters during the ascent towards the surface; (5) the geothermal liquid does not precipitate any relevant minerals along the upflow path (Marini, 2004). In most situations it is difficult to prove that these assumptions are met (Ferguson et al., 2009).

The geothermometers that are applied in this report to the Project Hotspot waters are: chalcedony and quartz (Fournier, 1973, 1977), Na/K (Fournier, 1979), Na/K (Giggenbach, 1988), Na-K-Ca (Fournier and Truesdell, 1973), Na-K-Ca-Mg (Fournier and Potter, 1979), and K^2/Mg (Giggenbach, 1988). The formulas used are displayed in Table 6.

The Na-K-Ca-Mg (Fournier and Potter, 1979) geothermometer is a magnesium correction to the Na-K-Ca (Fournier and Truesdell, 1973) geothermometer. In these two

Table 6. Geothermometer equations.

Chalcedony (Fournier, 1977)

$$T(^{\circ}C) = \frac{1032}{4.69 - \log(SiO_2)} - 273.15$$

Quartz (Fournier, 1977)

$$T(^{\circ}C) = \frac{1309}{5.19 - \log(SiO_2)} - 273.15$$

Na/K (Fournier, 1979)

$$T(^{\circ}C) = \frac{1217}{\log\left(\frac{Na}{K}\right) + 1.483} - 273.15$$

Na/K (Giggenbach, 1988)

$$T(^{\circ}C) = [1390/(1.75 + \log(Na/K))] - 273.15$$

Na-K-Ca (Fournier and Truesdell, 1973)

$$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$$

Na-K-Ca-Mg (Fournier and Potter, 1979)

$$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$$

- Δt_{Mg}

K²/Mg (Giggenbach, 1988)

$$T(^{\circ}C) = [4410/(14.0 + \log(K^2/Mg))] - 273.15$$

geothermometers there is a variable, β , that is dependent upon the ratio of Ca to Na. β is determined as follows.

1. If $\log\sqrt{(\text{Ca}/\text{Na})} + 2.06 < 0$, then $\beta = 1/3$
2. If $\log\sqrt{(\text{Ca}/\text{Na})} + 2.06 > 0$, then $\beta = 4/3$
3. If $\beta = 4/3$ and the temperature calculated is greater than 100 °C, then

temperature is recalculated using $\beta = 1/3$.

For the Na-K-Ca-Mg geothermometer, the procedure suggested by Fournier and Potter (1979) is as follows.

1. Calculate the temperature with the Na-K-Ca (Fournier and Truesdell, 1973) geothermometer. A magnesium correction is not applied if the calculated temperature is below 70 °C.

2. Calculate $R = [\text{Mg}/(\text{Mg} + \text{Ca} + \text{K})] \times 100$, using units of concentration that are equivalent.

3. If $R > 50$, then it is assumed that the water came from a cool source that has a temperature that is equivalent to the measured water temperature, irrespective of high calculated Na-K-Ca temperature.

4. If the calculated Na-K-Ca temperature is above 70 °C and $R < 50$ then Δt_{Mg} must be calculated as follows:

(a) If $5 < R < 50$ then,

$$\Delta t_{\text{Mg}} = 10.66 - 4.7415R + 325.87(\log R)^2 - 1.032 \times 10^5(\log R)^2/T - 1.968 \times 10^7(\log R)^2/T^2 + 1.605 \times 10^7(\log R)^3/T^2,$$

where Δt_{Mg} is the temperature to be subtracted from the calculated Na-K-Ca temperature,

and, where

T = the calculated Na-K-Ca temperature in Kelvin

$R = [\text{Mg}/(\text{K} + \text{Ca} + \text{Mg})] \times 100$,

with all concentrations in equivalent units.

(b) If $0.5 < R < 5$ then,

$\Delta t_{\text{Mg}} = -1.03 + 59.971 \log R + 145.05(\log R)^2 - 36711(\log R)^2/T - 1.67 \times 10^7 \log R/T^2$,

using the same variables.

5. No magnesium correction is applied if $R < 0.5$, or if Δt_{Mg} is negative.

Otherwise Δt_{Mg} (in °C) is subtracted from the calculated Na-K-Ca temperature.

There are a few other geothermometers that are widely used (Na/Li and Mg/Li (Kharaka and Mariner, 1989)), but one of the chemical analyses required for them is lithium (Li), which was not analyzed for in this sample set.

Chemical analyses of the Project Hotspot waters (Table 2) were used to estimate subsurface reservoir temperatures. Temperatures calculated by the geothermometers used for the Project Hotspot waters are summarized in Table 7 (calculations are shown in Appendix C). Temperatures calculated using ThermoChem and UVDL results are not displayed in Table 7, but the results can be found in Appendix C (Tables C.6 and C.7). These results were not included in the body due to being received late in the writing process.

Kimama

There were two water samples, KA-W and KA-1, taken from the Kimama site.

Table 7. Geothermometer calculations (all results in °C).

Sample	Chalcedony (Fournier, 1977)	Quartz (Fournier, 1977)	Na/K (Fournier, 1979)	Na/K (Giggenbach, 1988)	Na-K-Ca (Fournier and Truesdell, 1973)	Na-K-Ca- Mg (Fournier and Potter, 1979)	K²/Mg (Giggenbach, 1988)
KA-W	82.1	111.2	294.4	303.3	44.4	85.4	42.0
KA-1	141.1	164.4	143.1	162.5	138.6	124.5	80.2
KB-38	107.0	134.1	135.3	155.0	141.8	86.4	79.7
KB-52	90.9	119.3	123.2	143.3	129.6	90.1	71.6
KB-63	94.7	122.9	120.0	140.2	129.8	82.9	73.3
MH-5,726	157.3	178.6	134.3	154.0	138.8	132.5	117.3

The KA-W sample was from the SRPA and is groundwater. It was taken from a shallower well (90 m). The chemistry for this sample produced erratic geothermometry results.

The geothermometry results for the KA-1 sample support the idea that the Kimama area is actually a good geothermal prospect area, but as will be shown later the SRPA suppresses the possible temperatures that could be reached at shallower depths. Six of the seven geothermometers for the KA-1 sample predict temperatures above 120 °C. The KA-1 sample gives high results for the quartz geothermometers (Fournier, 1977) and Na/K (Giggenbach, 1988), but these may be affected due to mixing with shallow groundwater. The Na-K-Ca (Fournier and Truesdell, 1973) geothermometer gives a more likely result of 138.6 °C. But KA-1 has a relatively high Mg concentration and when the correction is applied (Fournier and Potter, 1979) and the estimated equilibrium temperature drops to 124.5 °C.

Kimberly

The three samples from the Kimberly well (KB-38, KB-52, and KB-63) had similar, but slightly different, chemistry values. This resulted in similar, but slightly different, geothermometer results. Similar to Kimama, the Kimberly samples show evidence of mixing with shallow groundwater, which affects the geothermometer results. All three samples had high Na-K-Ca (Fournier and Truesdell, 1973) results, but when the Mg correction was applied the results dropped significantly. This suggests that there is

either mixing or some reaction taking place that is affecting the equilibrium of the water in the Kimberly area.

Mountain Home

The Mountain Home sample (MH-5,726) was unique in that it was taken directly from the wellhead when it was flowing. This increases the likelihood that the chemical analysis was representative of the chemistry of the formation water. The geothermometer pattern for MH-5,726 is similar to the other samples, except that the results are higher in temperature. Similar to the Kimama sample the quartz geothermometer (Fournier, 1977) gives higher results than the other geothermometers. The Mountain Home sample has a lower Mg content when compared to KA-1. This results in a smaller correction when the Na-K-Ca-Mg geothermometer (Fournier and Potter, 1979) is used, which results in an estimated equilibrium temperature of 132.5 °C and is similar to the value for the Na-K-Ca geothermometer (Fournier and Truesdell, 1973) of 138.8 °C.

Graphic Techniques

The water chemistry analyses (Table 2) were also used in geothermometric techniques proposed by Giggenbach (1988). The first technique discriminates between “immature waters” and “fully equilibrated waters” coming from deep geothermal reservoirs. The technique is a simultaneous evaluation of three independent variables, which is carried out by plotting on a triangular diagram. This technique evaluates the water/rock equilibration for the system of Na-K-Mg. It does this by combining the Na/K and K^2/Mg geothermometers. Geothermal fluids are divided into three main groups

depending on the ratio of Na, K, and Mg ions as (1) fully equilibrated waters (2) partially equilibrated waters and (3) immature waters. This triangular diagram is known as a Giggenbach plot. A Giggenbach plot of Project Hotspot samples is shown in Figure 23. From the Giggenbach plot the Kimama and Kimberly samples plot on the bottom line of being partially equilibrated. The Mountain Home sample plots closer to the full equilibration curve.

Another technique used by Giggenbach (1988) is to plot relative Cl, SO₄, and HCO₃ contents of waters in order to characterize them. Acid, neutral chloride, and soda springs waters are the three broad classification types. Plotting the water samples from Project Hotspot in this diagram shows that all three classification types are represented by Project Hotspot samples (Figure 24). The KA-1 sample plots close to the neutral chloride/acid water boundary. The MH-5,726 sample plots as an acid water. All of the Kimberly samples plot as soda spring waters, as does KA-W. Note that none of the samples plot as mature waters as defined by this diagram.

Giggenbach (1988) figures for the MH-5,726 sample results from ThermoChem and UVDL are included in Appendix C (Figures C.1 and C.2). These samples plot closer to the full equilibration line on the triangular plot.

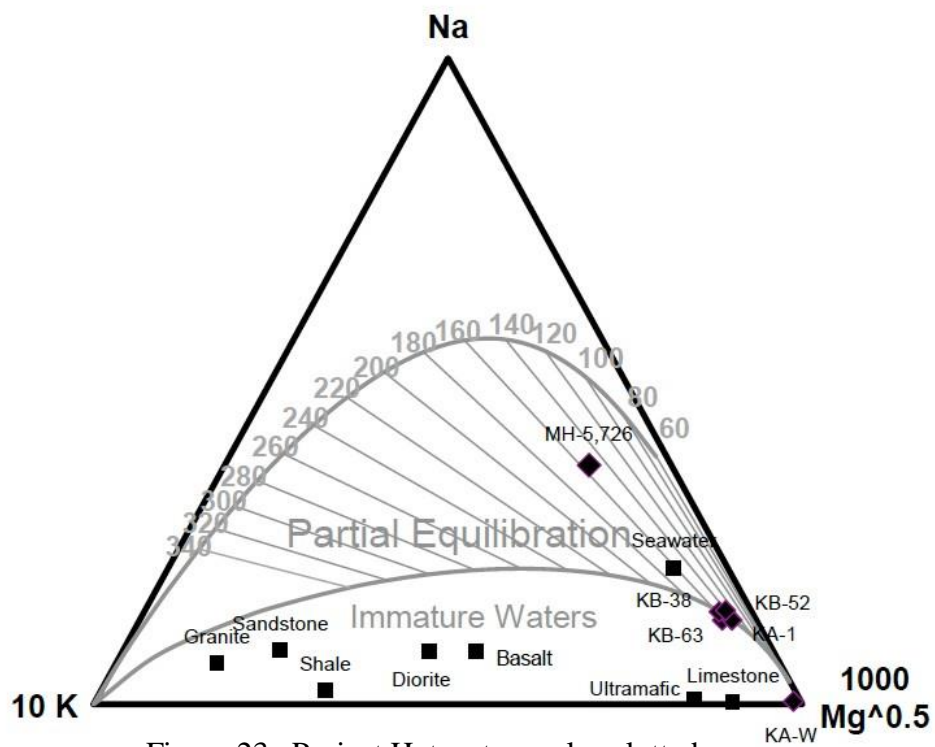


Figure 23. Project Hotspot samples plotted on Giggenbach triangular plot (Giggenbach, 1988).

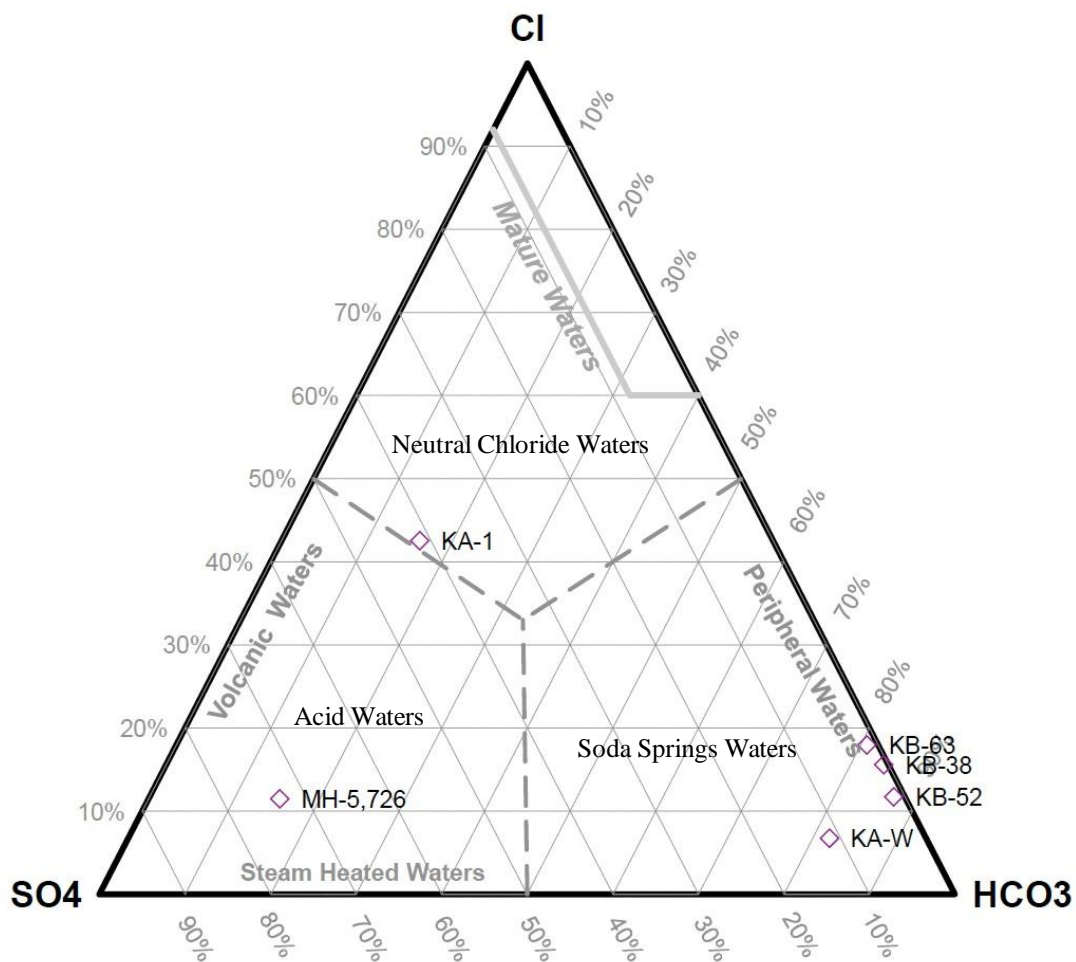


Figure 24. Project Hotspot samples plotted on Cl, SO₄, and HCO₃ triangular plot (Giggenbach, 1988).

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Project Hotspot was an attempt to explore the SRP for geothermal resources. Three different areas of the SRP were targeted by Project Hotspot: (1) the axis of the eastern SRP at Kimama; (2) the edge of the SRP at Kimberly; (3) and the western SRP at Mountain Home. Three wells were drilled for the project (one at each site). The well depths ranged from 1,821.5 - 1,953 m. Core logging, geophysical logging, temperature logging, and water sampling took place at each well. The results of the temperature logs were used to calculate geothermal gradients for each well. Results of the chemical analyses of the water samples were used in conjunction with geothermometric techniques to estimate equilibrium temperatures of the geothermal systems in the wells.

Kimama

Results of the water chemistry analyses for the Kimama wells showed that there is a distinction between the deeper geothermal waters (KA-1) and shallow SRPA waters (KA-W). The KA-W sample is distinct from all other Project Hotspot samples. KA-W is characterized as a Ca-Mg-bicarbonate water. KA-1 is characterized as a Na-chloride water. KA-W and KA-1 have isotopic compositions indicating that they are both meteoric waters.

The highest temperature recorded in the Kimama well was 59.3 °C at a depth of 1,824 m, which was recorded by DOSECC. The geothermal gradient was 6.7 and 5.5 °C/km from 520-1,014 m and 280-960 m using DOSECC and OSG measurements,

respectively, while below 960 m (SMU data) the gradient increased to 88.9 °C/km. The projected temperature at TD, extrapolated from the SMU gradient, would be approximately 110 °C. The suppression of the gradient is due to the cold SRPA water, which ends at approximately 960 m. The SRPA is approximately 300 m in thickness at the INL (McLing et al., 2002), while at Kimama it is closer to 960 m.

Geothermometers for the Kimama well suggest that deeper waters reach higher temperatures than were actually recorded in the well. KA-1 plots on the bottom line of being partially equilibrated on the Giggenbach (1988) triangular plot (Figure 23). This indicates that it is acceptable for the application of ionic solute geothermometers. The Na-K-Ca (Fournier and Truesdell, 1973) gives inconsistent results for temperatures below 200 °C (Paces, 1975). Kimama is below 200 °C, therefore the Na-K-Ca-Mg (Fournier and Potter, 1979) geothermometer should give the best results. The Na-K-Ca (Fournier and Truesdell, 1973) geothermometer results in an estimate of 138.6 °C, while the Na-K-Ca-Mg (Fournier and Potter, 1979) geothermometer gives an estimate of 124.5 °C. This suggests that there are Mg reactions taking place that are affecting the geothermometer estimates. The Mg concentrations are over 20 times those of the Mountain Home sample.

Isotopic data indicate that the Kimama waters are meteoric. If the Kimama waters are indeed meteoric then they have moved down flow paths to these depths and have begun equilibrating with the geothermal system.

Kimberly

Results of the water chemistry analyses of the three Kimberly samples (KB-38,

KB-52, and KB-63) were all similar. The samples all had the same dominant cation, Na, as the Kimama well. But the dominant anion was bicarbonate, which is different from Kimama. The KB-52 sample was depleted in ^{13}C , but this may be due to contamination by grease and drilling mud.

The temperature in the Kimberly well reaches almost its highest, $51.8\text{ }^{\circ}\text{C}$, at a comparatively shallow 800 m and increases to $57.3\text{ }^{\circ}\text{C}$ at the TD of 1,953 m. The geothermal gradient for the entire Kimberly well (3-1,953 m) was the lowest of all the wells at $15.1\text{ }^{\circ}\text{C}/\text{km}$. The gradient from 800-1,953 m is only $5\text{ }^{\circ}\text{C}/\text{km}$.

Geothermometer results from the Kimberly well indicate that there is mixing with shallow groundwater. Similar to KA-1, the high Mg levels significantly affect the Na-K-Ca-Mg (Fournier and Potter, 1979) geothermometer.

It is evident from the low temperatures recorded in the Kimberly well that the system is not in equilibrium. If the geothermal gradient for the entire well is used, the temperatures suggested by the geothermometers would not be reached until a depth of greater than 5 km. Regardless of the geothermometers the gradient ($15.1\text{ }^{\circ}\text{C}/\text{km}$) does not suggest that high temperatures are capable of being reached in the Kimberly area until much greater depths ($> 5\text{ km}$).

Mountain Home

Results of the water chemistry analyses for MH-5,726 classify it as a Na-sulfate type water. The isotopic composition of the MH-5,726 sample indicates that these waters are not meteoric, which suggests that they may be equilibrated with the geothermal

system.

The highest temperature recorded in the Mountain Home well was ~140 °C. The geothermal gradient for Mountain Home was 73 °C/km for the entire well (3-1,675 m).

The Mountain Home sample plots as partially equilibrated on the Giggenbach ternary plot (1988) (Figure 17). Samples that plot as partially equilibrated indicate that the samples are acceptable for the application of ionic solute geothermometers. The geothermometer that seems to be most applicable to MH-5,726 is the Na-K-Ca (Fournier and Truesdell, 1973), which gives an equilibrium temperature of 138.8 °C. This is 6 °C higher than the Na-K-Ca-Mg (Fournier and Potter, 1979) geothermometer. It is possible that the water analyzed for this sample is not fully equilibrated with the system and therefore the chemistry does not represent the temperatures that are actually occurring at depth in the system, as the highest recorded formation temperature and calculated equilibrium temperatures are essentially the same (Breckenridge et al., 2012; Lachmar et al., 2012; Nielson et al., 2012).

The Mountain Home well was the only well to flow. This is a good indicator of permeability.

Conclusions

It is clear from the data that the Mountain Home well is located in the best potential area for further exploration. All the components needed for a hot water geothermal system (heat, water, and permeability) are present in the Mountain Home well. It is the only well in Project Hotspot that recorded a temperature (~140 °C) close to

being hot enough to produce power. It also has an artesian zone, which would be crucial to further operations. The artesian zone is a significant indicator of permeability.

Kimama is not as good a prospect as Mountain Home due to the effect of the SRPA on the geothermal gradient. The data for Kimama indicate that high temperatures are likely, but a number of things (such as a thin SRPA and high geothermal gradient) would have to be present in order for the Kimama area to be more favorable for geothermal exploration. Also, the depths that Kimama could reach these higher temperatures are greater than at Mountain Home. Also, basalts at Kimama may not be as permeable as those at Mountain Home.

Kimberly has the weakest indicators for geothermal potential. The highest recorded temperature was low (57.3 °C) for geothermal purposes. The temperature reached is on the edge of use for passive geothermal operations, which may be a target for future use as the SRP area is agriculturally intensive. Passive geothermal can be used to heat greenhouses, heat processing water, and heat a vegetable or fruit drying facility.

Recommendations

Further work should include hydraulic testing at Mountain Home and Kimama, starting with the Mountain Home area as it already showed the potential to have non-induced flow. Hydraulic tests could give an idea of the rate of water that these two areas are capable of producing. Should the results of flow testing be positive the next step would be to drill a full size exploration well.

Agriculture and space heating needs would also be an area for more research as

these needs could possibly be fulfilled by low temperature geothermal resources. The

Kimberly area could be a possible target for low temperature geothermal resources.

Further work (geophysical and drilling) in the Kimama area could be conducted to look for areas where the SRPA is not as deep such as along the margins of the SRP.

REFERENCES CITED

- Blackwell, D.D., 1989, Regional implications of heat flow of the Snake River Plain, northwestern United States: *Tectonophysics*, v. 157, p. 241-250.
- Blackwell, D.D., and Richards, M., 2004, Geothermal map of North America: American Association of Petroleum Geologists, scale 1:6,500,000, 1 sheet.
- Breckenridge, R. P., Shervais, J. W., Nielson, D. E., and Wood, T. R., 2012, Exploration and resource assessment at Mountain Home Air Force Base, Idaho using an integrated team approach: *Geothermal Resources Council Transactions*, v. 36, p. 615-619.
- Craig, H., 1961, Isotopic variations in meteoric waters: *Science*, v. 133, p. 1702-1703.
- Delahunty, C., Nielson, D. L., and Shervais, J. W., 2012, Coring of three deep geothermal holes, Snake River Plain, Idaho: *Geothermal Resources Council Transactions*, v. 36, p. 641-647.
- Ferguson, G., Grasby, S. E., and Hindle, S. R., 2009, What do aqueous geothermometers really tell us? *Geofluids*, v. 9, p. 39-48.
- Fournier, R.O., 1973, Silica in thermal waters: Laboratory and field investigations: *Biogeochemistry*, p. 122-139.
- Fournier, R.O., 1977, Chemical geothermometers and mixing models for geothermal systems: *Geothermics*, v. 5, p. 41-50.
- Fournier, R.O., 1979, A revised equation for Na-K geothermometer: *Geothermal Resources Council Transactions*, v. 3, p. 221-224.
- Fournier, R.O., and Truesdell, A., 1973, An empirical Na-K-Ca geothermometer for natural waters: *Geochimica Et Cosmochimica Acta*, v. 37, no. 5, p. 1255-1275.
- Fournier, R.O., and Potter, R.W., 1979, Magnesium correction to the Na-K-Ca chemical geothermometer: *Geochimica Et Cosmochimica Acta*, v. 43, p. 1543-1550.

- Fridleifsson, I.B., Bertani, R., Huenges, E., Lund, J.W., Ragnarsson, A., and Rybach, L., 2008, The possible role and contribution of geothermal energy to the mitigation of climate change, *in* Hohmeyer, O., and Trittin, T. eds., Proceedings, IPCC Scoping Meeting on Renewable Energy Sources: Luebeck, Germany, 20-25 January 2008, p. 59-80.
- Giggenbach, W.F., 1988, Geothermal solute equilibria: Derivation of Na–K–Mg–Ca geothermometers: *Geochimica Et Cosmochimica Acta*, v. 52, p. 2749-2765.
- Gupta, H.K., and Roy, S., 2007, *Geothermal Energy: An Alternative Resource for the 21st Century*: Elsevier, Amsterdam.
- Hackett, W.R., and Morgan, L.A., 1988, Explosive basaltic and rhyolitic volcanism of the eastern Snake River Plain, Idaho, *in* Link, P.K., and Hackett, W.R., eds., *Guidebook to the geology of central and southern Idaho*: Idaho Geological Survey Bulletin 27, p. 283-301.
- Hackett, W.R., and Smith, R.P., 1992, Quaternary volcanism, tectonics, and sedimentation in the Idaho National Engineering Laboratory area, *in* Wilson, J.R., ed., *Field guide to geologic excursions in Utah and adjacent areas of Nevada, Idaho, and Wyoming*: Geological Society of America Rocky Mountain Section Guidebook, Utah Geological Survey Miscellaneous Publication 92-3, p. 1-18.
- Hughes, S.S., Smith, R.P., Hackett, W.R., and Anderson, S.R., 1999, Mafic volcanism and environmental geology of the eastern Snake River Plain, Idaho, *in* Hughes, S.S., and Thackray, G.D., eds., *Guidebook to the geology of eastern Idaho*: Idaho Museum of Natural History, p. 143-168.
- Kendall, C., and McDonnell, J.J., 1998, *Isotope Tracers in Catchment Hydrology*: Elsevier, Amsterdam.
- Kharaka, Y., and Mariner, R., 1989, Chemical geothermometers and their application to formation waters from sedimentary basins, *in* Naeser, N.D., and McCulloch, T., eds., *Thermal History of Sedimentary Basins: Methods and Case Histories*: Springer Verlag, New York, p. 99-117.
- Lachmar, T. L., Freeman, T. G., Shervais, J. W., and Nielson, D. E., 2012, Preliminary results: chemistry and thermometry of geothermal water from MH-2B test well: *Geothermal Resources Council Transactions*, v. 36, p. 689-692.

- Mann, L. J., 1986, Hydraulic properties of rock units and chemical quality of water for INEL-1 ~ a 10,365-foot deep test hole drilled at the INEL, Idaho: U.S. Geological Survey Water-Resources Investigations Report 86-4020, 23 p.
- Mann, L.J., and Knobel, L.L., 1990, Radionuclides, metals, and organic compounds in water, eastern part of A & B Irrigation District, Minidoka County, Idaho: U.S. Geological Survey Open-File Report 90-191 (DOE/ID-22087), 36 p.
- Marini, L., 2004, Geochemical techniques for the exploration and exploitation of geothermal energy: Laboratorio di Geochimica, Universita degli di Genova, Genova, Italia.
- McLing, T.L., Smith, R.W., and Johnson, T.M., 2002, Chemical characteristics of thermal water beneath the eastern Snake River Plain, *in* Link, P.K., and Mink, L.L., eds., Geology, hydrogeology, and environmental remediation: Idaho National Engineering and Environmental Laboratory, eastern Snake River Plain, Idaho: Boulder, Colorado, Geological Society of America Special Paper 353, p. 205-211.
- McNitt, J.R., 1973, The role of geology and hydrology in geothermal exploration, *in* Armstead, H.C.H., ed., Geothermal Energy: UNESCO, Paris, p. 33-40.
- Morgan, L.A., Doherty, D.J., and Leeman, W.P., 1984, Ignimbrites of the eastern Snake River Plain: Evidence for major caldera-forming eruptions: *Journal of Geophysical Research*, v. 89, p. 8665-8678.
- Morse, L.H., and McCurry, M., 2002, Genesis of alteration of Quaternary basalts within a portion of the eastern Snake River Plain aquifer, *in* Link, P.K., and Mink, L.L., eds., Geology, hydrogeology, and environmental remediation: Idaho National Engineering and Environmental Laboratory, eastern Snake River Plain, Idaho: Boulder, Colorado, Geological Society of America Special Paper 353, p. 213-224.
- Nielson, D. L., Delahunty, C., and Shervais, J. W., 2012, Geothermal systems in the Snake River Plain, Idaho, characterized by the Hotspot Project: *Geothermal Resources Council Transactions*, v. 36, p. 727-730.
- Paces T., 1975, A systematic deviation from Na-K-Ca geothermometer below 75°C and above 10⁻⁴ atm PCO₂: *Geochimica Et Cosmochimica Acta*, v. 39, p. 541-544.
- Piper, A.M., 1944, A graphic procedure in the geochemical interpretation of water analyses: *American Geophysical Union Transactions*, v. 25, p. 914-923.

- Potter, K.E., Bradshaw, R., Sant, C.J., King, J., Shervais, J.W., and Christiansen, E.H., 2011, Project Hotspot: insight into the subsurface stratigraphy and geothermal potential of the Snake River Plain: Geothermal Resources Council Transactions, v. 35, p. 967-971.
- Sant, C.J., 2012, Geothermal Alteration of Basaltic Core from the Snake River Plain, Idaho [M.S. thesis]: Logan, Utah State University, 113 p.
- Sant, C.J., and Shervais, J.W., 2011, Project Hotspot: Preliminary analysis of secondary mineralization in basaltic core, central Snake River Plain: Geothermal Resources Council Transactions, v. 35, p. 987-989.
- Schmitt, D.R., Liberty, L.M., Kessler, J.E., Kück, J., Kofman, R., Bishop, R., Shervais, J.W., Evans, J.P., and Champion, D.E., 2012, The ICDP Snake River geothermal drilling project: Preliminary overview of borehole geophysics: Geothermal Resources Council Transactions, v. 36, p. 1017-1022.
- Shervais, J.W., Nielson, D.L., Evans, J.P., Christensen, E.J., Morgan, L., Shanks, W.C., Delahunty, C., Schmitt, D.R., Liberty, L.M., Blackwell, D.D., Glenn, J.M., Kessler, J.E., Potter, K.E. Jean, M.M. Sant, C.J., and Freeman, T.G., 2012, Hotspot: The Snake River Plain geothermal drilling project – Initial report: Geothermal Resources Council, v. 36, p. 767-772.
- Shervais, J.W., Schmitt, D.R., Nielson, D.L., Evans, J.P., Christiansen, E.H., Morgan, L., Shanks, W.C.P., Lachmar, T., Liberty, L.M., Blackwell, D.D., Glen, J.M., Champion, D., Potter, K.E., and Kessler, J.A., 2013, First results from Hotspot: The Snake River Plain scientific drilling project, Idaho, USA: Scientific Drilling, no. 15, doi:10.2204/iodp.sd.15.06.2013.
- Smith, R.B., and Braile, L.W., 1994. The Yellowstone hotspot: Journal of Volcanology and Geothermal Research, v. 61, p. 121-187.
- Smith, R.B., Jordan, M., Steinberger, B., Puskas, C.M., Farrell, J., Waite, G.P., Husen, S., Chang, W., and O'Connell, R., 2009, Geodynamics of the Yellowstone hotspot and mantle plume: Seismic and GPS imaging, kinematics, and mantle flow: Journal of Volcanology and Geothermal Research, v. 188, p. 26-56.
- Smith, R.P., 2004, Geologic setting of the Snake River Plain aquifer and vadose zone: Vadose Zone Journal, v.3, p.47-58.

- U.S. Department of Energy EERE, 2011, Geothermal technologies program: The Snake River geothermal drilling project – Innovative approaches to geothermal exploration: [http:// www4.eere.energy.gov/geothermal/projects/85](http://www4.eere.energy.gov/geothermal/projects/85) (August 2011).
- U.S. Environmental Protection Agency, 2011, Sole source aquifer protection program, source water protection: <http://water.epa.gov/infrastructure/drinkingwater/sourcewater/protection/solesourceaquifer.cfm> (August 2011).
- U.S. Geological Survey, 1985, National water summary, 1984: Hydrologic events, selected water-quality trends, and ground-water resources: U.S. Geological Survey Water-Supply Paper 2275, 467 p.
- Welhan J. A., Johannesen C.A., Davis L.L., Reeves K.S., and Glover J.A., 2002a, Overview and synthesis of lithologic controls on aquifer heterogeneity in the eastern Snake River Plain, Idaho, *in*, Bonnicksen, B., White, C., and McCurry, M., eds., Tectonic and magmatic evolution of the Snake River Plain volcanic province: Bulletin of the Idaho Geological Survey 30, p. 455–460.
- Welhan, J.A., Johannesen, C.M., Reeves, K.S., Clemo, T.M., Glover, J.A., and Bosworth, K.W., 2002b, Morphology of inflated pahoehoe lavas and spatial architecture of their porous and permeable zones, eastern SRP, Idaho, *in* Link, P.K., and Mink, L.L., eds., Geology, hydrogeology, and environmental remediation: Idaho National Engineering and Environmental Laboratory, eastern Snake River Plain, Idaho: Boulder, Colorado, Geological Society of America Special Paper 353, p. 135-150.
- Winston, R.B., 2000, Graphical user interface for MODFLOW, version 4: U.S. Geological Survey Open-File Report 00-315, 27 p.
- Whitehead, R.L., 1994, Ground water atlas of the United States, Idaho, Oregon, Washington: U.S. Geological Survey Publication HA 730-H.
- Wood, W.W., and Low, W.H., 1986, Aqueous geochemistry and diagenesis in the eastern Snake River Plain aquifer system, Idaho: Geological Society of American Bulletin, v. 97, p. 1456-1466.

APPENDICES

Appendix A. Chemical Results

Table A.1. USUAL chemical results (all values in mg/L).

Element	KA-W	KA-1	KB-38	KB-52	KB-63	MH- 5,726	Detection Limits
Al	<	1.89	<	<	0.25	0.26	0.12
As	<	<	<	<	<	<	0.01
B	0.02	0.54	0.10	0.15	0.10	1.16	0.02
Ba	0.01	0.03	0.30	0.16	0.29	0.02	0.001
Ca	25.0	21.1	24.7	15.4	23.8	8.71	0.08
Cd	<	<	<	<	<	<	0.001
Cl	13.1	315	204	128	189	74.8	6.0
Co	<	<	<	<	<	<	0.005
Cr	<	<	<	<	<	<	0.006
Cu	<	<	<	<	<	<	0.008
Fe	0.03	1.61	0.45	1.10	0.94	0.16	0.003
K	3.60	10.3	17.9	9.38	13.2	9.02	0.46
Mg	12.7	3.21	10.1	5.43	9.33	0.16	0.007
Mn	0.001	0.102	0.367	0.270	0.339	0.01	0.001
Mo	<	0.27	<	<	<	0.51	0.15
Na	16.5	284	562	363	541	288	0.08
Ni	0.009	0.019	0.012	0.003	0.015	<	0.003
P	<	<	<	<	<	<	0.08
Pb	<	<	<	<	<	<	0.03
S	7.38	102	2.43	4.69	4.60	159	0.07
Se	<	<	<	<	<	<	0.04
Si	28.4	73.6	44.1	33.4	35.8	91.4	0.15
Sr	0.13	0.11	0.32	0.19	0.30	0.16	0.03
Zn	<	<	<	<	0.01	0.04	0.005

Table A.2. ThermoChem and UVDL chemical results (all values in mg/L).

Element	ThermoChem-5,726	UVDL-5,726
Al	N/A	0.03
As	0.0026	< 0.01
B	1.44	0.99
Ba	N/A	0.01
Ca	9.64	11.15
Cd	N/A	<0.01
Cl	76.7	N/A
Co	N/A	< 0.01
Cr	N/A	< 0.01
Cu	N/A	0.01
Fe	N/A	0.01
K	9.11	9.25
Mg	<0.02	0.07
Mn	N/A	< 0.01
Mo	N/A	0.51
Na	313	313.76
Ni	N/A	< 0.01
P	N/A	0.03
Pb	N/A	< 0.01
S	N/A	N/A
Se	N/A	0.01
Si	101	47.15
Sr	N/A	0.14
Zn	N/A	< 0.01

Appendix B. Core Photos



Figure B.1. Kimama core (1,070.5 - 1,073.3 m).

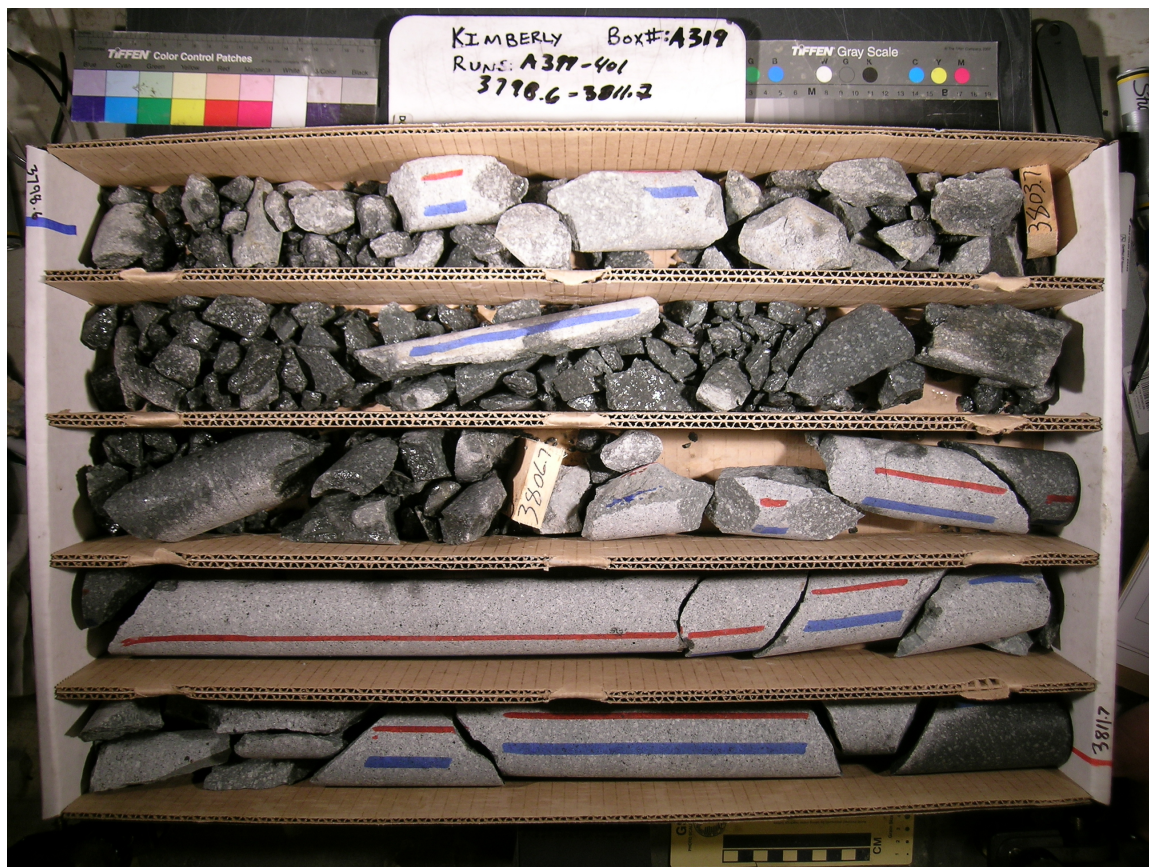


Figure B.2. Kimberly core (1,157.8 - 1,161.7 m).



Figure B.3. Kimberly core (1,581.5 - 1,585.0 m).



Figure B.4. Kimberly core (1,917.8 - 1,921.4 m).



Figure B.5. Mountain Home core (1,743.5 - 1,748.6 m).

Appendix C. Geothermometer Calculations

Table C.1. Geothermometer calculations for KA-1.

Sample	KA-1	
Chalcedony (Fournier, 1977)	Variables (in mg/l)	Result (Temperature °C)
$T(^{\circ}C) = \frac{1032}{4.69 - \log(SiO_2)} - 273.15$	SiO ₂ = 158	141.1
Quartz (Fournier, 1977)		
$T(^{\circ}C) = \frac{1309}{5.19 - \log(SiO_2)} - 273.15$	SiO ₂ = 158	164.4
Na/K (Fournier, 1979)		
$T(^{\circ}C) = \frac{1217}{\log\left(\frac{Na}{K}\right) + 1.483} - 273.15$	Na = 284 K = 10.3	143.1
Na/K (Giggenbach, 1988)		
$T(^{\circ}C) = [1390/(1.75 + \log(Na/K))] - 273.15$	Na = 284 K = 10.3	162.5
Na-K-Ca (Fournier and Truesdell, 1973)		
$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$	Na = 284 K = 10.3 Ca = 21.1	138.6
Na-K-Ca-Mg (Fournier and Potter, 1979)		
$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$ - Δt _{Mg}	Na = 284 K = 10.3 Ca = 21.1	124.5
K ² /Mg (Giggenbach, 1988)		
$T(^{\circ}C) = [4410/(14.0 + \log(K^2/Mg))] - 273.15$	K = 10.3 Mg = 3.21	80.2

Table C.2. Geothermometer calculations for KB-38.

Sample	KB-38	
Chalcedony (Fournier, 1977)	Variables (in mg/l)	Result (Temperature °C)
$T(^{\circ}C) = \frac{1032}{4.69 - \log(SiO_2)} - 273.15$	SiO ₂ = 94.5	107.0
Quartz (Fournier, 1977)		
$T(^{\circ}C) = \frac{1309}{5.19 - \log(SiO_2)} - 273.15$	SiO ₂ = 94.5	134.1
Na/K (Fournier, 1979)		
$T(^{\circ}C) = \frac{1217}{\log\left(\frac{Na}{K}\right) + 1.483} - 273.15$	Na = 562 K = 17.9	135.3
Na/K (Giggenbach, 1988)		
$T(^{\circ}C) = [1390/(1.75 + \log(Na/K))] - 273.15$	Na = 562 K = 17.9	155.0
Na-K-Ca (Fournier and Truesdell, 1973)		
$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$	Na = 562 K = 17.9 Ca = 24.7	141.8
Na-K-Ca-Mg (Fournier and Potter, 1979)		
$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$ - Δt _{Mg}	Na = 562 K = 17.9 Ca = 24.7	86.4
K ² /Mg (Giggenbach, 1988)		
$T(^{\circ}C) = [4410/(14.0 + \log(K^2/Mg))] - 273.15$	K = 17.9 Mg = 10.1	79.7

Table C.3. Geothermometer calculations for KB-52.

Sample	KB-52	
Chalcedony (Fournier, 1977)	Variables (in mg/l)	Result (Temperature °C)
$T(^{\circ}C) = \frac{1032}{4.69 - \log(SiO_2)} - 273.15$	SiO ₂ = 71.6	90.9
Quartz (Fournier, 1977)		
$T(^{\circ}C) = \frac{1309}{5.19 - \log(SiO_2)} - 273.15$	SiO ₂ = 71.6	119.3
Na/K (Fournier, 1979)		
$T(^{\circ}C) = \frac{1217}{\log\left(\frac{Na}{K}\right) + 1.483} - 273.15$	Na = 363 K = 9.38	123.2
Na/K (Giggenbach, 1988)		
$T(^{\circ}C) = [1390/(1.75 + \log(Na/K))] - 273.15$	Na = 363 K = 9.38	143.3
Na-K-Ca (Fournier and Truesdell, 1973)		
$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$	Na = 363 K = 9.38 Ca = 15.4	129.6
Na-K-Ca-Mg (Fournier and Potter, 1979)		
$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$ - Δt _{Mg}	Na = 363 K = 9.38 Ca = 15.4	90.1
K ² /Mg (Giggenbach, 1988)		
$T(^{\circ}C) = [4410/(14.0 + \log(K^2/Mg))] - 273.15$	K = 9.38 Mg = 5.43	71.6

Table C.4. Geothermometer calculations for KB-63.

Sample	KB-63	
Chalcedony (Fournier, 1977)	Variables (in mg/l)	Result (Temperature °C)
$T(^{\circ}C) = \frac{1032}{4.69 - \log(SiO_2)} - 273.15$	SiO ₂ = 76.7	94.7
Quartz (Fournier, 1977)		
$T(^{\circ}C) = \frac{1309}{5.19 - \log(SiO_2)} - 273.15$	SiO ₂ = 76.7	122.9
Na/K (Fournier, 1979)		
$T(^{\circ}C) = \frac{1217}{\log\left(\frac{Na}{K}\right) + 1.483} - 273.15$	Na = 541 K = 13.2	120.0
Na/K (Giggenbach, 1988)		
$T(^{\circ}C) = [1390/(1.75 + \log(Na/K))] - 273.15$	Na = 541 K = 13.2	140.2
Na-K-Ca (Fournier and Truesdell, 1973)		
$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$	Na = 541 K = 13.2 Ca = 23.8	129.8
Na-K-Ca-Mg (Fournier and Potter, 1979)		
$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$ - Δt _{Mg}	Na = 541 K = 13.2 Ca = 23.8	82.9
K ² /Mg (Giggenbach, 1988)		
$T(^{\circ}C) = [4410/(14.0 + \log(K^2/Mg))] - 273.15$	K = 13.2 Mg = 9.33	73.3

Table C.5. Geothermometer calculations for MH-5,726 (USUAL).

Sample	MH-5,726 (USUAL)	
Chalcedony (Fournier, 1977)	Variables (in mg/l)	Result (Temperature °C)
$T(^{\circ}C) = \frac{1032}{4.69 - \log(SiO_2)} - 273.15$	SiO ₂ = 196	157.3
Quartz (Fournier, 1977)		
$T(^{\circ}C) = \frac{1309}{5.19 - \log(SiO_2)} - 273.15$	SiO ₂ = 196	178.6
Na/K (Fournier, 1979)		
$T(^{\circ}C) = \frac{1217}{\log\left(\frac{Na}{K}\right) + 1.483} - 273.15$	Na = 288 K = 9.02	134.3
Na/K (Giggenbach, 1988)		
$T(^{\circ}C) = [1390/(1.75 + \log(Na/K))] - 273.15$	Na = 288 K = 9.02	154.0
Na-K-Ca (Fournier and Truesdell, 1973)		
$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$	Na = 288 K = 9.02 Ca = 8.71	138.8
Na-K-Ca-Mg (Fournier and Potter, 1979)		
$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$ - Δt _{Mg}	Na = 288 K = 9.02 Ca = 8.71	132.5
K ² /Mg (Giggenbach, 1988)		
$T(^{\circ}C) = [4410/(14.0 + \log(K^2/Mg))] - 273.15$	K = 9.02 Mg = 0.16	117.3

Table C.6. Geothermometer calculations for MH-5,726 (ThermoChem).

Sample	MH-5,726 (ThermoChem)		
Chalcedony (Fournier, 1977)	Variables (in mg/l)	Result (Temperature °C)	
$T(^{\circ}C) = \frac{1032}{4.69 - \log(SiO_2)} - 273.15$	SiO ₂ = 216	111.0	
Quartz (Fournier, 1977)			
$T(^{\circ}C) = \frac{1309}{5.19 - \log(SiO_2)} - 273.15$	SiO ₂ = 216	137.8	
Na/K (Fournier, 1979)			
$T(^{\circ}C) = \frac{1217}{\log\left(\frac{Na}{K}\right) + 1.483} - 273.15$	Na = 313 K = 9.11	130.0	
Na/K (Giggenbach, 1988)			
$T(^{\circ}C) = [1390/(1.75 + \log(Na/K))] - 273.15$	Na = 313 K = 9.11	150.0	
Na-K-Ca (Fournier and Truesdell, 1973)			
$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$	Na = 313 K = 9.11 Ca = 9.64	136.0	
Na-K-Ca-Mg (Fournier and Potter, 1979)			
$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$ - Δt _{Mg}	Na = 313 K = 9.11 Ca = 9.64	136.0	
K ² /Mg (Giggenbach, 1988)			
$T(^{\circ}C) = [4410/(14.0 + \log(K^2/Mg))] - 273.15$	K = 9.02 Mg = 0.02	154.0	

Table C.7. Geothermometer calculations for MH-5,726 (UVDL).

Sample		MH-5,726 (UVDL)	
Chalcedony (Fournier, 1977)	Variables (in mg/l)	Result (Temperature °C)	
$T(^{\circ}C) = \frac{1032}{4.69 - \log(SiO_2)} - 273.15$	SiO ₂ = 101	69.0	
Quartz (Fournier, 1977)			
$T(^{\circ}C) = \frac{1309}{5.19 - \log(SiO_2)} - 273.15$	SiO ₂ = 101	100.0	
Na/K (Fournier, 1979)			
$T(^{\circ}C) = \frac{1217}{\log\left(\frac{Na}{K}\right) + 1.483} - 273.15$	Na = 314 K = 9.25	131.0	
Na/K (Giggenbach, 1988)			
$T(^{\circ}C) = [1390/(1.75 + \log(Na/K))] - 273.15$	Na = 314 K = 9.25	151.0	
Na-K-Ca (Fournier and Truesdell, 1973)			
$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$	Na = 314 K = 9.25 Ca = 11.15	136.0	
Na-K-Ca-Mg (Fournier and Potter, 1979)			
$T(^{\circ}C) = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta \left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06 \right] + 2.47} - 273.15$ - Δt _{Mg}	Na = 314 K = 9.25 Ca = 11.15	135.0	
K ² /Mg (Giggenbach, 1988)			
$T(^{\circ}C) = [4410/(14.0 + \log(K^2/Mg))] - 273.15$	K = 9.25 Mg = 0.07	133.0	

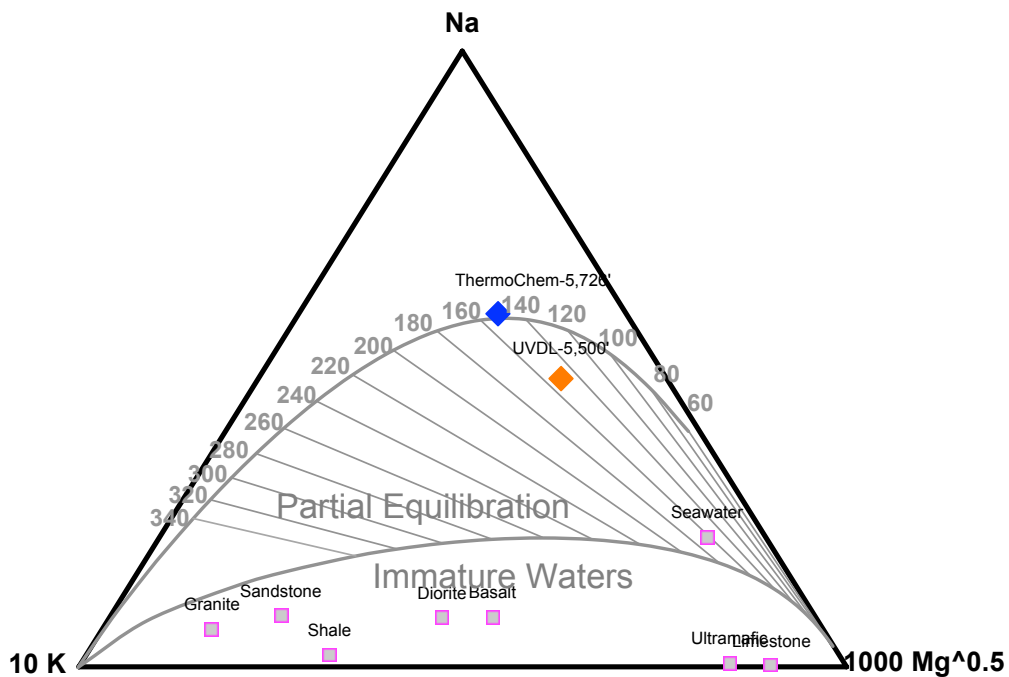


Figure C.1. Giggenbach diagram for MH-5,726 (ThermoChem and UVDL) (Giggenbach, 1988).

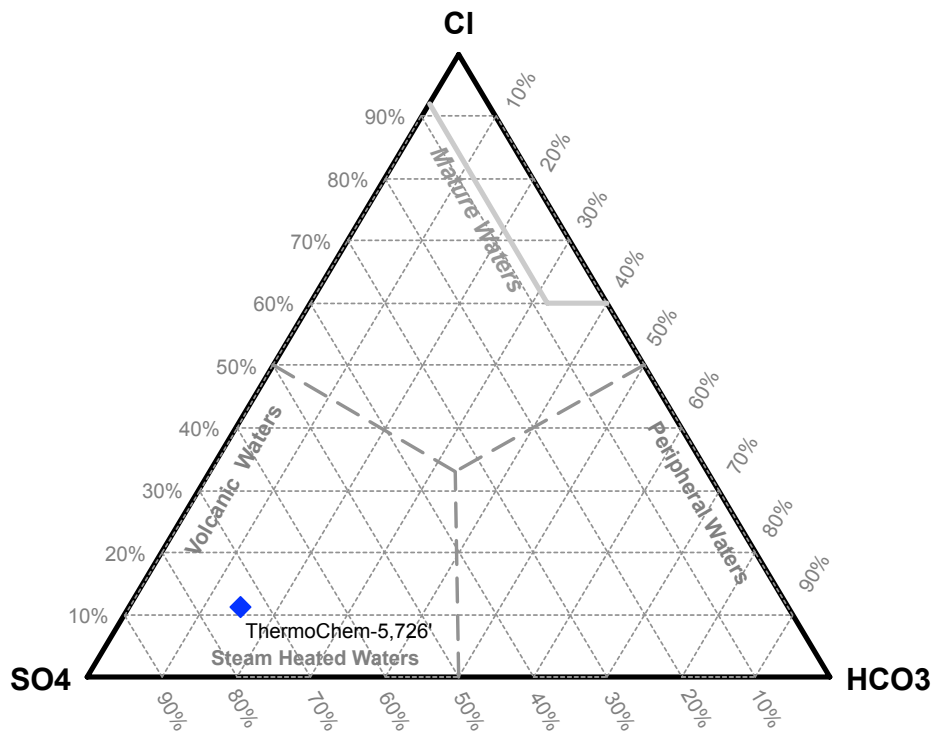


Figure C.2. MH-5,726 (ThermoChem) plotted on Cl, SO₄, and HCO₃ triangular plot (Giggenbach, 1988).