HYDROGEOCHEMISTRY, GEOTHERMOMETRY, AND STRUCTURAL SETTING OF THERMAL SPRINGS IN NORTHERN UTAH AND SOUTHEASTERN IDAHO

by Brennan Young, Katherine Shervais, Moises Ponce-Zepeda, Sari Rosove, and James Evans

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Cover photo: *Crystal Hot Springs, Box Elder County, Utah. Photo courtesy of Crystal Hot Springs.*

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HYDROGEOCHEMISTRY, GEOTHERMOMETRY, AND STRUCTURAL SETTING OF THERMAL SPRINGS IN NORTHERN UTAH AND SOUTHEASTERN IDAHO

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EXECUTIVE SUMMARY

Thermal springs in northern Utah and southeastern Idaho mostly lie near active or inactive Basin and Range normal faults. They are dynamic systems, and the character of some has changed drastically since work as early as the 1980's (Blackett and Wakefield, 2002; IDWR, 2001). We examined and sampled 60 thermal springs and most samples met criteria for cation geothermometers, or mathematical-geochemical tools used to estimate the maximum temperature of hydrothermal reservoirs. Of the 60 springs, 51 met criteria for the Na-K-Ca geothermometer and the remaining nine springs did not meet the criteria for the K-Mg, Na-K, Na-K-Ca, or Na-K-Ca-Mg cation geothermometers used in this project (Fournier and Truesdell, 1973; Fournier and Potter, 1979; Giggenbach, 1988). Of those 51 springs, only one is considered to be in partial equilibrium with the thermal reservoir, and estimates a reservoir temperature of 79°C (Giggenbach, 1988). Though the majority of springs exhibit a chemical signature of having mixed with shallow groundwater (Giggenbach, 1988), the Na-K-Ca geothermometer gives the most reliable results for springs in northern Utah and southeastern Idaho, but only for springs with surface temperatures exceeding 30°C and with greater than 1000 ppm total dissolved solids (TDS). Geothermometer results for these springs yield reservoir temperature estimates between 193 and 249°C.

INTRODUCTION

The purpose of this work is to update geothermal resource databases compiled by workers in the Utah Geological Survey (Blackett and Wakefield, 2002) and the Idaho Department of Water Resources (IDWR, 2001) for hot springs in northern Utah and southeastern Idaho. This project verifies the existence and locations of hot springs, provides chemical composition data, performs geothermetic analyses on spring waters, and places the springs into a basic structural context.

The study area occupies the northeastern corner of the Basin and Range Province and extends from central Box Elder County, UT, to the East Bear Lake Fault in Bear Lake County, ID (figure 1). Four undergraduate students from Utah State University, University of British Columbia, Wesleyan University, and East Los Angeles Community College (some funded through the Southern California Earthquake Center's [SCEC] Summer Undergraduate Research Experience [SURE] program) visited springs in the existing database that were within 1.5 miles of a known fault. Initially, we intended to survey 27 springs, but in the course of three months of field work we found 60 springs total.

REGIONAL GEOLOGY

The region consists of an eastward thinning wedge of Neoproterozoic, Paleozoic, and Mesozoic strata, including marine and continental deposits, deposited on Archean and Proterozoic basement (Camilleri and others, 1997; Stokes, 1986). This wedge was deformed by east-northeast-verging folds and thrust faults within the Sevier orogenic belt from the Jurassic to early Tertiary, with thrust sheets, like the Willard thrust sheet, moving as much as 50 km eastward (figure 2; Camilleri and others, 1997). This was followed by at least two episodes of extension that began as early as 21 Ma, the first characterized by low-angle normal faults and the second by regularly-spaced, north-south-trending, steeply-dipping, planar and listric normal faults typical of today's active Basin and Range Province (figure 2; Evans and Oaks, 1996; Janecke and others, 2003; Stokes, 1986). Granitic intrusions began to form in western Utah during the Jurassic, and additional intrusions formed during the Quaternary, with the most recent volcanic activity in western Utah occurring during the Holocene (Stokes, 1986).

Most geothermal systems in the Basin and Range Province derive their heat from the deep circulation of groundwater, rather than cooling of igneous bodies (Wisian and Blackwell, 2004). The systems tend to be convective, with

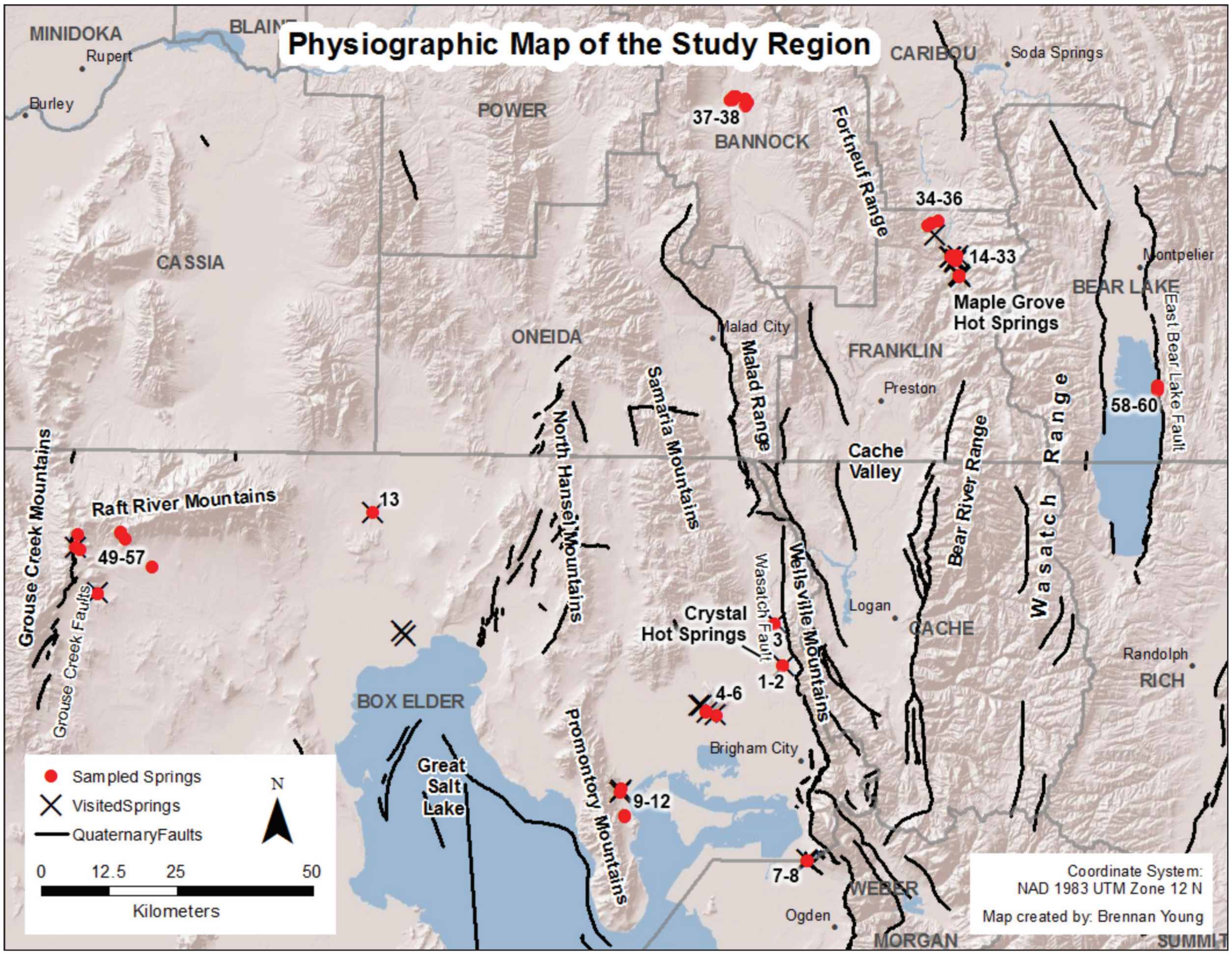

Figure 1. *Physiographic map of study region, with faults, important mountain ranges, and visited and sampled springs indicated. Numbers near springs represent spring feature identification. Not all springs could be measured because they did not exist or no source could be found. Twenty-seven springs were initially planned to be visited and 60 were measured. Political boundaries and county seats provided by the Utah SGID (http://gis.utah.gov/) and IDWR (http://www.idwr.idaho.gov/GeographicInfo/GISdata/gis_data.htm).*

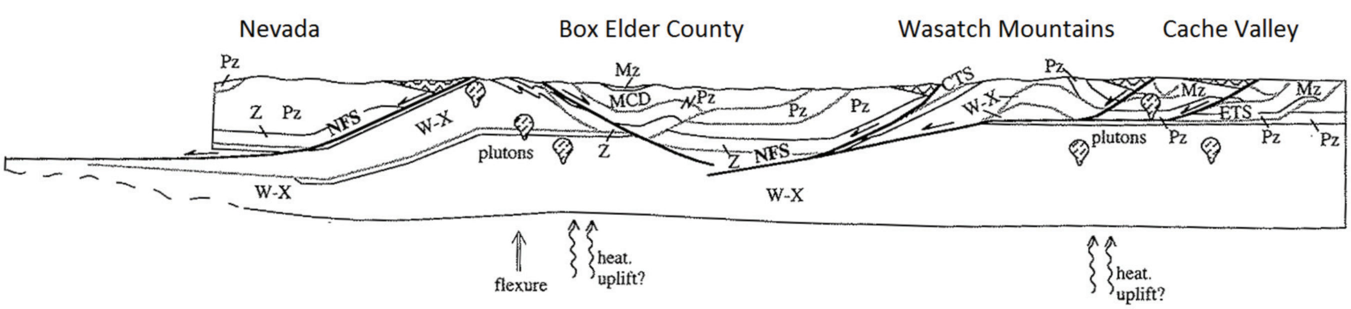

Figure 2. *Simplified late Eocene-Oligocene tectonic model for the Sevier orogenic wedge (modified from Camilleri and others, 1997). W-X = Archean to Lower Proterozoic basement rocks; Z = Neoproterozoic sedimentary and metasedimentary rocks; Pz = Paleozoic sedimentary and metasedimentary rocks; Mz = Mesozoic sedimentary rocks and synorogenic deposits; and Cz = post-thrust Cenozoic deposits. MCD = Manning Canyon decollement; CTS = central thrust system; and ETS = eastern thrust system. NSF = normal fault system.*

groundwater descending, remaining at the bottom of the system for some length of time, and then rising rapidly enough to retain some of the reservoir temperature and chemical properties through permeable fracture and fault systems (McKenna and Blackwell, 2004; Wisian and Blackwell, 2004).

METHODS

Springs were located using the geothermal resource databases compiled by the Utah Geological Survey (UGS) and the Idaho Department of Water Resouces (IDWR) (Blackett and Wakefield, 2002; IDWR, 2001) using GISRoam for the iPad2, developed by Cogent3D, and updated digitally in the field using GISRoam. The data was later reduced using Microsoft Excel and Esri ArcGIS 10 software.

Water samples were collected in plastic tubes using standard sampling techniques. Temperature, pH, electrical conductivity, and total dissolved solids were measured directly in the field using a three-foot temperature probe and the Omega products PHH-5012, CDH-5021, and TDH-5031, respectively. The samples were sealed and refrigerated until they could be delivered to the Utah State University Analytical Laboratories (USUAL) within 48 hours of collection. USUAL analyzed water samples for salinity, chloride, and concentrations of Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Se, Si, Sr, and Zn. Ion balance could not be determined because the analysis performed by USUAL did not determine the concentrations of anions, and only determined the amount of the elemental components (H, S, etc.) of ions in the water.

GEOTHERMOMETRY

Geothermometers are mathematical-geochemical tools that estimate the maximum reservoir (equilibrium) temperatures of geothermally-heated waters. Geothermometers are often used in the exploration of geothermal resources. Cation geothermometers take advantage of specific mineral-solute reactions and assume that heated waters rise rapidly through the subsurface and are slow to re-equilibrate at cooler temperatures, virtually locking in the chemical signature of hot waters, and that there is negligible mixing with shallow groundwater (Karingithi, 2009).

The study area (figure 1) hosts a number of mapped faults that exhibit normal offset during the Quaternary. Though most visited hot springs are not spatially associated with these mapped Quaternary faults, most springs do occur on or near mountain fronts and older faults, suggesting buried Basin and Range faults may serve as highly permeable conduits for rapid fluid flow from geothermal reservoirs to the surface. This rapid flow would permit spring water to remain somewhat in equilibrium with reservoir water, thereby allowing the use of certain appropriate geothermometers.

The cation geothermometers used to estimate maximum reservoir temperature were compiled by Karingithi (2009). Geothermometers used in this study include: K-Mg (Giggenbach, 1988), Na-K (Fournier and Potter, 1979; Giggenbach, 1988), Na-K-Ca (Fournier and Truesdell, 1973), and the Mg correction for the Na-K-Ca geothermometer (Fournier and Potter, 1979), referred to in this work as the Na-K-Ca-Mg geothermometer. These geothermometers are reproduced in Appendix C. Inconsistencies can exist because of the assumption that water-mineral reactions occur with end-member minerals, which is rarely the case in natural systems, and sometimes the presence of specific minerals (Fournier, 1989). Under ideal conditions, cation geothermometers have an error of ± 5-10˚C, and commonly have an error greater than 20°C (Fournier, 1989).

The K-Mg geothermometer is based on relationships that adjust rapidly and attain equilibrium values at low temperatures, so it is unsuitable for waters that yield equilibrium temperatures less than 100˚C (Giggenbach, 1988; Karingithi, 2009).

The Na-K geothermometer gives poor results, tending to overestimate reservoir temperature below 100˚C and is unsuitable for waters that contain high concentrations of Ca (Fournier and Potter, 1979; Giggenbach, 1988; Karingithi, 2009). This geothermometer should only be used if waters indicate reservoir temperatures greater than 100˚C, contain low Ca (the value of $\log 10(\sqrt{Ca}/Na) + 2.06$ is negative), and are near-neutral pH chloride waters (Karingithi, 2009).

The Na-K-Ca geothermometer is a more robust geothermometer developed for application to waters with high concentrations of Ca, and gives less erroneous results than the Na-K geothermometer for low-temperature geothermal waters (Fournier and Truesdell, 1973; Karingithi, 2009). This geothermometer should only be used if $\log 10 (\sqrt{Ca}/Na) + 2.06$ is positive (Karingithi, 2009).

The Mg correction to the Na-K-Ca geothermometer (the Na-K-Ca-Mg geothermometer) is used to correct for solutions that contain high dissolved Mg, because they are saline, or because the reservoir temperature is greater than 180˚C (Fournier and Potter, 1979; Karingithi, 2009). The correction is not applied if the Na-K-Ca temperature is less than 70˚C, if 100 x Mg / (Mg + Ca + K) is greater than 50, or if the correction is negative (Karingithi, 2009).

The Na-K-Ca-Mg geothermometer is the preferred geothermometer because it isn't as strongly influenced by high Ca content, isn't as likely to overestimate equilibrium temperatures of low-temperature reservoirs like the Na-K geothermometer is liable to do, and corrects for the influence of high magnesium concentrations that make the Na-K-Ca geothermometer less reliable. Geothermometers were used preferentially in the following order (if one was invalid, the next was used): Na-K-Ca-Mg, Na-K-Ca, Na-K, K-Mg. If the K-Mg did not fit conditions properly, then no geothermometer was used.

As additional criteria to determine geothermometer validity, Giggenbach (1988) proposed a ternary diagram to graphically determine the maturity of geothermally-heated waters (figure 3). If waters do not plot in the "fully" or "partly equilibrated" area, they are not in equilibrium with the geothermal reservoir and hence are not good indicators of reservoir conditions. Fournier (1989) cautioned when using this method to determine geothermometer validity, as low salinity or high acidity in the water could cause the system to become depleted in sodium and potassium because of the weathering of feldspars, and inundated with magnesium because of rapid interactions between wall rock and relatively cold, non-saline water. For this reason, springs were categorized as "Non-Saline" (TDS < 1000 ppm), "Slightly Saline" (TDS 1000-3000 ppm), and "Saline" (TDS > 3000 ppm).

RESULTS

Twenty-seven springs were visited based on locations from prior databases (Blackett and Wakefield, 2002; IDWR, 2001), plus an additional 33 springs not previously listed. Some springs reported in the previous database did not exist, no source of water could be found, or springs were unreachable (figure 1). In some locations, several springs were found where only one was expected, and some were dried up. One landowner claimed that his hot spring dried up after the 1959 Hebgen Lake earthquake and then became active again after the 1975 Malad earthquake. Some hot springs are adjacent to cold springs, such as the Crystal Hot Springs resort that has both a hot and a cold spring within 10 meters of each other. A few springs, such as those at Maple Grove Hot Springs, also exhibit mineralization of travertine. Many springs were on or near (within 10 km) Quaternary faults. Those that were not were within the same distance of mountain fronts and geologic contacts between Quaternary units and Mesozoic or older units (figure 1, figure 4).

Fifty-one of the 60 springs met criteria for geothermometers to estimate maximum reservoir temperature given by Karingithi (2009). All 51 of those springs met criteria for the Na-K-Ca geothermometer. Only two springs, sample 7 and sample 10, were deemed "mature" by plotting them on Giggenbach's ternary diagram (figure 3; Giggenbach, 1988), one of which, 7, did not meet criteria for any of the geothermometers used in this study. Almost every spring had a very high √Mg value compared to Na/1000 and K/100, had low salinity (TDS < 1000 ppm), and/or was acidic, indicating that these springs were strongly influenced by shallow groundwater (figure 5). Geothermometry was calculated for these springs despite having failed the ternary diagram criteria for mature waters, though they may not reflect reservoir conditions.

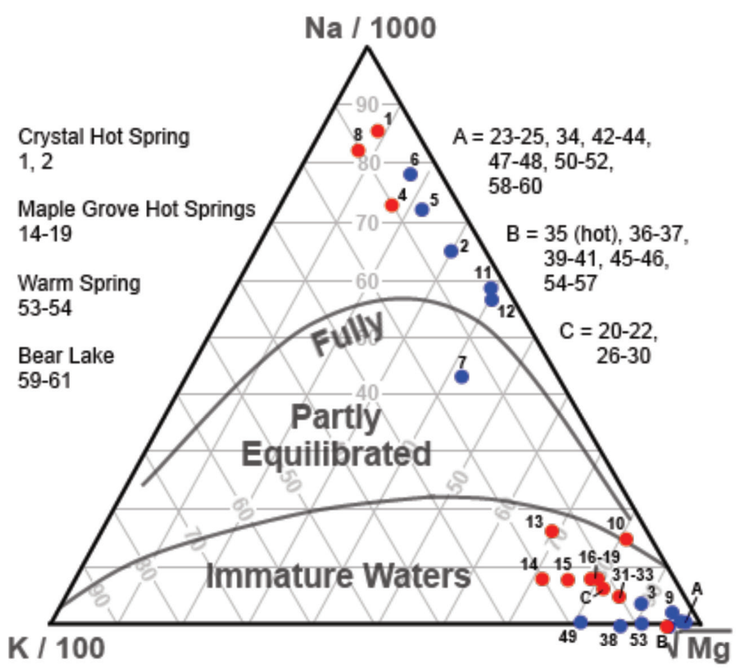

Figure 3. *Ternary diagram for evaluating Na/K and K/Mg*$^{-½}$ *temperatures in geothermal waters (modified from Giggenbach, 1988). Spring samples from this project are plotted with their feature identification numbers. Red represents hot springs (> 30°C) and blue represents cold springs (≤ 30°C).*

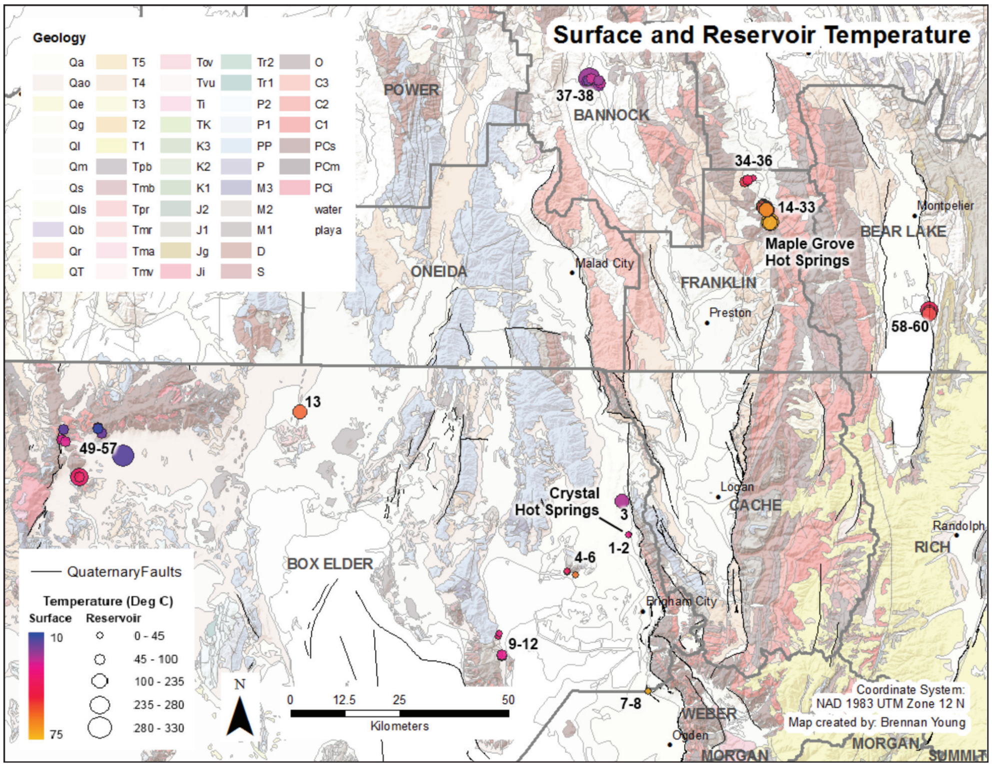

Figure 4. *Locations of hot springs with symbols reflecting surface temperature (color) and estimated reservoir temperature from the Na-K-Ca geothermometer (size) for springs that were measured. Numbers near springs represent spring feature identification. Geology and Quaternary fault data provided by USGS (Ludington and others, 2005). Political boundaries and county seats provided by the Utah SGID (http://gis.utah.gov/) and IDWR (http://www.idwr.idaho.gov/GeographicInfo/GISdata/gis_data.htm).*

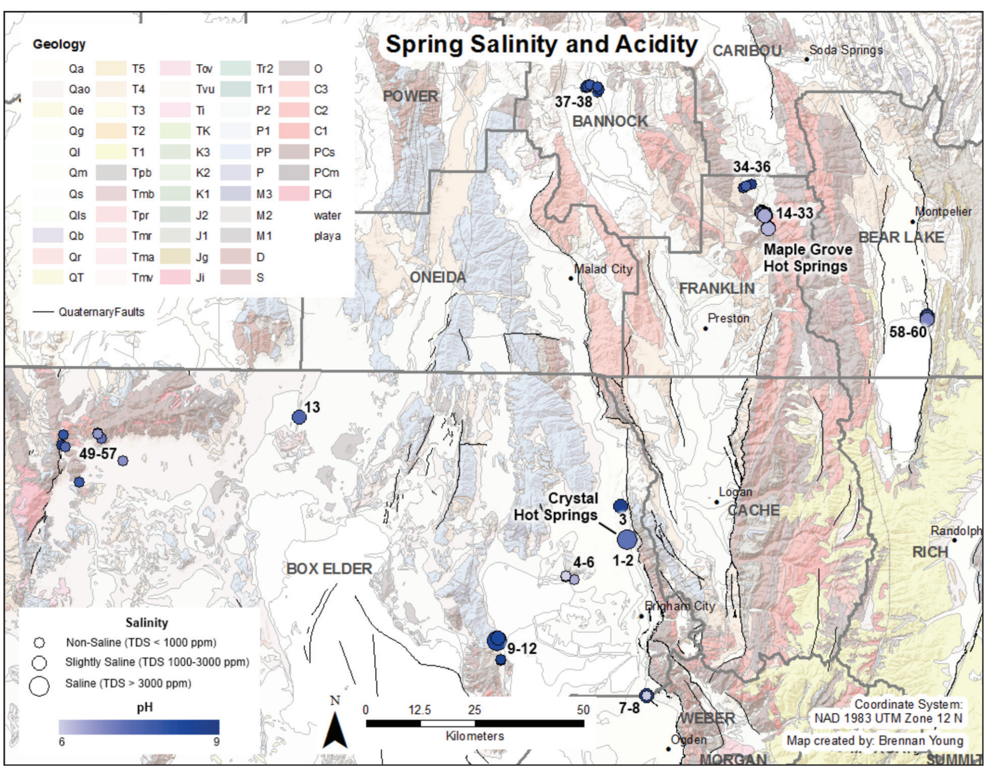

Figure 5. *Locations of hot springs with symbols reflecting spring salinity and acidity. Numbers near springs represent spring feature identification. Geology and Quaternary fault data provided by USGS (Ludington and others, 2005). Political boundaries and county seats provided by the Utah SGID (http://gis.utah.gov/) and IDWR (http://www.idwr.idaho.gov/GeographicInfo/GISdata/gis_data.htm).*

Sample 10, which plots in the "partly equilibrated" area of Giggenbach's ternary diagram (figure 3), had a surface temperature of only 18.3°C, is non-saline (TDS 470 ppm), is slightly basic (pH 7.6), and yields a reservoir temperature of 79°C.

Of the 51 springs for which geothermometery was calculated, 29 are cold springs, with surface temperatures less than or equal to 30˚C, 22 are hot springs, with surface temperatures greater than 30˚C, 29 are non-saline, with TDS less than 1000 ppm, and 22 are slightly saline, with TDS between 1000 and 3000 ppm (table 1). Hot and slightly saline waters tended to yield higher reservoir temperatures, generally 200–250˚C (table 1, figure 6). Cold and non-saline waters tended to yield colder reservoir temperatures, generally 50–100˚C, but with a very wide range of results (table 1, figure 6). Acidic and warm springs exhibited less scatter or variability in geothermometer results than basic and cold springs (figure 6). The results of other geothermometers, though invalid or unused, are presented in table 2.

DISCUSSION

It is likely that these springs are associated with Basin and Range-style normal faulting and that these springs sit on or near both buried and exposed faults that separate structural horsts and grabens. Some springs have dried up since the databases were originally made, and the number of additional springs at sites where only one spring was expected is surprising. In the past 50 or so years, these springs have exhibited a large amount of variability, drying out, springing anew, and changing temperature. Hot spring systems can be discrete, as exemplified by Crystal Hot Springs, where a hot spring and a cold spring exist within 10 m of one another. Perhaps the reason for both of these phenomena is because these are fault-related systems. As a fault slips or creeps, conduits of flow may change dramatically, especially during seismic events. Another possibility, not exclusive to the other, is that as waters flow upward, the change in local temperature and pressure permits mineralization, which would also influence the shape, size, and continuity of flow conduits.

While 51 springs were validated by at least one geothermometer, only two were deemed to be mature, or in equilibrium with their geothermal reservoir, by the graphical Giggenbach ternary diagram method (figure 3), most having been acidic, non-saline, and/or inundated with magnesium, indicating mixture with shallow groundwater (Giggenbach, 1988).

The scatter and low reservoir temperature estimates in cold, non-saline springs (surface temperatures less than or equal to 30˚C and TDS less than or equal to 1000 ppm) could be because these springs are primarily groundwater discharge that did not circulate into a geothermal system before rising to the surface. However, their reservoirs could also have merely been more removed from the source of heat or the waters had risen more slowly to the surface than warm springs, mixing with shallower waters and losing their equilibrium with the geothermal reservoir. Whether or not these cold, non-saline springs came from a geothermal reservoir at all cannot be answered within the scope of this project, and thus their geothermometer results cannot be considered reliable.

The Na-K-Ca-Mg geothermometer often gave negative correction values, to the degree of resulting in impossi-

Table 1. *Surface temperature and salinity of springs compared to estimated reservoir temperature using geothermometry calculations for the Na-K-Ca geothermometer. "Cold" springs have surface temperatures below or equal to 30˚C and "Hot" springs above 30˚C; "Non-Saline" springs have total dissolved solids less than or equal to 1000 ppm, and "Slightly Saline" springs between 1000 and 3000 ppm.*

Spring Type	Count	Min (°C)	Max (°C)	Range (°C)	Mean (°C)
Cold and Non-Saline	27	33	327	294	92
Cold and Slightly Saline	2	213	257	44	235
Hot and Non-Saline	2	72	79	6	76
Hot and Slightly Saline	20	193	249	55	220
Overall	51	33	327	294	147

Table 2. *Geothermometer results (reservoir temperature in ˚C) for the 51 of 60 springs sampled that met criteria for any of the geothermometers used in this study, whether or not the geothermometers presented were valid.*

Geothermometer	Source	Min	Max	Range	Mean
K-Mg	Giggenbach, 1988	39	42	3	40
Na-K	Fournier and Potter, 1979	65	765	700	336
Na-K	Giggenbach, 1988	86	693	607	338
Na-K-Ca	Fournier and Truesdell, 1973	33	327	294	147
Na-K-Ca-Mg	Fournier and Potter, 1979	-479	327	806	126

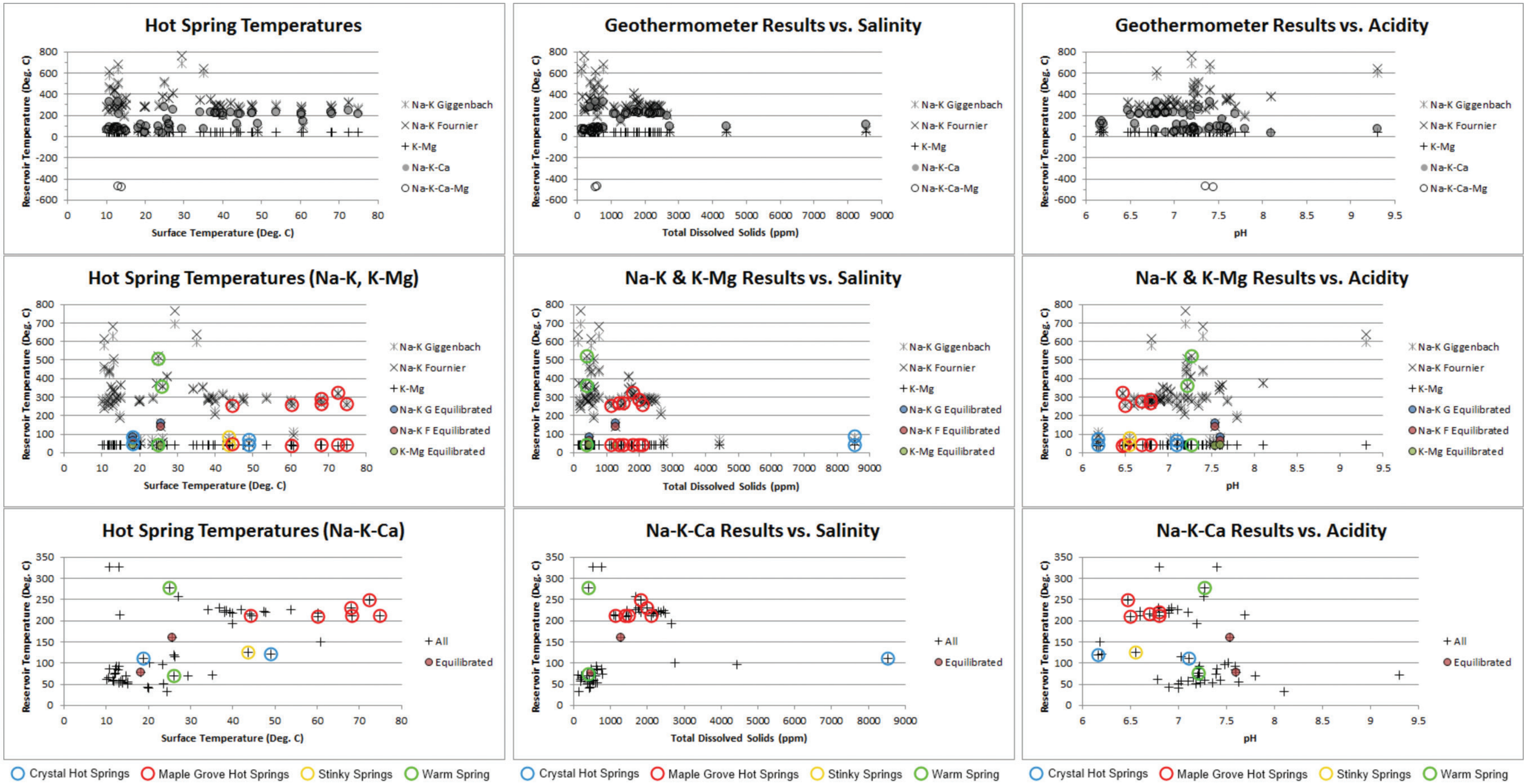

Figure 6. *Plots of geothermometer-calculated temperature against surface measurements of temperature, salinity, and acidity.*

bly cold reservoirs. The Na-K geothermometers grossly overestimated many reservoir temperatures, giving results only possible within the Earth's mantle. The K-Mg geothermometer yielded cold results, perhaps reasonable for some springs, but some even colder than the measured surface temperature. The Na-K-Ca geothermometer seems to be the most reliable geothermometer for warm springs at sites studied in northern Utah and southern Idaho, but only for springs warmer than 30°C at the surface and that have at least 1000 ppm total dissolved solids. Even so, these results are dubious at best, as most of these springs carry a chemical signature that suggests mixing with shallow groundwater and hence are not representative of conditions at depth (figure 3; Giggenbach, 1988).

CONCLUSIONS AND DELIVERABLES

The database of springs visited during this project accompanies this report as a Microsoft Excel file and is titled "GeothermalUSU.xlsx." There are four spreadsheets in this file: "Samples," "Metadata_Samples," "VisitedSprings," and "Metadata_VisitedSprings." "Samples" is the database generated over the course of this project and "VisitedSprings" are springs from the original databases that were visited. The Metadata spreadsheets describe the meaning of each of the attributes, and "Metadata_Samples" is reproduced in Appendix A. An ArcGIS shapefile titled "GeothermalUSU" and a Google Earth shapefile titled "GeothermalUSU.kmz," which were created from the "Samples" spreadsheet in "GeothermalUSU.xlsx" also accompany this report.

Hot springs seem to be associated with Basin and Range extension, but not necessarily with mapped Quaternary faults, and are concentrated at or near horst-graben boundaries. Hot springs are also dynamic systems that can change significantly over time, drying up to make old springs vanish or upwelling to create new springs. Closely spaced springs cannot always be expected to be similar, as is the case with Crystal Hot Springs, with a hot spring adjacent to a cold spring.

Only two of the 60 sampled springs were considered mature using the Giggenbach ternary diagram method (figure 3). The Na-K-Ca-Mg geothermometer was not valid for any of the springs, and the K-Mg and Na-K geothermometers yielded obviously erroneous results. The Na-K-Ca geothermometer yielded the most consistent, trustworthy results of the cation geothermometers used in this study, but only for springs with surface temperatures greater than 30°C and containing at least 1000 ppm total dissolved solids. Hot, slightly saline (surface temperature greater than 30°C and TDS 1000-3000 ppm) springs yielded reservoir temperature estimates between 193 and 249°C. However, most of these springs seem to have mixed with shallow groundwater, making them unfit for the Na-K-Ca geothermometer. The one spring that both met criteria for the Na-K-Ca geothermometer and is partly equilibrated with the reservoir at depth yields a temperature estimate of 79°C.

FUTURE WORK

Water maturation for stable isotopes is dependent on the isotopic fractionation that occurs during exchange between groundwater and rock minerals and during evaporation and condensation of geothermal waters (Domenico and Schwartz, 1990; Karingithi, 2009). A high-temperature exchange of ^{18}O from reservoir rocks to reservoir water causes an enrichment in $\delta^{18}O$, or the $^{18}O/^{16}O$ ratio in the water as compared to a standard (figure 7; Domenico and Schwartz, 1990). This enrichment is proportional to the difference in original $\delta^{18}O$ between the water and rock, temperature, and the time of contact, and is inversely proportional to the water-rock ratio (Domenico and Schwartz, 1990). Similar relationships have been observed in hydrogen and carbon isotopes (Karingithi, 2009). As these interactions are temperature-dependent, they can and have been used as geothermometers.

Closer inspection of geologic maps near the springs will help confirm if springs are associated with faults, determine the typical type of fault with which springs are associated, and the ages of faults along which springs are likely to appear.

Small seismic and resistivity geophysical surveys could also help to gain a better understanding of hydrothermal flow along fault zones and help confirm association with faults.

More correspondence with local communities will also help locate additional hot springs, as will remotely analyzing thermal imagery, such as Band 8 from the ASTER satellite mission.

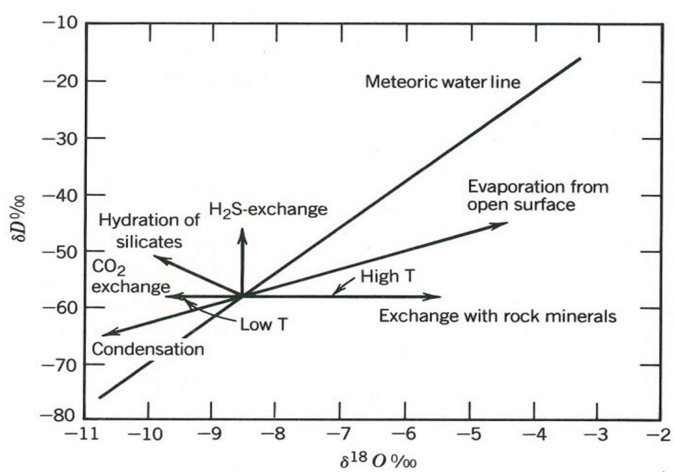

***Figure 7.** Deviations in isotopic composition away from the meteoric water line (from Domenico and Schwartz, 1990).*

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APPENDICES

Appendix A. Database Explanation

"Attribute" is the name of the attribute.

"Data Type" describes the type of data as a string of characters, integer, double (Real numbers), or calendar date.

"Source" describes the origin of the data. A blank field means that the data was collected by the authors of this report.

"Description" briefly describes the attribute and gives any units if applicable.

Elemental analysis performed by Utah State University Analytical Laboratories (USUAL) included Co, Mo, Pb, and Se, but these were all below detection limits, so are not included in this report.

Attribute	Data Type	Source	Description
FID	Integer		Feature identification number.
Collected	Date		Date on which sample was collected.
Received	Date	USUAL	Date on which sample was received by USUAL.
State	String		State in which spring was collected.
County	String		County in which spring was collected.
Longitude	Double		Longitude, taken with the GPS on the iPad2 using GISRoam.
Latitude	Double		Latitude, taken with the GPS on the iPad2 using GISRoam.
UTME	Double		UTM NAD 83 Zone 12N easting coordinate (m).
UTMN	Double		UTM NAD 83 Zone 12N northing coordinate (m).
TempC	Double		Spring surface temperature (degrees C).
pH	Double		pH.
EC	Double		Electrical conductivity (µS/cm).
TDS	Double		Total dissolved solids (ppm).
Salinity	Double	USUAL	Electrical conductivity (dS/cm).
Chloride	Double	USUAL	Chloride concentration (mg/L).
Al	Double	USUAL	Aluminum (mg/L). Detection limit of 0.12.
As	Double	USUAL	Arsenic (mg/L). Detection limit of 0.01.
B	Double	USUAL	Boron (mg/L). Detection limit of 0.02.
Ba	Double	USUAL	Barium (mg/L). Detection limit of 0.001.
Ca	Double	USUAL	Calcium (mg/L). Detection limit 0.08.
Cd	Double	USUAL	Cadmium (mg/L). Detection limit 0.001.
Cr	Double	USUAL	Chromium (mg/L). Detection limit 0.006.
Cu	Double	USUAL	Copper (mg/L). Detection limit of 0.008.
Fe	Double	USUAL	Iron (mg/L). Detection limit 0.003.
K	Double	USUAL	Potassium (mg/L). Detection limit 0.46.
Mg	Double	USUAL	Magnesium (mg/L). Detection limit 0.007.
Mn	Double	USUAL	Manganese (mg/L). Detection limit 0.001
Na	Double	USUAL	Sodium (mg/L). Detection limit 0.08.
Ni	Double	USUAL	Nickel (mg/L). Detection limit 0.003.
P	Double	USUAL	Phosphorus (mg/L). Detection limit 0.08.
S	Double	USUAL	Sulfur (mg/L). Detection limit 0.07.
Si	Double	USUAL	Silica (mg/L). Detection limit 0.15.
Sr	Double	USUAL	Sr (mg/L). Detection limit 0.03.
Zn	Double	USUAL	Zinc (mg/L). Detection limit 0.005.

Attribute	Data Type	Source	Description
logCaNa	Double		$\log_{10}[\sqrt{(Ca)}/Na] + 2.06$. Important in some geothermometer calculations and validations.
NaK_F	Double	Fournier and Potter, 1979	Na-K geothermometer (˚C). See Appendix C.
NaK_G	Double	Giggenbach, 1988	Na-K geothermometer (˚C). See Appendix C.
NaK_Valid	String	Karingithi, 2009	The Na-K geothermometer is valid if a) calculated temperatures are above 100 C, b) logCaNa is negative, and c) waters are near-neutral.
KMg	Double	Giggenbach, 1988	K-Mg geothermometer (˚C). See Appendix C.
Beta	Double	Fournier and Truesdell, 1973	Part of NaKCa calculation. See Appendix C.
NaKCa_1_3	Double	Fournier and Truesdell, 1973	Na-K-Ca geothermometer, where $\beta = 1/3$ (˚C). Use if $\sqrt{Mca/MNa} < 1$ or if the temperature produced with $\beta = 4/3$ is greater than 100 C.
NaKCa_4_3	Double	Fournier and Truesdell, 1973	Na-K-Ca geothermometer, where $\beta = 1/3$ (˚C). Use if $\sqrt{Mca/MNa} > 1$ and if the temperature produced with $\beta = 4/3$ is less than 100 C.
NaKCa	Double	Fournier and Truesdell, 1973	Na-K-Ca geothermometer (˚C) with the appropriate β value, as explained in the descriptions of NaKCa_1_3 and NaKCa_4_3.
NaKCa_Valid	String	Karingithi, 2009	The Na-K-Ca geothermometer is valid if -logNaCa is positive.
R	Double	Fournier and Potter, 1979	Part 1 to the Mg correction to the Na-K-Ca geothermometer. See Appendix C.
dT	Double	Fournier and Potter, 1979	Part 2 to the Mg correction to the Na-K-Ca geothermometer. See Appendix C.
NaKCaMg	Double	Fournier and Potter, 1979	The Mg correction to the Na-K-Ca geothermometer (˚C). NaKCa-dT.
NaKCaMg_Valid	String	Karingithi, 2009	The Mg correction to the Na-K-Ca geothermometer is valid if the temperature from the Na-K-Ca geothermometer is greater than 70 C and R < 50.
Best_Geothermometer	String		The most robust valid geothermometer for the spring.
Res_TempC	Double		Reservoir temperature, calculated from the best-fit geothermometer.
GT_grad	Double	SMU, 2010	Geothermal gradient (˚C / km).
Depth_km	Double		Estimated reservoir depth (km).
Notes	String		Additional notes and insights.

Appendix B. Database

Database Part 1: Date and Locations

FID	Collected	Received	State	County	Lat	Long	UTME	UTMN
1	6/17/2011	6/24/2011	UT	Box Elder	41.65976	-112.088	409440.2	4612572
2	6/17/2011	6/24/2011	UT	Box Elder	41.65987	-112.088	409436.6	4612584.1
3	6/17/2011	6/24/2011	UT	Box Elder	41.72912	-112.107	407968.4	4620292.2
4	6/17/2011	6/24/2011	UT	Box Elder	41.57629	-112.234	397152.3	4603467.8
5	6/17/2011	6/24/2011	UT	Box Elder	41.58198	-112.256	395266.9	4604127.4
6	6/17/2011	6/24/2011	UT	Box Elder	41.58352	-112.257	395198.2	4604298.7
7	6/18/2011	6/24/2011	UT	Box Elder	41.3376	-112.03	413819.3	4576746
8	6/18/2011	6/24/2011	UT	Box Elder	41.3369	-112.03	413843.5	4576667.9
9	6/18/2011	6/24/2011	UT	Box Elder	41.4068	-112.43	380468.3	4584903.4
10	6/18/2011	6/24/2011	UT	Box Elder	41.4075	-112.431	380435.3	4584981.7
11	6/18/2011	6/24/2011	UT	Box Elder	41.447	-112.442	379522.9	4589383.4
12	6/18/2011	6/24/2011	UT	Box Elder	41.4516	-112.441	379631.7	4589892.4
13	7/19/2011	7/20/2011	UT	Box Elder	41.90055	-113	334140	4640667.2
14	7/21/2011	7/22/2011	ID	Franklin	42.30806	-111.707	441707.4	4684221.6
15	7/21/2011	7/22/2011	ID	Franklin	42.30798	-111.707	441713.3	4684213.7
16	7/21/2011	7/22/2011	ID	Franklin	42.30805	-111.707	441708.1	4684220.6
17	7/21/2011	7/22/2011	ID	Franklin	42.30653	-111.706	441796.1	4684051.8
18	7/21/2011	7/22/2011	ID	Franklin	42.30584	-111.706	441781.6	4683974.8
19	7/21/2011	7/22/2011	ID	Franklin	42.30556	-111.706	441808.2	4683943.2
20	7/27/2011	8/1/2011	ID	Franklin	42.33165	-111.715	441095.2	4686847.2
21	7/27/2011	8/1/2011	ID	Franklin	42.33167	-111.715	441100.2	4686849.3
22	7/27/2011	8/1/2011	ID	Franklin	42.33205	-111.715	441102.6	4686891.1
23	7/27/2011	8/1/2011	ID	Franklin	42.34043	-111.713	441299.5	4687820.2
24	7/27/2011	8/1/2011	ID	Franklin	42.34051	-111.713	441303.1	4687828.7
25	7/27/2011	8/1/2011	ID	Franklin	42.34077	-111.714	441171.8	4687859.1
26	7/27/2011	8/1/2011	ID	Franklin	42.33922	-111.725	440290.7	4687694.2
27	7/27/2011	8/1/2011	ID	Franklin	42.33884	-111.724	440329.9	4687651.3
28	7/27/2011	8/1/2011	ID	Franklin	42.33823	-111.724	440319.7	4687583.7
29	7/27/2011	8/1/2011	ID	Franklin	42.33776	-111.725	440256.2	4687532.5
30	8/4/2011	8/5/2011	ID	Franklin	42.33682	-111.723	440467.8	4687426.4
31	8/4/2011	8/5/2011	ID	Franklin	42.33383	-111.717	440943.1	4687090.9
32	8/4/2011	8/5/2011	ID	Franklin	42.33386	-111.717	440901	4687095
33	8/4/2011	8/5/2011	ID	Franklin	42.33314	-111.717	440905	4687014
34	8/9/2011	8/25/2011	ID	Franklin	42.39694	-111.755	437895.5	4694120.9
35	8/9/2011	8/25/2011	ID	Franklin	42.39029	-111.776	436102.9	4693404.1
36	8/9/2011	8/25/2011	ID	Franklin	42.39355	-111.769	436689.8	4693676.4
37	9/17/2011	9/19/2011	ID	Bannock	42.59963	-112.215	400344.7	4717071
38	9/17/2011	9/19/2011	ID	Bannock	42.59961	-112.215	400343.8	4717069.3
39	9/17/2011	9/19/2011	ID	Bannock	42.59555	-112.219	400002.2	4716622.6
40	9/17/2011	9/19/2011	ID	Bannock	42.59347	-112.221	399795.2	4716394.8
41	9/17/2011	9/19/2011	ID	Bannock	42.59297	-112.221	399863.6	4716338
42	9/17/2011	9/19/2011	ID	Bannock	42.59382	-112.216	400255.4	4716426.7
43	9/17/2011	9/19/2011	ID	Bannock	42.59435	-112.216	400256.6	4716485.6
44	9/17/2011	9/19/2011	ID	Bannock	42.59812	-112.208	400865.2	4716895.9
45	9/17/2011	9/19/2011	ID	Bannock	42.58438	-112.187	402604.4	4715345.3

Database Part 1 (Continued): Date and Locations

FID	Collected	Received	State	County	Lat	Long	UTME	UTMN
46	9/17/2011	9/19/2011	ID	Bannock	42.58438	-112.187	402604.4	4715345.3
47	9/17/2011	9/19/2011	ID	Bannock	42.59015	-112.182	403051.5	4715979.9
48	9/17/2011	9/19/2011	ID	Bannock	42.59472	-112.188	402549.1	4716494.5
49	9/24/2011	9/27/2011	UT	Box Elder	41.80031	-113.483	293691.7	4630586
50	9/24/2011	9/27/2011	UT	Box Elder	41.84493	-113.545	288733.7	4635690.4
51	9/24/2011	9/27/2011	UT	Box Elder	41.85643	-113.555	287921.5	4636992.7
52	9/24/2011	9/27/2011	UT	Box Elder	41.85533	-113.556	287799.8	4636873.4
53	10/1/2011	10/3/2011	UT	Box Elder	41.75505	-113.604	283511.9	4625857.4
54	10/1/2011	10/3/2011	UT	Box Elder	41.7549	-113.604	283515	4625840.5
55	10/1/2011	10/3/2011	UT	Box Elder	41.82967	-113.655	279529.3	4634273.1
56	10/1/2011	10/3/2011	UT	Box Elder	41.85025	-113.651	279953.6	4636547.2
57	10/1/2011	10/3/2011	UT	Box Elder	41.82704	-113.644	280399.2	4633953.3
58	10/15/2011	10/17/2011	ID	Bear Lake	42.12624	-111.264	478215.9	4663826.7
59	10/15/2011	10/17/2011	ID	Bear Lake	42.12363	-111.264	478195	4663536.7
60	10/15/2011	10/17/2011	ID	Bear Lake	42.11964	-111.264	478138.4	4663093.9

Database Part 2: Basic Chemistry

FID	TempC	pH	EC	TDS	Salinity	Chloride
1	49	6.2			48.4	
2	18.8	7.11	10990	8540	7.72	
3	13.3	7.69	1230	1080	1.02	
4	43.7	6.55			40.4	
5	26.2	7.03			18.2	
6	26.1	6.16			34.2	
7	25.7	7.54	1970	1280	1.95	
8	60.8	6.18			33.6	
9	14.7	7.8	880	600	0.98	
10	18.3	7.6	700	470	0.75	
11	23.3	7.48	6910	4420	7.11	
12	20.3	7.52	6650	2740	6.96	
13	40	7.19	4210	2660		2020
14	72.5	6.47	1910	1820		733
15	68	6.79	3020	2000		695
16	74.9	6.74	3130	2100		728
17	44.5	6.6	2520	1140		797
18	68.2	6.8	2570	1500		731
19	60.3	6.5	2570	1420		603
20	47.7	6.8	2520	2150		644
21	60.2	6.9	3090	2160		629
22	53.7	6.9	3110	2140		648
23	20	7.0	670	430		29.9
24	19.8	6.9	660	450		35.8
25	23.5	7.0	520	380		44.3
26	44	6.7	3600	2240		616
27	38.4	6.9	3860	2430		842
28	38.1	6.8	3500	2360		759
29	40	6.9	3630	2480		650
30	38.1	6.8	3070	1450	3.86	827
31	42.1	6.9	2500	1770	2.37	493
32	39.4	7.1	2570	1820	2.75	676
33	47.4	6.6	3170	2300	3.36	616
34	24.4	8.1	130	150	0.29	8.55
35	35.1	9.3	160	120	0.14	6.53
36	29.4	7.2	290	200	0.34	8.23
37	12.1	7.4	850	760		61.8
38	13	7.4	850	760		97.6
39	10.7	7.21	500	480		36.4
40	13.1	7.22	650	610		52.2
41	12.1	7.21	600	520		31.1
42	13.4	7.03	480	510		40.0
43	12	7.39	860	780		125
44	13.9	7.23	710	630		42.3
45	12.5	7.59	700	610		55.5

Database Part 2 (Continued): Basic Chemistry

FID	TempC	pH	EC	TDS	Salinity	Chloride
46	12.9	7.59	800	640		65.5
47	13.9	7.44	600	540		37.1
48	13	7.35	640	590		34.6
49	10.7	6.8	660	530	0.76	173
50	11.8	7.1	230	190	0.24	22.9
51	10.5	7.15	200	220	0.31	37.4
52	10.1	6.78	170	190	0.23	23.2
53	25	7.27	390	390	0.42	64.2
54	26	7.22	400	350	0.37	51.7
55	15	7.63	430	370	0.43	42.9
56	11.5	7.27	530	420	0.54	81.5
57	15	7.18	420	380	0.44	57.2
58	27.2	7.26	2000	1680	1.96	86.3
59	34.1	6.99	2040	1680	1.98	70.9
60	36.8	6.93	2050	1740	2.05	76.7

Database Part 3a: Elemental Components

FID	Al	As	B	Ba	Ca	Cd	Cr	Cu	Fe	K	Mg
1		0.03	3.04	0.32	499					642	165
2		0.01	0.44	0.17	134					98.8	46.3
3			0.07	0.09	49.9					40.7	23.6
4		0.05	3.11	6.93	570					488	321
5		0.01	1.55	0.15	210					194	92.1
6		0.03	2.47	0.19	342				0.25	368	176
7			0.30	0.13	47.2					67.6	3.58
8			4.02	0.63	896					949	30.5
9			0.15	0.03	49.0					7.10	16.1
10			0.11	0.03	52.0					5.34	14.8
11			0.63	0.05	100					54.3	54.3
12			0.68	0.11	87.3					57.8	58.2
13		0.15	0.85	0.20	78.9	0.003			0.01	82.4	15.2
14		0.04	1.57	0.09	87.39	0.002			0.11	132	22.1
15		0.06	1.60	0.09	85.83	0.001		0.05	0.15	103	22.2
16		0.05	1.57	0.09	84.35	0.006			0.13	74.2	22.0
17		0.04	1.60	0.07	86.04	0.003			0.01	73.3	21.6
18		0.05	1.58	0.06	86.21				0.02	70.7	21.4
19		0.04	1.58	0.08	86.92	0.002			0.02	70.4	21.4
20		0.01	1.83	0.03	155				0.144	102	48.3
21		0.04	1.73	0.03	150				0.074	92.5	44.6
22		0.02	1.87	0.04	142				0.004	98.2	43.0
23			0.11	0.03	86.3				0.004	5.76	28.3
24			0.11	0.03	85.0				0.008	6.20	28.1
25			0.11	0.03	91.7					8.24	27.3
26			1.87	0.03	209				0.008	97.6	54.4
27			2.16	0.04	203				0.021	113	60.9
28			2.11	0.05	222				0.008	109	56.6
29			2.10	0.04	226				0.037	109	57.7
30			1.99	0.04	186				0.01	104	52.4
31			1.39	0.04	154					78.2	36.7
32			1.38	0.05	164				0.04	75.0	40.7
33		0.02	1.74	0.05	197					90.2	46.3
34			0.02	0.12	32.9		0.006		0.017	3.48	12.1
35	1.69		0.03	0.02	17.2				2.46	9.81	3.09
36	0.91	0.12	0.08	0.10	42.2				0.53	15.8	10.1
37			0.08	0.13	102				0.06	26.2	24.3
38	0.60		0.10	0.22	96.5				0.36	64.4	20.9
39			0.04	0.09	71.6					22.5	14.1
40			0.06	0.21	91.1				0.20	31.6	17.0
41			0.03	0.10	79.4					18.3	15.6
42			0.04	0.10	84.5				0.02	10.1	15.9
43	0.81		0.10	0.19	108				0.68	15.6	25.2
44			0.10	0.12	111				0.14	9.50	25.5
45			0.14	0.18	69.2					21.3	23.1

Database Part 3a (Continued): Elemental Components

FID	Al	As	B	Ba	Ca	Cd	Cr	Cu	Fe	K	Mg
46			0.14	0.26	80.4					19.1	23.3
47			0.08	0.13	52.4					7.87	39.9
48			0.09	0.08	60.7					6.46	38.3
49	0.45		0.04	0.08	45.1				0.31	67.1	9.88
50			0.04	0.03	16.0				0.02	3.75	4.19
51	2.10		0.04	0.03	18.7				0.98	4.81	4.95
52	0.02		0.02	0.01	16.0					4.42	4.51
53			0.03	0.06	35.4				0.01	23.7	7.66
54			0.03	0.06	35.5				0.02	9.50	7.74
55				0.03	55.6				0.01	8.09	9.03
56	0.25		0.08	0.08	52.7				0.10	7.57	9.87
57			0.03	0.04	49.5				0.02	6.11	8.49
58			0.68	0.02	177					70.3	51.0
59			0.74	0.02	187					48.3	53.2
60			0.77	0.03	195					53.7	53.3

Database Part 3b: Elemental Components

FID	Mn	Na	Ni	P	S	Si	Sr	Zn
1	0.013	116400			11.8	23.7	16.1	
2		14640		0.34	2.48	14.1	2.56	
3		218		0.27	0.84	11.2	0.39	
4	0.041	66310			3.20	37.5	19.1	
5	0.003	30640			5.60	19.2	5.59	
6	0.016	60220			8.91	17.8	10.1	
7	0.003	1973			1.35	20.4	0.85	
8	2.048	66630			5.99	36.8	21.2	
9		106			1.10	18.0	0.16	
10		707			0.94	16.9	0.19	0.11
11		11220			7.14	15.8	0.72	
12		10660			6.48	18.7	0.70	
13	0.01	915			21.6	28.4	2.26	
14	0.12	496			76.9	51.3	1.85	
15	0.12	515			78.5	52.0	1.82	0.10
16	0.12	479	0.01	0.14	77.8	51.9	1.80	
17	0.14	486			78.3	55.6	1.84	
18	0.12	444			78.0	52.4	1.81	
19	0.12	481			77.1	53.0	1.82	
20	0.048	542			157	34.6	2.18	
21	0.032	502		0.29	162	40.6	2.07	
22	0.023	467	0.01		169	47.2	2.15	
23		31.0			10.7	17.1	0.43	
24		33.3		0.26	10.4	18.2	0.46	
25		39.1		1.41	10.1	12.2	0.47	
26	0.054	524		0.42	209	29.9	2.60	
27	0.003	559			230	30.4	3.02	
28		550			226	37.5	2.82	
29	0.036	580			232	44.4	2.86	
30	0.02	496	0.01		209	40.9	2.62	
31		317			139	36.4	1.88	
32		338			143	36.0	2.01	
33	0.06	424			185	36.1	2.43	
34	0.002	8.54		0.02	3.48	14.1	0.38	
35	0.087	6.95		1.60	0.97	26.9	0.07	
36	0.072	7.72	0.005	1.01	0.65	38.2	0.18	
37	0.001	43.0		0.16	11.9	34.6	0.26	
38	0.006	39.8		0.09	10.6	35.7	0.24	
39	0.001	32.9			5.62	26.1	0.18	
40	0.141	37.6		0.08	8.40	28.7	0.22	
41		31.1			5.37	25.9	0.19	
42	0.001	35.4			5.06	31.4	0.21	
43	0.357	72.3	0.01	1.09	21.3	27.5	0.30	0.01
44	1.078	44.1			15.8	47.1	0.33	
45	0.010	60.5			18.3	66.1	0.47	

Database Part 3b (Continued): Elemental Components

FID	Mn	Na	Ni	P	S	Si	Sr	Zn
46		61.6			20.4	68.9	0.50	
47		35.7			12.8	45.4	0.34	
48		42.9			13.0	61.1	0.34	
49	0.00	51.8			6.07	17.5	0.20	
50	0.00	25.6			3.25	10.8	0.10	
51	0.01	37.6			4.09	18.2	0.11	
52	0.00	23.5			4.85	11.7	0.08	
53	0.01	26.6			4.27	16.4	0.15	
54		26.5			4.18	16.8	0.16	
55		21.5			3.12	13.4	0.15	
56	0.10	40.2			5.83	25.0	0.24	
57	0.01	27.5			5.19	19.0	0.18	
58	0.006	137			229	26.4	4.03	
59	0.004	151			251	28.7	4.38	
60	0.002	157			263	30.4	4.60	

Database Part 4a: Geothermometers

FID	Mature	logCaNa	NaK_F	NaK_G	NaK_Valid	KMg
1	NO	-1.66	52.2	73.7	NO	38.5
2	NO	-1.04	60.1	81.5	NO	39.5
3	NO	0.570	277	288	NO	40.0
4	NO	-1.38	63.5	84.9	NO	39.0
5	NO	-1.26	57.6	79.0	NO	39.2
6	NO	-1.45	56.2	77.7	NO	39.0
7	YES	-0.398	140	159	NO	38.7
8	NO	-1.29	92.5	114	NO	37.4
9	NO	0.880	185	202	NO	41.4
10	YES	0.0686	64.6	86.0	NO	41.6
11	NO	-0.989	47.4	68.9	NO	40.1
12	NO	-0.997	51.6	73.1	NO	40.1
13	NO	0.0471	208	224	NO	39.2
14	NO	0.335	318	325	NO	39.0
15	NO	0.315	285	295	NO	39.2
16	NO	0.343	258	270	NO	39.5
17	NO	0.341	255	268	NO	39.5
18	NO	0.380	260	272	NO	39.5
19	NO	0.347	252	265	NO	39.5
20	NO	0.421	278	288	NO	39.5
21	NO	0.447	276	286	NO	39.6
22	NO	0.467	290	300	NO	39.5
23	NO	1.54	276	287	NO	41.8
24	NO	1.50	277	287	NO	41.8
25	NO	1.45	290	300	NO	41.5
26	NO	0.501	277	288	NO	39.6
27	NO	0.467	285	295	NO	39.5
28	NO	0.493	283	293	NO	39.5
29	NO	0.474	278	288	NO	39.5
30	NO	0.499	290	299	NO	39.5
31	NO	0.653	309	317	NO	39.6
32	NO	0.638	296	305	NO	39.7
33	NO	0.580	292	301	NO	39.6
34	NO	1.89	377	377	NO	41.8
35	NO	1.84	640	596	NO	40.4
36	NO	1.98	765	693	NO	40.5
37	NO	1.43	443	434	NO	40.4
38	NO	1.45	682	629	NO	39.6
39	NO	1.47	465	453	NO	40.3
40	NO	1.47	508	489	NO	40.1
41	NO	1.52	437	429	NO	40.5
42	NO	1.47	327	332	NO	41.0
43	NO	1.22	293	302	NO	40.9
44	NO	1.44	293	302	NO	41.3
45	NO	1.20	356	358	NO	40.6

Database Part 4a (Continued): Geothermometers

FID	Mature	logCaNa	NaK_F	NaK_G	NaK_Valid	KMg
46	NO	1.22	338	342	NO	40.7
47	NO	1.37	296	305	NO	41.7
48	NO	1.32	255	268	NO	41.8
49	NO	1.17	615	576	NO	39.2
50	NO	1.25	252	265	NO	41.3
51	NO	1.12	239	253	NO	41.2
52	NO	1.29	278	288	NO	41.2
53	NO	1.41	521	499	NO	40.0
54	NO	1.41	358	360	NO	40.8
55	NO	1.60	365	366	NO	41.0
56	NO	1.32	278	289	NO	41.1
57	NO	1.47	297	305	NO	41.2
58	NO	1.05	413	408	NO	39.9
59	NO	1.02	342	346	NO	40.2
60	NO	1.01	351	354	NO	40.1

Database Part 4b: Geothermometers

FID	Beta	NaKCa_4_3	NaKCa_1_3	NaKCa	NaKCa_Valid
1	1/3	384	121	121	NO
2	1/3	234	111	111	NO
3	4/3	143	213	213	VALID
4	1/3	324	125	125	NO
5	1/3	279	115	115	NO
6	1/3	327	119	119	NO
7	1/3	211	160	160	NO
8	1/3	361	151	151	NO
9	4/3	68.9	145	68.9	VALID
10	4/3	78.7	83.9	78.7	VALID
11	1/3	202	96.7	96.7	NO
12	1/3	210	101	101	NO
13	4/3	187	193	193	VALID
14	4/3	199	249	249	VALID
15	4/3	186	230	230	VALID
16	4/3	168	212	212	VALID
17	4/3	167	211	211	VALID
18	4/3	163	212	212	VALID
19	4/3	164	208	208	VALID
20	4/3	165	221	221	VALID
21	4/3	160	218	218	VALID
22	4/3	164	226	226	VALID
23	4/3	40.7	170	40.7	VALID
24	4/3	43.5	172	43.5	VALID
25	4/3	51.3	181	51.3	VALID
26	4/3	153	216	216	VALID
27	4/3	162	223	223	VALID
28	4/3	157	220	220	VALID
29	4/3	157	218	218	VALID
30	4/3	159	224	224	VALID
31	4/3	144	227	227	VALID
32	4/3	141	221	221	VALID
33	4/3	148	221	221	VALID
34	4/3	33.4	199	33.4	VALID
35	4/3	72.5	289	72.5	VALID
36	4/3	69.7	311	69.7	VALID
37	4/3	85.6	248	85.6	VALID
38	4/3	119	327	327	VALID
39	4/3	85.4	254	85.4	VALID
40	4/3	93.1	270	93.1	VALID
41	4/3	75.7	241	75.7	VALID
42	4/3	57.6	197	57.6	VALID
43	4/3	73.1	192	73.1	VALID
44	4/3	52.8	182	52.8	VALID
45	4/3	91.3	223	91.3	VALID

Database Part 4b (Continued): Geothermometers

FID	Beta	NaKCa_4_3	NaKCa_1_3	NaKCa	NaKCa_Valid
46	4/3	84.3	213	84.3	VALID
47	4/3	59.8	187	59.8	VALID
48	4/3	53.1	168	53.1	VALID
49	4/3	147	326	326	VALID
50	4/3	57.9	170	57.9	VALID
51	4/3	66.1	168	66.1	VALID
52	4/3	61.9	181	61.9	VALID
53	4/3	101	278	278	VALID
54	4/3	70.3	213	70.3	VALID
55	4/3	54.6	207	54.6	VALID
56	4/3	59.6	180	59.6	VALID
57	4/3	51.2	183	51.2	VALID
58	4/3	123	257	257	VALID
59	4/3	108	225	225	VALID
60	4/3	112	230	230	VALID

Database Part 4c: Geothermometers

FID	R	dT	NaKCaMg	NaKCaMg_Valid	Best_Geothermometer	Res_TempC
1	12.6	0.477	121	VALID	-	
2	16.6	-243	111	NO	-	
3	20.7	-651	213	NO	Na-K-Ca	213
4	23.3	-45.6	125	NO	-	
5	18.6	-133	115	NO	-	
6	19.9	-48.6	119	NO	-	
7	3.02	-104	160	NO	-	
8	1.63	-0.901	151	NO	-	
9	22.3	-1470	68.9	NO	Na-K-Ca	68.9
10	20.6	-1400	78.7	NO	Na-K-Ca	78.7
11	26.0	-334	96.7	NO	-	
12	28.6	-297	101	NO	-	
13	8.61	-344	193	NO	Na-K-Ca	193
14	9.14	-311	249	NO	Na-K-Ca	249
15	10.5	-377	230	NO	Na-K-Ca	230
16	12.2	-483	212	NO	Na-K-Ca	212
17	11.9	-486	211	NO	Na-K-Ca	211
18	12.0	-506	212	NO	Na-K-Ca	212
19	12.0	-501	208	NO	Na-K-Ca	208
20	15.8	-516	221	NO	Na-K-Ca	221
21	15.5	-545	218	NO	Na-K-Ca	218
22	15.2	-523	226	NO	Na-K-Ca	226
23	23.5	-1600	40.7	NO	Na-K-Ca	40.7
24	23.6	-1620	43.5	NO	Na-K-Ca	43.5
25	21.4	-1940	51.3	NO	Na-K-Ca	51.3
26	15.1	-592	216	NO	Na-K-Ca	216
27	16.2	-538	223	NO	Na-K-Ca	223
28	14.6	-563	220	NO	Na-K-Ca	220
29	14.7	-561	218	NO	Na-K-Ca	218
30	15.3	-554	224	NO	Na-K-Ca	224
31	13.6	-647	227	NO	Na-K-Ca	227
32	14.6	-674	221	NO	Na-K-Ca	221
33	13.9	-623	221	NO	Na-K-Ca	221
34	24.9	-711	33.4	NO	Na-K-Ca	33.4
35	10.3	-1830	72.5	NO	Na-K-Ca	72.5
36	14.8	-1890	69.7	NO	Na-K-Ca	69.7
37	16.0	-1410	85.6	NO	Na-K-Ca	85.6
38	11.5	-860	327	NO	Na-K-Ca	327
39	13.1	-1450	85.4	NO	Na-K-Ca	85.4
40	12.2	-1280	93.1	NO	Na-K-Ca	93.1
41	13.7	-1720	75.7	NO	Na-K-Ca	75.7
42	14.4	-2460	57.6	NO	Na-K-Ca	57.6
43	17.0	-1690	73.1	NO	Na-K-Ca	73.1
44	17.4	-2450	52.8	NO	Na-K-Ca	52.8
45	20.3	-1190	91.3	NO	Na-K-Ca	91.3

Database Part 4c (Continued): Geothermometers

FID	R	dT	NaKCaMg	NaKCaMg_Valid	Best_Geothermometer	Res_TempC
46	19.0	-1350	84.3	NO	Na-K-Ca	84.3
47	39.8	539	-479	NO	Na-K-Ca	59.8
48	36.3	524	-471	NO	Na-K-Ca	53.1
49	8.10	-533	326	NO	Na-K-Ca	326
50	17.5	-2200	57.9	NO	Na-K-Ca	57.9
51	17.4	-1890	66.1	NO	Na-K-Ca	66.1
52	18.1	-1990	61.9	NO	Na-K-Ca	61.9
53	11.5	-1110	278	NO	Na-K-Ca	278
54	14.7	-1880	70.3	NO	Na-K-Ca	70.3
55	12.4	-2770	54.6	NO	Na-K-Ca	54.6
56	14.1	-2370	59.6	NO	Na-K-Ca	59.6
57	13.2	-2980	51.2	NO	Na-K-Ca	51.2
58	17.1	-837	257	NO	Na-K-Ca	257
59	18.4	-996	225	NO	Na-K-Ca	225
60	17.6	-962	230	NO	Na-K-Ca	230

Database Part 5: Notes

FID	Notes
1	"Crystal Hot Springs"
2	"Crystal Hot Springs"; lots of biological growth; stagnant water
3	Fish pond with lots of algae
4	"Stinky Springs"; strong smell of sulfur; piped in from source
5	Modified by owner; gas bubbling in most contaminated pool (tires, bovine disturbance, etc.) off of main highway entrance
6	Some algae in sample; modified to flow under road
7	Modified by rock company under power lines; about 130 m from sample 8
8	About 130 m from sample 7
9	Landowner claims it dried out after the 1959 Hebgen Lake Earthquake and came back after the 1975 Malad Earthquake
10	
11	
12	
13	
14	Maple Grove Hot Springs
15	Maple Grove Hot Springs
16	Maple Grove Hot Springs; Travertine deposits
17	Maple Grove Hot Springs
18	Maple Grove Hot Springs
19	Maple Grove Hot Springs
20	Gas bubbles; 58.1°C, 63.7°C in underlying sediment
21	Gas bubbles; 64.5°C in underlying sediment
22	57.6°C in underlying sediment
23	Small pond with lily pads
24	Piped under the road
25	
26	
27	Temperature at edge of large pond, temperature may be higher at center
28	
29	"Bidwell / Bartleson Trail Hot Springs." Temperature at edge of large pond, temperature may be higher at center
30	Gas bubbling up in center; temperature at edge of large pond, temperature may be higher at center
31	Lots of gas; steam; sulfur smell; temperature 42.5°C in nearby pond
32	Lots of gas; steam; sulfur smell; mud temperature 50°C
33	Lots of places with bubbles rising to surface in pond where streams converge; temperature varies from place to place; concrete spring bath
34	Large pond, landowner claims source is likely near the middle of the pond, fish-finder indicates very deep hole at lake bottom
35	Some gas bubbles
36	Stagnant pond, highly trafficked by bovine
37	Bog; 12.9 and 13.0°C in underlying sediment
38	Bog; water pooled in small dug pit; same spring as 37
39	
40	
41	
42	
43	11.5°C in underlying sediment
44	13.7°C in underlying sediment
45	Spring was piped; about 3 meters from sample 46

Database Part 5 (Continued): Notes

FID	Notes
46	Spring was piped; about 3 meters from sample 45
47	Soggy ground; some bovine disturbance
48	12.8 C in underlying sediment; plants on surface
49	Developed; impacted by cattle; not well-drained; maybe more acidic due to decaying organic matter
50	Spring coming from rocks
51	
52	
53	"Warm Spring." 20°C at lake below where sample was taken; significant portion of main flow
54	"Warm Spring." remaining portion of main flow; feeds into same lake as sample 53
55	Flowing out of rock
56	Spring below quarry; some disturbance by cattle
57	Some disturbance by cattle
58	Near Bear Lake; sulfuric smell
59	Near Bear Lake; sulfuric smell; precipitation of soft white mineral
60	Near Bear Lake; sulfuric smell

Appendix C: Geothermometers

Na-K (Fournier and Potter, 1979):

$$\frac{1217}{\log_{10}\left(\frac{\mathrm{Na}}{\mathrm{K}}\right) + 1.4831} - 273$$

Na-K (Giggenbach, 1988):

$$\frac{1390}{\log_{10}\left(\frac{\mathrm{Na}}{\mathrm{K}}\right) + 1.75} - 273$$

K-Mg (Giggenbach, 1988):

$$\frac{4410}{14 - \log_{10}\left(\frac{\mathrm{K}^2}{\mathrm{Mg}}\right)} - 273$$

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

$$\beta = \frac{4}{3}\,\text{when}\ \log_{10}\left(\frac{\sqrt{\mathrm{Ca}}}{\mathrm{Na}}\right) > 1\ \mathit{and\ reservoir\ temperature} < 100°C$$

$$\beta = \frac{1}{3}\,\text{when}\ \log_{10}\left(\frac{\sqrt{\mathrm{Ca}}}{\mathrm{Na}}\right) < 1\ \mathit{or\ reservoir\ temperature\ for}\ \beta = \frac{4}{3}\,\text{is} > 100°C$$

$$\frac{1647}{\log_{10}\left(\frac{\mathrm{Na}}{\mathrm{K}}\right) + \beta \times \left(\log_{10}\left(\frac{\sqrt{\mathrm{Ca}}}{\mathrm{Na}}\right) + 2.06\right) + 2.47} - 273$$

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

$$\mathrm{R} = \frac{\mathrm{Mg}}{\mathrm{Mg} + \mathrm{Ca} + \mathrm{K}} \times 100$$

If R > 50, then 0.

If 0.5 < R < 5, then:

$$-1.03 + 59.97 \times \log_{10}(\mathrm{R}) + 145.05 \times \log_{10}(\mathrm{R})^2 - 36711 \times \frac{\log_{10}(\mathrm{R})^2}{\mathrm{NaKCa}} - 1.67 \times 107 \times \frac{\log_{10}(\mathrm{R})^2}{\mathrm{NaKCa}^2}$$

Otherwise:

$$10.66 - 4.7415 \times \mathrm{R} + 325.87\mathrm{x}\log_{10}(\mathrm{R})^2 - 1.032 \times 105 \times \frac{\log_{10}(\mathrm{R})^2}{\mathrm{NaKCa}} - 1.968 \times 107 \times \frac{\log_{10}(\mathrm{R})^2}{\mathrm{R}^2} + 1.605 \times 107 \times \frac{\log_{10}(\mathrm{R})^3}{\mathrm{NaKCa}^2}$$