EVIDENCE FOR MIXING AND RE-EQUILIBRATION IN THE TWIN FALLS – BANBURY HYDROTHERMAL SYSTEM AND ITS EFFECTS ON RESERVOIR TEMPERATURE ESTIMATION

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by

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AUTHORIZATION TO SUBMIT THESIS

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DEDICATION

This work is dedicated to my incredible wife, Emily Cannon, for her unconditional love, unwavering support, and steadfast belief in me even through the tough times when I don’t believe in myself. She is my best friend and the best friend any man could ask for. To my parents, Ellen and Gary Cannon, for believing in me from the beginning, convincing me that nothing is impossible, and teaching me that I am never alone. To my sister, Christi Cannon, for reminding me to never take myself too seriously. Lastly and chiefly, this thesis is dedicated to Jesus Christ in whose mighty company I am blessed to be counted. For making me a new man, His constant companionship, and grace through His selfless finished work, I am and will continue to be eternally grateful.

“He is a man in a way that we have forgotten men can be; truthful, blunt, emotional, nonmanipulative, sensitive, compassionate.” – Brennan Manning

ABSTRACT

The Twin Falls - Banbury area is one of many Known Geothermal Resource Areas located along the periphery of the Eastern Snake River Plain (ESRP). The ESRP is a topographical plain, which was formed by the bimodal volcanism of successive caldera formations associated with the migration of the Yellowstone Hot Spot over the last 16 Ma. Despite temperature gradients of 45-60 ^{o}C/km (double the global average) and high heat flow values (110 mW/m^2), geothermal utilization within the ESRP is largely limited to direct use with no commercial geothermal development. A gradational trend between deep rhyolite derived Na-K-HCO_3 waters of the deep system and basalt hosted Ca-Mg-HCO_3 thermal water is observed in deep exploration wells. Mixing between the fluids of the deep system and cooler overlying groundwater as well as re-equilibration of thermal fluids during ascension are considered possibilities that may explain this trend and the low geothermometry temperature estimations of the area. The Twin Falls – Banbury area was chosen as the location for an in depth investigation into the possibility of geothermal mixing and re-equilibration as an explanation for the lower than expected geothermometry.

Evidence for mixing is provided by partial equilibration conditions in most thermal samples as well as a variety of linear mixing trends between both conservative chemical species (Cl, B, δD, etc.) and more reactive species (Ca, Mg, Na, and K). The reactive species show two distinct chemical trends between the two water types that may constitute evidence for different flow paths and/or re-equilibration of thermal fluids at lower temperatures. Multicomponent equilibrium geothermometry (MEG) analysis through the inverse modeling tool RTEst (Palmer, 2013) provides more reliable reservoir temperature estimates for the area through the use of likely reservoir mineral assemblages and the compensation of a mixing component. Results from MEG also support the possibility of re-equilibration. The combination of MEG, high temperature water-rock interaction experiments, and local geological and hydrological data have resulted in a revised conceptual flow model of the Twin Falls – Banbury hydrothermal system.

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CHAPTER 1: INTRODUCTION

The Twin Falls – Banbury hydrothermal area is one of many Known Geothermal Resource Areas (KGRA) located along the periphery of the Eastern Snake River Plain (ESRP). The ESRP is considered to be one of the most favorable areas for geothermal development within the state of Idaho (Tester et al., 2006) which the USGS estimates is home to over 4,900 MWe of undiscovered geothermal resources with a mean power production potential of 30 GWe (Williams, 2008). Regional subsurface temperature gradients of 45-60 ^{o}C/km (double the global average) have been calculated throughout the region and heat flow values of over 150 mW/m^2 have been projected for depths to 6 km (Brott et al., 1976; Blackwell and Richards, 2004). Despite the high observed potential, utilization of geothermal fluids has been limited to direct use applications (direct use heating, greenhouses, fisheries, etc.) for over a century with no commercial geothermal development within or along the plain proper. This is likely due to the masking of the deep geothermal signature by the Eastern Snake River Plain Aquifer (ESRPA), a prolific basalt hosted aquifer system that overlies the rhyolites, which are thought to host thermal reservoirs throughout the region.

The ESRP is a topographical lowland which was formed by the middle Miocene to recent bimodal volcanism by a succession of caldera formations associated with the migration of the North American Plate over the Yellowstone Hot Spot (Hughes et. al., 2002; Rodgers et. al., 2002; Pierce and Morgan, 2009). Caldera formation resulted in a series of younger to the east rhyolite units (Morgan et al., 1984; Leeman et al., 2008) that are overlain by extensive younger basalt flows of Tertiary to Holocene age. The basalt sequence forms the ESRPA which carries cold water from the Yellowstone Plateau down gradient to the Thousand Springs area in Twin Falls, ID. Because of the thick overlying cold water aquifer, most of the thermal springs and wells throughout the area are observed along the margins of the ESRP. It is thought that deep thermal water is able to make its way to the surface through a variety of structurally and geologically controlled conduits.

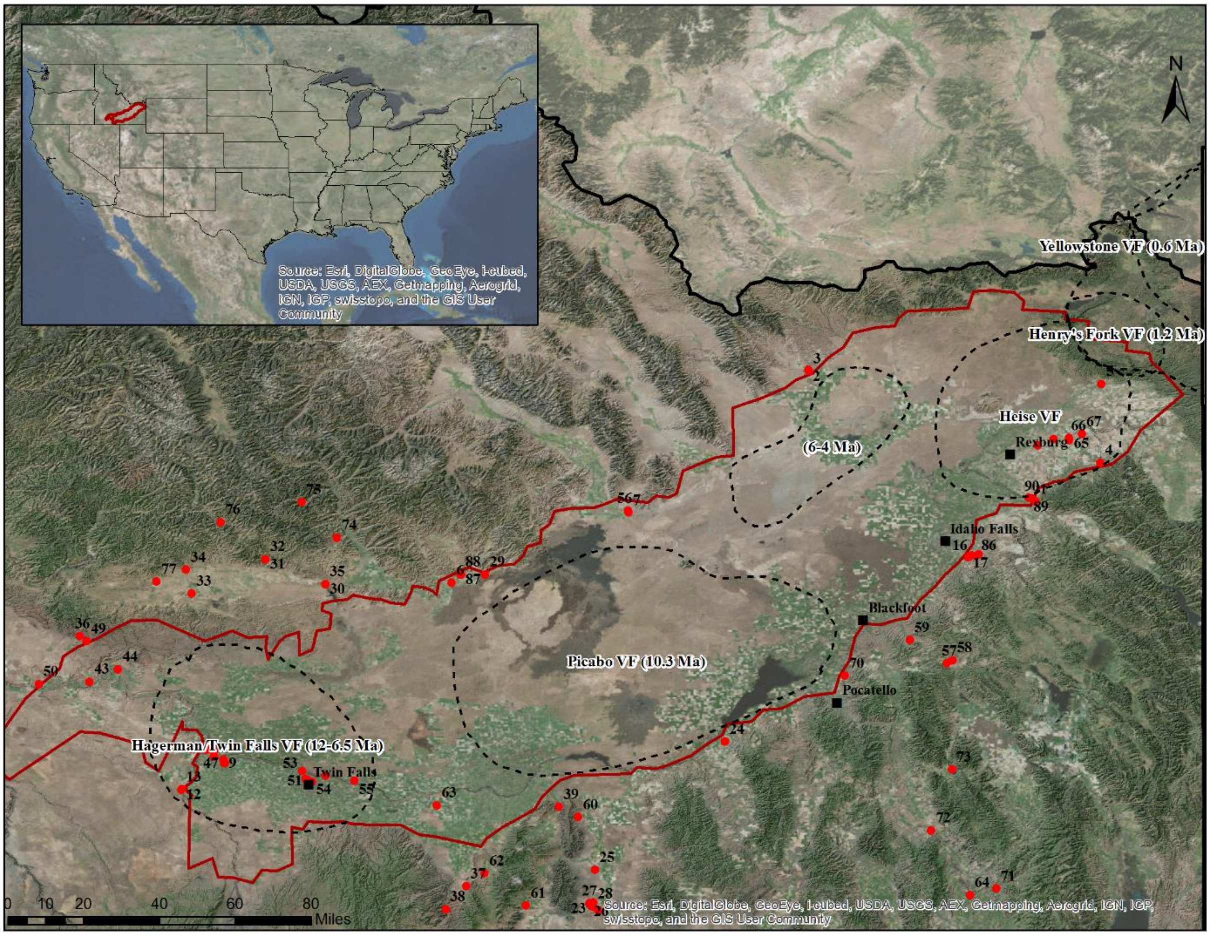

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Figure 1. Map of the ESRP showing location relative to the United States (inset) and the approximate locations of caldera centers. Red points represent thermal samples collected in the 2014.

Many compositions for thermal fluids of the ESRP have been recorded (e.g., Ross, 1971; Young and Mitchell, 1973; Ralston et. al., 1981; Lewis and Young, 1982; Wood and Low, 1988; Parliman and Young, 1992; Mariner et al., 1991, 1997; McLing et al., 2002). However, most of the previous studies do not attempt to account for mixing with a cooler groundwater component though some acknowledge it. A gradational trend between Na-K-HCO_3 type waters associated with deep rhyolites and shallower Ca-Mg-HCO_3 thermal waters has been observed in deep wells that penetrate the upper aquifer system (McLing et al., 2002; Mann, 1986). Many have explained this trend through mixing between thermal waters and groundwater where mixed waters exhibit a composition between the two end member waters (McLing et al., 2002; Neupane et al., 2014; Cannon et al., 2014).

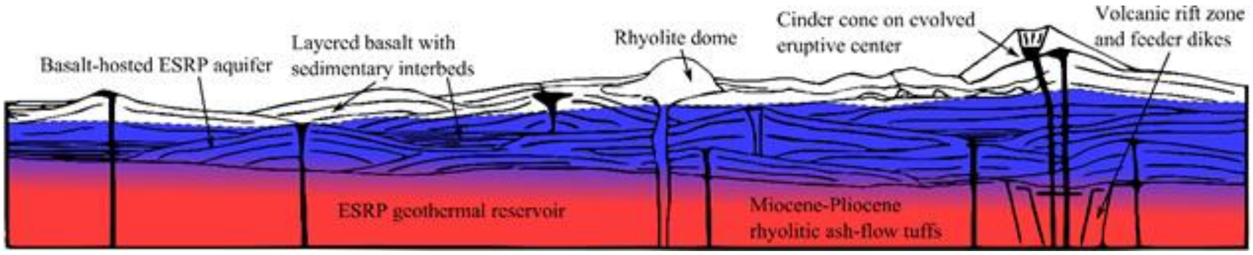


Figure 2. Schematic cross-section across the ESRP (Neupane et. al., 2014) showing underlying rhyolitic ash-flow tuffs and overlying basalt flows with few sedimentary layers. The rhyolite ash-flow tuffs underlying the basalt aquifer system are assumed to be the ESRP geothermal reservoir.

Although there are many historical thermal fluid compositions for the ESRP, many of them are incomplete in that they lack important trace elements. This study is part of a larger Department of Energy Geothermal Technologies Office funded project to provide more accurate reservoir temperature estimations throughout the ESRP by using a modern technique called multicomponent equilibrium geothermometry (MEG). MEG utilizes trace elements (particularly aluminum) to estimate temperature using the saturation states of hydrothermal alteration minerals, many of which are aluminosilicates. MEG is also capable of accounting for mixing between thermal fluids and groundwater through inverse modeling. To this end, a collaboration between the University of Idaho, the Lawrence Berkeley National Laboratory, and the Idaho National Laboratory collected samples in 2014 in order to provide more reliable temperature estimates that are corrected for the effects of mixing.

The Twin Falls – Banbury area (Figure 3) was chosen as the location for an in depth investigation into the possibility of geothermal mixing and re-equilibration as an explanation

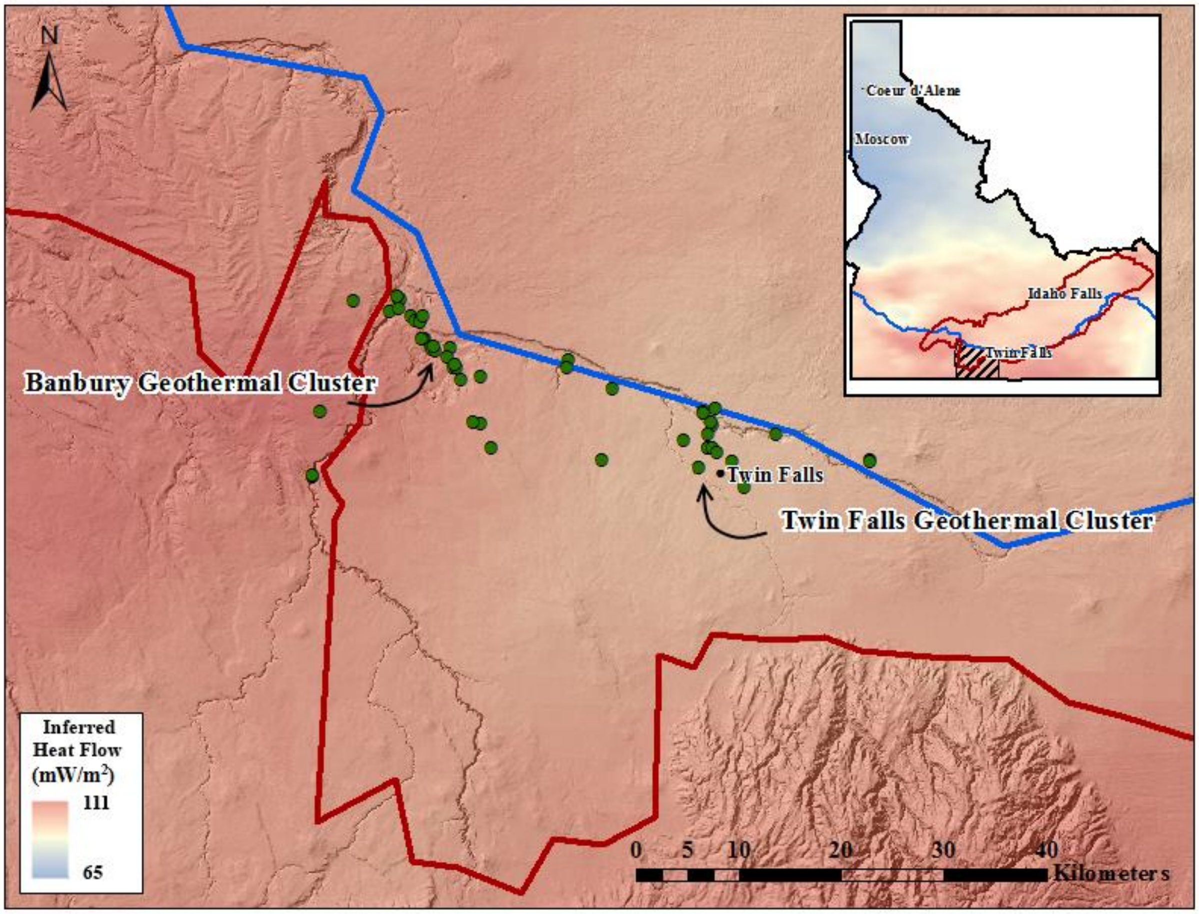


Figure 3. Study area map superimposed on the USGS heat flow map (Williams and Deangelo, 2011). Map depicts the Twin Falls – Banbury hydrothermal area relative to the ESRP margin (red line). Green points correspond to thermal waters utilized in this study.

for the lower than expected reservoir temperature estimations of the area. The area was chosen due to the high sample density obtained in the 2014 sampling campaign as well as the amount of historical data available for the area. The area is comprised of two dense clusters of geothermal surface manifestations along the trend of the Snake River near the southwestern end of the ESRP. This study attempts to combine various geochemical techniques with local hydrology and geology to provide evidence for mixing, estimate reservoir temperature while accounting for mixing, consider the possibility of re-equilibration, and refine the conceptual model for the Twin Falls – Banbury hydrothermal system. However, before investigating the

Twin falls – Banbury area in detail, it is important to identify exactly what is meant by "mixing" and the different scenarios by which mixing can occur.

Mixing Scenarios Defined

The chemical signature of geothermal water is often impacted or altered by mixing with shallower waters, thereby masking the actual reservoir temperatures calculated using geothermometry. This study examines the effects of mixing on calculated temperatures via an in-depth investigation on a relatively well known geothermal area, the Twin Falls – Banbury thermal system in south-central Idaho. Dilution corrections will be made using established mixing models and the multicomponent equilibrium geothermometry (MEG) tool RTEst (Reservoir Temperature Estimator) (Palmer et al., 2013). The effect of chemical re-equilibration with rocks outside the geothermal reservoir at sub-reservoir temperatures is also considered. Mixing and re-equilibration is a practical problem facing geothermal explorationists in many areas, e.g. ESRP and similar thermal regimes. For the purposes of this work, three mixing scenarios are defined:

1) "simple mixing" or non-reactive mixing;

2) flow pathway mixing (both reactive and non-reactive)

3) re-equilibration.

Simple mixing involves the ascension of thermal water from depth through a conduit like a fault or fracture. The thermal water component is uninterrupted during ascension, cooling only through conduction and/or advection. Upon discharging at the surface, the thermal water is quickly mixed with surface water such as precipitation, a stream, or spring. In this case the thermal water is undiluted (no mixing prior to discharge) until it is mixed with surface water. Most mixing models are setup to directly address this type of dilution (Fournier, 1977; Arnòrsson, 1983; 1985). Solute-enthalpy mixing models developed in the 1970s and 80s can be utilized to adjust for simple mixing and refine the calculated reservoir temperatures. MEG methods including RTEst can remove the influence of the cold water component based on the convergence of multiple mineral saturation indices.

The second scenario, flow path mixing, involves mixing of thermal water as it makes its way from depth to the surface. In the case of the ESRP, thermal water ascending through a fracture may be mixed with cooler groundwater as the conduit is intersected by permeable cold water zones prior to discharging at the surface or through a well. This scenario may constitute a combination of both simple and reactive mixing depending on sufficient residence times that allow for reactions to occur between the two waters and/or surrounding rock. Reactive mixing is made evident through the alteration of ratios of some chemical constituents while other more conservative species (i.e. Cl^-, B) will mix non-reactively as their ratios remain constant through dilution.

The third scenario involves the re-equilibration of thermal water or mixed thermal water with a new reservoir rock. The geochemical signature of re-equilibrated waters does not reflect the temperature of the deep thermal reservoir but only the temperature at which the waters last attained equilibrium. Because re-equilibration violates a key assumption in all geothermometry techniques (Huenges and Ledru, 2011), it has largely been ignored in geothermal investigations. Many researchers have warned about re-equilibration when discussing the applicability of their techniques (Fournier, 1977; Arnòrsson, 1985; Reed and Spycher, 1984; Giggenbach, 1988, Neupane, 2015) but few have attempted to quantify or account for its effects. Unlike the previous two scenarios, re-equilibration presents a significant problem that can’t be solved by MEG nor can it be accounted for with conventional geothermometry and mixing model techniques. To better understand if re-equilibration is at play in this area, water-rock interaction and mixing experiments based on the Twin Falls – Banbury geothermal system and aquifer pumping tests to gain insight into vertical travel times (residence times for re-equilibration) are performed in this study.

CHAPTER 2: LITERATURE REVIEW OF THE TWIN FALLS – BANBURY HYDROTHERMAL SYSTEM

The hydrothermal system in Twin Falls, Idaho is the most utilized and perhaps the most prolific geothermal prospect throughout southern Idaho. Substantial use of the system began in the 1970s with the utilization of thermal water for fish propagation, irrigation, heating, and resorts (Street and Detar, 1987). All of these applications are still in operation today. One of the most promising areas for further development is located near Hagerman, Idaho where the Thousand Springs Resort produces 72 ^{o}C geothermal water from a 750 foot well. Electrical production and further geothermal investigations have been considered but limited due to concerns over observed declining thermal water levels although temperature declines are not evident (Fleischmann, 2006). Reservoir temperature estimations made by earlier researchers utilizing geothermometry techniques produced results that are insufficient for power production. However, preliminary results of this study show that mixing between groundwater and thermal water may have masked the true higher temperature signature of this area. The following section provides a review of the relevant literature pertaining to the Twin Falls – Banbury hydrothermal area.

2.1 Geology

Mabey (1982) stated that the Snake River Plain was one of the least understood geologic provinces in the United States. While it has been described as a graben and various rift structures, it is described by most as a regional down warping associated with the bimodal volcanism due to the successive caldera formations of the Yellowstone Hotspot beginning approximately 16 Ma (Hughes et. al., 1999; Rodgers et. al., 2002; Pierce and Morgan, 2002).

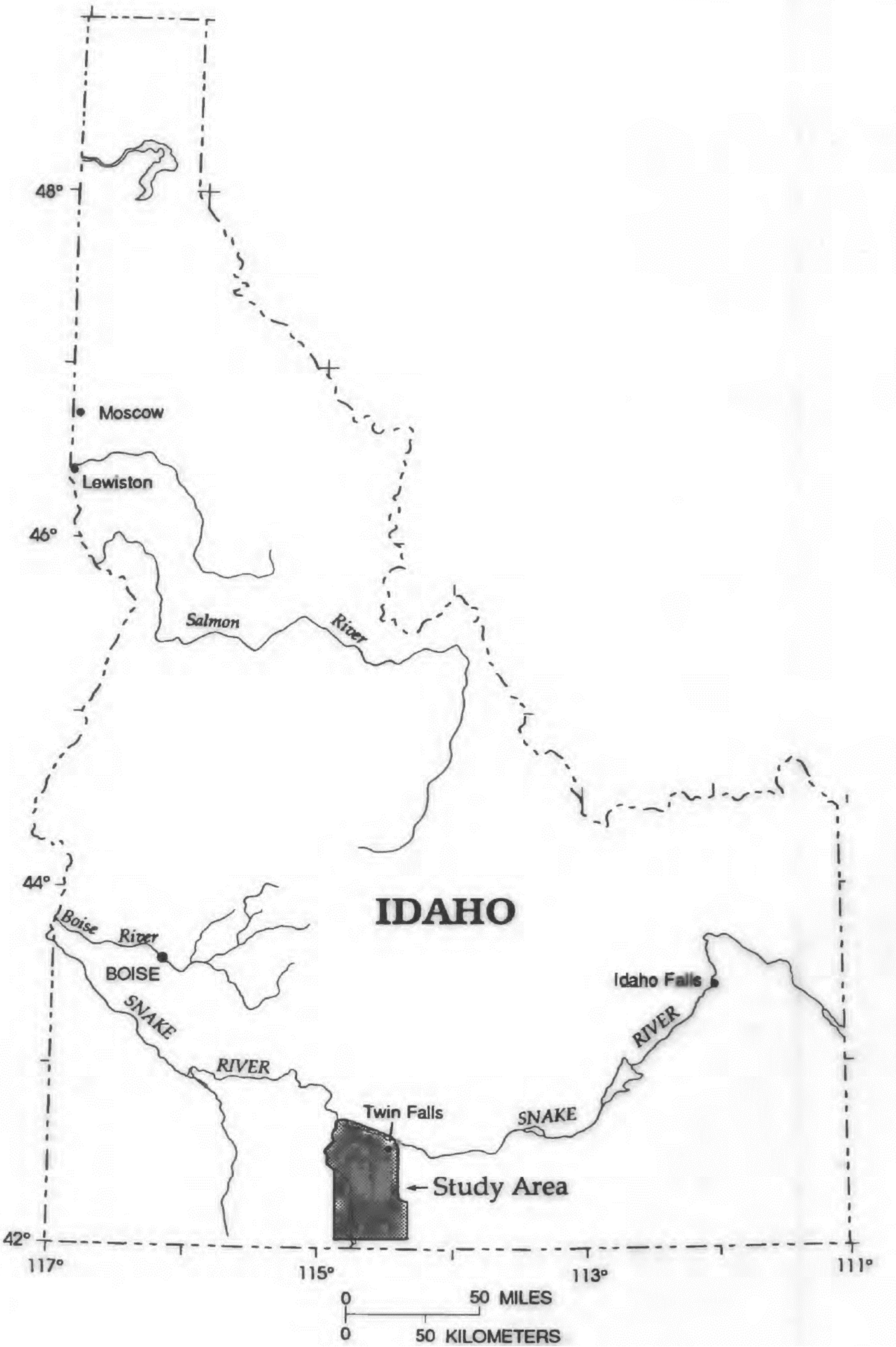


Figure 4. Map of the Twin Falls – Banbury hydrothermal study area, Lewis and Young (1982)

The Twin Falls and Banbury hydrothermal areas show characteristics of both the ESRP and basin and range regional extension. Tertiary rhyolitic volcanic rocks underlie younger quaternary and tertiary basaltic units throughout the study area. The rhyolitic units of the Idavada volcanics dip northward from the Cassia Mountains in the southern portion of the study area disappearing beneath the basaltic units of the ESRP with no clear evidence of down faulting supporting the conceptual model of ESRP regional down warping (Street and Detar, 1987). However, normal faults associated with Basin and Range extension are present in the northwestern portion of the study area. Many of these faults do not cut across basalts and are constrained to the Idavada volcanics trending north to northwest along the Salmon Falls Creek. These structures mark the beginning of the Western Snake River Plain and continue across the Bruneau Desert to the west (Kuntz, 1977).

Miocene Banbury basalts are the most predominant basalt units in the study area and may be up to 305 meters (1,000 ft.) thick (Lewis and Young, 1989). Along with overlying and interbedded Pleistocene lacustrine sediments of the Glenn's Ferry Formation (Malde and Powers, 1972), these basalts make up a locally significant shallow groundwater system. However, the most ubiquitous unit in the study area are the Tertiary volcanics of the Idavada formation which are predominantly comprised of welded rhyolitic ash flow tuff units with secondary rhyolite lava flows, andesites, and intercalated lacustrine sediments (Rember and Bennett, 1979). The Idavada volcanics are likely representative of many undifferentiated volcanic episodes from 12 to 6 Ma (Street and Detar, 1987). Electrical resistivity data shows that the Idavada volcanics are continuous over most of the area ranging in thickness from 700 to 3,000 ft. (2,000 ft average) (Lewis and Young, 1989). Lithologic logs from the recently drilled deep exploration well of Project Hotspot in nearby Kimberly, ID shows the Idavada volcanics are at least 3,800 ft. thick and reach depths up to 6,423 ft. (Shervais et al., 2013). General stratigraphy of the study area is depicted in Figure 5 below showing Tertiary rhyolites

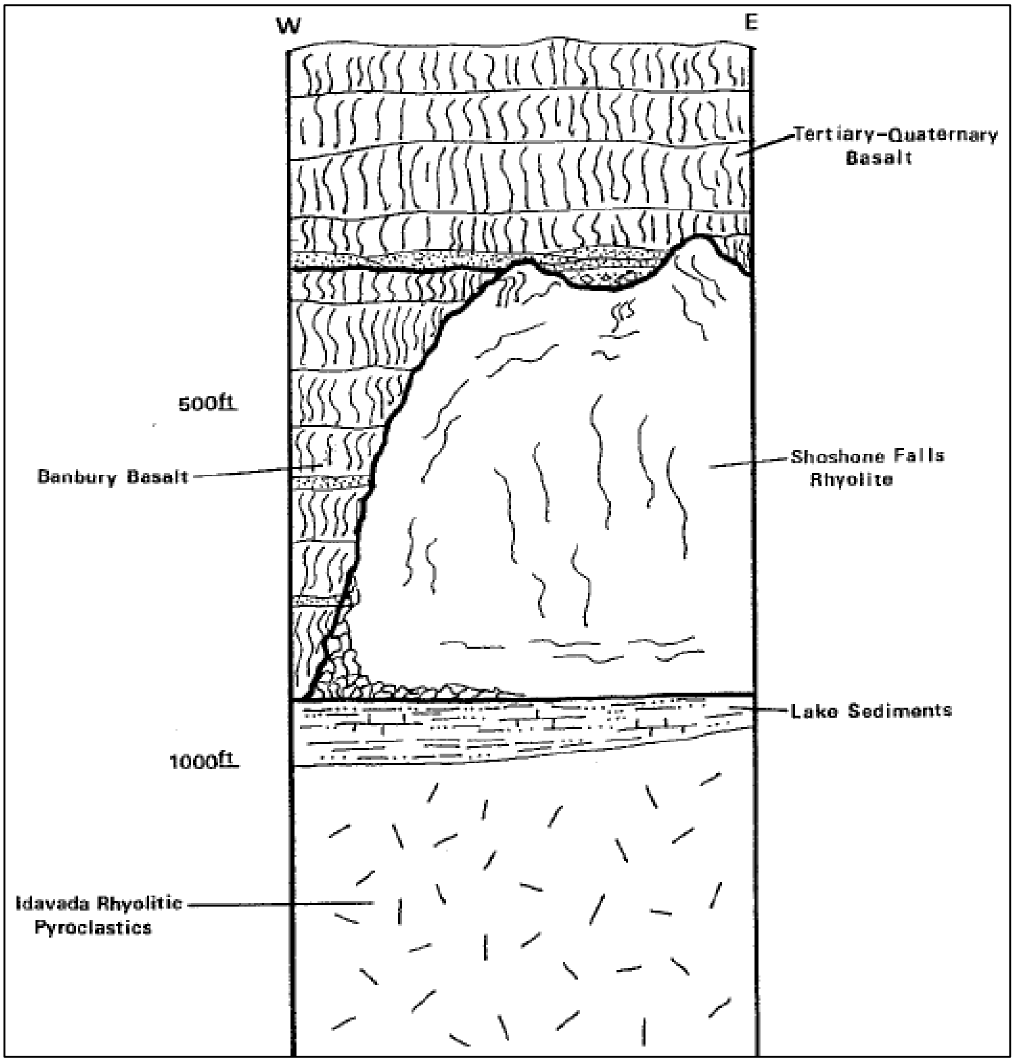


Figure 5. General stratigraphy of the Twin Falls – Banbury area (Street and DeTar, 1987).

underlying the entire study area, lacustrine sediments, Tertiary Banbury basalts, a distinct single andesitic flow layer of the Idavada called the Shoshone Falls rhyolite, and finally overlying Tertiary and Quaternary basalts.

Although none of the well logs within the study area penetrate the extent of the Idavada volcanics, Paleozoic marine sediments are thought to underlie the entire area (Lewis and Young, 1989). Pennsylvanian age carbonates outcrop just to the southeast of the town of Buhl, ID and make up the core of the Cassia Mountains near the Idaho-Nevada border to the south. The extent of the Paleozoic carbonates beneath the Idavada volcanics is unknown but over 5,000 feet of carbonates have been reported in the mountains of northern Nevada (Schroeder, 1912).

2.2 Hydrology

The Twin Falls area hydrology is separated into two separate and distinct aquifer systems. There exists a shallow, cold water aquifer system in which flow paths between areas of recharge and discharge are relatively short. This system contains aquifer sub units within Banbury Basalts and thin sedimentary interbeds. Groundwater flow direction is generally northward or northwestward (in southeastern portions of the area near the city of Twin Falls) toward the Snake River. The majority of recharge to this system comes from the south and southeast in the low hills where annual precipitation reaches 45 inches. Hydraulic heads are below land surface. The aquifer is considered to be unconfined but may be confined in some areas. Water from this shallow system is typically around 20 ^{o}C while some shallow groundwater reaches elevated temperatures due to the mixing of cooler water with thermal water (Lewis and Young, 1989).

The thermal aquifer system (20 ^{o}C to 72 ^{o}C) is located beneath basalt units within the Idavada volcanics and is under artesian conditions with temperatures of the waters increasing to the northwest. Lewis and Young (1982) produced a generalized potentiometric surface map showing an overall north and northwestern gradient in the aquifer. Permeability within the reservoir rock itself is associated with fractures developing from tectonic movement, joints and fractures resulting from cooling during emplacement, intergranular porosity of the non-welded ash flow tuffs, and contacts between flow boundaries. Street and Detar (1987) described the results of a pumping test during the development of two deep thermal heating wells (450 and 675 meters) completed in the Idavada volcanics at the College of Southern Idaho in Twin Falls. Transmissivity (554-923 m^2/d (44,600 – 74,300 gpd/ft)) and storativity (5.8E-4 to 6.2E-4) values were measured for the Idavada rhyolites. It was concluded that no hydrologic boundaries exist between the Twin Falls and Banbury area systems.

Thermal waters are thought to originate from deep circulation paths from the Cassia Mountain recharge zone to the south and through fractures in the overlying basalts of the thermal area. The waters are subsequently heated by either a regionally high gradient (Lewis and Young, 1989) or the young basaltic sill complexes associated with ESRP volcanism (McLing et al., 2014, Dobson et al., 2015).

2.3 Geochemistry

Lewis and Young (1982) characterized the highest temperature thermal waters of this area as sodium-bicarbonate type and stated that they are slightly alkaline. In 1989, they showed that water chemistry of the thermal waters indicates mixing with a shallow cold water component through relationships of stable isotopes, chloride, and enthalpy. They highlighted a mixing trend from cooler $Ca\text{-}HCO_3$ to $Na\text{-}HCO_3$ using a Piper trilinear diagram but made no effort to address the effects of dilution on geothermometry calculations. Traditional geothermometry calculations were performed using the Na-K-Ca geothermometer and silica geothermometers (chalcedony and quartz). Mg corrections to the Na-K-Ca geothermometer were not made as the corrections were deemed insignificant for waters with around 1 ppm Mg concentration despite a concentration of 0.2 ppm Mg being widely regarded as the boundary for correction (Fournier and Potter, 1979).

The 19 samples taken in the Lewis and Young (1982) study were near saturation with calcite thus giving skeptical temperature estimations for the Na-K-Ca geothermometer. A simple mixing analysis was done by plotting the Na-K-Ca temperature predictions versus the silica geothermometer predictions. Waters that plotted on or near the equal temperature line for these two geothermometers were considered to be representative of reservoir water (not mixed). These waters include several of the highest temperature waters including the 72 ^{o}C water of the 1000 Springs Resort. The authors drew the conclusion that 70 – 100 ^{o}C was the likely reservoir temperature from these conventional geothermometry methods. Young and Mitchell (1973) came up with a similar but slightly higher estimate of 85-135 ^{o}C.

In 1997, Mariner et al., conducted a study in Twin Falls and Jerome Counties using sulfate-water isotope geothermometry. They estimated a reservoir temperature of 90-106 ^{o}C. However, recent sulfate-water isotope geothermometry results show temperature estimates of 159 ^{o}C for this area (Conrad et al., 2015). Lead isotopic values from this study showed that thermal waters in the area have a signature reflective of Paleozoic carbonates. This suggests that despite the overprinting of a rhyolitic signature (high silica and high fluoride), thermal waters may be originating even deeper in the system within Paloezoic carbonates.

^{14}C isotopes were used to date the waters of the Twin Falls geothermal system. Age estimations for Twin Falls area thermal are around 4,000 to 10,000 years old (Mariner et al., 1991). Lewis and Young (1982) attributed low deuterium values in the waters to a historically cooler climate making the waters at least 8,000 years old and possibly up to 15,000 years old. Discharge measurements for wells in the area in early 1979 indicated a thermal water discharge of 10,300 acre-ft annually (Lewis and Young, 1982). However, there have been significant declines to the utilization of this system for heating, low-head hydro power production, and fish propagation (Street and Detar, 1987). Fleischmann (2006) listed this area in his *Geothermal Development Needs in Idaho* stating that more exploration is warranted due to the masking of the high temperature resource by the overlying cold water system. The report states that more exploration is needed to determine the source of heat and a resource may be confirmed with deep drilling.

2.4 Methods

With advancements in geothermal science, there exists more substantial evidence for mixing in this region. Recent geothermometry studies have shown that the Twin Falls – Banbury hydrothermal system may represent a higher temperature resource than what was previously estimated (Cannon et al., 2014; Conrad et al., 2015). The following sections describe the geochemical methods utilized in this study.

2.4.1 Solute Chemical Geothermometry

Geothermal fluids have widely varied chemistries, reflecting the geologic setting and the host rock from which they emanate. Geothermometers are experimentally and empirically based equations that take advantage of specific high temperature mineral-solute reactions that are slow to equilibrate at lower temperature. These equations give geoscientists insight into the reservoir temperature achieved by the thermal water at depth prior to ascent to the surface. Several assumptions are made in order for geothermometers to be useful. The first assumption is that equilibrium between host rock and water is obtained at depth. This assumption has been proven valid through research on several commercial geothermal power plants. The second major assumption is that the thermal fluid composition is not altered by secondary processes (boiling, mixing, reactive processes, etc.) during its ascent to the surface. This assumption is made but is often invalid and corrections need to be made to the predicted temperatures.

Utilization of geothermometers began in the late 1970s with the development of the silica geothermometers, which are perhaps the most widely used geothermometers. The quartz and amorphous silica geothermometers were first developed by Fournier (1977) and are based on the experimentally determined prograde relationship between silica concentration and increasing temperature. Different polymorphs of silica dominate at different temperatures and thus not all silica geothermometers are appropriate at all temperatures. This led to the development of the chalcedony geothermometer by Arnorsson et al. (1983). However, not all thermal fluids are hosted within silicic reservoirs leading to the development of cation geothermometers.

Cation geothermometers are based on temperature-dependent cation exchange reactions. For example, the Na-K geothermometer (Fournier, 1979; Giggenbach et al. 1988) uses the ratio of sodium to potassium based on the reaction between albite ($NaAlSi_3O_8 + K^+$) and the K-feldspar adularia ($KAlSi_3O_8 + Na^+$). The Na-K-Ca geothermometer (Fournier and Truesdell, 1973) was developed to deal with waters having high concentrations of calcium making the Na-K geothermometer unsuitable. However, high concentrations of Mg (>0.2 ppm) yield anomalously high results for the Na-K-Ca geothermometer. As a result the Mg correction for the Na-K-Ca geothermometer was developed to account for the higher Mg concentrations at temperatures less than 180 ^{o}C and where Mg is present in clays and carbonates. This correction was intended for unmixed waters although high magnesium concentrations are often an indication of mixing with a cooler groundwater component. Other cation geothermometers include the Na-Li geothermometer (Fouillac et al., 1981), which uses the ratio of sodium to lithium and is based on cation exchange reactions that take place with clays and zeolites and the K-Mg geothermometer (Giggenbach et al. 1988) which is useful when sodium and calcium have not equilibrated between fluid and rock.

2.4.2 Silica-Enthalpy Mixing Models

While the Quartz geothermometer is capable of correcting for steam loss due to boiling, none of the conventional geothermometers mentioned previously are capable of accounting for mixing. As a result, models were developed to better account for mixing. The silica-enthalpy mixing model used in this study is based on the positive relationship between silica solubility and increasing temperatures. However, in this model, respective enthalpies of sample waters calculated from field temperatures are used as plot coordinates rather than temperature because enthalpy is conserved as waters mix and boil whereas temperature is not (Fournier, 1977). This model can be applied with two separate scenarios. A trend line is drawn from the point representing the non-thermal component of the mixed water (lowest silica and enthalpy), through the mixed water from thermal springs. The intersection of this line with a silica solubility curve approximates the enthalpy of the hot-water component at reservoir conditions if there was no boiling prior to mixing. The enthalpy at the boiling temperature (100°C) which is 419 J/g is intersected with the projected trend line. From this intersection, a horizontal line is drawn to the quartz maximum steam loss line. This new enthalpy value can be used to calculate the reservoir temperature if boiling occurred prior to mixing (Fournier, 1977).

While mixing models have aided in making better predictions in areas where rapid simple mixing occurs, they are not comprehensive enough to compensate for reactive secondary processes that may affect waters prior to or after mixing. Finally, the prediction of a reservoir temperature based solely on two or three chemical species contains more error than is desirable. Estimations that utilize an entire reservoir mineral assemblage based on likely alteration minerals within the reservoir are considered, in theory, to provide much more accurate temperature predictions.

2.4.3 Multicomponent Equilibrium Geothermometry

Reed and Spycher developed the basic concept of multicomponent equilibrium geothermometry (MEG) in 1984. The major advantage of MEG over more conventional geothermometry techniques is the use of a reservoir mineral assemblage (RMA) that represents the full suite of minerals likely to be present in a geothermal reservoir. The approach uses the calculated ion activity products (Q) of chemical species within the RMA to determine the degree of saturation (log Q/K_T) where K_T is the temperature dependent mineral-water equilibrium constant. The temperature at which all minerals have near zero saturation indices is taken to be the temperature at which thermal fluid last equilibrated.

While there is an obvious advantage to utilizing an entire RMA as opposed to a few basis chemical species, MEG also allows for adjustments to be made to account for secondary alteration processes that effect calculated temperatures; including the amount of water gained (dilution/mixing) or lost (boiling) and the effects of degassing. The loss of CO_2 has been shown to affect the pH of geothermal waters and is commonly shown by the oversaturation of calcite (Palandri and Reed, 2001).

Despite the advantages of MEG over conventional geothermometry methods, there has been little application in geothermal assessment and development. Some previous investigators (e.g., D'Amore et al., 1987; Tole et al., 1993; Hull et al., 1987) have used this technique for predicting geothermal temperature. The first two of these authors utilized a MEG technique to predict reservoir temperatures and develop conceptual models. However, both noted the difficulty that secondary processes pose to predicting an accurate equilibrium temperature. Hull et al. (1987) made an attempt to account for the dilution of thermal water by a cooler groundwater component (similar to the ESRP conceptual model). They noted that the use of a real groundwater component from a nearby source was problematic due to the production of bulk compositions with negative molalities of Mg, Al, Fe, and Ca. The use of deionized water as a mixing agent resulted in more successful temperature predictions. Hull et al. (1987) explained this phenomena by stating that either 1) the nearby cold water component is dissimilar to the actual mixing agent or 2) the mixture of thermal water and groundwater undergoes additional reactions (precipitation, exchange, etc.) and thereby re-equilibrate at a cooler temperature or within a new host rock.

More recent efforts by some researchers (e.g., Bethke, 2008; Cooper et al., 2013; Neupane et al., 2013; Spycher et al., 2014; Neupane et al., 2014) have focused on improving temperature predictability of the MEG method. The two latest tools (computer codes) are the GeoT tool developed by Spycher et al. (2014) and the Reservoir Temperature Estimator (RTEst) tool developed by Palmer (2014). RTEst is the method used in this study. RTEst couples the React module of The Geochemist's Workbench® (GWB) (Bethke and Yeakel, 2012) and the optimization program PEST (Doherty, 2013) to optimize parameters including temperature, water, and CO_2 fugacity. RTEst works to obtain an estimated reservoir temperature by repeatedly calculating mineral saturation indices while allowing temperature, solvent mass, and CO_2 fugacity to fluctuate. The ultimate goal of this inverse modeling is to minimize the objective function Φ given here by:

$\Phi = \sum (SI_i w_i)^2$ where $SI = (\log Q/K_T)$ and w_i = weighting factor for a mineral.

The minimization of the objective function represents the minimization of the collective distances away from zero for all saturation indices within the RMA. In theory, the reservoir temperature is obtained when Φ is essentially zero. The weighting factor (w_i) ensures that each mineral contained in a chosen mineral assemblage is considered equally and the results are not skewed by reaction stoichiometry (Neupane et al., 2014).

2.4.4 High Temperature Water-Rock Interaction Experiments

Geothermal alteration in aqueous solutions has been extensively studied but application in geothermal reservoir characterization and development is limited. High temperature water-rock interaction experiments can provide valuable information on alteration temperature, rock composition, and especially fluid composition (Browne, 1978; Lesher et al., 1986; Reyes, 1990; Davis et al., 2003). Research into water-rock interaction at high temperatures began in the late 1950s. Khitarov (1959) investigated the interaction of high temperature waters with particular interest in granite, feldspars, and micas. Basharina (1958) successfully extracted many water-soluble constituents from an andesitic ash and in 1963, Ellis and Mahon targeted silicic volcanic rocks in particular comparing experimentally determined fluid compositions with natural ones in New Zealand.

Data from natural geothermal systems shows that local equilibria between geothermal fluids and alteration minerals controls major component concentration (except Cl^- and other mobile elements) in fluids at temperatures as low as 50 ^oC (Ellis, 1970; Arnórsson et al., 1983; Stefánsson and Arnórsson, 2002). Although primary rock type is important, it is considered to have less of an effect on geothermal alteration than permeability, temperature, and fluid composition (Henley and Ellis, 1983; Rodriguez, 2001). Browne (1978) showed that Quartz, K-feldspar, albite, chlorite, Fe-epidote, calcite, illite, and pyrite were the principal alteration minerals in many rock types including rhyolites, sandstones, basalts, and andesites. However, later studies showed that significant differences occur between alteration minerals in different rock types particularly at lower temperatures (<150 ^oC) (Bethke, 1986; Reyes, 1990; Mas et al., 2006, Weisenberger and Selbekk, 2009; Rodriguez, 2011). This study utilizes the differences in alteration minerals between silicic volcanic type rocks like the Idavada volcanics and the basalts of the ESRP in which smectite clays and zeolites are dominant (Morse and McCurry, 2002; Sant, 2012).

The aforementioned geochemical techniques are utilized in this study to better understand the role of mixing and re-equilibration within the Twin Falls – Banbury hydrothermal system and the implications such secondary processes have on geothermal temperature estimation within other areas of the ESRP.

CHAPTER 3: GEOCHEMISTRY OF THE THERMAL WATERS IN THE TWIN FALLS - BANBURY GEOTHERMAL AREA

The following section details the aqueous geochemistry for the Twin Falls – Banbury hydrothermal system as it relates to the problem of mixing between the deep thermal water and shallow groundwater components of the system. Water chemistry data from previous hydrothermal studies of both the Twin Falls and Banbury Hot Springs areas are compiled and combined here with the new data obtained from the 2014 ESRP sampling campaign in order to establish sufficient sample density to:

1) Classify the waters based on their respective chemistries;
2) Observe mixing and water-rock interaction trends with both conservative and reactive chemical species through the use of binary diagrams;
3) Observe the areal distribution of water types and its relation to local geology and geologic structures
4) Apply conventional geothermometry and mixing model techniques to all of the waters; and
5) Delineate appropriate mixing components for use within the multicomponent equilibrium geothermometry (MEG) tool RTEst.

3.1 Sample Chemistry

Sample compilation focused predominately on hydrothermal water samples within the study area but also include cooler groundwater samples from the assumed recharge zone located in the hills to south (to the east and south of the town of Robertson, ID). Interestingly, recharge area groundwater samples (4.5 – 12 ^{o}C) and cooler thermal waters within the region (< 30 ^{o}C) contain high amounts of silica (average 61 ppm) providing particularly valuable evidence for mixing (Arnórsson, 1985) in that high silica concentrations are likely due to mixing with a thermal component. Thermal waters range in temperature from 25 ^{o}C to 70 ^{o}C. Sample selection criteria include temperature, location, and extensiveness of chemical data (possessing data from both conservative [Cl^-, F^-, Li, B, δD] and reactive [Ca^{2+}, Mg^{2+}, K^+, Na^+, CO^{3-}, $SiO2^-$] species). Samples meeting the criteria were omitted only if they share the same location as a newly collected sample or lie outside of the study area. In this case is bound to the north by the Snake River which represents a groundwater boundary from the Twin Falls – Banbury area.

Chemical data for both the Banbury and Twin Falls area were compiled from four previous studies including the two isotopic studies conducted by R.H. Mariner et al. (1991 and 1997) and the USGS geothermometry studies of the Banbury (1982) and Twin Falls (1989) areas produced by R. E. Lewis and H.W. Young. These data sets are the most complete sets in terms of chemical constituents reported as compared to some of the earlier work presented in the Geothermal Investigations of Idaho series (Street and Detar, 1987; Young and Mitchell, 1974; Mitchell et al., 1980). Reported concentrations from these sources remain original and unaltered in this study with the exception of the calculation of total dissolved solids (TDS and the conversion of alkalinity listed as mg/L $CaCO_3$ to alkalinity as HCO_3 from samples originating from the Geothermal Resources in the Banbury Hot Springs Area (Lewis and Young, 1982). In total, 62 samples comprise the data set including 17 new samples collected under this study. Chemical concentrations are shown in Table 2. New samples contain trace elemental analyses that are absent from previous studies. New samples were collected primarily to satisfy the need for a more extensive chemical data set (particularly Al) to more effectively utilize the MEG tool RTEst. The new analyses enabled the use of a variety of hydrothermal alteration mineral assemblages comprised of various aluminosilicates.

Information regarding the chemical analysis of new samples as well as the QA/QC reports can be found in Appendix B. Charge balance calculations show that most waters are within ± 15% of a 1:1 charge balance and are presented in Appendix C. The waters range in TDS from as low as 62 mg/L in cold groundwater samples to 565 mg/L in thermal water samples. Waters from these samples seem to comprise two distinct groups based on differences in several constituents. One group of waters, which comprises a mix of all of the cold water samples and several thermal waters exhibit much higher calcium and magnesium concentrations and tend to have lower TDS concentrations than the other group. Groundwaters in the area and throughout the ESRP are considered Ca-Mg-HCO_3 in type and contain similarly high magnesium concentrations. This is to be expected as magnesium is largely absent in geothermal waters. Because of increased water-rock interaction at higher temperatures, magnesium is taken up by magnesium bearing clay minerals (Ellis, 1971; Fournier and Potter, 1979; Giggenbach, 1988). The second group of waters exhibits higher sodium, silica, chloride, and TDS concentrations. This is to be expected with ESRP geothermal waters due to the prograde relationship between temperature and solubility (chloride/silica) and the increase in cation-exchange reaction within deep rhyolites (sodium) (Fournier, 1977, Arnórsson, 1985; McLing et al., 2002). These differences and others are taken into account in the classification of the waters. Thermal waters were categorized in order to investigate the effects of secondary processes on thermal waters that may be shown in chemical trends between water types. Rather than arbitrarily separate the water types (i.e. graphically), multivariate cluster analysis was performed on selected chemical data.

Table 1. Chemical concentrations of hydrothermal water samples from the Twin Falls – Banbury area taken in 2014 for this study. All concentrations are given in units of mg/L. HCO_3 and CO_3 values are alkalinity measurements given in mg/L.

Site	Lat	Long	TEMP	pH	Ca	Mg	Na	K	Li	Cl	F	SO4	B	SiO2
8	42.69940	-114.91040	24.7	9.47	5.74	0.74	112.83	4.16	0.009	46.460	12.155	90.872	0.1897	52.04
9	42.64497	-114.78706	34.5	7.98	23.47	3.00	57.54	7.69	0.057	23.094	2.213	40.459	0.1074	71.89
10	42.64432	-114.78294	34.4	7.96	26.66	3.47	55.93	8.04	0.056	20.031	2.455	31.777	0.1057	69.37
11	42.69457	-114.85592	58.4	9.53	0.84	0.00	128.20	1.87	0.046	31.692	22.368	33.720	0.3320	99.53
12	42.54479	-114.94855	37.5	8.59	11.23	0.36	149.41	1.38	0.188	53.312	2.415	188.043	0.1167	45.54
13	42.54348	-114.94897	36.2	8.65	11.14	0.79	146.61	1.92	0.190	53.588	2.445	186.647	0.1135	48.37
14	42.58318	-114.47496	38.1	8.79	4.54	0.19	94.90	3.27	0.011	26.445	9.636	46.811	0.1501	64.23
40	42.70399	-114.85699	72.0	9.37	0.94	0.00	136.44	1.59	0.054	50.446	24.222	30.057	0.4988	93.53
42	42.68841	-114.82680	58.5	9.15	1.04	0.00	94.90	1.60	0.034	16.759	11.357	23.543	0.2190	102.85
45	42.66851	-114.82436	35.0	8.69	5.95	0.19	61.69	3.41	0.060	13.972	3.423	31.303	0.1290	54.05
46	42.66778	-114.82673	35.5	8.41	7.62	0.45	56.44	4.10	0.060	11.689	3.435	24.773	0.1318	54.47
48	42.70501	-114.85701	31.8	9.55	1.93	0.01	121.63	1.62	0.043	51.925	24.128	33.132	0.5790	83.31
51	42.58050	-114.47089	37.7	8.81	3.99	0.22	86.28	2.99	0.021	25.815	8.609	45.376	0.1851	60.92
52	42.59755	-114.40018	43.0	9.16	1.22	0.01	118.11	2.19	0.027	21.127	15.821	36.321	0.2846	69.27
53	42.61390	-114.48799	43.0	9.18	1.30	0.01	109.33	2.12	0.014	26.716	16.473	30.771	0.3172	71.55
54	42.57256	-114.45175	31.0	7.77	39.91	8.98	55.41	4.92	0.031	37.515	2.353	76.026	0.1073	59.11
55	42.57750	-114.28870	37.0	9.05	1.50	0.02	126.50	3.10	0.070	34.418	23.373	37.391	0.4955	66.02

Site	HCO3	dD	d18O	TDS	CO3	Be	Al	As	Rb	Sr	Ba	Br	NO3
8	80.52	-145	-18.3	396.5	-	<LOD	0.00703	0.04621	0.00423	0.02194	0.0012	0.796	1.211
9	143.96	-134	-17.0	251.6	-	<LOD	0.0001	0.00769	0.0188	0.15614	0.00356	0.374	5.372
10	126.88	-133	-17.2	292.5	-	<LOD	0.00019	0.00678	0.01918	0.17674	0.00187	0.351	4.746
11	92.72	-142	-18.0	422.5	-	<LOD	0.02234	0.06626	0.00617	0.00117	<LOD	ND	ND
12	95.16	-	-	559	-	<LOD	0.00492	0.02335	0.00494	0.06262	0.00636	0.818	1.435
13	97.6	-134	-17.0	565.5	-	<LOD	0.01628	0.02386	0.00737	0.0652	0.01489	2.975	ND
14	127	-134	-17.3	331.5	-	<LOD	0.00136	0.01742	0.00788	0.01879	0.0005	<LOD	4.893
40	212	-139	-17.8	494	-	0.0001	0.0744	0.0611	0.0084	0.0013	0.0004	ND	ND
42	168	-137	-17.5	331.5	-	<LOD	0.0146	0.0420	0.0067	0.0012	0.0004	ND	ND
45	140	-	-	227.5	-	0.0001	0.0023	0.0248	0.0085	0.0098	0.0009	0.037	ND
46	139	-	-	221.7	-	<LOD	0.0107	0.0176	0.0104	0.0176	0.0016	0.011	0.025
48	232	-	-	429	-	<LOD	0.0108	0.0604	0.0024	0.0074	0.0015	0.031	ND
51	153.72	-	-	312	-	0.0001	0.0028	0.0172	0.0072	0.0168	0.0006	ND	3.501
52	187.88	-	-	396.5	-	0.0003	0.0053	0.0143	0.0071	0.0024	0.0007	ND	36.824
53	153.72	-	-	377	-	<LOD	0.0042	0.0292	0.0045	0.0038	0.0002	ND	1.087
54	161.04	-	-	390	-	0.0001	0.0020	0.0060	0.0115	0.1854	0.0161	ND	6.737
55	246.44	-	-	422.5	-	<LOD	0.0236	0.1410	0.0086	0.0039	0.0019	ND	0.100

Table 2. Selected chemical concentrations of hydrothermal water samples from previous studies. All concentrations are given in units of mg/L. Decimal degree coordinates (WGS84) are approximated from original township and range values. Bold values correspond to TDS values generated by summing major cation and anion concentrations. Site names correspond to a particular study: LY82/89 = Lewis and Young, 1982; 89 and M91 = Mariner et al., 1991.

Site	Lat	Long	TEMP	pH	Ca	Mg	Na	K	Li	Cl	F	SO4	B	SiO2	Alkalinity as HCO3	δD	$\delta^{18}O$	TDS
M91-7	42.603164	-114.477722	39	9.3	1.6	0.06	96	2.8	0	15	11	20	-	67	145	-	-	331
M91-8	42.569362	-114.606826	27	8.6	5.1	0.17	61	4.3	0	11	3.6	16	-	77	134	-	-	253
M91-11	42.583616	-114.48118	30.5	8.6	8.6	0.4	74	6.3	0	21	11	26	-	55	121	-	-	267
M91-12	42.549979	-114.436857	30.5	7.8	37	6.8	31	4.9	0.03	31	1	51	-	50	100	-	-	266
M91-13	42.589664	-114.509924	41.5	9	1.7	0.08	130	2.5	0	36	26	28	-	60	195	-	-	408
M91-14	42.578624	-114.287802	42	9.2	1.5	0.01	120	1.9	0	17	14	32	-	66	207	-	-	-
LY89-1	42.66191	-114.812514	33	8.4	11	0.5	61	3.9	0.06	11	3.6	24	0.11	53	150	-132	-16.9	246
LY89-2	42.661228	-114.791887	37	8.1	13	1.2	58	4.1	0.06	12	3.6	25	0.09	60	140	-132	-17.2	246
LY89-3	42.654022	-114.795266	28.5	8	16	2.3	55	5.8	0.06	13	2.5	27	0.09	64	150	-	-	259
LY89-4	42.636971	-114.754192	26	8.3	7.4	0.2	62	5.6	0.08	9.9	4.8	21	0.014	82	140	-	-	262
LY89-5	42.646829	-114.785566	32.5	7.8	18	2.2	54	6	0.06	13	2.5	27	0.09	71	150	-131	-17.1	268
LY89-6	42.63448	-114.778469	25	8.1	17	1.1	53	7.5	0.05	14	2.4	22	0.02	87	160		-	283
LY89-7	42.597701	-114.760739	29	7.9	36	5.4	61	10	0.07	31	1.9	61	0.12	66	170	-130	-16.8	356
LY89-8	42.654938	-114.650688	44	9	1.5	0.1	96	1.5	0.03	14	16	24	0.2	75	78	-134	-17.2	304
LY89-9	42.648856	-114.652208	23	9.1	8.9	2.4	73	1.9	0.02	20	11	28	0.3	52	95	-	-	263
LY89-10	42.596158	-114.751276	31	8	39	5.6	65	11	0.07	38	1.7	75	0.1	72	160	-	-	388
LY89-11	42.631739	-114.597327	30.5	9	2	0.05	82	2.9	0.021	11	12	20	0.11	67	110	-131	-16.9	272
LY89-12	42.617975	-114.473657	27	9	1.9	0.1	110	3.5	0.02	10	22	18	0.33	82	140	-137	-17.7	341
LY89-13	42.615389	-114.488068	42	8.8	2.5	0.1	110	1.9	0.004	16	16	15	0.22	74	140	-135	-16.9	326
LY89-14	42.594962	-114.481012	39.5	9	1.9	0.1	99	1.9	0.006	15	14	25	0.16	66	110	-132	-17	301
LY89-15	42.605808	-114.478121	39	9.3	1.6	0.06	96	2.8	0	15	11	20	0.11	67	120	-138	-17	299
LY89-17	42.575903	-114.738609	25	8	35	4.5	63	12	0.07	35	1.6	69	0.08	71	160	-129	-16.4	371
LY89-18	42.566417	-114.490768	31.5	8	20	3.9	37	7	0.03	11	3.7	17	0.08	59	130	-127	-16.7	223
LY89-22	42.583859	-114.480819	30.5	9	8.6	0.4	74	6.3	0	21	11	26	0.1	55	110	-132	-17.1	262
LY89-29	42.395919	-114.691588	18.5	7.8	23	8.4	13	2.9	0.006	9	0.2	11	0.02	48	120	-123	-15.4	175
LY89-30	42.345552	-114.509176	37	8	31	13	43	11	0.05	6.3	1.9	21	0.12	19	270	-133	-17	279
LY89-32	42.27131	-114.359743	9	6.7	5.4	1.3	6	5	0.004	1.6	0.2	2	0.02	56	34	-127	-16.4	95
LY89-33	42.222385	-114.785594	12	7	7.2	1.2	5.9	2.6	0.004	3.1	0.2	5	0.02	35	30	-126	-17.1	76

Site	Lat	Long	TEMP	pH	Ca	Mg	Na	K	Li	Cl	F	SO4	B	SiO2	Alkalinity as HCO3	δD	δ^{18}O	TDS
LY89-34	42.20179	-114.664984	32	7.8	21	2	18	6.9	0.034	6.8	0.7	10	0.05	58	120	-130	-16.9	200
LY89-35	42.201144	-114.697878	26	7.5	22	2.6	19	5.8	0	6.4	6	12	0.01	60	110	-131	-16.7	183
LY89-36	42.158264	-114.66585	32	7.6	18	2.3	18	4.7	0.02	6.5	0.8	8.8	0.02	65	100	-132	-16.8	174
LY89-37	42.200441	-114.586984	7.5	7.6	34	5.4	19	3.6	0.004	16	0.3	17	0.06	52	120	-120	-14.6	208
LY89-38	42.213508	-114.306916	4.5	6	2.6	0.7	3.4	2.6	0.004	1.3	0.1	3.4	0.005	38	20	-123	-16.2	62
LY82-3	42.701575	-114.856527	62	9.4	0.7	0.1	150	1.4	0.05	48	15	35	0.49	84	168	-	-	**503**
LY82-4	42.701842	-114.854331	71.5	9.5	1.5	0.1	140	1.5	0.06	51	27	33	0.51	82	168	-	-	**505**
LY82-5	42.691328	-114.866789	57	9.4	0.9	0.1	130	1.5	0.04	34	21	34	0.34	86	177	-	-	**485**
LY82-6	42.6881	-114.84012	45.5	9.1	0.9	0.1	100	1.8	0.04	30	26	29	0.23	86	163	-	-	**438**
LY82-7	42.683574	-114.834978	42.5	9.3	1.3	0.1	90	1.7	0.04	14	9.4	28	0.17	67	148	-	-	**359**
LY82-11	42.684873	-114.829093	44.5	9.4	3.3	0.1	100	1.8	0.04	22	12	27	0.23	88	160	-	-	**414**
LY82-12	42.68251	-114.82902	30	9.3	0.9	0.1	97	1.6	0.03	20	13	28	0.21	64	154	-	-	**379**
LY82-13	42.599928	-114.943824	42	9.2	26	3.9	35	7.9	0.05	16	1.8	35	0.06	86	120	-	-	**331**
LY82-15	42.669042	-114.8236	34	8.7	5.4	0.2	66	2.9	0.05	13	3.7	30	0.12	56	124	-	-	**302**
LY82-18	42.661493	-114.814894	32	8.4	8	0.2	62	2.8	0.05	11	3.1	26	0.11	53	144	-	-	**310**
LY82-19	42.660011	-114.81414	31.5	8.6	7.5	0.3	63	2.8	0.05	11	3.2	26	0.12	51	134	-	-	**299**
LY82-20	42.658855	-114.810791	32.5	8.3	10	0.5	62	3.5	0.05	11	2.9	25	0.11	51	150	-	-	**316**

3.2 Principle Component and Hierarchical Cluster Analysis

With each sample being characterized by several chemical and physical variables, the aqueous geochemistry study of the area becomes a multivariate problem. The multivariate statistical method chosen for this study is hierarchical cluster analysis (HCA). This method was chosen as an unbiased means to separate waters into discrete groupings based on concentrations of several chemical components as opposed to the more graphical means provided by Piper diagram analysis. HCA is a widely utilized data classification practice in Earth sciences (Davis, 1986) and has begun to be utilized more extensively in groundwater geochemical studies in recent years (Meng and Maynard, 2001; Cloutier et al., 2008; Kanade and Gaikwad, 2011). HCA produces a hierarchy of clusters, ranging from small clusters of very similar items to larger clusters of increasingly dissimilar items without assuming any underlying trend in the data as opposed to several partitioning methods which assume a specific number of clusters outright. The measure of similarity in this instance of HCA is provided by the Euclidean distance, given by the Pythagorean Theorem. Sample groups are joined with a linkage rule until all of the observations are sorted into different clusters. The linkage method utilized in this study is Ward’s methods which uses an analysis of variance approach to establish the distance between clusters. Many studies have found that the use of the Euclidean distance and Ward’s method produce the most distinctive groupings within which samples are more or less homogeneous (Adar et al., 1992; Guler et al., 2002; and Zumlot et al., 2012).

It is usually suggested that prior to HCA, some sort data reduction be done in order to both gain insight into the correlation of variables and source of major variance, and ultimately to simplify the data into a more meaningful and manageable set. Principle component analysis

(PCA) is utilized for data reduction in this study. The premise of PCA is that every sample can be represented as a single point in a K-dimensional space (depending the number of variables being analyzed). All points within the data set can essentially be approximated by a single plane (whose axes are principle components and Eigen vectors) space by a least squares regression. The result is a few orthogonal components (Eigenvalue > 1) that explain the majority of the variance within the data set (Meng and Maynard, 2001).

PCA produces factor or component scores which are essentially coordinates corresponding to individual data points within each principle component. These scores can then be utilized in HCA as opposed to clustering based on the raw values for all variables. Like the Piper diagram analysis, major cations and anions were chosen in this study as the variables for PCA. Other constituents such as SiO^{2-} and F^- did not account for much of the variance within the data and were omitted. Both PCA and HCA ordinarily require a normal distribution of all variables included or a transformation is suggested. Key components (K^+ and Na^+) are normally distributed within this data set while other components contain a slight right skew. A log transformation was performed prior to PCA and HCA but resulted in erroneous partitioning of water samples incongruent with Piper diagram classification. For this reason, the data presented here are not transformed. The Eigenvalues for the principle components produced are shown below in Table 3. The principle components used are highlighted in bold.

Table 3. Principle components and corresponding % variance

	F1	F2	F3	F4	F5	F6	F7
Eigenvalue	**3.096**	**2.088**	**1.068**	0.373	0.210	0.111	0.054
Variability (%)	44.225	29.828	15.258	5.330	3.007	1.584	0.768
Cumulative %	**44.225**	**74.052**	**89.311**	94.641	97.648	99.232	100.0

Pearson's correlation coefficients are shown below in Table 4. Na^+ and Cl^-, K^+ and Ca^{2+}, Mg^+ and K^+, and SO_4^{2-} and Cl^- are all significantly and positively correlated as is the case in a majority of groundwater studies. In contrast, K^+ and Cl^- are shown to be very weakly correlated in this study where they are commonly correlated in many groundwater studies (Rani and Babu, 2008; Muthulakshmi et al., 2013). However, the groundwater samples in this study tend to have higher potassium concentrations and do not follow the $Na^+ > Ca^{2+} > Mg^+ > K^+$ trend exhibited in other studies. This source of potassium is significant in mixing trends and will be discussed further in section 3.5. Additionally, it is worth noting that bicarbonate alkalinity does not seem to be correlated strongly with any other chemical component and may not be useful in further evaluation of mixing trends. Figure 6 (below) is a biplot of the first two principle components representing about 74% of the variance within the data set. Negative and positive correlations can be seen here. It is important to note that SO_4^{2-} and HCO_3- lie close to the principle component (F2) axis meaning they are not responsible for much of the variance within the dataset.

Table 4. Pearson's (n) correlation table of PCA variables (chemical components)

Variables	Ca	Mg	Na	K	Cl	SO4	HCO3
Ca	**1**	0.855	-0.568	0.784	-0.021	0.184	0.012
Mg		**1**	-0.507	0.631	-0.073	0.059	0.135
Na			**1**	-0.518	0.715	0.436	0.421
K				**1**	-0.160	0.007	0.100
Cl					**1**	0.684	0.323
SO4						**1**	-0.019
HCO3							**1**

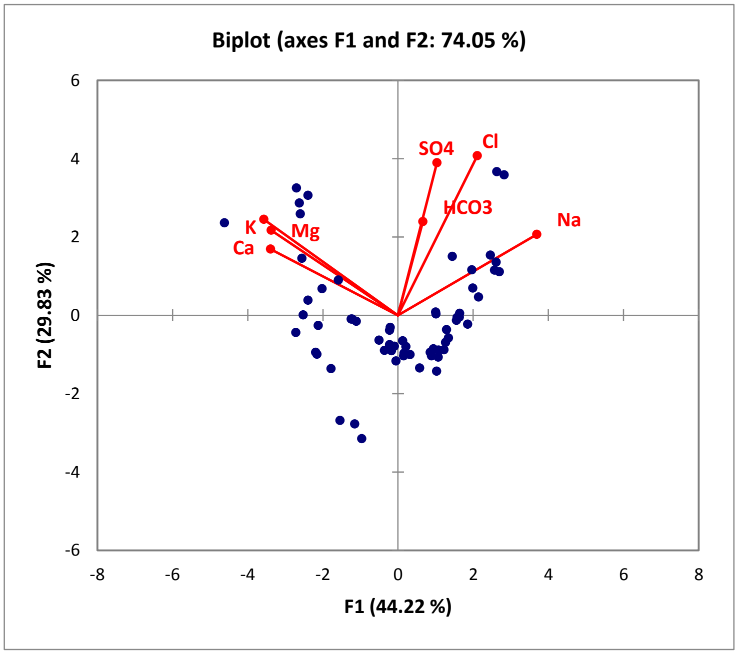


Figure 6. Biplot of principle components 1 and 2 with variables (red lines) and samples (blue dots

HCA was run using the XLSTAT ® add-in for Microsoft ® Excel. HCA was run using both principle component scores and raw chemical data. The PCA proved valuable in producing only three water types as opposed to the six produced without data reduction. The dendrograms in Figures 7 and 8 represent the final cluster output. Water types are listed in Tables 5-8 with the corresponding author initials and dates preceding the sample numbers. Two of the waters classified as type 3 waters (CC-12 and CC-13) are believed to have been influenced by local irrigation water (evident by much higher sulfate and chloride values than surrounding areas). For this reason, they have been grouped into type 2 waters for mixing trend applications. The waters fall into two main end members:

1) Na-HCO_3 (Type 1) waters characterized by high temperatures, high Na^+ concentrations, and low Ca^{2+} and Mg^+ concentrations.
2) Ca-HCO_3 (Type 2) waters characterized by lower temperatures, low Na^+ concentrations, and high Ca^{2+} and Mg^+ concentrations.

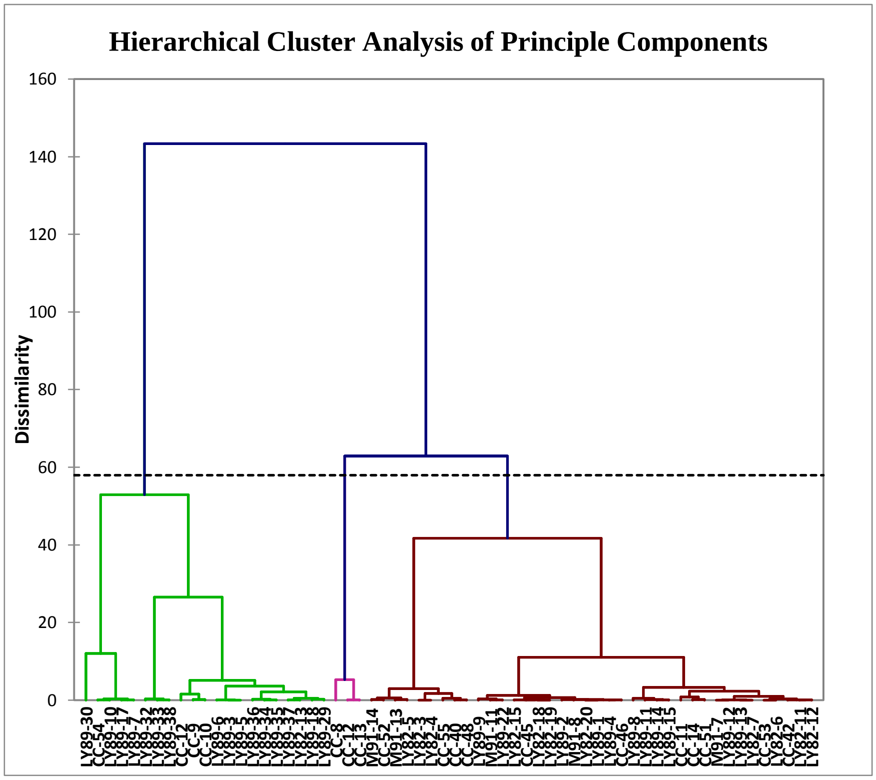


Figure 7. Dendrogram showing clusters of samples provided by HCA on principle components.

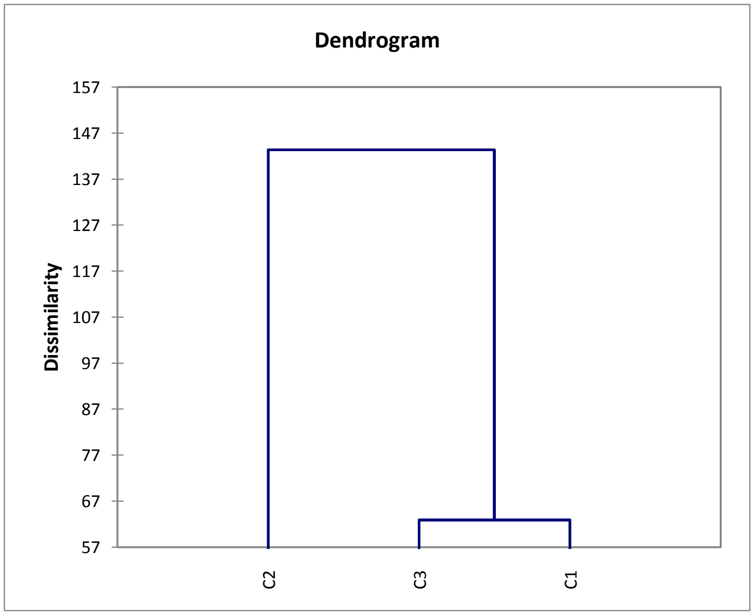


Figure 8. Simple dendrogram showing the resultant 3 water types.

3.3 Evidence for Mixing Between Thermal Water and Groundwater

After the completion of water classification by cluster analysis, the samples were plotted on a Piper diagram (Piper, 1944) to gain a visual representation of sample distribution. The Piper diagram is perhaps the most common method used in classifying waters (Fetter, 2001) due to it being an easy to comprehend graphical representation based on concentrations of all major anions (SO_4^{2-}, Cl^-, and $CO_3^{2-} + HCO_3^-$) and major cations (Ca^{2+}, Mg^{2+}, and $Na^+ + K^+$). Two separate trilinear diagrams are used to plot the relative percentages of cations and anions. These two separate points are then projected onto the Piper diagram diamond using a matrix transformation to form a single point, which can then be used to classify a water.

Earlier hydrothermal studies in regions of the ESRP have noted the characteristic trend between the two aforementioned end member waters (Mann, 1986; Wood and Lowe, 1988, Mariner et al., 1991; McLing et al., 2002). Na-HCO_3 type waters are generally associated with deeper groundwater sources with increased ion-exchange reactions replacing calcium with sodium during hydrothermal alteration of feldspars as a result of longer residence times and higher temperatures (White, 1967; Edmunds and Shand, 2009). Giggenbach (1991) described the formation of Ca-Na-HCO_3 and Ca-HCO_3 type thermal waters as a result of mixing with a ground water component like the Ca-Mg-HCO_3 waters that dominate the upper aquifer system of the ESRP (McLing et al., 2002; Wood and Lowe, 1988). Deep wells (> 1km) that penetrate the upper basalt hosted portion of the aquifer, e.g. the INEL-1 and Project Hotspot: Kimberly and Kimama wells (Shervais et al., 2013), reveal the pure Na-HCO_3 thermal end member. Mann (1986) described the change in composition from deep rhyolite hosted Na-HCO_3 water to mixed Ca-Na-HCO_3 basalt hosted water in the INEL-1. McLing et al. (2002) showed perhaps the best visual representation of this trend with a Piper diagram consisting of thermal waters throughout the ESRP. Lewis and Young (1989) also observed this trend in the Twin Falls area. However, due to sporadic and regional sample population and small sample density, these studies lacked a significant number of mixed intermediate Ca-Na-HCO_3 type samples to fully support this mixing hypothesis (Figure 9).

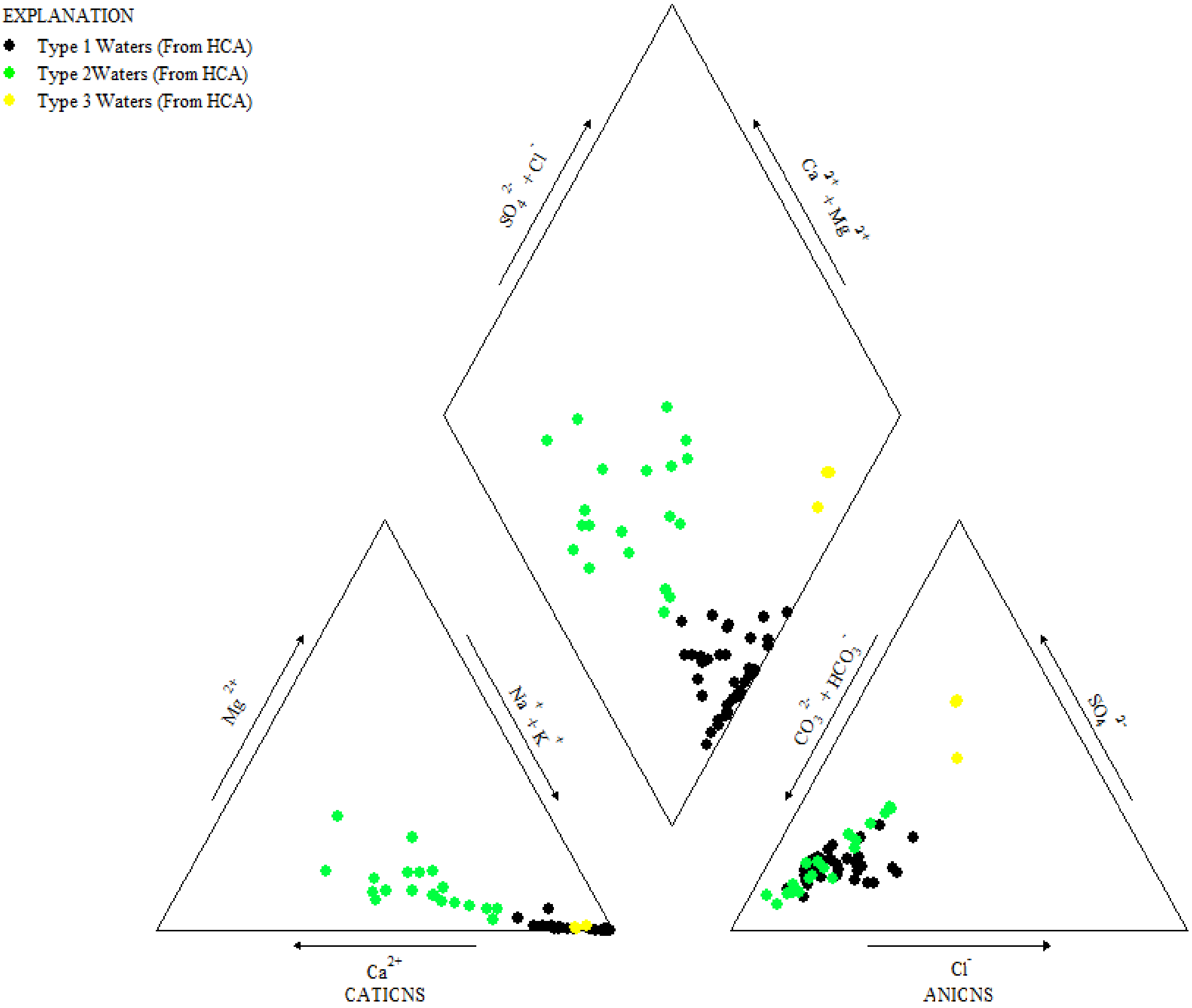


Figure 9. Piper trilinear diagram showing the relationship between Na-HCO_3 thermal waters (black) and Ca-HCO_3 thermal waters (green). Yellow samples appear to have been altered by nearby irrigation.

Piper diagram analysis for the 62 water samples utilized in this study gives a strong visual representation of the trend between water types. Figure 9 shows the distribution between Type 1 (Na-HCO_3) waters in the upper left corner of the diagram and Type 2 (Ca-

HCO_3) type waters in the lower right corner. A significant trend and overlap can be seen between water types. In particular, the trend observed in the cation portion of the diagram demonstrates the gradual exchange between Na^+ and Ca^{2+}. It is important to note that anion concentrations (Cl, HCO_3^-, and SO_4^{2-}) seem to be independent of water type and the degree of mixing.

Sample compositions are also plotted on a Giggenbach ternary diagram (Figure 10) to determine evidence of equilibration and/or mixing. The Giggenbach ternary diagram (1988) was developed as a means to classify waters into fully equilibrated (mature) waters, partially equilibrated, and immature waters (dissolution of rock without equilibration). The latter two categories show evidence of mixing with cool meteoric waters. The diagram uses the full range of equilibrium relationships between the Na, K, and Mg alteration minerals expected to form after recrystallization to determine the degree of equilibration between the water and the rock of thermal influence at depth. Few previous geothermal investigations in south central Idaho and the ESRP made use of the Giggenbach diagram as evidence for mixing. No previous studies in the Twin Falls – Banbury thermal area have utilized this diagram.

In Figure 10 below, most samples plot in the partially equilibrated and immature portions of the diagram with only a few plotting near or within the mature portion. The majority of Ca-HCO_3 type waters are grouped in the far right corner of the diagram reflecting the influence of high magnesium concentrations presumably from mixing with groundwater. Both the Piper and Giggenbach diagram sample distributions provide particularly valuable evidence for mixing in this area.

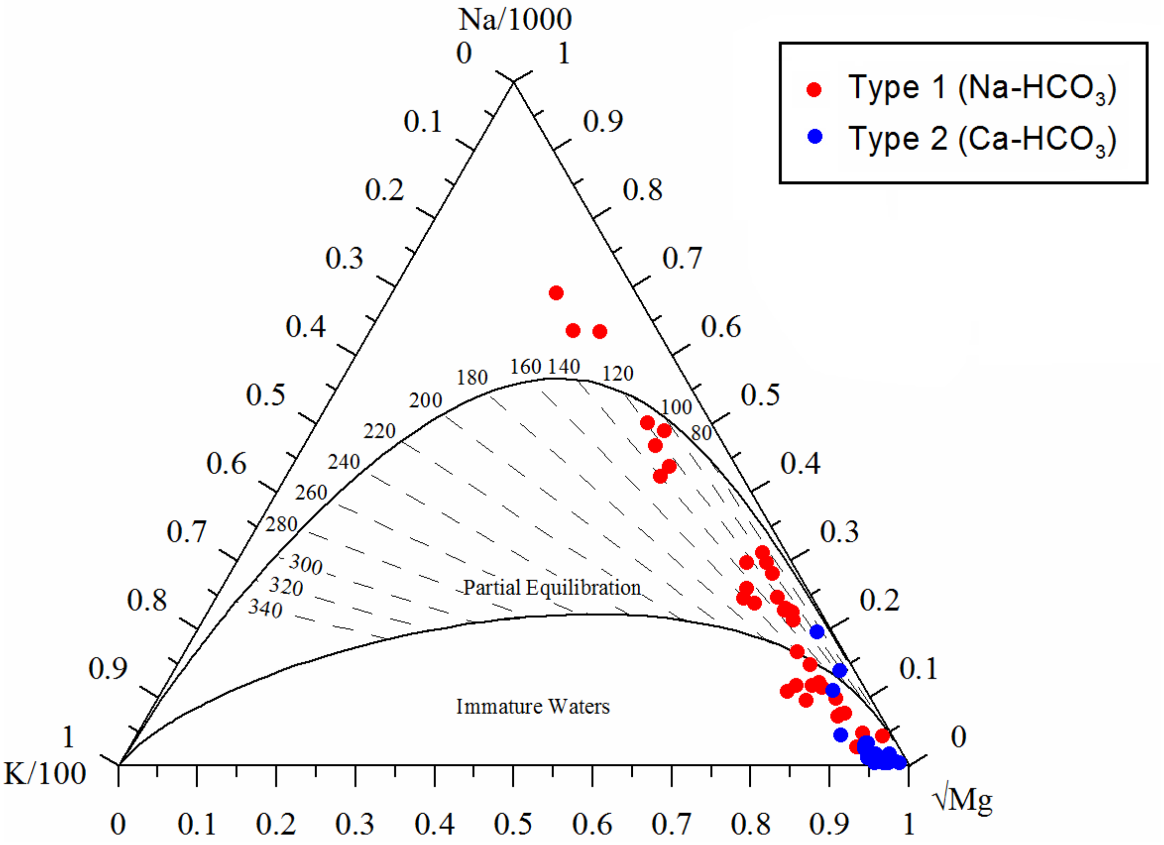


Figure 10. Giggenbach ternary diagram showing the distribution of the two water types with respect to degree of equilibration. Blue points represent Ca-HCO$_3$ thermal waters and red points represent Na-HCO$_3$ waters.

3.4 Binary Diagram Mixing Trend Analysis

Binary diagrams consisting of conservative species that are not be incorporated into geothermal minerals have been utilized in mixing evaluations for many years (Fournier, 1979; Arnórsson, 1985; Huenges and Ledru, 2011). The evaluation of linear relationships between components including Cl^-, B, F^- and δD provide particularly good evidence for mixing as the ratio between conservative elements will remain fixed as concentrations are simply lowered through dilution. This study utilizes mixing relationships between conservative components (non-reactive mixing) and also those between reactive components in order to obtain a more complete picture of the overall controls on mixing. Preliminary results show that the MEG tool RTEst does not result in satisfactory convergence of mineral saturation index lines when a local groundwater sample is mixed with Na-HCO$_3$ thermal waters. While Na-HCO$_3$ thermal waters show evidence for mixing, they may not mix directly with groundwater. Instead, an "intermediate" composition between the two thermal waters may be the mixing component. Additionally, secondary reactive processes may alter thermal waters after mixing resulting in re-equilibration. Binary diagram trends between the two water types may reveal controls on mixing in greater detail and may determine an intermediate end member composition for use in MEG reservoir temperature predictions.

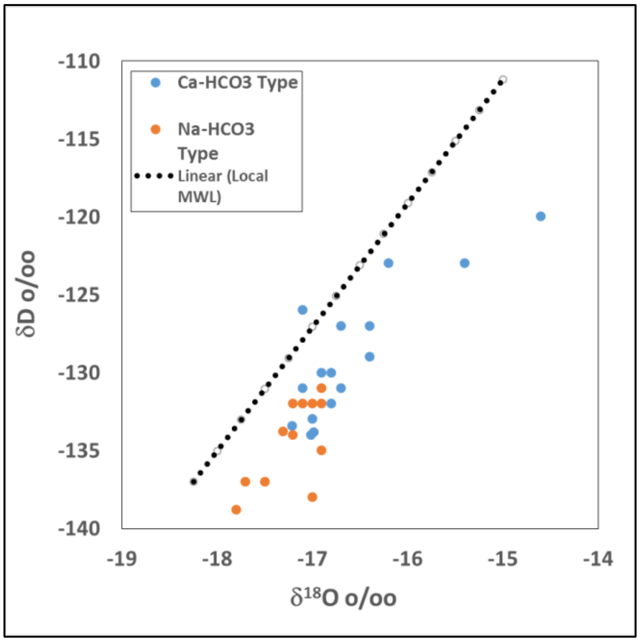


Figure 11. Plot of δD vs δ^{18}*O showing the shift of sample waters from the local meteoric water line.*

Thermal water samples with available deuterium and oxygen-18 isotope data are plotted in Figure 11 above. Samples display a significant right shift from the local meteoric water line (USGS, 2004). The isotopic shift in ^{18}O is typical of geothermal waters and is most likely a result of increased water-rock interaction at depth resulting in oxygen enrichment (Taylor, 1974; Clark, 2015). Deuterium shifts, on the other hand, are likely not explained by any hydrothermal process as it is conserved through these processes. A likely explanation is that recharge occurred during an older and colder time (Pleistocene) in which precipitation concentrations were isotopically lighter with respect to deuterium. This explanation is consistent with carbon-14 age data of waters in the area provided by Mariner et al. (1991). Another possible explanation for shifts in δD concentration is the enrichment of deuterium through isotopic fractionation due to boiling (Bottinga, 1968; Taylor, 1974; Truesdell, et al.; 1978) .The possibility of boiling is discussed further in chapter 4.2. The relationship between these two isotopes shows a gradational trend with waters becoming more depleted with

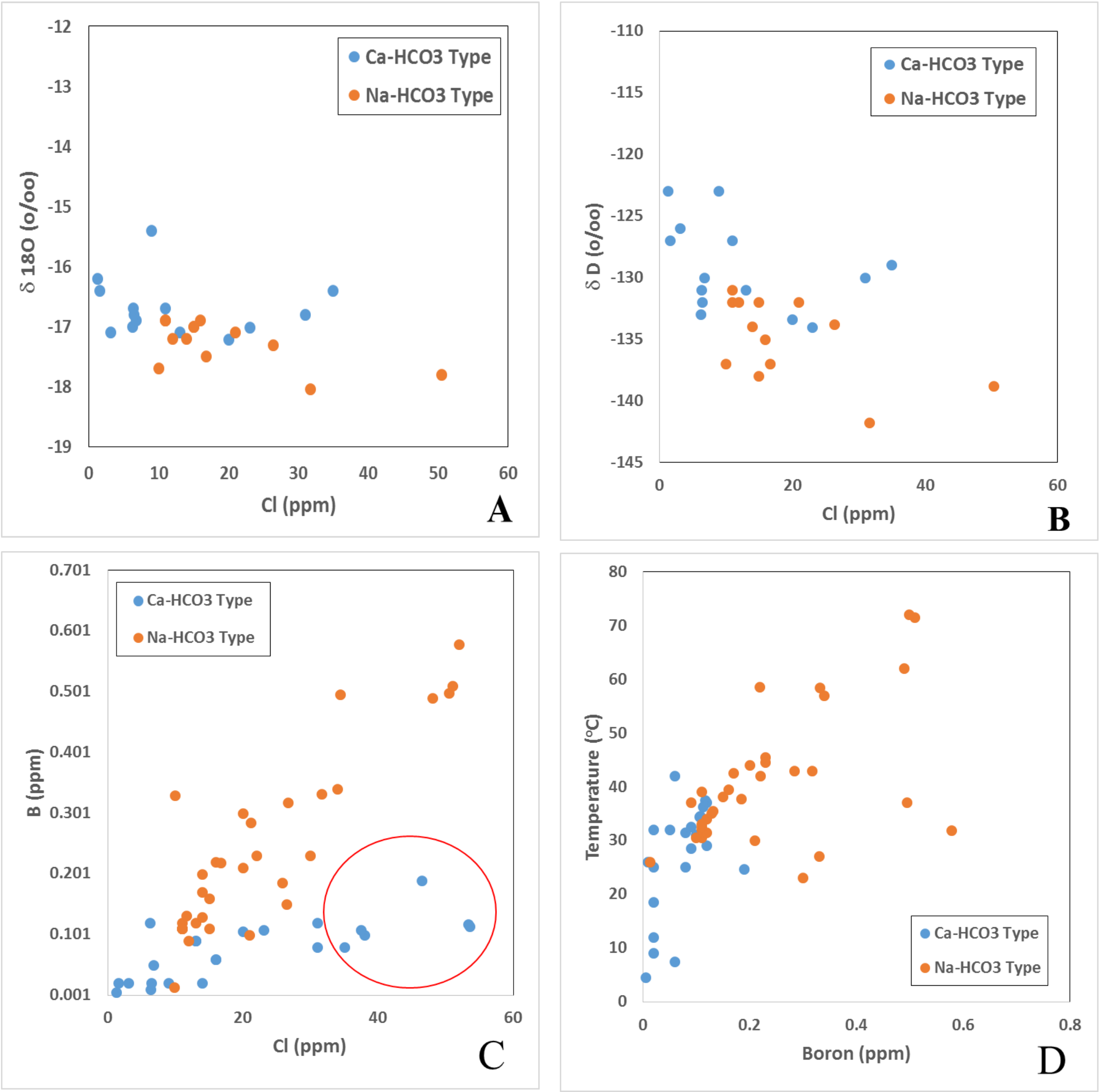


Figure 12. Plots of conservative components (Cl^-, B, δ^{18}O, and δD).

respect to oxygen-18 in the deeper Na-HCO$_3$ type waters.

Gradational trends between conservative constituents such as boron and chloride are thought to constitute some of the best evidence for mixing (Huenges and Ledru, 2011). Boron and chloride concentrations are much higher in geothermal waters than in cold waters as can be seen by the linear relationship between boron and surface water temperature in the Figure 12D. The ratio of chloride to boron will not be affected by mixing, as these constituents are not considered to be incorporated into geothermal minerals. The concentrations will simply decrease with dilution from mixing between thermal and cold waters will result in a steady decline as seen in Figure 12C with a B/Cl$^-$ slope of about 0.1/10 with the exception of a few circled values from the Lewis and Young (1982) study. The intersection of the Cl$^-$/B trend is expected to meet the chloride axis in the range of 10 ppm (chloride precipitation and cold water range) with a 0 ppm boron concentration (Arnórsson, 1985). Linear relationships between these two components and δ^{18}O and δ^2H also constitute sufficient evidence for mixing (Huenges and Ledru, 2011).

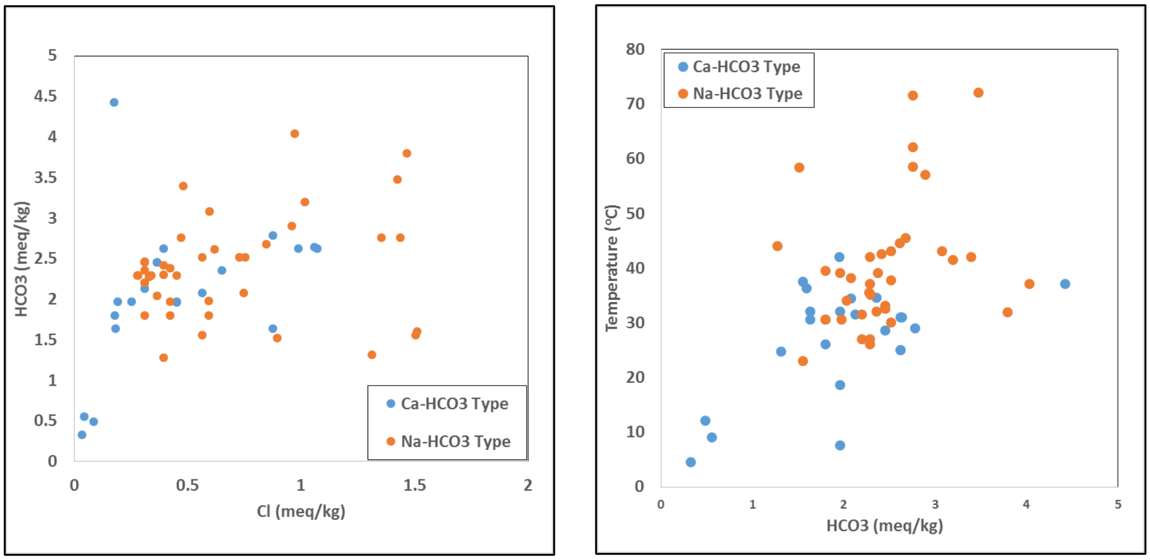
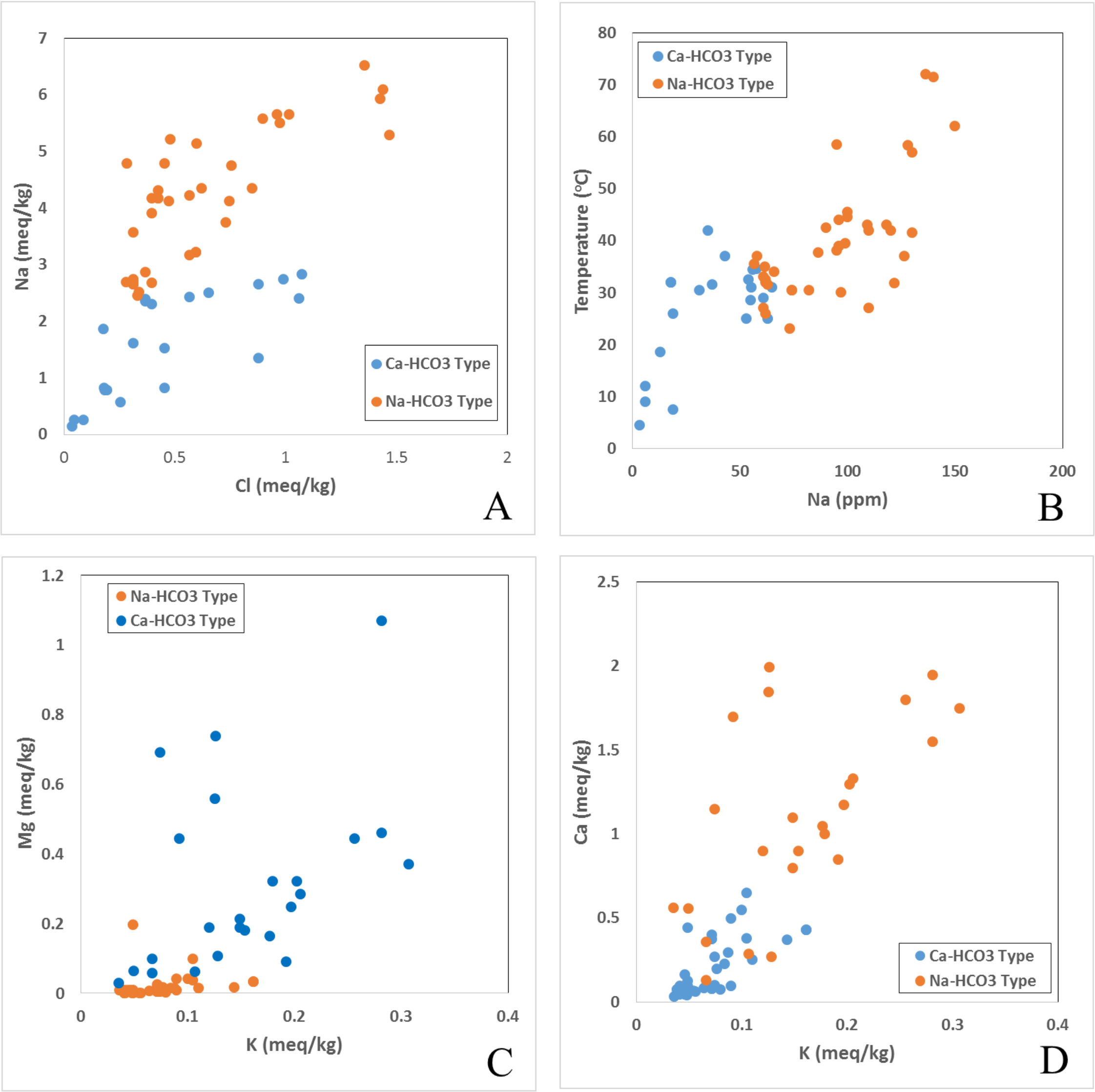


Figure 13. Plot showing the lack of relationship between HCO3$^-$and Cl- and Temperature.

It is important to note that some chemical components cannot be used in distinguishing between the two waters and that no mixing trend may manifest itself. This is the case with carbonate alkalinity of this system, seen in Figure 13 above. There does not appear to be any discernible relationship between bicarbonate concentrations and temperature or chloride. This observation signifies that bicarbonate concentration acts



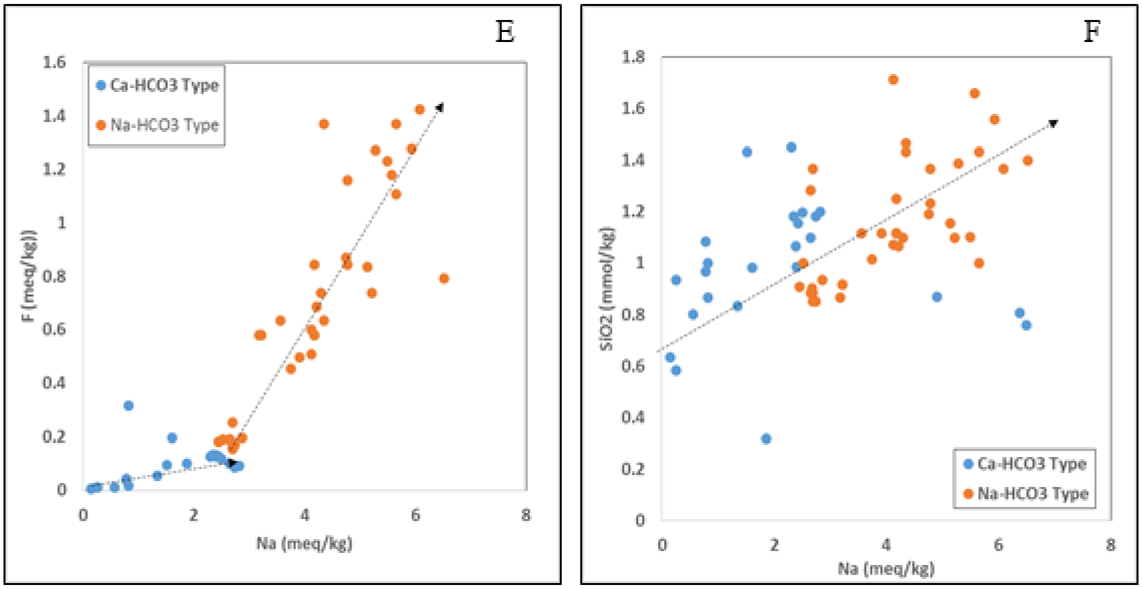


Figure 14. Binary plots between several reactive components showing simple mixing relationships.

independently of the mixing process. For this reason, either a local groundwater bicarbonate concentration or an average bicarbonate concentration should be utilized in RTEst modeling.

When examining relationships between major cations and anions for the thermal water samples, some distinct linear relationships become evident. The Na^+/Cl^- relationship as well as the Na^+ vs temperature relationship observed in Figures 14A and B shows the distinct transition between the sodium rich thermal end member to cooler more dilute waters. The Na^+/Cl^- trend passes through the origin signifying that little to no sodium and chloride need to be utilized in the dilution portion of MEG modeling. Figures 14 C and D show the positive relationship between both Mg^{2+} and K^+ and Ca^{2+} and K^+. Na-HCO_3 thermal waters are depleted with respect to Mg^+ and K^+ compared with the Ca-HCO_3 type waters. The Na-HCO_3 type waters begin with virtually no magnesium and grade into higher concentrations perhaps with increasing dilution. The same trend is seen between Ca^{2+} and K^+ where Na-HCO_3 type waters begin with little to no calcium and grade into more calcium rich waters. An important observation gained here is that if an “intermediate” reactive mixing component is to be used in RTEst modeling, it will require the addition of potassium.

Fluoride concentrations in the thermal water samples yield two separate trends. The Ca-HCO$_3$ type waters contain little to no amount of fluoride while the Na-HCO$_3$ type shows a steep trend in fluoride concentrations. Elevated fluoride concentrations are common throughout the ESRP and are often attributed to increased reaction with rhyolites (Mitchell et al., 1980). The sharp separation in fluoride trends between the two waters could signify that the Ca-HCO$_3$ type waters are mixed with a small amount of thermal water or have had little water-rock interaction with rhyolites. There is also a positive relationship between SiO$_2^-$ and Na$^+$ as shown in Figure 14 F showing increased silica concentration towards Na-HCO$_3$ thermal end member waters. Unlike many other solute trends, which begin at near zero concentrations, SiO$_2^-$ begins at around 40 ppm corresponding to high SiO$_2^-$ concentrations in the groundwater of the study area compared to most of the ESRPA (Lewis and Young, 1989).

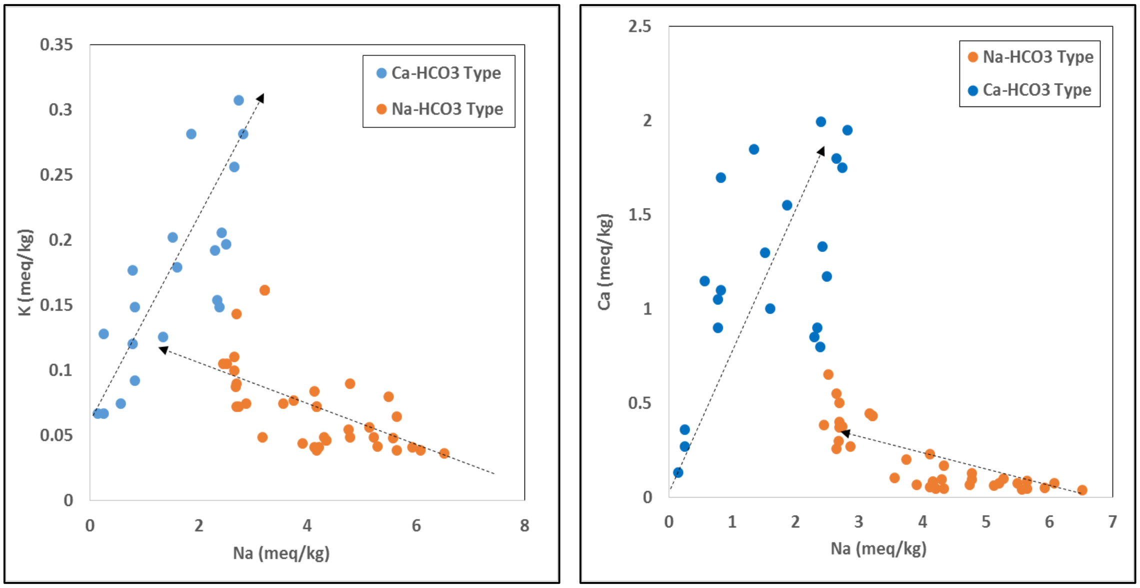


Figure 15. Binary plots showing the complex relationship between Na$^+$ and K$^+$ and Na$^+$ and Ca^{2+}

While the previously discussed relationships have been relatively simple, the relationships between K^+, Ca^{2+}, and Mg^{2+} vs Na^+ are more complex. In both these trends (shown in Figure 15 above) there is a sharp near-vertical boundary that separates the trends of the two water types. Possible explanations for the sharp increase in Ca^{2+} and K^+ exhibited by the Ca-HCO_3 type waters include:

1) A significant source of Ca^{2+}, K^+, and Mg^{2+} within the basalts and sediments of the Banbury formation that overly the rhyolites of the Idavada volcanics (source of Na-HCO_3 waters).
2) Re-equilibration via an exchange reaction resulting in an increase in Na^+ and K^+ and a decrease in Ca^{2+} and Mg^{2+} concentrations resulting in the formation of Ca-HCO_3 thermal waters.
3) Two separate and distinct flow paths (different temperatures and host rocks) resulting in the two thermal water types.

The use of binary diagrams presented in this section provides support for mixing between thermal water and groundwater as well as provides information about the concentrations of constituents to be used in the mixing portion of inverse MEG modeling. Mixing and/or re-equilibration mechanisms will be explored further in Chapters 4-6.

3.5 Areal and Geologic Distribution of Water Types

Water samples were plotted by type (according to HCA) on digital orthoimagery (USDA, 2011) and geologic maps (Gillerman et al., 2005; Othberg et al., 2005). The spatial distribution shown below in Figure 16 shows the progression from Ca-HCO_3 type waters from the Cassia Mountain recharge zone to Na-HCO_3 type waters towards the boundary of the Snake River. Figure 16 shows the direction of groundwater movement from a potentiometric surface created using water level data from the USGS National Water Information System. Figures 17 and 18 show detailed views of the Banbury and Twin Falls area clusters. All of the thermal samples within the Banbury cluster fall along a major normal fault, which parallels the path of the Snake River. This distribution shows the gradation from Ca-HCO_3^- type waters to more thermal Na-HCO_3^- type waters northward along the fault away from the recharge zone. A likely scenario for this observed gradation is the ascension of thermal waters through the normal fault and the increase in the amount of mixing southward of the fault. The Twin Falls cluster shows the same gradation away from the area of recharge towards the Snake River. Shervais et al. (2013) suggest that the thermal system in the Twin Falls area is controlled by a caldera margin. The geology and hydrology of these two areas will be discussed further in Chapter 5.

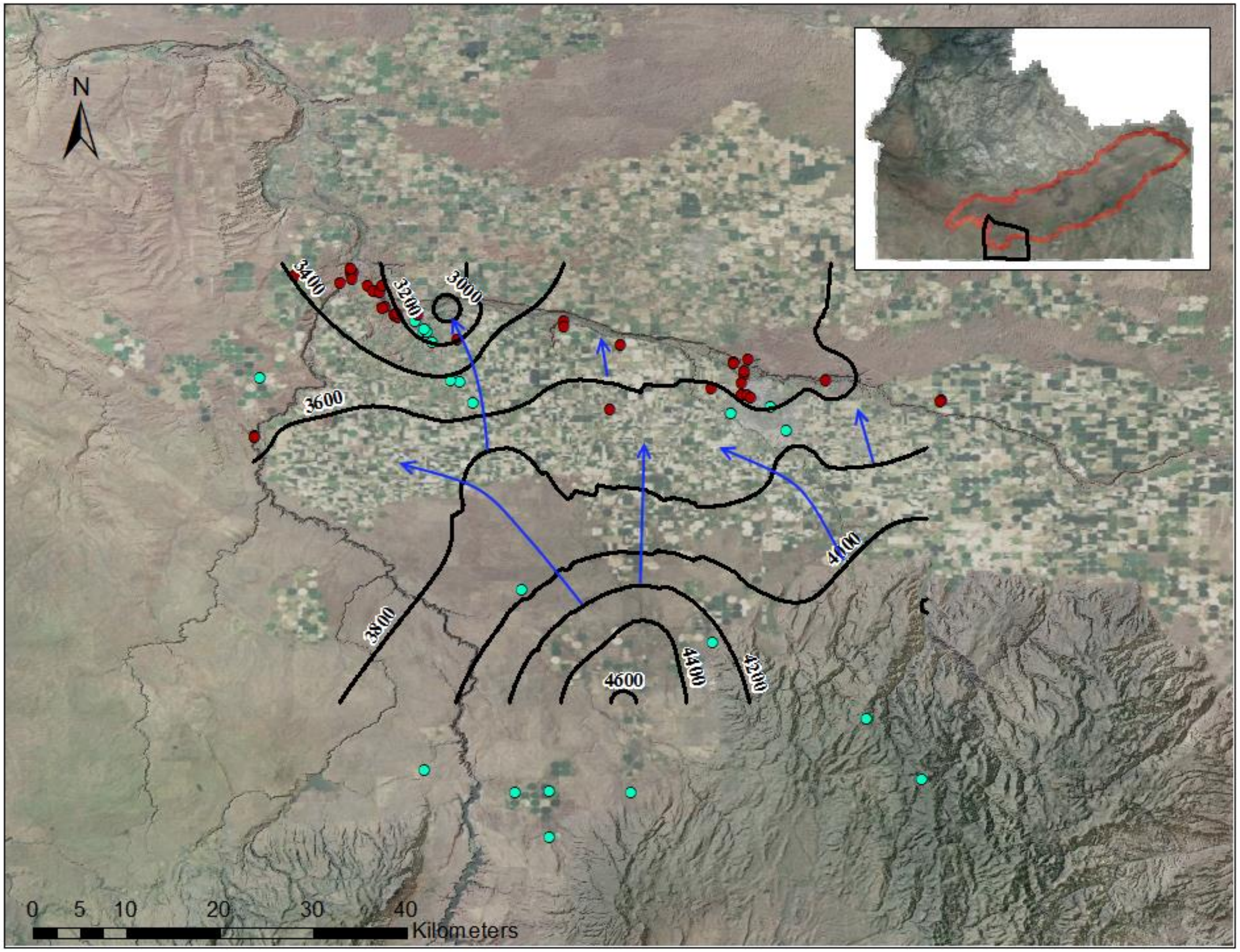


Figure 16. Map of water samples showing the gradation from $Ca\text{-}HCO_3^-$ *type (blue) waters to* $Na\text{-}HCO3^-$ *type waters (red) away from the recharge zone. Groundwater flow lines (blue) produced from inverse distance weighting of water level data from the USGS National Water Information System.*

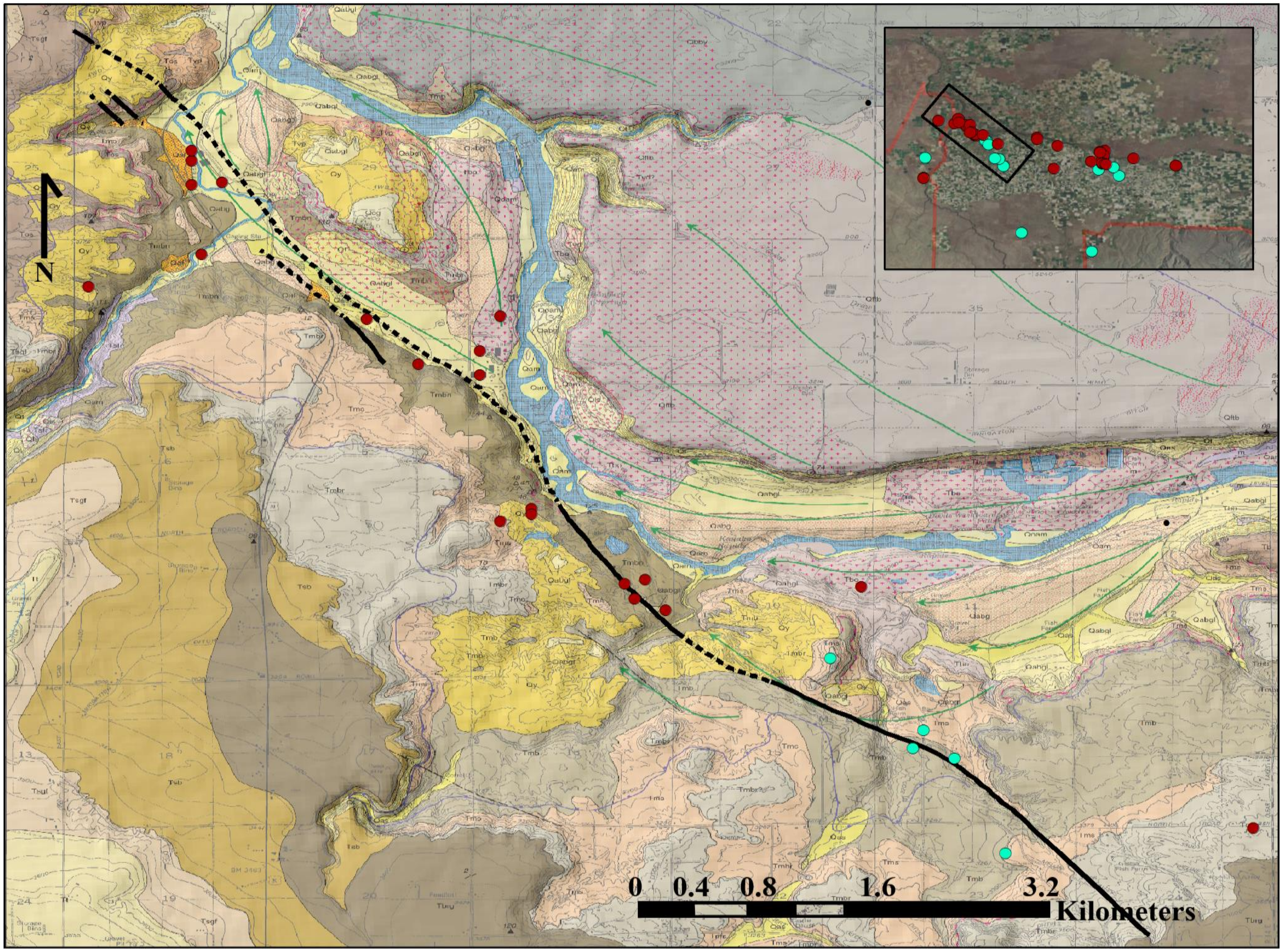


Figure 17. Banbury thermal area geologic map showing distribution of Ca-HCO$_3$ (blue) and Na-HCO$_3$ (red) waters along a normal fault. Geologic map (Gillerman et al., 2005) shows transition from Tertiary basalt flows south of the river to Quaternary basalt flows to the north. Green lines represent flood lines of the Bonneville Flood (c.15 ka). Red stipple areas correspond to dune trends.

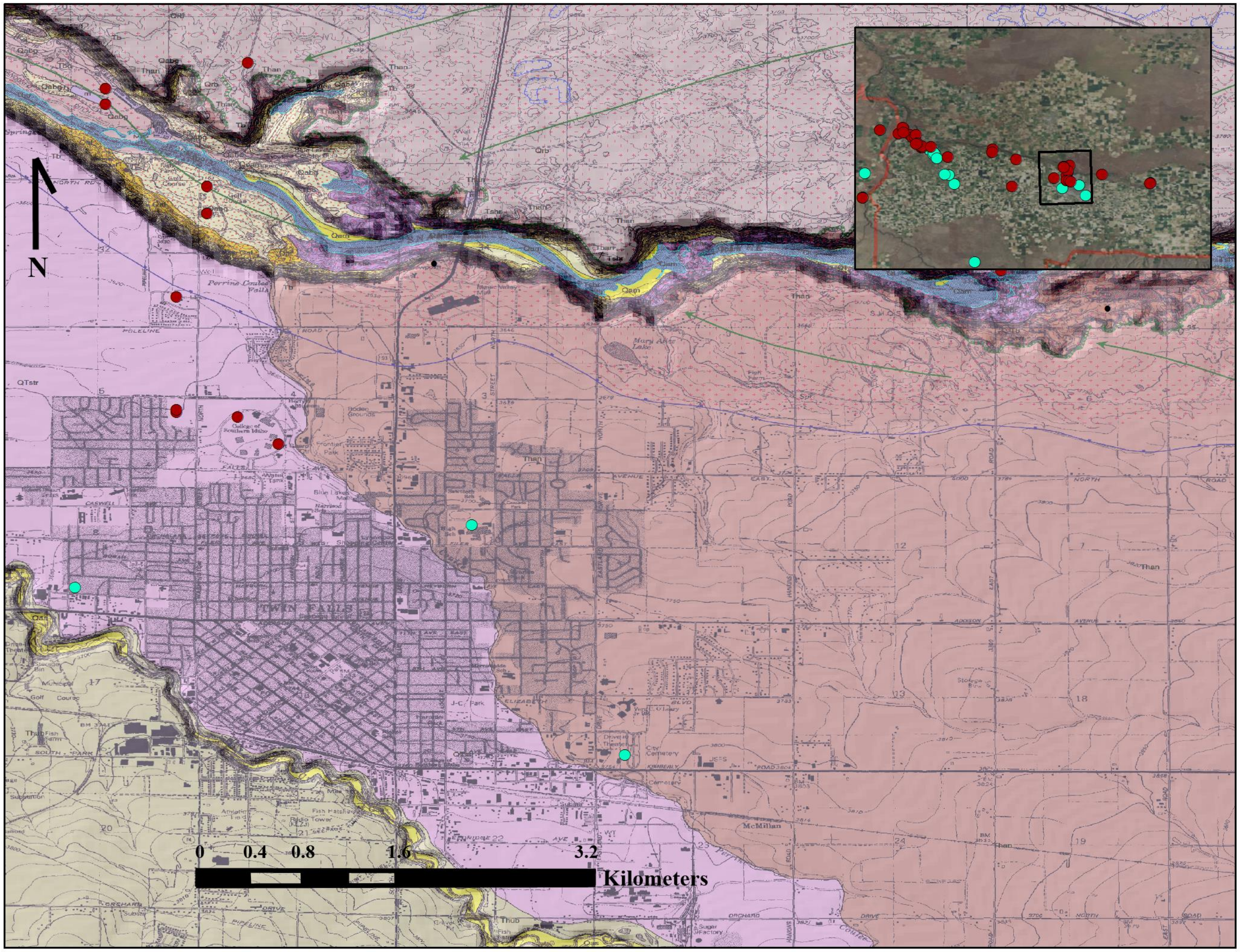


Figure 18. Twin Falls thermal area showing distribution of Ca-HCO$_3$- (blue) and Na-HCO$_3^-$ (red) waters. Geologic map (Othberg et al., 2005) shows the contacts between different Quaternary basalt flows south of the river and the outcropping of Idavada Volcanics (Shoshone Falls Rhyolite) near the river (dark purple).

CHAPTER 4: GEOTHERMOMETRY ESTIMATION OF RESERVOIR TEMPERATURES IN THE TWIN FALLS – BANBURY THERMAL AREA

The following section details the various approaches to calculate reservoir temperatures using geothermometry techniques as well as account for the effects of the mixing described in the previous section. Conventional along with recently developed techniques are utilized in order to show differences in temperature estimation and also to account for both simple and reactive mixing. While chemical and isotope geothermometry have been applied to the Twin Falls – Banbury area, mixing models and multicomponent equilibrium geothermometry techniques have not been applied prior to this study.

4.1 Conventional Geothermometry

Conventional geothermometers (as referred to in this study) are empirically or experimentally determined equations that are often utilized in geothermal exploration to predict deep reservoir temperatures from surface expressions or water wells. They are based on the relationship between fluid constituents (solutes, gases, and isotopes of elements) and fluid temperature. Most are based on temperature dependent chemical equilibrium reactions involving an assemblage of hydrothermally altered minerals. Various solute geothermometers have been continuously developed and improved upon since the 1960s. Of the many chemical and isotope geothermometers developed, the most prevalent cation geothermometers and silica geothermometers will be discussed and utilized in this study. It is important to note that all of the geothermometers discussed in this section make several key assumptions as outlined by Fournier et al. (1974):

1) Dissolved “indicator” constituent concentrations are fixed by temperature-dependent reactions between water and rock.
2) An adequate supply of all reactants is available.
3) Equilibrium with respect to indicator constituents in the reservoir is attained.
4) No re-equilibration occurs after the water leaves the reservoir
5) There is no mixing of different waters during ascension.

The assumption of equilibrium has been generally accepted as valid in the geothermal community through the study of well discharges among several geothermal fields. However, the assumption that no secondary processes have altered the fluid during its ascent from reservoir to the surface is rarely a reality. Fluids may cool adiabatically (boil) during ascent or mix with more dilute waters resulting in oversaturation and undersaturation of certain geothermal indicator constituents respectively. While some conventional geothermometers have attempted to account for the effects of boiling, none of the conventional geothermometers presented herein have accounted for dilution. For these reasons, it is important to keep the limitations and suitability of a particular geothermometer to a rock/fluid type in mind when utilizing for temperature estimation.

4.1.1 Silica Geothermometers

Silica geothermometers were first proposed by Fournier and Rowe (1966). They are based on the prograde relationship between silica solubility and rising fluid temperature. They are widely used in almost all geochemical investigations of geothermal systems around the world (Verma, 2000). Silica geothermometers have been developed for a variety of silica mineral species but they are based on the basic reaction producing dissolved silica in the form H_4SiO_4 from various silica minerals:

$$SiO_2\,(s) + 2H_2O \rightarrow H_4SiO_4\,(aq)$$

Dissolved silica concentrations in most natural waters are not influenced by “common ion effects” or the formation of complex ions like other geothermal indicators (Fournier, 1977). Additionally, the assumption of adequate reactant supply is generally valid for dissolved silica. In the case of the Twin Falls – Banbury thermal area, thermal waters are hosted within rhyolites of the Idavada volcanics making the silica geothermometers the most appropriate of the conventional geothermometers for temperature estimation.

Quartz solubility seems to control the dissolved silica content of most geothermal systems > 180 ^{o}C. Quartz geothermometers are suggested for use in the temperature range of 120-330 ^{o}C if certain conditions are met: equilibrium with quartz, pore-fluid pressure fixed by vapor pressure of pure water, no mixing, no conductive cooling or adiabatic cooling (Fournier and Rowe, 1966). The quartz geothermometer was later modified to account for oversaturation produced by steam loss (Fournier, 1973). Two geothermometers were produced, one based on silica concentration with maximum steam loss at 100 ^{o}C and one with no steam loss at all. However, the most widely used quartz geothermometer was developed by Fournier and Potter (1982). All are shown below where concentrations of silica (SiO_2 and S) are in units of mg/kg.

Quartz - Maximum Steam Loss (Fournier, 1977)

$$t = \frac{1522}{5.75 - \log(SiO_2)} - 273.15$$

Quartz - No Steam Loss (Fournier, 1977)

$$t = \frac{1309}{5.19 - \log(SiO_2)} - 273.15$$

Quartz Geothermometer (Fournier and Potter, 1982)

$$t = -42.198 + 2.883x10^{-1}S - 3.668x10^{-4}S^2 + 3.1665x10^{-7}S^3 + 70.34\log S$$

Another widely utilized silica geothermometer is the chalcedony geothermometer. Chalcedony is widely regarded to be applicable for lower temperatures. However, Fournier (1991) pointed out the ambiguity between Quartz and Chalcedony as quartz controls solubility below 180 ^{o}C at some locations and chalcedony at others. Residence time, fluid temperature, rock type and fluid type all effect the controlling phase. Chalcedony, which is comprised largely of very fine quartz and mogonite crystals, probably all changes to quartz with time which makes the age of a thermal fluid of particular importance (Gíslason et al., 1997).

Chalcedony – Maximum Steam Loss (Arnòrsson et al., 1983)

$$t = \frac{1264}{5.31 - \log(SiO_2)} - 273.15$$

Chalcedony – No Steam Loss (Arnòrsson et al., 1983)

$$t = \frac{1112}{4.91 - \log(SiO_2)} - 273.15$$

A less commonly applied silica geothermometer is the amorphous silica geothermometer (Fournier, 1977). Due to the much higher solubility of amorphous silica compared to other silica polymorphs (Figure 19 below), the amorphous silica geothermometer yields very low temperature estimates for waters if amorphous silica is not the dominant species.

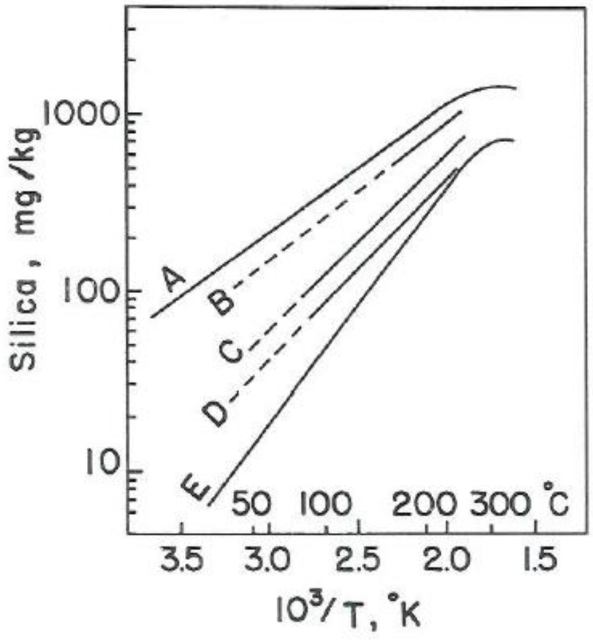


Figure 19. Solubility of silica polymorphs vs. temperature: A = Amorphous silica, B = Opal – CT, C = α-cristobalite, D = chalcedony, and E = quartz (Fournier, 1977).

Amorphous Silica (Fournier, 1977)

$$t = \frac{731}{4.52 - \log(SiO_2)} - 273.15$$

Unfortunately, there is a wide dispersion in temperature predictions amongst silica geothermometers even when applying one geothermometer to all the wells in a geothermal field (Verma, 2000). This is primarily due to secondary alteration effects: steam loss, mixing, and re-equilibration (Trusedell and Fournier, 1977).

The silica geothermometers applied to the two water types of the Twin Falls – Banbury thermal area give varied results with the chalcedony temperature estimates being consistently less than the quartz estimates. This is to be expected and the amorphous silica estimates yielding unrealistically low (below surface temperature and negative values). Overall, The Ca-HCO_3 type waters yield lower temperature estimates than the Na-HCO_3 type waters due to the higher silica concentrations of the Na-HCO_3 type waters. Quartz temperature estimates for the Na-HCO_3 type waters averaged 117 ^oC with a 36 ^oC range between all measurements while the Ca-HCO_3 type waters yielded a 108 ^oC average with a much higher range of 68 ^oC due to the larger range of SiO_2^- concentrations. Chalcedony temperature estimates yield an average of 91 ^oC with a 39 ^oC range for the Na-HCO_3 type waters while the Ca-HCO_3 type waters averaged 80 ^oC with a range of 73 ^oC. There appears to be no significant correlation between silica-based predicted temperatures and field temperatures with many cooler water samples yielding higher estimates than some hotter samples.

4.1.2 Cation Geothermometers

The other often utilized type of chemical geothermometers are called cation geothermometers. These geothermometers are based on empirical and experimental cation exchange reactions with temperature-dependent equilibrium constants. A widely used cation geothermometer is the Na/K geothermometer (Fournier, 1979; Giggenbach 1988; Truesdell, 1976; Arnòrsson et al., 1983) based on the exchange of Na^+ and K^+ between two coexisting alkali feldspars like the exchange between albite and various K-feldspars shown in the equation below.

$$NaAlSi_3O_8 + K^+ \rightarrow KAlSi_3O_8 + Na^+$$

The reaction results in a decreasing Na/K ratio with increasing fluid temperature. While ratios may be still affected by secondary processes they are considered less likely to be affected by dilution and steam loss. The Na/K geothermometer is suitable for temperatures between 100 ^{o}C and 350 ^{o}C as it is slower to re-equilibrate than the quartz geothermometers. However, the Na/K geothermometer is not useful in acidic waters which would not be in equilibrium with feldspars. More importantly for this study, the Na/K geothermometer is not useful in waters with high calcium concentrations like many of the mixed thermal waters found in and around the ESRP.

Na/K (Truesdell, 1976)

$$t = \frac{856}{\log(\frac{Na}{K})+0.857} - 273.15$$

Na/K (Fournier, 1979)

$$t = \frac{1217}{\log(\frac{Na}{K})+1.483} - 273.15$$

Na/K (Arnòrsson, 1983)

$$t = \frac{933}{\log(\frac{Na}{K}) + 0.993} - 273.15$$

To account for the effects of increased calcium concentrations, Fournier and Truesdell (1973) suggested the use of a Na-K-Ca geothermometer. While the amount of total Ca in most hydrothermal systems is controlled by the solubility of calcium-bearing carbonates (usually calcite), calcium also enters into various silicate reactions and in turn is in competition with sodium and potassium. Because natural waters are generally comprised of much more sodium than potassium and aqueous potassium tends to change so as to satisfy an equilibrium expression with a given Na/Ca ratio; a change in aqueous potassium in response to an increase in calcium will be far more evident in calculations involving the Na/K ratio. If waters pick up additional calcium as they migrate upward, the temperature estimates made using the Na/K geothermometer will be too low. Waters already containing increased concentrations in calcium ($\sqrt{M_{ca}}/M_{Na} > 1$) capable of depositing calcium carbonate upon descent will result in temperature estimations that are too high. For this reason, the reaction configurations involving only Ca^{2+}, Na^{+}, K^{+} were transposed into a generalized form:

Log $K_e = \log(Na/K) + \beta \log(\sqrt{Ca} / Na)$, where β depends upon the stoichiometry of the reaction.

Based on the distribution of natural thermal waters, Fournier and Truesdell (1973) originated a geothermometer equation which could be used to calculate temperatures based upon the relationship between Ca^{2+}, Na^{+}, and K^{+}. The equation works for two possible β values: $\beta = 1/3$ for waters equilibrating above 100 ºC and $\beta = 4/3$ for waters equilibrating under 100 ^{o}C. The user of the geothermometer must calculate log (√Ca / Na) + 2.06. If the value is positive, the user applies β = 4/3 and if negative β = 1/3. The equation utilizes the assumptions of: 1) excess silica is present (generally valid) and 2) aluminum is conserved in solid phases (not true but so little aqueous aluminum is usually present that it can be neglected).

$$t = \frac{1647}{\log\frac{Na}{K} + \beta\log\frac{\sqrt{Ca}}{Na} + 2.24} - 273.15$$

Mg correction for the Na-K-Ca geothermometer

Because most geothermal fluids > 180 ^{o}C contain < 0.2 mg/kg magnesium, a correction is necessary for those fluids which contain higher amounts of magnesium (Fournier and Potter, 1979). The temperature dependence of magnesium is largely controlled by formation of chlorite in thermal waters and also biotite and actinolite at very high temperature. In cooler thermal systems, magnesium may be incorporated into clays and carbonates. The correction was devised empirically to account for waters that have high magnesium concentrations because they are saline or because the reservoir temperature is below 180 ^{o}C. It was not intended to deal with waters that have been subjected to mixing and have high magnesium concentrations because of cold groundwater influence. In general, the presence of high magnesium gives anomalously high temperature results when using the Na-K-Ca geothermometer. However, the use of a magnesium correction on a mixed thermal water will result in an underestimation of true reservoir temperature. The correction is applied as such:

1) If the temperature estimate from the Na-K-Ca geothermometer is < 70 ^{o}C, do not apply.

2) Calculate correction factor R using equivalent units:
3) Do not apply the correction if R > 50 and assume the water is from cool equilibrium conditions with temperatures close to measured surface temperature regardless of geothermometry.
4) If the Na-K-Ca estimated temperature is > 70 ^{o}C and R < 50, apply the correction equation (Fournier and Potter, 1979) to obtain Δt.
5) Subtract Δt from the Na-K-Ca estimated temperature.

$$R = \frac{Mg}{Mg+Ca+K}(100)$$

$$\triangle t_{mg} = 10.66 - 4.7415(R) + 325.867\log(R) - \frac{1.0321x10^{5}(\log R)^{2}}{T} - \frac{1.96683x10^{7}(\log R)^{2}}{T^{2}} + \frac{1.6053x10^{7}(\log R)^{3}}{T^{2}}$$

K-Mg Geothermometer

The K-Mg geothermometer (Giggenbach et al., 1988) was developed for application to systems where sodium and calcium are not in equilibrium between the thermal fluid and rock. Unfortunately, the K-Mg system is distinct from other geothermal indicators in that fluid-rock equilibrium is often attained at lower temperatures. Due to this fast re-equilibration, results from the K-Mg geothermometer are often underestimations particularly in mixed waters with elevated magnesium concentrations.

$$t = \frac{4410}{14.0 + \log(K^{2}/Mg)} - 273.15$$

Na-Li Geothermometer

The Na-Li geothermometer (Fouillac et al., 1981) is based on the decrease in the Na/Li ratio with increasing fluid temperature. Lithium is regarded as one of the more conservative elements in hydrothermal systems and is slow to re-equilibrate during ascent. The controlling equilibria of this geothermometer are based on cation exchange reactions between clays and zeolites. Two geothermometers were created: one to be applied for low to moderately saline waters (<11000 mg/kg Cl^-) and the other for marine waters. All of the waters in this study fall in the first category with the applicable geothermometer listed below.

$$t = \frac{1195}{0.130 + \log(mNa/mLi)} - 273.15$$

When applied to the water samples collected in this study, the cation geothermometers give highly varied results for the exact same well/spring. The Na/K geothermometers tend to yield very high results for Ca-HCO_3 waters likely because of high calcium concentrations. In contrast, Na-HCO_3 waters with lower calcium concentrations likely picking up additional calcium during ascent to the surface yield much lower Na/K temperature predictions some of which are below measured field temperatures. Because of the presence of calcium and the lack of magnesium in the Na-HCO_3 waters, the Na-K-Ca geothermometer is likely to yield more realistic results for these thermal features. Temperature estimates for Na-HCO_3 waters using this technique range from 98 ^oC to 166 ^oC with an average of 126 ^oC. In contrast, the abundance of magnesium in the Ca-HCO3 waters yields much higher temperature predictions ranging from 82 ^oC to 258 ^oC.

The high magnesium concentrations of the Ca-HCO_3 waters also makes the Mg-correction for the Na-K-Ca geothermometer inapplicable likely resulting in overcorrections yielding lower than actual temperature estimates according to its originators (Fournier and Potter, 1979). The Na-Li geothermometer results are highly variable while the K-Mg geothermometer yields temperature estimates that are unrealistic (below surface temperatures or negative values). All of the temperature estimates produced by conventional geothermometry are listed below in Tables 5-8. The large disparity in temperature estimates produced by these techniques highlights the shortcomings of estimators based on few chemical species under very precise conditions that may not be present in the thermal reservoir of this study area. The results from conventional geothermometry methods support further evaluation using both models to account for mixing and multicomponent equilibrium geothermometry methods that utilize reservoir specific alteration minerals to provide more realistic temperature estimates.

Table 5. Silica geothermometer temperature estimates for the Na-HCO_3 type waters of the Twin Falls – Banbury hydrothermal system. All estimates are given in degrees Celsius.

Na-HCO3 Type Waters	Qtz (No Steam Loss)	Qtz (Steam Loss)	Amorphous Silica	Chalcedony	Quartz	Chalcedony (Steam Loss)	Chalcedony (No Steam Loss)
	Fournier (1977)				Fournier and Potter (1982)	Arnorsson et al. (1983)	Arnorsson et al. (1983)
CC-11	137	132	17	110	137	108	109
CC-14	114	113	-4	85	114	88	85
CC-51	111	111	-6	82	112	85	83
CC-52	118	116	0	89	118	91	89
CC-53	119	118	1	91	120	93	91
CC-55	115	114	-2	86	116	89	87
CC-40	133	130	14	106	134	105	105
CC-42	139	134	18	112	139	110	111
CC-45	105	106	-11	76	106	80	77
CC-46	106	106	-11	76	106	81	77
CC-48	127	124	8	100	127	100	99
LY82-3	128	125	8	100	128	100	99
LY82-4	126	124	7	99	127	99	98
LY82-5	129	126	10	101	129	101	101
LY82-6	129	126	10	101	129	101	101
LY82-7	116	115	-2	87	116	90	87
LY82-11	130	127	11	103	130	102	102
LY82-12	114	113	-4	85	114	88	85
LY82-15	107	107	-9	78	108	82	79
LY82-18	105	105	-12	75	105	79	76
LY82-19	103	103	-13	73	103	78	74
LY82-20	103	103	-13	73	103	78	74
LY89-1	105	105	-12	75	105	79	76
LY89-2	111	110	-7	81	111	85	82
LY89-4	126	124	7	99	127	99	98
LY89-8	122	120	3	93	122	95	93
LY89-9	104	104	-12	74	104	79	75
LY89-11	116	115	-2	87	116	90	87
LY89-12	126	124	7	99	127	99	98
LY89-13	121	119	3	93	121	94	93
LY89-14	115	114	-2	86	115	89	87
LY89-15	116	115	-2	87	116	90	87
LY89-22	106	106	-10	77	107	81	78
M91-7	116	115	-2	87	116	90	87
M91-8	123	121	4	95	123	96	95
M91-11	106	106	-10	77	107	81	78
M91-13	111	110	-7	81	111	85	82
M91-14	115	114	-2	86	115	89	87

Table 6. Silica geothermometer temperature estimates for the Ca-HCO_3 type waters of the Twin Falls – Banbury hydrothermal system. All estimates are given in degrees Celsius.

Ca-HCO3 Type Waters	Qtz (No Steam Loss)	Qtz (Steam Loss)	Amorphous Silica	Chalcedony	Quartz	Chalcedony (Steam Loss)	Chalcedony (No Steam Loss)
	Fournier (1977)				Fournier and Potter (1982)	Arnorsson et al. (1983)	Arnorsson et al. (1983)
CC-8	104	104	-12	74	104	79	75
CC-9	120	118	1	91	120	93	91
CC-10	118	116	0	89	118	91	89
CC-12	98	99	-18	67	98	73	69
CC-13	100	101	-15	70	101	75	72
CC-54	110	109	-7	80	110	84	81
LY82-13	129	126	10	101	129	101	101
LY89-3	114	113	-4	85	114	88	85
LY89-5	119	117	1	90	119	92	90
LY89-6	130	126	10	102	130	102	101
LY89-7	115	114	-2	86	115	89	87
LY89-10	120	118	1	91	120	93	91
LY89-17	119	117	1	90	119	92	90
LY89-18	110	109	-7	80	110	84	81
LY89-29	100	101	-16	70	100	75	71
LY89-30	62	67	-48	29	62	40	33
LY89-32	107	107	-9	78	108	82	79
LY89-33	86	89	-28	55	86	62	57
LY89-34	109	109	-8	79	109	83	80
LY89-35	111	110	-7	81	111	85	82
LY89-36	114	113	-3	86	115	88	86
LY89-37	104	104	-12	74	104	79	75
LY89-38	89	92	-25	59	90	66	61
M91-12	102	103	-14	72	102	77	73

Table 7. Cation geothermometer temperature estimates for the Na-HCO_3 type waters of the Twin Falls – Banbury hydrothermal system. All estimates are given in degrees Celsius.

Na-HCO3 Type Waters	Na-K				Na-K-Ca	Na-K-Ca (Mg Corrected)	Na-Li	K-Mg
	Truesdell (1976)	Fournier (1979)	Giggenbach (1988)	Arnorsson (1983)	Fournier and Truesdell (1973)	Fournier and Potter (1979)	Fouilliac et al. (1988)	Giggenbach et al. (1988)
CC-11	45	93	114	57	112	112	119	-19
CC-14	96	140	160	107	132	132	63	7
CC-51	96	140	160	107	131	131	99	9
CC-52	58	105	126	69	118	118	95	-7
CC-53	60	108	128	72	118	118	69	-6
CC-55	74	120	141	85	129	129	144	-9
CC-40	34	83	104	46	103	103	124	-11
CC-42	52	101	121	64	112	112	119	-17
CC-45	132	171	189	141	144	144	184	6
CC-46	156	191	208	164	154	140	190	10
CC-48	40	89	110	52	102	102	118	-3
LY82-3	23	73	95	35	98	98	114	15
LY82-4	30	79	101	42	98	98	128	14
LY82-5	33	83	104	45	103	103	110	14
LY82-6	56	104	125	68	116	116	124	11
LY82-7	59	106	127	70	114	114	131	12
LY82-11	56	104	125	68	108	108	124	11
LY82-12	51	100	120	63	113	113	110	13
LY82-15	113	155	174	124	136	136	165	9
LY82-18	116	157	176	126	133	133	169	10
LY82-19	114	156	175	125	133	133	168	13
LY82-20	133	172	190	143	141	136	169	13
LY89-1	144	181	199	153	146	140	184	12
LY89-2	153	189	206	162	149	118	188	18
LY89-4	177	208	224	185	166	165	205	-1
LY89-8	48	97	118	60	107	107	111	14
LY89-9	77	124	144	89	112	61	104	38
LY89-11	98	142	161	109	136	136	100	-1
LY89-12	90	135	155	101	136	136	84	1
LY89-13	54	102	123	65	109	109	22	10
LY89-14	59	107	128	71	114	114	39	10
LY89-15	85	130	150	96	132	132	-	0
LY89-22	171	204	220	179	165	154	-	3
M91-7	85	130	150	96	132	132	-	0
M91-8	153	189	206	162	157	156	-	2
M91-11	171	204	220	179	165	154	-	3
M91-13	60	107	128	71	118	118	-	4
M91-14	49	97	118	61	110	110	-	-7

Table 8. Cation geothermometer temperature estimates for the Ca-HCO_3 type waters of the Twin Falls – Banbury hydrothermal system. All estimates are given in degrees Celsius.

Ca-HCO3 Type Waters	Na-K				Na-K-Ca	Na-K-Ca (Mg Corrected)	Na-Li	K-Mg
	Truesdell (1976)	Fournier (1979)	Giggenbach (1988)	Arnorsson (1983)	Fournier and Truesdell (1973)	Fournier and Potter (1979)	Fouilliac et al. (1988)	Giggenbach et al. (1988)
CC-8	101	144	163	111	135	107	50	14
CC-9	221	243	257	227	175	107	184	15
CC-10	231	250	263	235	177	106	186	16
CC-12	23	73	94	35	82	82	203	26
CC-13	39	88	110	51	94	94	206	27
CC-54	175	207	223	183	150	65	144	32
LY82-13	296	298	307	296	194	102	214	17
LY89-3	194	222	237	200	165	99	192	18
LY89-5	199	226	241	206	167	108	193	17
LY89-6	229	249	262	233	180	148	181	8
LY89-7	248	263	275	251	183	98	196	16
LY89-10	252	267	278	256	186	102	191	14
LY89-17	270	279	290	271	193	113	193	11
LY89-18	269	279	289	271	188	84	170	19
LY89-29	294	297	306	294	176	39	133	42
LY89-30	318	313	320	315	204	40	197	21
LY89-32	641	506	487	597	258	106	156	15
LY89-33	433	389	387	419	211	101	157	26
LY89-34	399	368	368	389	215	140	239	14
LY89-35	351	336	340	345	201	119	-	19
LY89-36	321	316	323	319	193	111	193	21
LY89-37	269	279	289	271	171	87	91	34
LY89-38	606	488	472	568	247	95	198	21
M91-12	243	260	272	247	169	78	183	30

4.2 Silica-Enthalpy Mixing Models for the Twin Falls – Banbury Thermal Area

The evidence for mixing provided by the use of binary diagram trends and Giggenbach diagram analysis (partial equilibration) suggests that conventional geothermometry techniques cannot be taken at face value. Adjustments for dilution should be made to enable more accurate temperature prediction. Several models have been developed to deal with simple mixing (non-reactive dilution) including the silica-enthalpy model (Fournier and Truesdell, 1974) and the silica-carbonate mixing model (Arnórsson, 1985). The silica-enthalpy diagram was chosen for use in this study due to the abundance of silica within the reservoir rocks satisfying the second geothermometry assumption discussed previously. The silica-carbonate model was excluded due to the variability in carbonate measurements from field titrations and the effects of CO_2 degassing on carbonate concentrations. The silica-enthalpy mixing model is based on the positive relationship between silica solubility and increasing temperature. To apply the model, temperatures for both the cold water and thermal components must be known. However, in this model, respective enthalpies of sample waters calculated from field temperatures are used as plot coordinates rather than temperature because enthalpy is conserved as waters mix and boil whereas temperature is not (e.g., Fournier and Truesdell, 1974).

The model yields two temperature estimates representing one situation in which waters are subjected to boiling prior to mixing and one where no boiling occurs. Enthalpy vs quartz solubility curves are used corresponding to the two separate scenarios. A straight line is drawn from the point representing the non-thermal component of the mixed water (lowest silica and enthalpy), through the mixed water thermal samples. The intersection of this line with the quartz solubility curve gives the enthalpy of the hot-water component at reservoir conditions if there was no boiling prior to mixing. The enthalpy at the boiling temperature (100°C) which is 419 J/g is intersected with the projected trend line. From this intersection, a horizontal line is drawn to the quartz maximum steam loss line. This new enthalpy value can be used to calculate the reservoir temperature if boiling occurred prior to mixing (Fournier, 1977).

In order to better constrain the temperature estimates from the mixing models, evidence for and against the possibility of boiling must be considered. As mentioned previously, shifts in δD concentrations may be explained by boiling. Truesdell et al. (1978) demonstrated the enrichment of deuterium from fractionation due to boiling in both a single-stage and continuous steam loss scenario. They observed increases of 1.44 times and 9.1% for chloride and δD concentrations respectively for single-stage steam loss and 1.41 times 3.1% for continuous steam loss for some of the thermal waters in Yellowstone National Park. These calculations were made utilizing a known recharge water deuterium concentration and assuming all heat loss was due to boiling from 360 °C parent water to the 93 °C boiling point.

Because local area groundwater deuterium concentrations differ from thermal water concentrations and thermal waters are likely much older (Pleistocene), a local Pleistocene deuterium concentration would be needed for such calculations. However, given a likely reservoir temperature of about 160 °C (Conrad et al., 2015) and a local boiling point of about 95 °C, one can approximate how much boiling may occur in the system. Assuming that all of the heat loss in the system is due to steam loss (not likely due to evidence for groundwater mixing), we can estimate a percentage of water lost to boiling. The total enthalpy lost due to vaporization from 160 °C to 95 °C is about 277 kJ/kg and the latent heat of enthalpy for water is about 2257 kJ/kg (Marsh, 1987). Relating heat loss and latent heat of vaporization to evaporative mass, a maximum of about 12 % of thermal water per kg could potentially be lost to boiling. Due to low chloride concentrations of thermal waters in the study area and lack of recharge deuterium values, effects from this small proportion of boiling are not likely to be evident in water chemistry. Additionally, the lack of fumaroles, sinter deposits, and supersaturation of silica suggest that influence of boiling is of minimal importance to this area.

The model developed by Fournier and Truesdell (1974) used only quartz as the controlling dissolved silica component. This approach has been modified in this study to include a chalcedony-enthalpy mixing model in addition to the quartz-enthalpy model in order to account for the possibility of chalcedony controlling silica solubility. The results are presented below in Figures 20-21. Because there is little evidence supporting a maximum boiling scenario in the study area, temperature estimates from these models are likely constrained to the lower (no steam loss) estimates. The estimated reservoir temperatures from the quartz-enthalpy diagram are about 143 ^{o}C (no steam loss) to 175 ^{o}C (max steam loss).The fraction of thermal water incorporated into mixing for the no steam loss scenario is about 39%. The chalcedony-enthalpy model yields a lower temperature range of 120 ^{o}C (no steam loss) to 142 ^{o}C (max steam loss). The fraction of thermal water incorporated into mixing for the no steam loss scenario is about 49%. While the temperature estimates of the mixing models may be more realistic than those of conventional geothermometers, the mixing models applied in this section account only for simple non-reactive mixing and are based on only one dissolved indicator constituent.

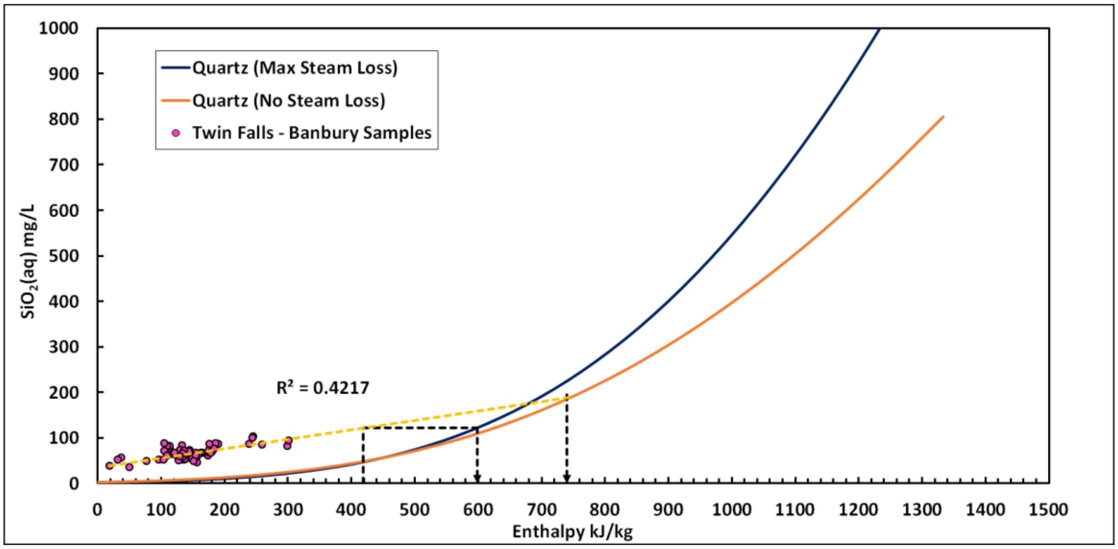


Figure 20. Silica-enthalpy model (quartz) applied to the thermal waters of the Twin Falls – Banbury system. The trend line (yellow) passes through both end member waters and is projected to the no steam loss line (orange). The intersection of the trend line with the boiling point (419 kJ/kg) is projected to the max steam loss line (blue). Temperature estimations are obtained from the resulting two enthalpy values.

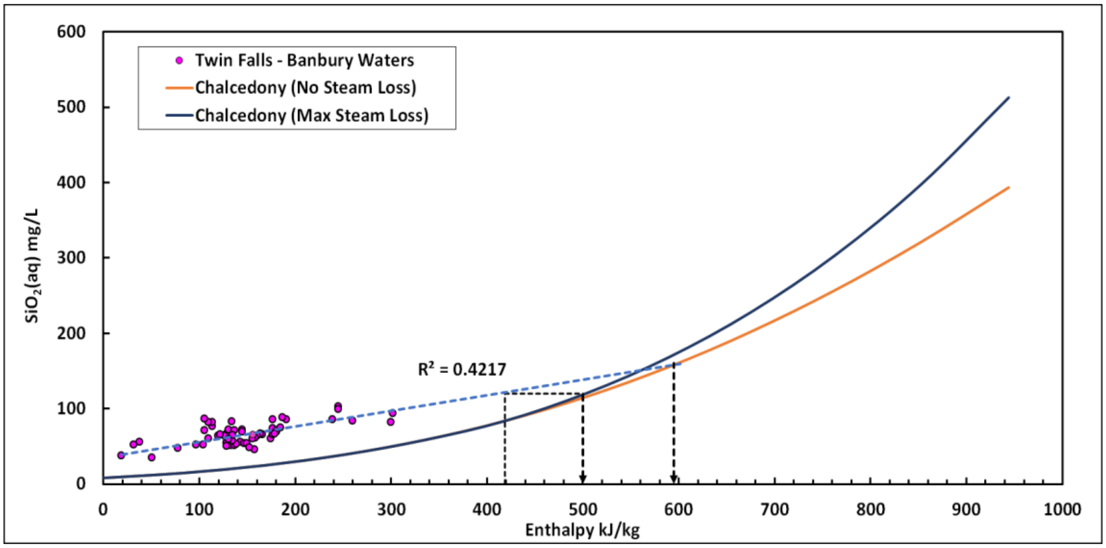


Figure 21. Silica-enthalpy model (chalcedony) applied to the thermal waters of the Twin Falls – Banbury system. The trend line (yellow) passes through both end member waters and is projected to the no steam loss line (orange). The intersection of the trend line with the boiling point (419 kJ/kg) is projected to the max steam loss line (blue). Temperature estimations are obtained from the resulting two enthalpy values.

4.3 MEG Analysis of the Twin Falls – Banbury Area

Recent developments in multicomponent equilibrium geothermometry (MEG) have led to appreciable improvement in the reliability and accuracy of reservoir temperature estimations compared with conventional geothermometry (Spycher et al., 2011; Smith et al., 2012; Neupane et al., 2013, 2014; Palmer et al., 2014; Cannon et al., 2014; Neupane et al., 2015). The concept behind MEG originated in the 1980s (Michard and Roekens, 1983; Reed and Spycher, 1984) and is based on the estimation of reservoir temperature through saturation indices of several minerals likely to be in equilibrium with the thermal water. The use of an entire chemical suite rather than a couple of basis species has an obvious advantage over conventional techniques. While MEG is still affected by the same secondary processes that violate the assumptions of geothermometry (boiling, dilution, etc.), new techniques allow for the correction of these processes if they can be identified. RTEst (Reservoir Temperature

Estimator) is one such tool that can accomplish these corrections by reconstructing the last equilibrated composition of a given thermal fluid (Palmer et al., 2014; Neupane et al., 2015). Validation of the RTEst tool was demonstrated by Neupane et al. (2015) through the successful matching of estimated reservoir temperatures and actual bottom-hole temperatures of five geothermal power plants.

RTEst uses a likely reservoir mineral assemblage (RMA) in the prediction of the thermal fluid temperature within the reservoir. The reservoir temperature is taken to be the one in which all of the mineral saturation indices are in equilibrium shown by having a summed $\log(Q_i/K_{i,T})$ of zero where Q_i and $K_{i,T}$ are the ion activity product and temperature dependent equilibrium constant for the i^{th} mineral respectively. RTEst accomplishes temperature estimation by utilizing the React module of The Geochemist's Workbench® (Bethke and Yeakel, 2012) in order to model equilibrium conditions among minerals, aqueous species, and gaseous phases with respect to geochemical reactions. RTEst couples the React module with the model-independent optimization software PEST (Doherty, 2013) to optimize parameters including CO_2 fugacity, amount of water gained or lost, and temperature. These parameters correspond to secondary alteration processes that affect fluid composition. Through the use of these parameters alone, RTEst is capable of compensating for the effects of boiling and simple (non-reactive mixing). However, if a cooler water end member composition is known, RTEst can "extract" this end member through inverse modeling thereby accounting for reactive mixing.

The equilibrium reservoir temperature is calculated through the minimization of the objective function, ϕ. The objective function is essentially a weighted sum of squares of the saturation indices of the chosen RMA where RTEst acts to minimize the collective distances away from zeros for all saturation indices. The objective function is given by the following equation:

$$\Phi = \sum (SI_i w_i)^2$$

where SI_i is the saturation index for the i^{th} mineral and w_i is the weighting factor. The weighting factor w_i is based on the number of thermodynamic components within each mineral to ensure that each mineral contributing to equilibrium with the thermal fluid is considered equally and not skewed by reaction stoichiometry (Neupane et al., 2015).

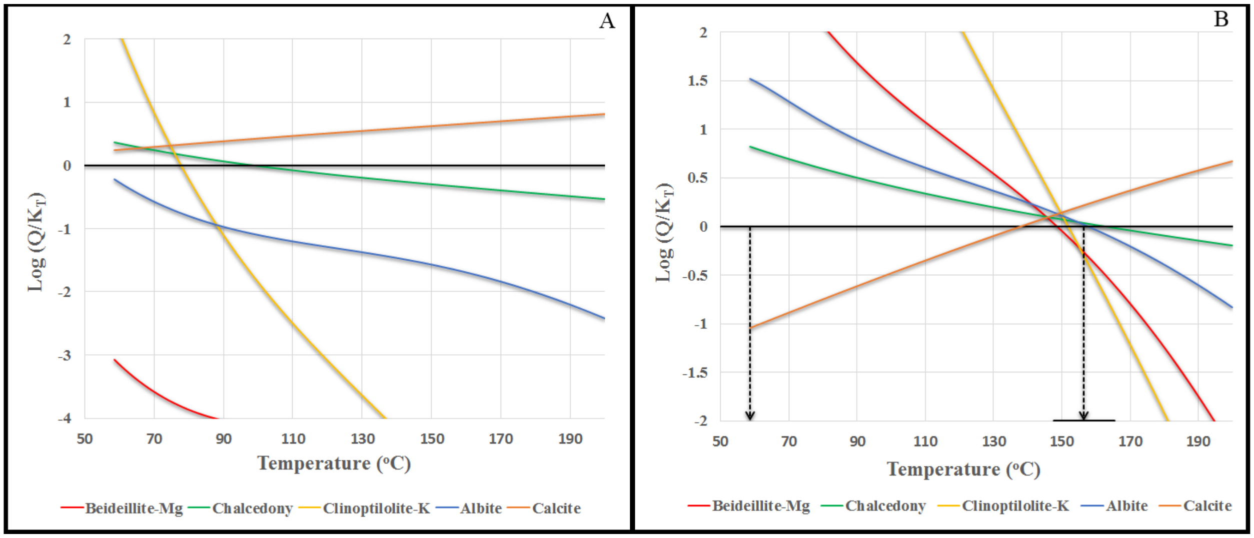


Figure 22. Temperature estimation for Banbury Hot Springs showing the log Q/K_T curves for minerals (Calcite, Chalcedony, Beidellite – Mg, Clinoptilolite-K, and Albite) calculated using original water chemistry. A) Without optimization of H_2O mass and CO_2 fugacity B) Optimized log Q/K_T curves showing field temperature (58.4°C), estimated temperature (158 °C), and error bar (black bar on x-axis).

The reservoir mineral assemblages used here are based on alteration mineral assemblages present in hydrothermally altered basalts and rhyolites. Early work has shown that rock type has less of an effect on geothermal alteration compared with temperature, fluid composition, and permeability (Browne, 1978; Henley and Ellis, 1983). Browne (1978) demonstrated that basalts, rhyolites, andesites, and sandstones were all dominated by an alteration mineral assemblage including illite, calcite, pyrite, epidote, k-feldspar, albite, and quartz in the temperature range of 250 – 285 ^{o}C. However, there are important differences between basalt and rhyolitic alteration mineral assemblages particularly at lower (<200 ^{o}C) temperatures. At lower temperatures, secondary mineralization within geothermally altered basalts and rhyolites typically includes phyllosilicates, zeolites, oxides, hydroxides, and carbonates (Neuhoff et al., 1999; Weisenberger and Selbekk, 2009; Rodriguez, 2011). As temperatures increase, zones of mixed illite-smectite clays begin to dominate at 200-250 ^{o}C, chlorite-epidote at 250-300 ^{o}C, and epidote-actinolite at >300 ^{o}C. At temperatures < 200 ^{o}C kaolinite and smectite clays predominate with other minerals including zeolites, quartz and chalcedony, K-feldspar, calcite, and chlorite (Lonker et al., 1993; Larsson et al., 2002).

The main differences in geothermal alteration between basalts and the more silicic rhyolites and andesites are observed in clay mineralogy. Clays formed from the alteration of rhyolites and andesites are more Na^+ and K^+ rich compared to those formed in basalts. These clays are typically mixed illite-smectite clays as well as montmorillonites. In addition to being enriched with respect to Na^+ and K^+, alteration clay and zeolites in rhyolites and andesites tend to be more deficient in magnesium due to the low magnesium concentrations within these rock types (Bethke, 1986; Reyes, 1990; Mas et al., 2006).

The alteration minerals particular to this study area were based largely on the work of Sant (2012) who analyzed the alteration minerals within basalt core samples from the Kimberly well of the Project Hotspot (Shervais et al., 2013). This well lies just to the east of the study area in Burley, ID and penetrates the basalts of the upper aquifer system. Of particular importance are the smectite clays observed in core samples from 1042 meters to

1829 meters (3126 – 5487 ft.). Morse and McCurry (2002) also analyzed basalt core samples from the deep aquifer penetrating INEL-1 well located to the northeast of the study area on the Idaho National Laboratory. Both of these studies have attributed the boundary between the upper and lower aquifer systems to the development of these smectite clays. RTEst provides a means of selecting minerals based on five rock types (Tholeitic, Calc-alkaline, Silicic, Siliciclastic, and Carbonates), 3 temperature ranges (low, 50-100 ^oC; moderate 150 to 300 ^oC; and high, >300 ^oC), and two water types (neutral and acidic) based on a review of 48 different geothermal systems (Palmer et al., 2014). Minerals used in this study along with their corresponding weighting factors are listed below in Table 9.

Table 9. Alteration minerals used in RTEst inverse modeling with corresponding weighting factors (W_i)

Mineral	W_i
Calcite	1/2
Chalcedony	1
Beidellite Mg	1/6.65
Kaolinite	1/4
Clinoptilolite-Ca	1/13
Clinoptilolite-K	1/14
Saponite-Na	1/7.33
Saponite-K	1/7.165
Illite	1/6.65
Heulandite	1/7
Fluorite	1/3
Talc	1/7
Muscovite	1/7
Paragonite	1/7

4.4 RTEst Results for the Twin Falls – Banbury Thermal Area

The following reservoir temperature estimates were made utilizing the MEG tool RTEst in order to both better predict temperatures as compared with more conventional techniques and also test the rationale behind the three mixing scenarios presented in Chapter 1 (Simple Mixing, Flow-Pathway Mixing, and Mixing with Re-equilibration). The inverse modeling performed using RTEst is capable of accounting for both simple mixing and reactive mixing through the removal of a mixing component. Pure water, local groundwater (recharge area), and an idealized intermediate water (based on binary diagram trends) were used in this study as mixing components.

No Mixing

Despite evidence for mixing, the possibility of no mixing was considered in the MEG approach. Allowing only temperature and CO_2 fugacity to fluctuate as optimization parameters, adequate convergence of saturation indices was not obtained for either Ca-HCO_3 or Na-HCO_3 type thermal waters using likely alteration mineral assemblages found in basalts and rhyolites. Results were slightly better for Ca-HCO_3 type waters but far from meaningful with objective function (ϕ) values greater than or equal to 0.1.

Simple Mixing

The possibility of simple mixing between groundwater and thermal waters was considered in RTEst modeling through the use of a 6 ^{o}C recharge area groundwater sample (Sample LY89-38) as the mixing component between the Ca-HCO_3 and Na-HCO_3 type thermal waters. Mixing between groundwater and the Na-HCO_3 type thermal waters is not supported through the use of RTEst as all attempts of modeling this scenario resulted in a lack of saturation index convergence for all likely mineral assemblages. However, mixing between groundwater and Ca-HCO$_3$ type thermal waters is supported through the use of RTEst. Objective function values (ϕ) of less than 1x10^{-6} are obtained for some waters. These values are better than all previous studies utilizing RTEst in MEG analyses including those which successfully validated actual bottom-hole temperatures of geothermal power plants (Cannon et al., 2014; Neupane et al., 2014; 2015). Simple mixing is also supported through the use of pure water as the mixing component in mixing with Na-HCO$_3$ type thermal waters.

Flow Pathway Reactive Mixing

Flow Pathway or reactive mixing was investigated using an "intermediate" composition water created from the binary diagram analysis in Chapter 3. Na-HCO$_3$ type thermal waters were mixed with water that contained amounts of K^+, Ca^{2+}, and Mg^{2+} taken from the intersection of the two trends presented in Figure 15. Na-HCO$_3$ type thermal waters were modelled with waters containing between 0.12-0.15 meq/kg K^+, 0.5-0.7 meq/kg Ca^{2+}, and 0.15-0.2 meq/kg Mg^{2+}. This type of mixing was not supported in the attempts to mix thermal water with this "intermediate" composition as adequate conversion was not attained and temperatures at or near surface temperatures were predicted with standard deviations of temperatures reaching over +/- 150 ^oC. Additionally, mixing between Ca-HCO$_3$ and Na-HCO$_3$ type thermal waters is not supported through the use of RTEst.

Re-equilibration

The possibility of re-equilibration may be gleaned from the RTEst results. The reconstructed equilibrium water compositions produced by RTEst modeling of the Ca-HCO$_3$ type thermal waters may be significant in that if the Ca-HCO$_3$ type thermal waters were the

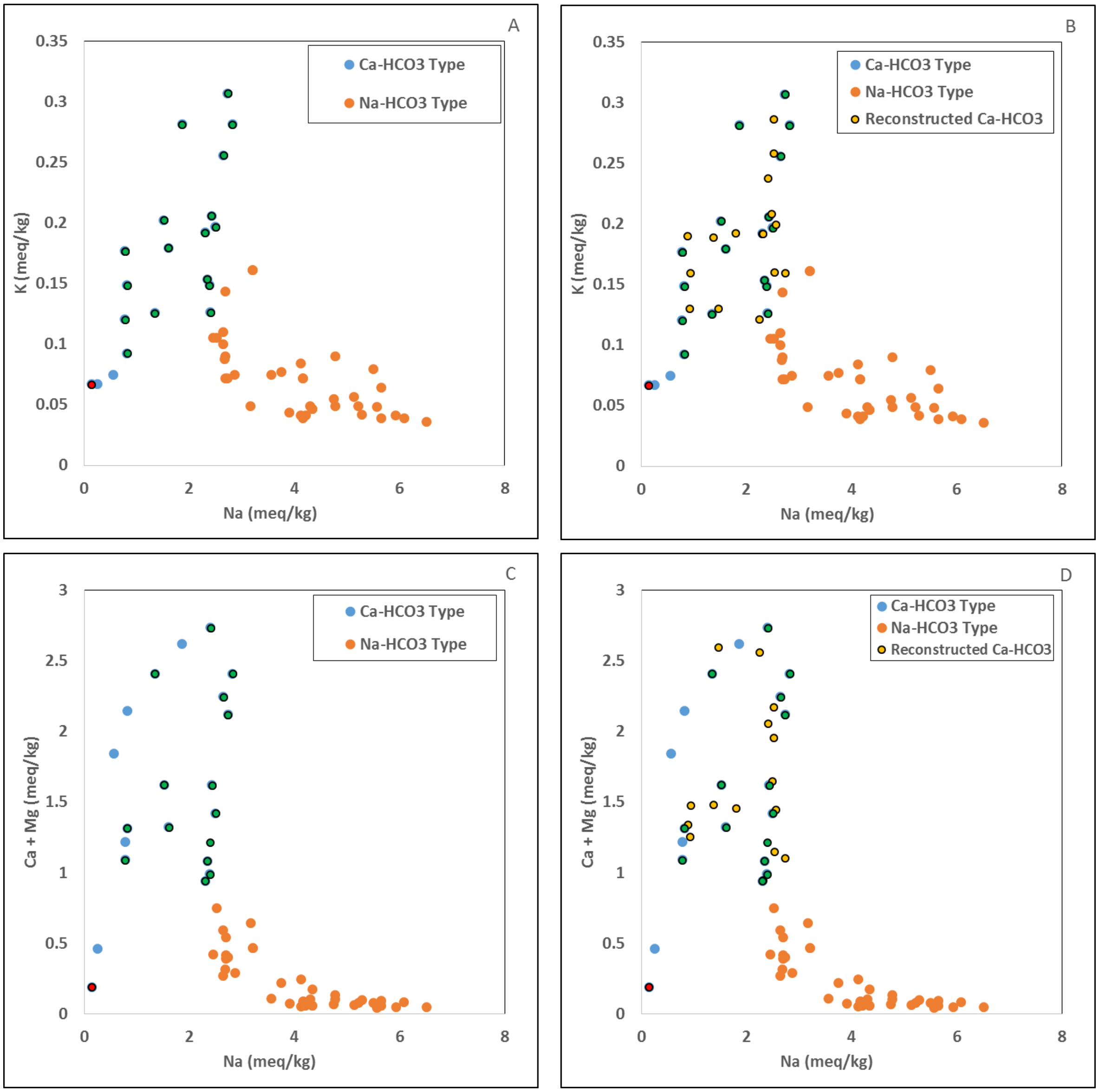


Figure 23. Initial (green) vs MEG reconstructed (yellow) compositions of Ca-HCO$_3$ thermal waters. A and B show the relationship between Na$^+$ vs K$^+$ while C and D show Ca^{2+} and Mg^{2+} vs Na$^+$.

result of simple mixing between groundwater and deep Na-HCO$_3$ type waters, the reconstructed (optimized) waters would be similar in composition to the Na-HCO$_3$ type waters and follow the general trends displayed in Figure 15. However, reconstructed water compositions do not resemble Na-HCO$_3$ waters suggesting that re-equilibration from the Na-HCO$_3$ waters to the Ca-HCO$_3$ is a possibility. The initial and reconstructed water compositions of the Ca-HCO_3 type waters are plotted with respect to K^+, Ca^{2+}, Mg^{2+}, and Na^+ concentrations in Figure 23.

The pure water mixing with Na-HCO_3 type thermal waters mentioned previously also opens up the possibility of re-equilibration in this system. In order for pure water to mix with the deep Na-HCO_3 type thermal waters of the system, a mechanism by which recharge area groundwater transitions into pure or very dilute water prior to mixing may be needed. A reaction in which Ca^{2+} and Mg^{2+} concentrations are diminished while Na^+ concentrations are increased would explain this phenomenon. Cation exchange reactions between alteration clays and zeolites or a precipitation reaction in which cation concentrations are diminished due to falling out of solution may be the driving forces behind this mechanism. Cation exchange reactions are more likely than reactions involving precipitation as precipitation reactions would likely result in a similar decrease of anion concentrations as both cations and anions would drop out of solution together due to the ionic bond formed during precipitation. A series of re-equilibration zones may explain the gradational change in composition from Na-HCO_3 to more Ca-rich thermal wares. This re-equilibration mechanism is supported by the apparent relationship between:

1) Mg-rich smectite clays (Beidellite-Mg) used in the Ca-HCO_3 RMA and the Na-rich smectite clays (Saponite-Na) used in the Na-HCO_3 RMA. The high cation exchange capacity of smectite clays supports these findings (Carroll, 1954; Robin et al., 2015).

2) Clinoptilolite-Ca (zeolite) used in Ca-HCO_3 RMA and Clinoptilolite-K used in the Na-HCO_3 RMA. Cation exchange between these two Clinoptilolite end members is explained by Pabalan and Bertetti (2001).

RTEst modeling of Na-HCO_3 type thermal waters mixing with pure water yields temperature estimates ranging from 108 ^oC to 160 ^oC. These results are in agreement with sulfate-water isotope geothermometry estimates of 150 ^oC for Banbury Hot Springs (Conrad et al., 2015). Modeling of Ca-HCO_3 type thermal waters mixing with local groundwater yields temperature estimates ranging from 84 ^oC to 104 ^oC. These results may either constitute evidence for two distinct flow paths and equilibration temperatures resulting in the two water types or relationship between the two waters defined by a re-equilibration. Possible conceptual models resulting from geothermometry results will be discussed in detail in Chapter 5. Below are the RTEst temperature estimations and mineral assemblages for both Ca-HCO3 and Na-HCO3 type thermal waters.

Table 10. RTEst temperature estimates (a), mass of thermal water component per 1 kg solution used in mixing (c), log of CO_2 fugacity, RTEst objective function (Φ), selected RMAs, and (b) associated standard deviations of each measurement.

Na-HCO3 Type Water RTEst Results - Pure Water Mixing						
Site ID	Name	$T^a \pm \sigma^b$	M^c $H_2O \pm \sigma^b$	$\log f_{CO_2} \pm \sigma^b$	ϕ	RMA
CC-11	Miracle Hot Springs	160 ± 2.5	0.49 ± 0.01	-0.56 ± 0.058	1.23E-4	Beidellite-Mg, Calcite, Chalcedony, Clinoptilolite-K, Paragonite
CC-14	CSI Well 2	136 ± 11	0.43 ± 0.06	-0.23 ± 029	2.05E-3	Saponite-K, Calcite, Chalcedony, Clinoptilolite-Ca,
CC-40	1000 Springs (Sliger's Well)	134 ± 2.1	0.34 ± 0.005	-0.1 ± 0.051	2.93E-4	Calcite, Chalcedony, Illite, Paragonite, Heulandite, Fluorite
CC-42	Banbury Hot Springs	158 ± 9	0.49 ± 0.04	-0.26 ± 0.21	2.25E-3	Beidellite-Mg, Calcite, Chalcedony, Clinoptilolite-K, Albite
CC-45	Leo Ray Hill	121 ± 6	0.46 ± 0.02	-0.4 ± 0.14	2.34E-3	Saponite-Na, Calcite, Chalcedony, Clinoptilolite-K, Paragonite
CC-46	Leo Ray Road	120 ± 1	0.48 ± 0.045	-0.31 ± 0.02	5.15E-5	Saponite-Na, Calcite, Chalcedony, Clinoptilolite-K, Paragonite
CC-48	Hensley Well	134 ± 17	0.52 ± 0.09	-0.36 ± 0.47	8.28E-3	Beidellite-Mg, Calcite, Chalcedony, Clinoptilolite-K, Paragonite
CC-51	CSI Well 1	134 ± 11	0.42 ± 0.06	-0.14 ± 0.3	2.28E-3	Calcite, Chalcedony, Clinoptilolite-Ca, Saponite-K
CC-52	Larry Anderson Well	108 ± 3	0.73 ± 0.09	-1.5 ± 0.09	5.75E-4	Saponite-Na, Calcite, Chalcedony, Fluorite, Talc
CC-53	Pristine Springs	130 ± 10	0.54 ± 0.08	-0.92 ± 0.3	2.18E-3	Saponite-Na, Calcite, Chalcedony, Fluorite, Talc
CC-55	Anderson Campground Well	123 ± 3	0.56 ± 0.01	-0.77 ± 0.07	7.43E-4	Beidellite-Mg, Calcite, Chalcedony, Clinoptilolite-K, Paragonite

Ca-HCO3 Type Water RTEst Results - Groundwater Mixing					
Site ID	$T^a \pm \sigma^b$	M^c $H_2O \pm \sigma^b$	$\log f_{CO_2} \pm \sigma^b$	ϕ	RMA
CC-9 (Campbell Well 1)	95 ± 0.46	0.97± 0.005	-1.17 ± 0.01	1.95E-05	Beidellite-Mg, Calcite, Chalcedony, Kaolinite, Clinoptilolite-Ca
CC-10 (Campbell Well 2)	93 ± 0.27	0.97± 0.003	-1.25 ± 0.007	6.48E-06	Beidellite-Mg, Calcite, Chalcedony, Kaolinite, Clinoptilolite-Ca
CC-54 (Twin Falls High School)	80 ± 2.3	1.0± 0.01	-1.32 ± 0.06	4.11E-04	Beidellite-Mg, Calcite, Chalcedony, Muscovite, Clinoptilolite-Ca
LY82-13	98 ± 0.91	1.0 ± 0.04	-1.06 ± 0.02	7.35E-05	Beidellite-Mg, Calcite, Chalcedony, Kaolinite, Clinoptilolite-Ca
LY89-3	94 ± 0.58	0.86 ± 0.006	-1.16 ± 0.01	2.95E-05	Beidellite-Mg, Calcite, Chalcedony, Kaolinite, Clinoptilolite-Ca
LY89-5	97 ± 0.59	0.91 ± 0.009	-1.13 ± 0.02	3.06E-05	Beidellite-Mg, Calcite, Chalcedony, Kaolinite, Clinoptilolite-Ca
LY89-6	104 ± 1.1	0.98 ± 0.012	-1.04 ± 0.03	9.67E-05	Beidellite-Mg, Calcite, Chalcedony, Kaolinite, Clinoptilolite-Ca
LY89-7	84 ± 2.1	1.0± 0.02	-1.23 ± 0.04	4.08E-04	Beidellite-Mg, Calcite, Chalcedony, Kaolinite, Clinoptilolite-Ca
LY89-10	88 ± 1.5	1.0 ± 0.008	-1.21 ± 0.02	2.01E-04	Beidellite-Mg, Calcite, Chalcedony, Kaolinite, Clinoptilolite-Ca
LY89-17	88 ± 1.3	1.0± 0.008	-1.20 ± 0.02	1.72E-04	Beidellite-Mg, Calcite, Chalcedony, Kaolinite, Clinoptilolite-Ca
LY89-18	89 ± 0.61	0.88 ± 0.002	-1.29 ± 0.003	3.44E-05	Beidellite-Mg, Calcite, Chalcedony, Kaolinite, Clinoptilolite-Ca
LY89-34	89 ± 0.69	0.88 ± 0.011	-1.33 ± 0.02	4.66E-05	Beidellite-Mg, Calcite, Chalcedony, Kaolinite, Clinoptilolite-Ca
LY89-35	91 ± 0.31	0.86 ± 0.0006	-1.37 ± 0.001	9.36E-06	Beidellite-Mg, Calcite, Chalcedony, Kaolinite, Clinoptilolite-Ca
LY89-36	98 ± 1.60	0.84 ± 0.018	-1.33 ± 0.03	2.34E-04	Beidellite-Mg, Calcite, Chalcedony, Kaolinite, Clinoptilolite-Ca
M91-12	80 ± 1.23	0.91 ± 0.02	-1.54 ± 0.04	1.35E-04	Beidellite-Mg, Calcite, Chalcedony, Kaolinite, Clinoptilolite-Ca

CHAPTER 5: CONCEPTUAL MODELS FOR THE TWIN FALLS – BANBURY HYDROTHERMAL SYSTEM

The following section details the competing possible conceptual models for the Twin Falls-Banbury hydrothermal system and provides evidence for the dismissal of all but one. Four conceptual models based on the previously defined mixing scenarios are presented herein. Results from chemical analyses, mixing analyses, reservoir temperature predictions, and regional geology are utilized to support or dismiss these models.

5.1 No Mixing Conceptual Model

Mixing between local groundwater and thermal waters is supported by the partial equilibration and immature classifications of thermal waters made by the Giggenbach ternary diagram, the linear relationships between conservative species chloride and boron, and the linear relationship between ^{18}O and Deuterium. Mixing has been attributed as a possible explanation for the masking of geothermal signatures throughout the ESRP (McLing et al., 2002; Neupane et al., 2014; Dobson et al., 2015). However, the possibility that no mixing occurs in this system is considered unlikely due to inadequate (high) Φ value for both Ca-HCO_3 and Na-HCO_3 thermal waters using only temperature and CO_2 fugacity as optimization parameters.

5.2 Simple Mixing Conceptual Model

The idea of simple mixing is supported by gradational trends exhibited by some chemical constituents (Cl/B, ^{18}O/D, ^{18}O/Cl, Na/Cl, Na/SiO_2, etc.) and is accounted for by silica-enthalpy mixing diagrams in Chapter 4. RTEst modeling of mixing between recharge area groundwater and Ca-HCO_3 type thermal water supports simple mixing between these two components (Table 10). However, trends exhibited in the relationships between Na^+, K^+, Ca^{2+}, and Mg^{2+} among Na-HCO_3 and Ca-HCO_3 thermal waters suggest that either some reaction has taken place in addition to mixing or that the two water types are representative of two distinct flow paths. Simple mixing between local groundwater and Na-HCO_3 type thermal waters is not supported by MEG modeling through RTEst while the use of pure water as the mixing component is supported. Simple mixing with pure water may be explained by dilution through precipitation as thermal water is rapidly mixed at the surface as is the case in conventional mixing models (Fournier, 1977; Arnorsson, 1985). While this concept may hold up for thermal springs, it does not provide a mechanism by which pure water is mixed with Na-HCO_3 thermal waters in deep wells.

5.3 Reactive Mixing

In order for pure water or dilute Na-HCO_3 water (as discussed in Chapter 4) to mix with thermal Na-HCO_3 type waters of the deep system, there must either be 1) a flow pathway by which pure water from precipitation infiltrates directly into the deep system and mixes with thermal water or 2) a mechanism by which Ca-Mg-HCO_3 type groundwater gradationally transitions into dilute Na-HCO_3 water during infiltration. For these reasons, a conceptual model with and without re-equilibration are investigated. Recharge area groundwater is thought to pick up its enriched Ca^+ and Mg^{2+} signature from the Paleozoic (Pennsylvanian and Permian) marine sediments that are exposed at the surface in the mountainous recharge area to the southeast of Buhl, ID (Lewis and Young, 1989; Mariner et al., 1997). While all non-thermal groundwater samples in between the recharge area and both the Twin Falls and Banbury hydrothermal areas are Ca-HCO_3 in type, the regional geology supports the possibility of a flow path for precipitation directly into the Idavada volcanics which are also exposed in the hills to the south of the study area. The depth and extent of the Paleozoic carbonates is largely unknown although over 1,524 meters (5,000 ft.) sections of carbonate sediments are reported in the mountains of northern Nevada (Schroeder, 1912). Additionally, lead isotope data from thermal waters in the study area provide a carbonate signature providing evidence that carbonates persist beneath the Idavada volcanics throughout the study area (Mariner et al., 1997)

While the possibility exists for a rhyolite exclusive flow pathway, the likelihood of pure water remaining dilute from the surface to depths up to 3 km (Lewis and Young, 1989) is not favorable. Data from many natural geothermal systems shows that local equilibria between fluid and host rock is attained at temperatures as low as 50 ^{o}C (Arnórsson et al., 1983; Stefánsson and Arnórsson, 2002). Pure water from precipitation would likely obtain a similar signature to that of the deep Na-HCO$_3$ thermal waters having flowed through rhyolites to extensive depths. Without the possibility of re-equilibration at a lower temperature, it would follow that an increase in the fraction of thermal water component in MEG analysis would result in higher temperature estimations. This is not found to be the case as can be seen in the RTEst results presented in Chapter 4, Table 10. For instance, Miracle Hot Springs has a predicted reservoir temperature of 160 ^{o}C with an optimized thermal water component of 0.49 whereas the Larry Anderson Well has an optimized thermal composition comprised of 73% thermal water at 130 ^{o}C.

5.4 Re-equilibration

The gradational transition between Na-HCO$_3$ type thermal waters of the deep system to more Ca-HCO$_3$ type thermal waters nearer to the surface is found throughout the ESRP (Mann, 1986; McLing et al., 2002;). A re-equilibration mechanism may explain this relationship. As shown in the Figure 24 below, a mechanism by which Ca^{2+} and Mg^{2+} are diminished with increasing temperature and depth while Na+ concentrations rise explains the rationale behind pure water or dilute Na-HCO_3 water mixing. Conversely, the reduction of Na+ and rise of Ca^{2+} and Mg^{2+} during ascension may explain the transition between deep Na-HCO_3 thermal waters to more Ca-HCO_3 type thermal waters through re-equilibration. This mechanism is supported by the apparent exchange between Ca^{2+} and K^+ rich zeolites and Na^+ and Mg^{2+} rich smectite clays. For the reasons mentioned in this chapter, a conceptual model including re-equilibration is the most likely. However, the possibility of two flow paths and equilibration temperatures resulting in the two observed thermal water types cannot be ruled out.

Figure 24 shows a cross sectional view of regional geology from the recharge area in the Cassia Mountains to Banbury Hot Springs. Suggested possible flow pathways, water types, and a re-equilibration mechanism are also represented and explained through the 4 stages listed below. This cross section was created from available well log data and local geologic maps (Gillerman et al., 2005; Othberg et al. 2005). Figure 25 shows the location of the cross section line in map view.

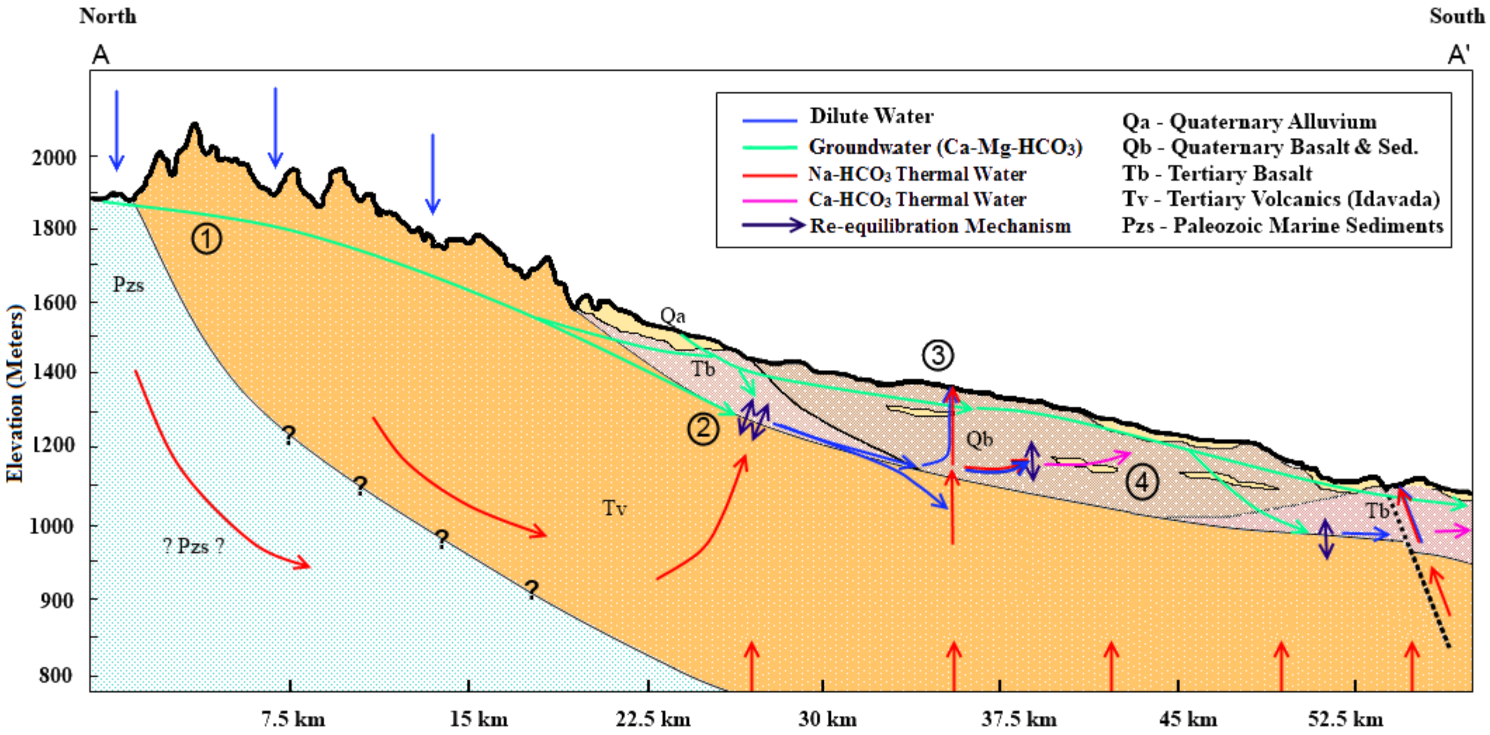
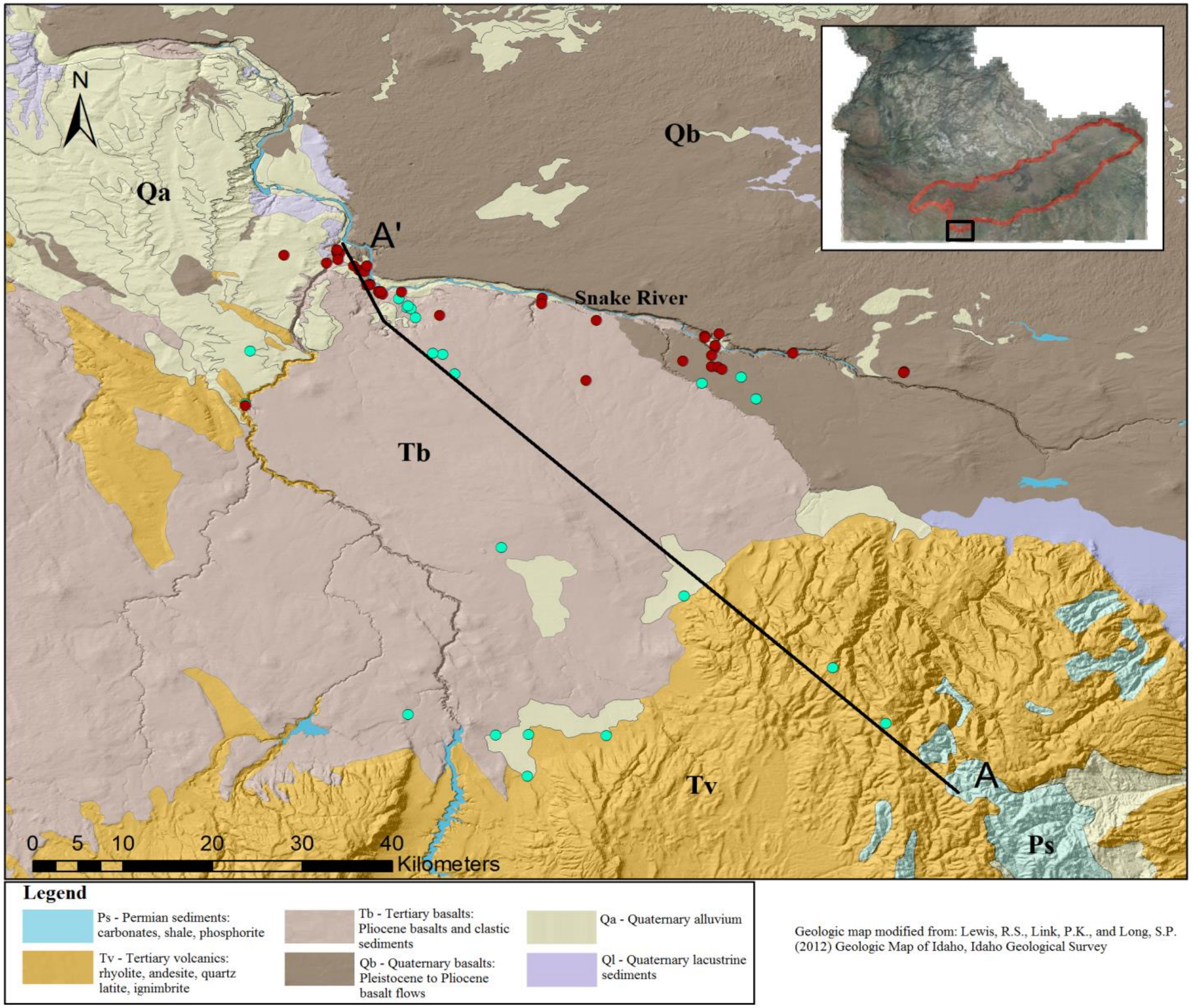


Figure 24. Conceptual model for the Twin Falls – Banbury thermal area showing possible flow pathways, water types, regional geology, and possible re-equilibration mechanism.

1) Precipitation infiltrates into the subsurface likely picking up Ca-Mg-HCO_3 signature from Paleozoic carbonates.
2) The mixing of Ca-Mg-HCO_3 groundwater with Na-HCO_3 thermal water at intermediate temperature and depth. Re-equilibration (purple arrows) results in the loss of Ca^{2+} and Mg^{2+} and the gaining of Na^+ resulting in dilute Na-HCO_3 water.
3) Na-HCO_3 thermal water mixes with dilute water during ascension resulting in the manifestation of mixed Na-HCO_3 thermal water at the surface.
4) An alternate flow path through basalt results in the re-equilibration of Na-HCO_3 thermal water into Ca-HCO_3 thermal water.



Geologic map modified from: Lewis, R.S., Link, P.K., and Long, S.P. (2012) Geologic Map of Idaho, Idaho Geological Survey

Figure 25. Cross sectional line of Figure 24 with geologic units and water type distribution (Red: Na-HCO_3*, Blue: Ca-*HCO_3*)*

5.5 Hydrogeology

Thermal water in the Banbury hydrothermal area seems to be structurally controlled with the majority of thermal surface manifestations located along a single northwest trending normal fault associated with Basin and Range extension (Street and DeTar, 1987; Lewis and Young, 1989). According to the Idaho Geological Survey, most of the normal faults within the study area are contained within the units of the Idavada volcanics and do not offset the overlying younger basalts (Othberg et al., 2012). The normal fault near the cluster of Na-HCO_3 thermal waters near Banbury Hot Springs appears to be one of the exceptions. Offset to both overlying Quaternary and Tertiary basalts (Banbury basalt) is shown in a nearly 2 km

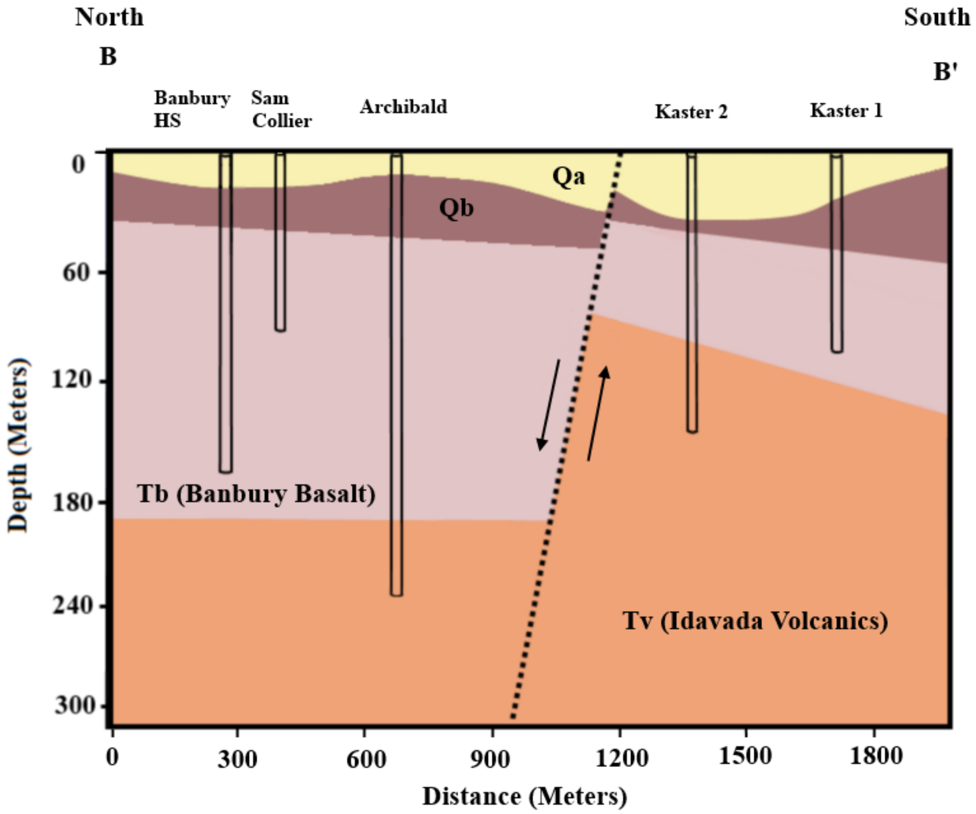


Figure 26. Geologic cross section through the Banbury Hot Springs area.

long cross section which cuts across the fault in this area. As discussed in Chapter 3, Ca-HCO_3 type thermal waters are more prevalent southward towards the area of recharge and within wells completed within basalts. A possible explanation for the spatial distribution of the two thermal waters is that the Ca-HCO_3 type thermal waters are found in areas where faults are constrained within Idavada volcanic units thus allowing for increased residence times and re-equilibration into Ca-HCO_3 type waters within basalt as shown in Figure 24. Logs of wells used in cross section construction are available in Appendix D.

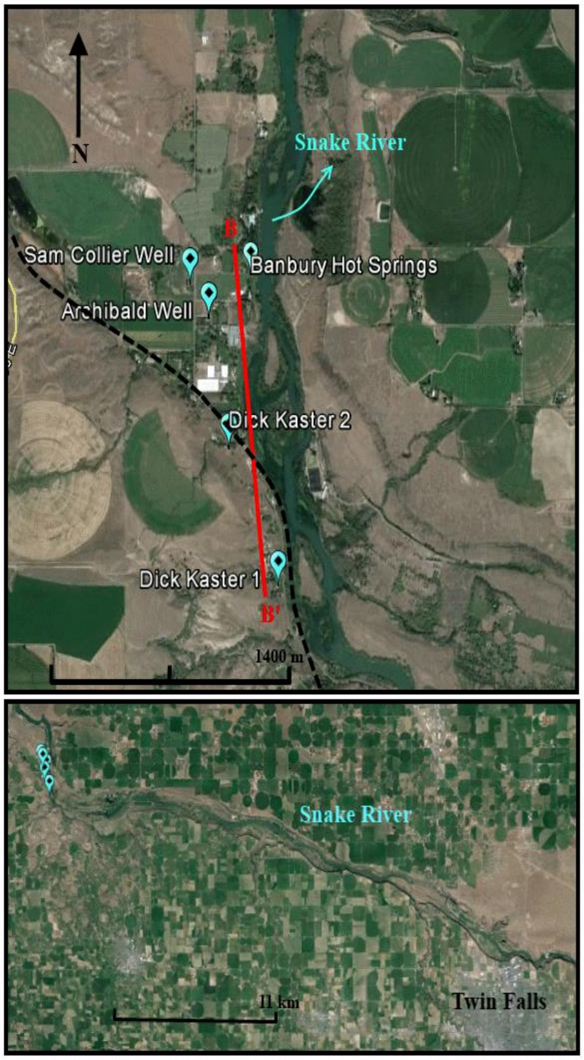


Figure 27. (Top Map of the cross section line through the Banbury area. (Bottom) Reference map.

A similar transition from Ca-HCO_3 thermal waters to Na-HCO_3 thermal waters away from the zone of recharge is observed in the cluster of thermal expressions near the city of Twin Falls, ID. However, there is no evidence for a fault-controlled system like the one observed in the Banbury area. Figure 28 depicts the local geology of the area in cross section view with no apparent offset. Shervais et al. (2013) suggests that upflow zones in this area may be controlled by permeability associated with a buried caldera margin. The concentration of hotter Na-HCO_3 type waters near the Snake River where units of Idavada volcanics are exposed shows that thermal water occurrence may be controlled by thinning basalt units. Aside from the lack of faulting in the Twin Falls area, the other major difference in geology from the Banbury area are the presence of the Shoshone Falls Rhyolite (andesite unit of the Idavada volcanics) and a significant layer of lacustrine sediments above the rhyolites of the

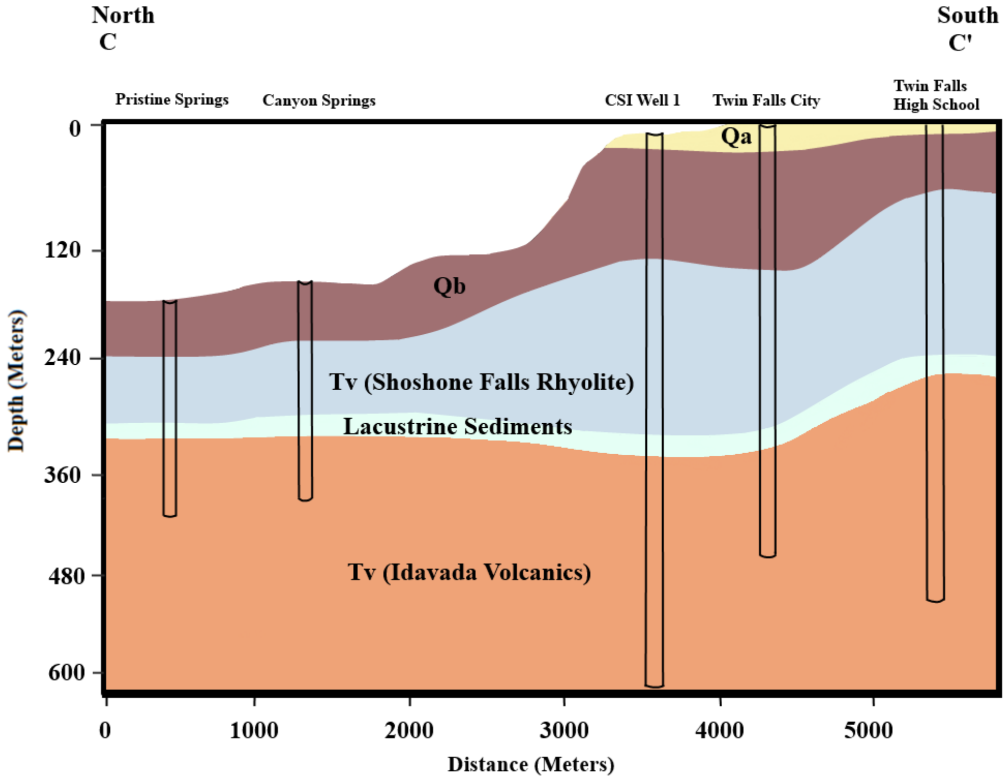


Figure 28. Geologic cross section through the Twin Falls thermal area.

Idavada volcanics. The lacustrine sedimentary layer comprised of oolitic siltsone and claystone (Street and DeTar, 1987) may serve as the confining layer for the artesian thermal aquifer in this area.

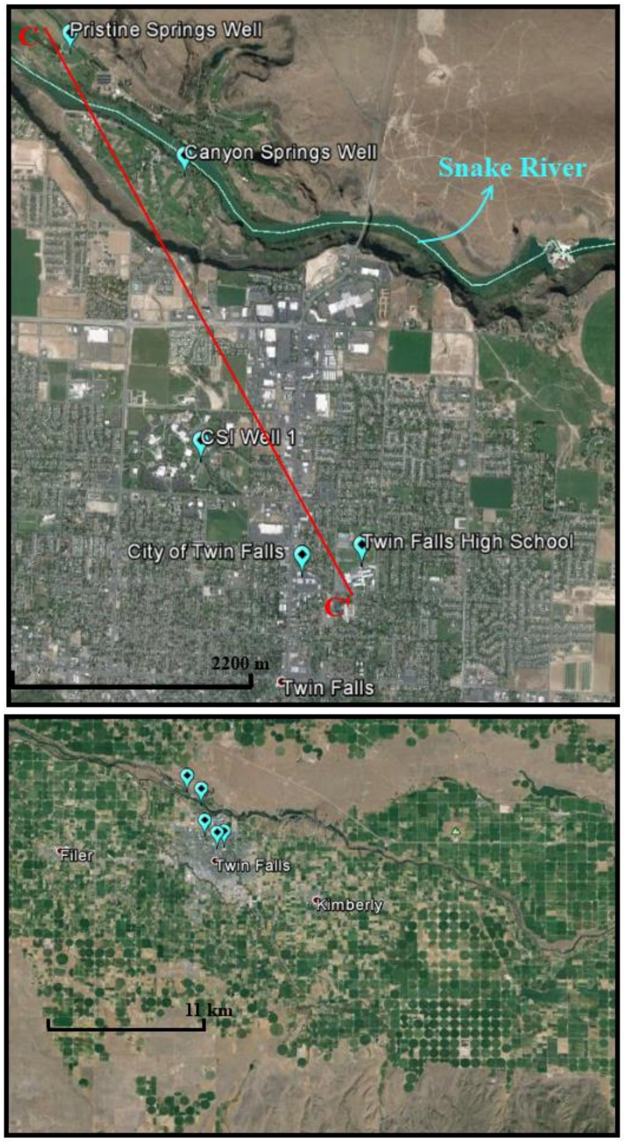


Figure 29. (Top) Map of the cross section line through the Twin Falls area. (Bottom) Reference map.

5.5.1 Aquifer Test and Analysis

As discussed previously, flow pathways and residence times may be very important in allowing for re-equilibration from Na-HCO_3 type waters into more Ca-rich thermal waters Declines in hydraulic head in the Twin Falls – Banbury area have been observed for over thirty years (Lewis and Young, 1982; 1989; Street and DeTar, 1987) due to increased utilization of the resource with several areas showing hydraulic heads below land surface. Monitoring of thermal wells in the study area revealed that the Twin Falls and Banbury hydrothermal areas are interconnected with development and increased utilization in one area resulting in declines in the other. Flow throughout the aquifer is thought to be controlled primarily by fractures resulting from tectonic movement, cooling joints, porosity of non-welded ash flow tuff units, and contacts between successive flows (Street and DeTar, 1987).

Aquifer parameters of the rhyolites of the Idavada volcanics were estimated first in 1982 through a pumping test of two of the deeper wells in the area (CSI 1 and 2) performed by CH2M Hill. CSI 1 and 2 (2200 and 1480 ft. deep) are geothermal wells used for space-heating located on the campus of the College of Southern Idaho and were sampled for chemical analysis (CC-51 and CC-14) as part of this study in 2014. While water temperatures seem to have remained constant (37 ^{o}C) since drilling was completed in 1979, a significant decline in hydraulic head has been observed. Street and DeTar (1987) reported hydraulic head values around 14 meters above land surface. Both of these wells are no longer flowing artesian with water levels of about 1.2 meters below land surface at present day. Due to the observed decline in water levels and the erroneous listing of CSI 1 at 1191 ft. deep (cased portion of the well) in the initial pump test report, a new pump test was conducted for both

CSI wells from 9/1/15 – 9/5/15 in an effort to establish a vertical gradient and thermal water travel times.

A 24-hr drawdown test and a 24-hr recovery test was performed for both wells. Pumping of CSI 2 began at 10:00 AM on 9/1/15 and continued until 10:00 AM on 9/2/15 after which it was allowed to recover for a full 24 hours. CSI 1 was pumped immediately after the recovery test of CSI 2 beginning around 10:00 AM on 9/3/15 continuing until around 10:00 AM on 9/4/15. Recovery of CSI 1 was also monitored and ended on 10:00 AM on 9/5/15. Solinst ® Levelogger ® (Model 3001) pressure transducers were installed in both wells and hung at approximately 50 ft. beneath land surface from ports on the well heads. A Solinst ® Barologger ® barometric pressure transducer was kept securely at the same location as CSI 1. All transducers were set to obtain measurements every minute. Both wells were pumped at a rate of 300 gpm although data from the pressure transducers show the pumping rate may have taken about an hour to stabilize after initial over pumping (Figure 30).

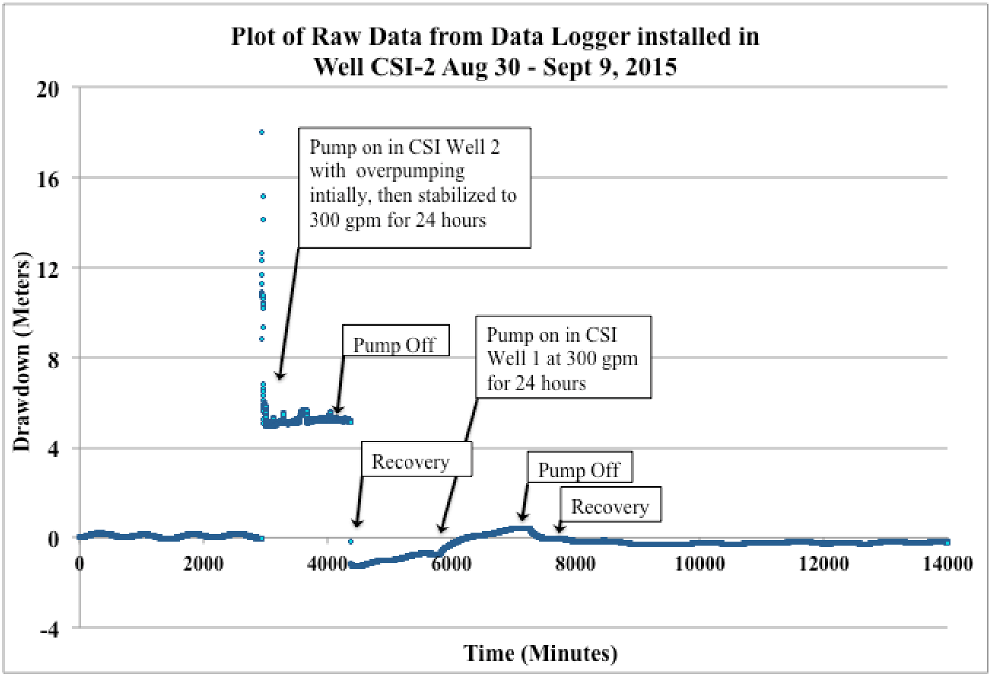


Figure 30. Plot of uncorrected drawdown from CSI Well 2 vs time since transducer installation.

Due to difficulty in retrieving the pressure transducer from CSI 1, only data from CSI 2 as the pumped well and observation well is available. Figure 30 shows the pressure readings (meters of water) from CSI 2 during the entirety of both pumping and recovery tests. A cyclic antecedent trend is observed prior to the start of pumping showing a sinusoidal fluctuation of about 0.1 meters every 600 minutes. This is probably caused by a pump cycling on and off somewhere within the aquifer. At the start of the test, it can be seen that 18 meters of over pumping occurred due to the pump rate exceeding the target rate of 300 gpm until flow was regulated. Drawdown was about 5 meters during the steady pumping rate of 300 gpm. When the pump was shut off at 1440 minutes, it can be seen that the water level over recovered by 1.2 meters as noted by the double headed arrow to the left in Figure 31. Also recorded in Figure 31 is the temperature (red line) during pumping which rose nearly 15 °C. There are at least two plausible explanations for the over recovery observed during the tests: 1) electronic

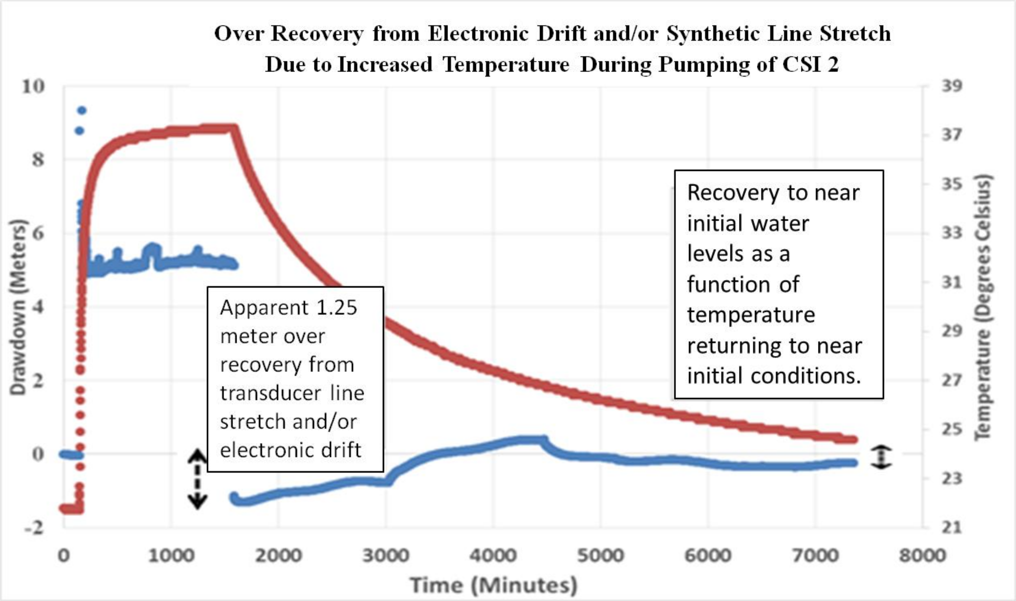


Figure 31. Plot of CSI Well 2 temperature (red) vs drawdown (blue) highlighting possibilities of electronic drift or stretch in synthetic line resulting in the observed overpumping.

instrument drift corresponding to heating; and 2) stretch in the graduated synthetic line used to hang the transducer. As temperatures approach initial values near the end of the CSI 1 pumping test, transducer water level measurements near background levels prior to pumping.

Over pumping in the early time data and the observed over recovery in the CSI 2 pumping tests deemed the data set from CSI 2 pumping as unusable. However, time-drawdown pairs were generated for both the pumping and recovery tests for this well when CSI 1 was being pumped. Aquifer parameters were estimated using the hydrologic type curve matching software AQTESOLV®. From previous hydrologic research in the area (Street and DeTar, 1987; Lewis and Young, 1989) and the local artesian conditions, analysis was focused on confined and leaky-confined aquifer solutions. Based on cross section analysis (Figure 28) and CSI well logs (Appendix D), the lacustrine sediment layer consisting of oolitic siltstone and sandstone (Street and Detar, 1987) may serve as the confining unit for this system. The best match of the data to type curves was achieved using the Cooper-Jacob (1946) straight-line method. This method is a variation of the classic Theis (1935) well function that relates the transmissivity (T), storativity, (S), radial distance of drawdown (r), and pumping time (t) to the pumping rate (Q) in an infinite series shown below:

$$W(u) = (-.5772 - \ln u + u - \frac{u^2}{2 \times 2!} + \frac{u^3}{3 \times 3!} ....)$$

where W(u) is the well function and (u) is given by:

$$u = \frac{r^2 S}{4Tt}$$

The final relationship between drawdown and aquifer parameters is given by:

$$dd = \frac{Q}{4\pi T} W(u)$$

Cooper and Jacob (1946) approximated the relationship between drawdown and log (t) as a straight-line relationship by making the recognition that the second-order and higher terms in the infinite series become negligible with small (u) values given by long pumping times (t) or short radial distances (r). Solutions to the pumping and recovery test for the CSI 1 wells are shown below in Figure 32. Calculated transmissivity values of 930 m^2/d (75,000 gpd/ft) are within the same order of magnitude and in close agreement with the values reported by Street and Detar (1987) of 554-923 m^2/d (44,600 – 74,300 gpd/ft). Based on the well logs of CSI 1 and 2, thermal water appears to come from a fracture zone at approximately 350 – 370 meters (1150 – 1215 ft) below land surface. Because both wells are open across the entire water bearing zone, calculation of a vertical gradient is not possible. Available data are insufficient to define the anisotropy of the Idavada volcanics. Thus, the data set precludes making a reasonable estimate of vertical travel times. Because of the strong artesian conditions of the deep thermal aquifer, the vertical gradient is known to be upward. However, without additional well data and depth discrete pumping tests, it is not possible to accurately quantify the vertical flow rate. Future work including detailed flow path analysis within the Idavada volcanics and the investigation into possible thermal flow paths between rhyolites and basalts is highly recommended.

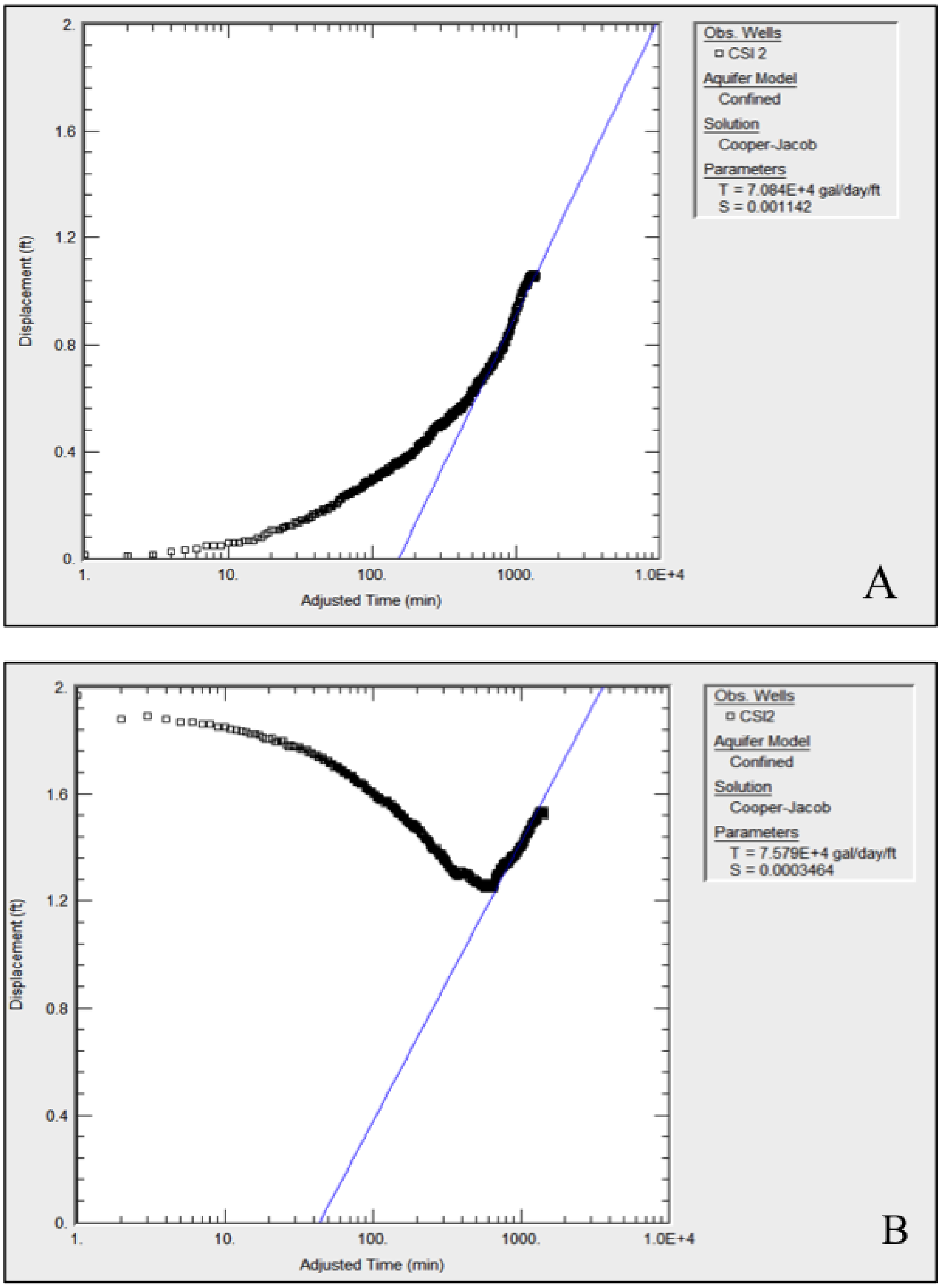


Figure 32. Cooper Jacob straight-line solution applied to barometric pressure corrected pumping (A) and recovery (B) limbs of the CSI Well 1 aquifer test.

CHAPTER 6: WATER-ROCK INTERACTION AND MIXING EXPERIMENTS

The concept of re-equilibration in the Twin Falls – Banbury hydrothermal system may explain the modeling results of pure water mixing with Na-HCO_3 type thermal waters and the apparent gradational transition between deep Na-HCO_3 waters and shallower Ca-HCO_3 thermal waters (Figure 24). Bench scale water-rock interaction and mixing experiments were constructed in order to test the validity of the potential re-equilibration mechanism which results in the exchange of Ca and Mg with Na. This exchange results in the downward transition from local groundwater to very dilute water after mixing with Na-HCO_3 thermal waters and the re-equilibration of Na-HCO_3 thermal waters into Ca-HCO_3 thermal waters after mixing during ascension.

Experiments were modelled after the study area with an initial thermal water coming into equilibrium within the Idavada volcanics at 150 ^{o}C (Banbury Hot Springs temperature estimate) and subsequently being mixed with a local groundwater sample within the basalts of the ESRP and maintained at an intermediate temperature (70 ^{o}C). Thermal water was produced within closed system stainless steel reactor cells maintained at 150 ^{o}C and saturation vapor pressure. This water was then mixed with local groundwater in three different proportions comprised of 60%, 40%, and 20% thermal water. Chemical concentrations of mixed water samples over time are used to better understand the implications of flow pathway mixing and re-equilibration.

6.1 Rock Samples

Rock sample for the initial water-rock interaction were collected from the Shoshone Falls Rhyolite within the Idavada volcanics. Because core samples in sufficient quantity were possible to obtain, samples were obtained from an outcropping unit of Idavada volcanics near the city of Twin Falls, ID. Street and Detar (1987) gave a sample location (42.598158°, -114.463464°) and detailed description of an easily accessed portion of the Shoshone Falls Rhyolite within the Snake River Canyon. Despite the apparent misnomer, this rock is actually thought to constitute a single andesitic flow unit within the Idavada volcanics. The sample location can be seen in Figure 33A below. Basalt rock samples for the second portion of the experiment were collected from an outcrop within the ESRP at the Pleistocene Hell's Half Acre basalt flow (Figure 33C). Samples were collected here and used as a proxy for Twin Falls area basalts due to difficulty in gaining access to basaltic outcrops on private property.

6.2 Rock Sample Preparation

In order to increase reaction rates through increased particle surface area (Savage et al., 1992; Neupane et al., 2013), blocky samples from outcrops were reduced to a finer grain size prior to heating and interaction with sample water. Rock samples were first cut using a rock a saw into manageable sized pieces prior to being crushed into approximately 5 cm diameter pieces using a ball peen hammer (Figure 34). Samples were then reduced to finer grain sizes using a Braun ® Chipmunk rock crusher. The pulverized samples were then sieved (dry) and wet sieved (Figure 34) through brass (ASTM Sieve # 60– 120) sieves to separate out 0.25 – 0.125 mm particle sizes. Grain sizes in this range have been utilized for past water-rock interaction experiments to increase reaction rates (Savage et al. 1992, Rodriguez, 2011; Neupane et al., 2013). Samples were then decanted using deionized water to remove any suspended fine-grained particles and organic material. Samples were then allowed to dry for 48 hours prior to obtaining dry mass values by scale.

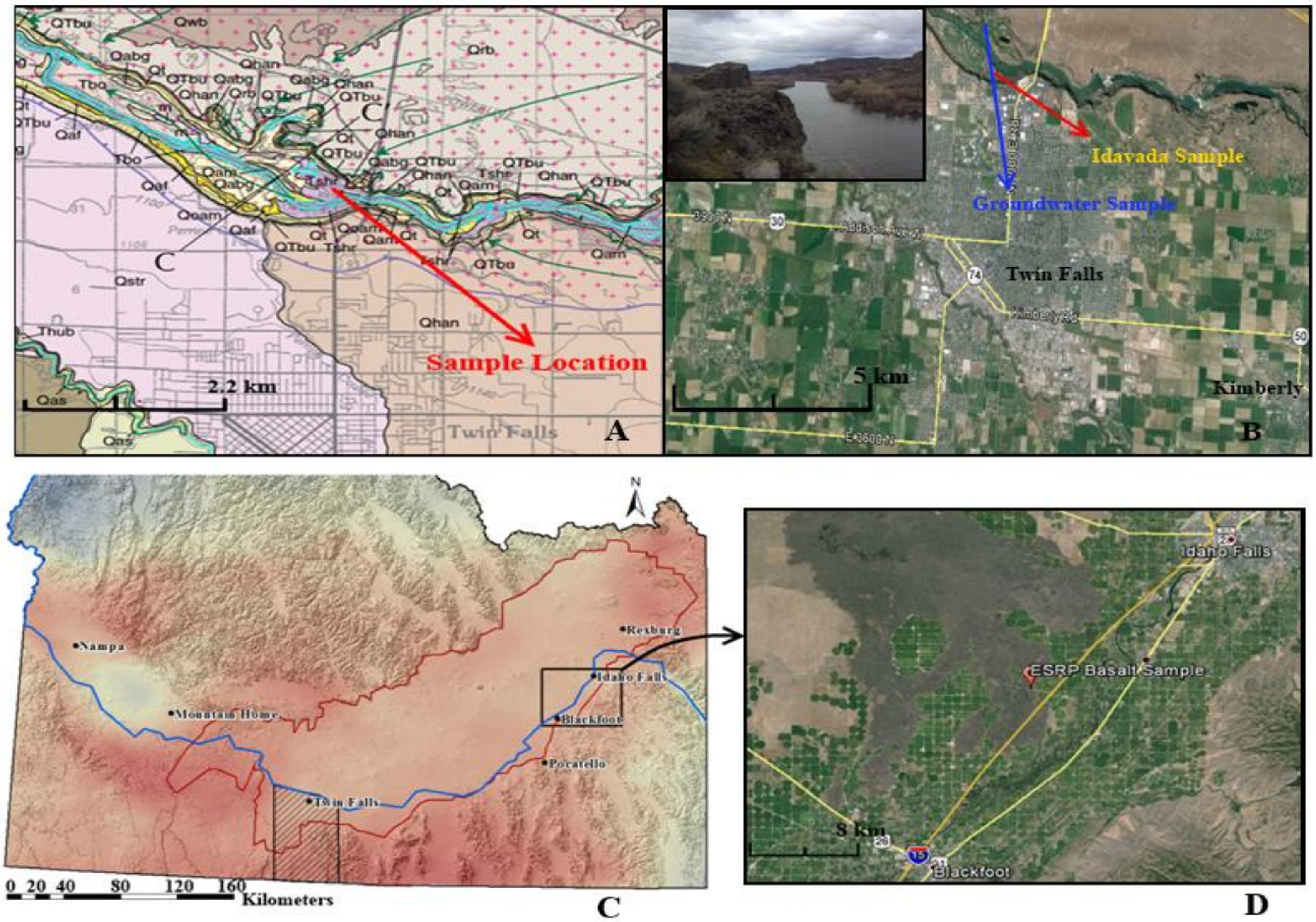


Figure 33. A) Idavada volcanics sampling location on a geologic map showing unit outcrop (dark pink). B) Idavada and groundwater sample locations map view. Inset – View of Idavada volcanics outcrop C) Reference map showing Hell's Half Acre location compared to study area. D) ESRP basalt sample location map view.

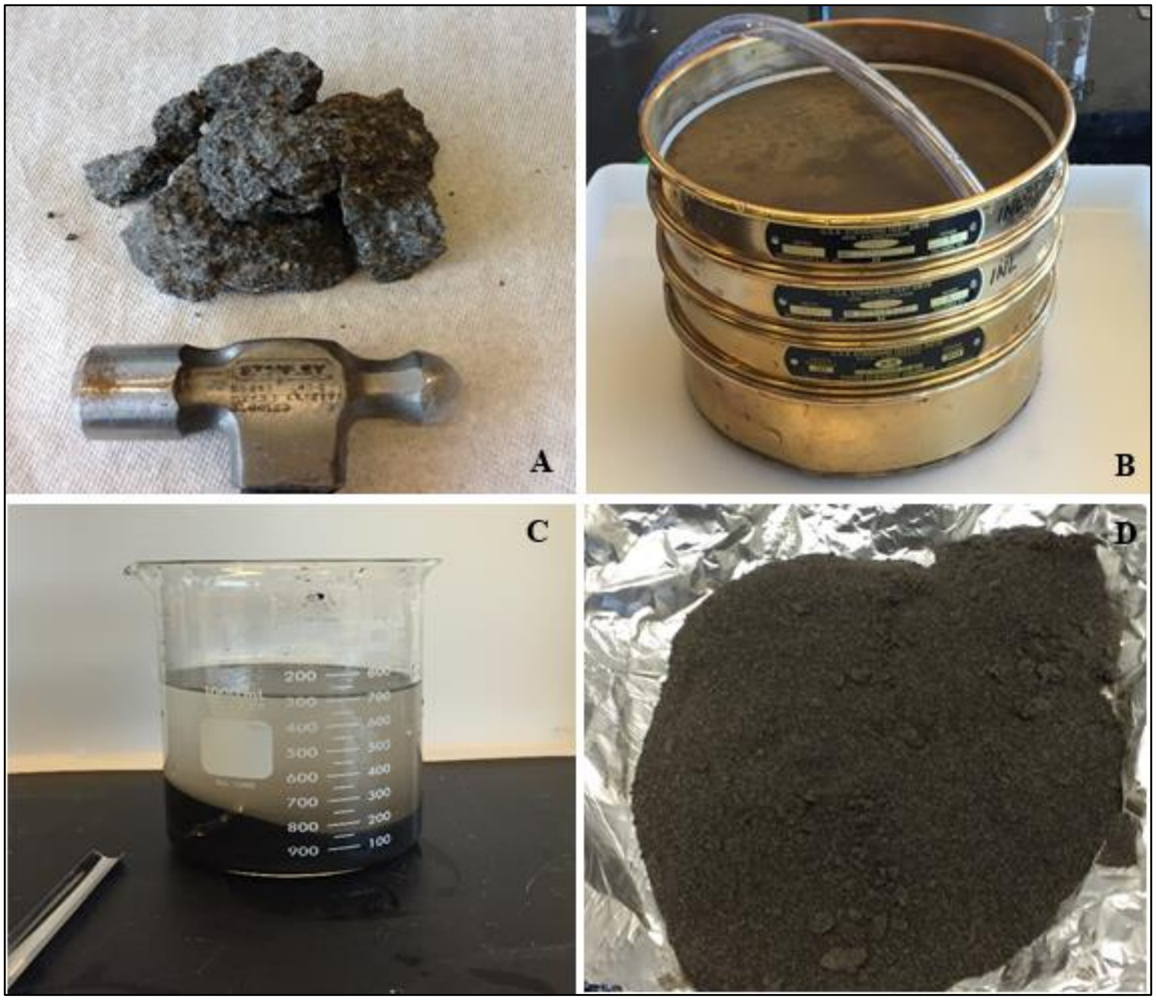


Figure 34. A) Idavada volcanics sample preparation prior to crushing. B) Wet sieving setup with deionized water line. C) Decanting process of rock sample after wet sieving. D) Final dry Idavada sample.

6.3 Initial Water Sample

A local groundwater sample was collected in order to use as both the source water for the formation of the Na-HCO_3 thermal water and as the mixing component in the second phase of the experiment. Samples were collected from a city water supply well (Blue Lakes Well) in coordination with the Twin Falls Department of Water Resources office. Sample location can be seen in Figure 33B. Samples were collected for major cation, major anion, and trace element analysis in the same manner as other geothermal samples throughout this study

(Appendix A). Five additional 1 liter non-acidified samples were collected for use in both portions of the experiment. Initial water chemistry is presented in Table 12 and is comparable to cooler groundwater samples from earlier studies of the area (Chapter 3, Table 2).

6.4 Experimental Procedure: Part 1

The thermal water component for the mixing experiment was created using two stainless steel 1.0 L (Type 316) reaction vessels (Model 4523 Parr® Instrument) in which temperature, pressure, and stirring within the reactors were controlled independently. Maximum operating pressures and temperatures of these reactors are rated at 1900 psig (131 bars) and 350 ºC, respectively (Parr Instruments Company, 2011). These reaction vessels are constructed so that fluids can be sampled at operating pressure and temperature without disassembling the reactor or affecting experimental conditions. Reactor vessels were cleaned thoroughly through sanding, acid washing with a 5% HNO_3 solution, rinsing with Milli-Q Nanopure water, and finally heating at 150 ºC while partially filled with Milli-Q Nanopure water for 24 hours. Additionally, reactor vessels were pressurized with ultra-pure N_2 gas and left for 24 hours in order to monitor any pressure leaks due to faulty connections and/or gaskets.

After assuring the reactor vessels were clean and there were no apparent pressure leaks or temperature losses in the test runs, samples were added to two clean and empty reactor vessels (4/8/2015). 60 grams of Idavada volcanics samples were added to each vessel with 600 mL of groundwater sample in accordance with Parr® instrument fill volume limitations. Reactors were then gradually heated to 150 ºC and a stirring frequency of 200 rpm for 30 seconds every hour was established in order for the fluid-rock mixture to remain well mixed. Temperature and pressure were monitored remotely to assure there were no deviations from the set temperature and saturation vapor pressure at 150 °C (∼4.76 bars). Reactors ran for a total of 101 days with sampling taking place at 82 days (6/28/15) and 101 days (7/17/15). Based on previous silicic water-rock interaction experiments where equilibrium conditions were observed in as few as 1-32 days (Rodriguez, 2011; Neupane et al., 2013) and personal communication with Dr. Hari Neupane, 101 days was deemed a sufficient time frame to

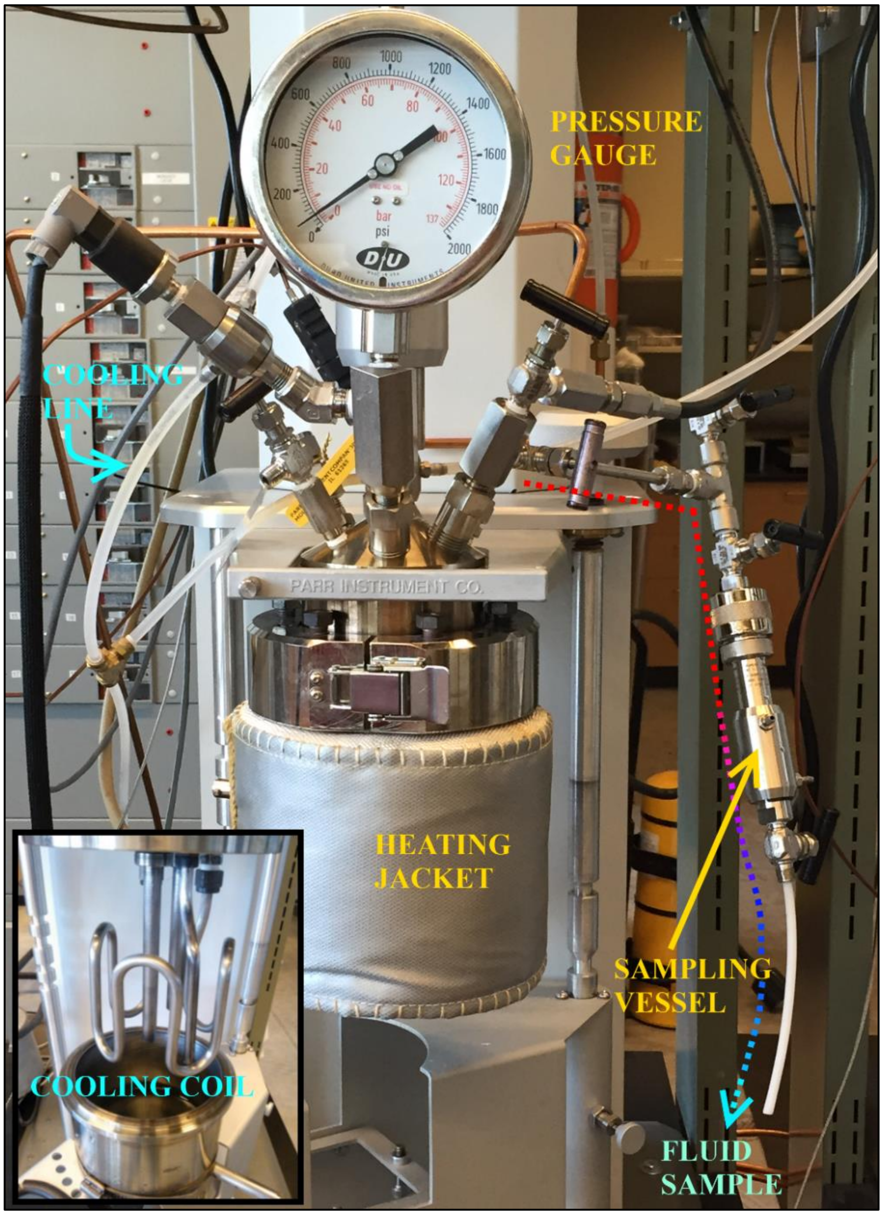


Figure 35. Water-rock interaction experiments conducted at 150 °C using bench top Parr 1 L reactor vessels. Inset – a reactor vessel and its cooling coil.

obtain equilibrium at 150 °C. Equilibrium conditions are also supported by reaction path modeling using The Geochemist's Workbench (Bethke and Yeakel, 2013) where calculated near zero saturation index values are observed for chalcedony, calcite, and fluorite. The absence of apparent equilibrium conditions with the clays and zeolites mentioned previously in Chapters 3 and 4 may be explained by the use of the andesitic Shoshone Falls Rhyolite sample as opposed to the more abundant rhyolites within the Idavada volcanics. Additionally, the remarkably high silica concentrations observed in initial water samples may suggest that volcanic silicic glass is controlling silica equilibrium. Future work examining secondary alteration mineralization within experimental rock samples along with experimental runs with varied rock types would aid in reducing uncertainties regarding equilibrium.

Prior to sample collection, a small 5-10 mL volume was extracted in order to purge the sampling vessel of "dead sample" stuck from the previous sample collection. Three samples of approximately 5-8 mL were taken for cation, anion, and trace elemental analyses in pre-washed 25 mL HDPE bottles. All samples were filtered through a 0.45 µm filter. Cation and trace metal samples were preserved through acidification to a $pH < 2$ with concentrated optima grade HNO_3. An additional 3-4 mL sample was taken to obtain a pH measurement immediately after sampling. Major anions were analyzed with ion chromatography (Dionex ICS-2100), major cations were analyzed with Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES iCAP 6500), and trace elements were analyzed with Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS Agilent 7500ce). Water chemistry results for the initial thermal component are shown in Table 12.

6.5 Experimental Procedure: Part 2

Prior to mixing thermal waters from Reactors #5 and #6 with groundwater and new host rock samples, the cleaning and leak test procedure described above was repeated for four new reactor vessels (#s 1,3,4, and 8). The water rock ratio of 600 mL water to 60 g of rock sample was maintained throughout the mixing portion of the experiment. Reactors #5 and #6 were brought down to 70^{o}C individually and transferred rapidly (5 min) into new reactors with cold groundwater where the mixture was heated to 70 ^{o}C, maintained at saturation vapor pressure, and stirred for 30 seconds at 200 rpm every hour. Thermal to mixed water ratios of 60%, 40%, and 20% thermal water were utilized for reactor #s 4, 3, and 1 respectively. Reactor #8 was established as the experimental control in which no ESRP basalt rock sample was added. Water to rock and thermal water to groundwater ratios are presented in Table 11.

Table 11. Water-rock Interaction Experimental Matrix

<table>
<tr><th colspan="7">Initial Experimental Waters</th></tr>
<tr><td>Reactor</td><td>T (^{o}C)</td><td>P_{H_2O} (bars)</td><td>Idavada Sample Mass (g)</td><td>Solution Volume (mL)</td><td>Duration (days)</td><td></td></tr>
<tr><td># 5</td><td>150</td><td>4.76</td><td>60</td><td>600</td><td>101</td><td></td></tr>
<tr><td># 6</td><td>150</td><td>4.76</td><td>60</td><td>600</td><td>101</td><td></td></tr>
<tr><th colspan="7">Mixed Experimental Waters</th></tr>
<tr><td>Reactor</td><td>T (^{o}C)</td><td>P_{H_2O} (bars)</td><td>Basalt Sample Mass (g)</td><td>Thermal Solution Volume (mL)</td><td>Groundwater Solution Volume (mL)</td><td>Duration (days)</td></tr>
<tr><td># 1</td><td>70</td><td>0.31</td><td>60</td><td>120</td><td>480</td><td>4</td></tr>
<tr><td># 3</td><td>70</td><td>0.31</td><td>60</td><td>240</td><td>360</td><td>40</td></tr>
<tr><td># 4</td><td>70</td><td>0.31</td><td>60</td><td>360</td><td>240</td><td>40</td></tr>
<tr><td># 8</td><td>70</td><td>0.31</td><td>0</td><td>240</td><td>360</td><td>40</td></tr>
</table>

Because reactor #s 3 and 8 contained thermal water derived from reactor #5, the thermal water to groundwater ratio of 40 % thermal water to 60% groundwater was utilized in control reactor # 8 to match the ratio of reactor # 3. 60 g of ESRP basalt sample was added to

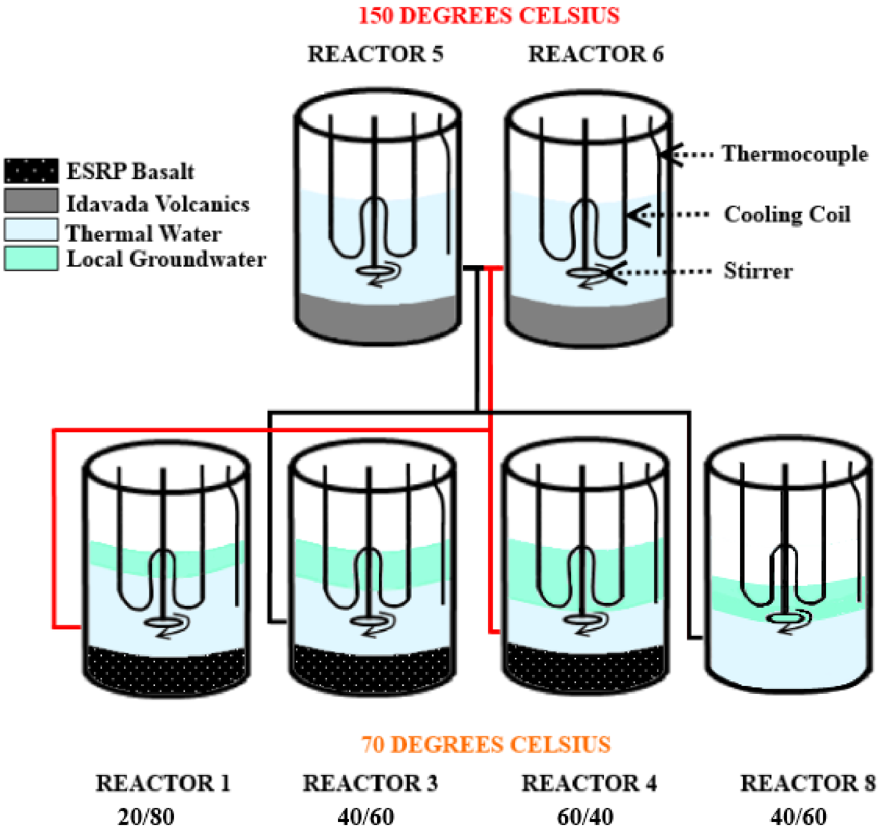


Figure 36. Experimental diagram showing the transfer of thermal water to mixed water reactors. Water to groundwater ratios are shown for Reactors # 1, 3, 4, and 8.

each reactor vessel. All reactors were sampled at 4 hr, 8 hr, 24 hr, 48 hr, 96 hr, 10 days, 20 days, 30 days, and 40 days with the exception of reactor # 1 which ran dry after the 96 hr sample most likely due to the development of a pressure leak. Samples were taken for major cations, anions, and trace metals and analyzed in the same manner as the first portion of the experiment. The water chemistry results for all reactors are presented in Table 12 below.

6.6 Results

Experimental results with respect to solution concentration over time are shown in Table 12 for all analyzed chemical constituents. Results are presented graphically for select chemical constituents of interest in Figures 37-40.

Table 12. Chemical analysis results from initial and mixed experimental waters.

	Initial Experimental Waters												
Sample	**pH**	**Temp °C**	**F mg/L**	**Cl mg/L**	**SO4 mg/L**	**NO3 mg/L**	**Ca mg/L**	**Mg mg/L**	**Na mg/L**	**K mg/L**	**SiO2 mg/L**	**Al mg/L**	**B mg/L**
Groundwater Sample	7.47	15.9	0.5	46.2	59.3	9.36	57.2	19.78	35.4	6.45	41.6	1.00E-04	-
CC-150-5 (6-28-15)	6.85	150	2.61	42.5	57.4	7.30	12.3	0.11	42.5	21.4	242	0.41	-
CC-150-6 (6-28-15)	6.91	150	3.42	49.3	61.8	9.26	2.65	0.21	69.1	38.6	270	1.79	-
CC-150-5 (7-17-15)	6.88	150	3.02	46.77	63.87	8.23	16.5	0.10	47.9	23.5	255	0.60	0.107
CC-150-6 (7-17-15)	6.96	150	3.55	47.48	58.71	8.95	<10	0.10	70.4	35.9	235	1.98	0.107

	Mixed Experimental Waters												
Sample	**pH**	**Temp °C**	**F mg/L**	**Cl mg/L**	**SO4 mg/L**	**NO3 mg/L**	**Ca mg/L**	**Mg mg/L**	**Na mg/L**	**K mg/L**	**SiO2 mg/L**	**Al mg/L**	**B ug/L**
CC-1-20/80-7-17-15 (4 Hr)	7.59	70	2.32	50.0	71.4	22.5	23.6	5.66	61.5	23.3	127	1.045	0.114
CC-1-20/80-7-17-15 (8 Hr)	7.96	70	2.08	48.9	70.4	9.12	22.4	5.31	66.7	24.0	109	0.119	0.136
CC-1-20/80-7-18-15 (24 Hr)	7.62	70	1.84	50.0	86.2	9.25	18.9	4.25	79.5	24.4	77.7	0.161	0.166
CC-1-20/80-7-19-15 (48 Hr)	7.35	70	1.29	49.7	107	8.99	13.9	2.82	91.7	23.8	60.5	0.221	0.162
CC-1-20/80-7-21-15 (96 Hr)	7.72	70	0.544	48.6	168	8.58	<1	1.21	138	23.6	27.9	0.476	0.150
CC-3-40/60-7-17-15 (4 Hr)	7.94	70	1.63	48.1	63.2	9.17	34.5	9.59	54.9	21.1	127	0.351	0.117
CC-3-40/60-7-17-15 (8Hr)	7.91	70	1.64	48.5	63.9	9.24	38.3	10.85	51.6	18.3	110	0.184	0.100
CC-3-40/60-7-18-15 (24 Hr)	7.75	70	1.58	47.9	66.1	9.12	37.2	10.32	51.8	17.8	103	0.074	0.119
CC-3-40/60-7-19-15(48 Hr)	7.28	70	1.53	48.5	70.1	9.26	39.6	10.41	55.6	18.4	109	0.072	0.104
CC-3-40/60-7-21-15 (96 Hr)	7.35	70	1.30	48.3	77.4	9.15	34.9	10.29	60.3	18.6	101	0.101	0.114
CC-3-40/60-7-28-15 (10Day)	7.1	70	1.01	48.7	90.0	9.10	29.7	10.26	70.6	19.1	94.1	0.130	0.122
CC-3-40/60-8-5-15 (20 Days)	6.86	70	0.851	48.2	98.8	9.09	27.2	9.91	75.6	19.2	90.3	0.110	0.122
CC-3-40/60-8-16-15 (30 Day)	6.98	70	0.771	48.3	104	8.91	25.8	9.23	83.0	18.7	91.2	0.130	0.111
CC-3-40/60-8-29-15 (40 Day)	7.15	70	0.65	47.95	107.18	8.98	21.1	8.58	87.4	18.9	78.7	0.117	0.126
CC-4-60/40-7-17-15 (4 Hr)	7.92	70	1.48	51.0	69.4	9.22	42.1	10.74	47.7	14.6	130	0.078	0.156
CC-4-60/40-7-17-15 (8 Hr)	7.82	70	1.49	50.8	70.2	9.18	40.6	10.37	46.5	14.3	119	0.050	0.157
CC-4-60/40-7-18-15 (24 Hr)	7.75	70	1.41	50.7	73.0	9.11	41.3	10.05	49.8	15.1	114	0.050	0.155
CC-4-60/40-7-19-15(48 Hr)	7.45	70	1.28	52.0	80.0	9.10	38.2	9.32	53.6	15.2	112	0.059	0.144
CC-4-60/40-7-21-15 (96 Hr)	7.36	70	0.939	51.9	91.7	9.06	31.0	8.54	60.6	15.2	93.6	0.092	0.342
CC-4-60/40-7-28-15 (10 day)	7.21	70	<0.5	50.6	122	9.05	25.6	7.56	72.0	15.7	74.9	0.067	0.175
CC-4-60/40-8-5-15 (20 Day)	7.01	70	<0.5	49.1	125	8.59	21.3	5.86	83.7	15.6	61.2	0.105	0.256
CC-4-60/40-8-16-15 (30 Day)	7.06	70	<0.5	47.6	127	8.33	14.6	3.80	96.6	16.2	47.3	0.192	0.162
CC-4-60/40-8-29-15 (40 Day)	7.21	70	<0.5	46.37	139.66	8.01	10.7	3.00	105	16.1	50.8	0.198	0.183
CC-8-NoRock-7-17-15- (4 Hr)	8.18	70	1.57	47.7	63.0	8.97	39.2	9.77	41.9	15.4	145	0.155	0.119
CC-8-NoRock-7-17-15 (8 Hr)	8.14	70	1.57	47.7	63.5	8.93	41.0	10.72	43.6	16.0	146	0.097	0.086
CC-8-NoRock-7-18-15 (24 Hr)	8.04	70	1.52	47.7	62.1	8.92	39.6	10.41	42.6	15.2	139	0.091	0.208
CC-8-NoRock-7-19-15 (48 Hr)	7.86	70	1.48	47.4	61.3	8.77	37.2	10.17	42.6	15.0	134	0.075	0.102
CC-8-NoRock-7-21-15 (96 Hr)	7.84	70	1.45	47.6	61.2	8.76	33.9	9.47	41.8	14.6	126	0.051	0.110
CC-8-NoRock-7-28-15 (10 Day)	7.44	70	0.872	46.8	54.9	8.64	19.2	5.68	36.1	12.6	69.9	0.050	0.144
CC-8-NoRock-8-5-15 (20 Day)	7.48	70	<0.5	44.1	45.5	8.09	<10	2.49	30.6	10.1	15.9	0.050	0.100
CC-8-NoRock-8-16-15 (30 Day)	7.5	70	<0.5	40.5	37.7	7.31	<10	1.12	26.2	8.5	<10	0.081	0.100
CC-8-NoRock-8-29-15 (40 Day)	7.4	70	<0.5	31.41	28.18	5.61	<10	1.07	35.4	11.8	<10	0.076	0.100

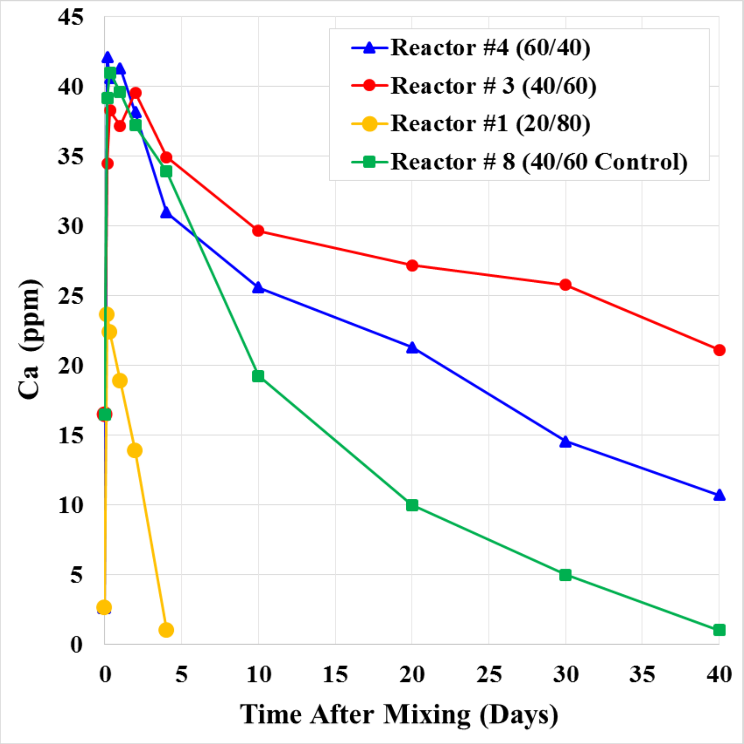


Figure 37. Calcium concentrations of experimental mixed thermal water samples over time. Ratios of thermal to groundwater are given in parentheses.

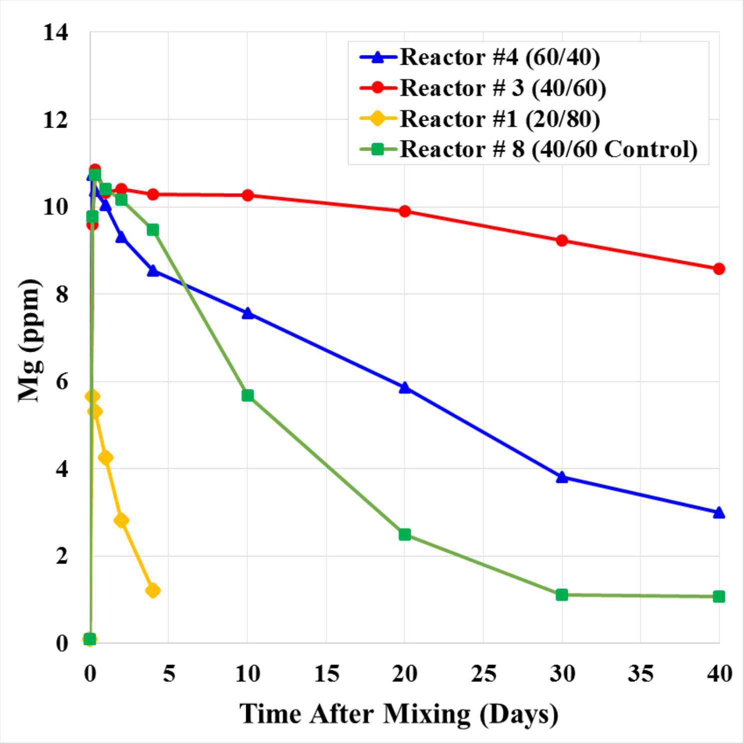


Figure 38. Magnesium concentrations of experimental mixed thermal water samples over time. Ratios of thermal to groundwater are given in parentheses.

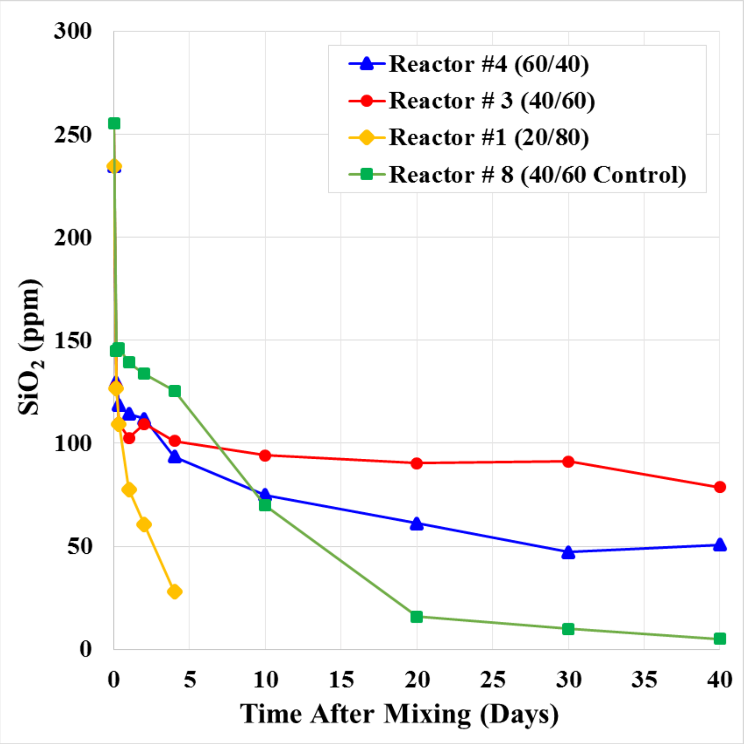


Figure 39. Silica concentrations of experimental mixed thermal water samples over time. Ratios of thermal to groundwater are given in parentheses.

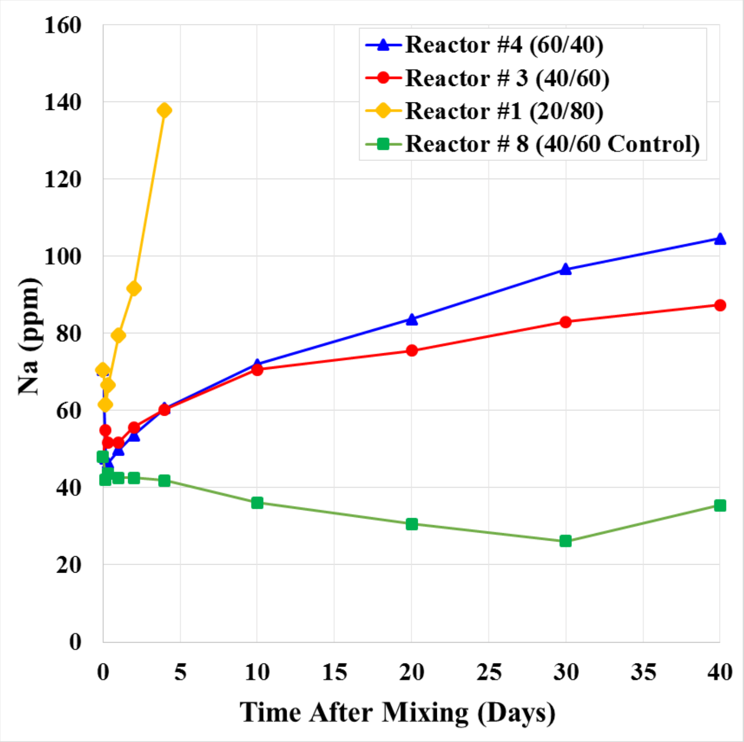


Figure 40. Sodium concentrations of experimental mixed thermal water samples over time. Ratios of thermal to groundwater are given in parentheses.

Ca and Mg concentrations show an immediate increase after initial mixing with groundwater progressing from initial concentrations (< 10 – 16.5 ppm Ca and 0.1 ppm Mg) to values around 35-40 ppm Ca and 9.5 – 10.5 ppm Mg (Reactors # 3,4, and 8). Reactor # 1, containing 20 % thermal water, exhibits a less prominent initial increase in Ca and Mg concentrations rising to only about 23.6 ppm Ca and 5.66 ppm Mg. After fluctuating about the initial point of increase, all reactors show significant declines in Ca and Mg concentration after the 4 day mark. The rate of decline of Ca and Mg seems to be effected by the ratio of initial thermal water to groundwater as a sharper decline for both constituents is exhibited in Reactor # 4 containing the highest ratio (60% thermal water) compared to Reactor # 3 (40 % thermal water). Reactor # 8 (control) shows a steeper decline than the previous two reactors for both Ca and Mg. Due to sample loss from a likely vessel leak, Reactor # 1 only has available data for 4 days. A very steep decline in both Ca and Mg is observed in Reactor # 1 but the rate of decline may be influenced by the open system created by the apparent leak.

SiO_2 concentrations show a dramatic decline after the initial mixing of thermal water and groundwater samples dropping from between 235-255 ppm SiO_2 to between about 130-145 ppm at the 4 hour mark in all reactors. However, unlike Ca and Mg concentration trends which show no sign of leveling off, SiO_2 seem to level off in Reactors # 3 and 4 at around the 20 day mark. Again, Reactor # 3 (60 % thermal water) with a greater percentage of thermal water component results in lower concentrations compared with Reactor # 4 (40% thermal water). Reactor # 8 (control) does not appear to be leveling off given its sharp decline.

In contrast to the previously discussed trends, Na concentrations increase in Reactor #s 1, 3, and 4 after initial mixing. Reactor # 4 (60 % thermal water) exhibits a steeper rate of increase over time than Reactor # 3 (40% thermal water). Reactor # 8 (control) is the only reactor which exhibits a fairly constant decline in Na concentrations over time. The steepest rate of increase of sodium concentrations is observed in Reactor # 1. However, this trend may or may not be significant due to the aforementioned equipment malfunctions manifesting around the 4 day mark.

6.7 Discussion

The experiments conducted in this chapter replicated the mixing of a felsic volcanic derived thermal water (150 ^{o}C) with a more dilute Ca-Mg-HCO_3 type groundwater at an intermediate temperature (70 ^{o}C) and the subsequent composition altering processes of the mixed water. These experiments show that the rates of change for select cations (Ca, Mg, and Na) and SiO_2 within mixed thermal waters may be dependent on the ratio of thermal water to groundwater within solution. A greater percentage of thermal water is correlated to a steeper rate of decline in Ca, Mg, and SiO_2 concentrations and a steeper rate of increase in Na concentrations. An increase number of experiments with varying thermal water to groundwater ratios may show whether this correlation is significant or not. Significant differences in concentrations between thermal water, groundwater, and mixed water are observed almost immediately.

After the 4 day mark, waters begin showing significant decreasing trends with respect to Ca, Mg, and SiO_2 concentrations and a significant rising trend with respect to Na concentrations. Reactor #8, which contained no basalt rock samples, is the only experiment to not show an increasing Na trend after mixing which may suggest that the transition into a more mafic rock type is necessary for the observed trends. With the exception of SiO_2, these trends do not show signs of levelling off. This observation is congruent with a mechanism for re-equilibration by a precipitation or cation exchange reaction explaining the apparent mixing between pure or dilute Na-HCO_3 water with thermal Na-HCO_3 type waters of the Twin Falls – Banbury hydrothermal system. The inverse of the trends displayed above may explain the possible re-equilibration of rising Na-HCO_3 type water into more Ca-HCO_3 type thermal waters at cooler temperatures.

CHAPTER 7: SUMMARY AND CONCLUSIONS

The Eastern Snake River Plain, formed by successive caldera formation associated with the migration of the Yellowstone hotspot, is considered to have some of the highest geothermal potential within the state of Idaho and the entire country (Tester et al., 2006). Geothermal potential is made evident through the many hydrothermal expressions (springs and wells) that line the periphery of the plain, anomalously high geothermal gradients (Brott et al., 1976) and heat flow values (Blackwell and Richards, 2004), and high mantle signature $^3He/^4He$ ratios (Dobson et al., 2015). Despite all of the potential within the region, geothermal development has been limited to low temperature resources and attempts at reservoir temperature estimation have resulted in lower than expected estimates. Many believe that this is due to the masking of the deep geothermal signature by the prolific overlying groundwater aquifer of the ESRPA (McLing et al., 2002; Neupane et al., 2014; Cannon et al., 2014; Dobson et al., 2015). While previous studies have acknowledged the possibility of mixing between ascending thermal waters and groundwater, few have attempted to compensate for its effects on reservoir temperature estimation through geothermometry. Because of sample density and preliminary temperature estimation results, the Twin Falls – Banbury hydrothermal system was chosen as the location for an in depth investigation into the possibility of mixing and re-equilibration in thermal waters of the ESRP.

Through principle component and hierarchical cluster analyses, two distinct thermal water types ($Na\text{-}HCO_3$ and $Ca\text{-}HCO_3$) were identified in the Twin Falls – Banbury area. $Na\text{-}HCO_3$ waters are separated by from $Ca\text{-}HCO_3$ waters by higher temperatures, higher TDS, and higher Na^+ concentrations. $Ca\text{-}HCO_3$ waters are characterized by high Ca^{2+} and Mg^{2+} concentrations and cooler temperatures. $Na\text{-}HCO_3$ waters emanate exclusively from thermal springs and a select few wells that are completed within the rhyolites of the Idavada volcanics whereas the Ca-HCO_3 thermal waters are found in wells completed within the overlying basalts. This is consistent with the trend from Na-K-HCO_3 thermal waters and Ca-Na-HCO_3 thermal waters with decreasing temperature and depth observed in the deep INEL-1 well that penetrates the basalt units of the ESRPA (Mann, 1986; McLing et al., 2002).

Evidence for mixing in the study area is provided by a linear trend between these two water types on a Piper diagram (Piper, 1944), partial equilibration and immature classification of most thermal water samples on the Giggenbach ternary diagram (Giggenbach, 1988), and linear trends between several conservative chemical constituents (Cl, B, δD, etc.). In addition to the evidence for simple mixing between the two water types, relationships between some reactive chemical constituents (Na, K, Mg, and Ca) display two separate and distinct trends for the two water types which suggests either:

1) The waters may be the result of two separate and unrelated flow pathways, host rocks, and/or equilibration temperatures.

   Or

2) The waters have undergone some form of reactive mixing and/or re-equilibration resulting in the transition from Na-HCO_3 thermal waters to Ca-HCO_3 thermal waters and vice versa depending on the reservoir temperature, rock types, and thermal water to groundwater ratio.

Reservoir temperature estimations were made utilizing conventional geothermometry techniques, silica-enthalpy mixing models, and multicomponent equilibrium geothermometry. Silica and cation conventional geothermometers yield highly varied results and many of them are limited in their application due to high calcium and magnesium concentrations of many thermal water samples. Silica-enthalpy mixing models are capable for accounting for dilution effects from simple mixing and are considered to yield more reliable temperature estimations. However, these models yield a wide range of possible reservoir temperatures and are incapable of accounting for the apparent reactive mixing and/or re-equilibration. In contrast, MEG through the use of the inverse modeling tool RTEst, is capable of accounting for a mixing component while utilizing an entire assemblage of likely reservoir alteration minerals to obtain a reservoir temperature. RTEst was utilized for both Ca-HCO_3 and Na-HCO_3 thermal waters. Simple mixing between groundwater and thermal water is not supported for Na-HCO_3 thermal waters yet is supported for Ca-HCO_3 thermal waters yielding temperature estimates between around 90 – 100 ^oC. The reconstructed compositions for Ca-HCO_3 waters produced by inverse modeling do not resemble the compositions of the Na-HCO_3 waters signifying that the Ca-HCO_3 thermal waters may be the result of re-equilibration if there exists a relationship between the two thermal water types.

An “intermediate” composition obtained from the intersection of the reactive constituent trends was utilized as the mixing component in RTEst modeling of Na-HCO_3 waters. This type of mixing is not supported through the use of RTEst as adequate saturation index convergence of likely reservoir minerals is not obtained. However, the use of pure water as the mixing component in RTEst modeling of Na-HCO_3 results in adequate saturation index convergence and reservoir temperatures as high as 160 ^oC. The same results are achieved when dilute Na-HCO_3 water is used as the mixing component for Na-HCO_3 RTEst modeling. In order to explain this phenomenon, a mechanism for re-equilibration was proposed in which groundwater (Ca-Mg-HCO_3 type) loses Ca^{2+} and Mg^{2+} and gains Na^+ upon mixing with a Na-HCO_3 thermal water with increasing temperature and depth resulting in dilute water that further mixes with Na-HCO_3 thermal waters. Conversely, this re-equilibration mechanism explains the transition from Na-HCO_3 thermal waters into more Ca-HCO_3 thermal waters by the increase of Ca^{2+} and Mg^{2+} and decrease of Na^+ from mixing during ascension through a series of equilibration zones. The RMAs utilized in MEG inverse modeling show that Ca-HCO_3 waters in equilibrium with Ca^{2+} and Mg^{2+} rich smectite clays and zeolites gradually shift to Na-HCO_3 waters in equilibrium with Na^+ and K^+ rich smectite clays and zeolites through several zones of re-equilibration resulting in thermal water types in between the two end members.

A possible re-equilibration mechanism was tested using high temperature water-rock interaction experiments. In the experiments, a 150 ^oC thermal water derived from equilibration with Idavada volcanics was mixed with a local groundwater at an intermediate 70 ^oC within the basalts of the ESRP. Samples taken over 40 days reveal that Ca^{2+}, Mg^{2+}, and SiO^{2-} concentrations decrease significantly at about 4 days after initial mixing. Na+ concentrations increase dramatically within the same observation time thus providing support for the possibility of re-equilibration of thermal waters within the Twin Falls – Banbury hydrothermal area.

A detailed look into local geology and hydrology reveals that the thermal system is likely recharged from the Cassia Mountains to the south of the study area. Groundwater likely picks up its Ca-Mg-HCO_3 signature from the Paleozoic carbonates exposed in the area before travelling northwesterly towards the Twin Falls and Banbury thermal clusters. The Banbury hydrothermal system appears to be controlled by a single northwest trending normal fault with Ca-HCO_3 thermal waters grading into Na-HCO_3 thermal waters away from the recharge zone. A similar distribution of thermal waters is observed in the Twin Falls thermal area without the presence of a major fault. Na-HCO_3 thermal waters are located near the Snake River where overlying Quaternary and Tertiary basalt units thin allowing for Tertiary Idavada volcanics to be exposed at the surface. A pumping test was performed on two deep rhyolite-penetrating wells on the campus of the College of Southern Idaho. Estimates of aquifer transmissivity from pump/recovery test analysis agree with a previous area study (Street and DeTar, 1987) at values of 930 m^2/d (7.5 x 10^4 gpd/ft). While there appears to be no decline in temperature of the Twin Falls area resource in the last 30 years, a significant decline in hydraulic head of about 15 meters (50 ft.) is observed with head values dropping from about 14 meters (45 ft.) above land surface to about 1.2 meters (4 ft.) below land surface at present day.

In its entirety, this work has resulted in the redefining of the conceptual model for the Twin Falls – Banbury thermal system. Advanced geothermometry techniques have been utilized to provide evidence for a high temperature (150+ ^{o}C) resource in the Twin – Falls Banbury area, historic and newly collected geochemical data have been used to provide evidence for both mixing and re-equilibration of thermal waters, and the possibility of a re-equilibration mechanism has been tested through a series of high temperature water-rock interaction and mixing experiments. The RTEst temperature estimates made for Na-HCO_3 waters are consistent with an estimate of 150 ^{o}C for Banbury Hot Springs made using sulfate-water isotope geothermometry earlier this year (Conrad et al., 2015).

In addition to providing new insights into reservoir temperature and mixing relationships, this study has raised questions that may be answered by future work. Although the possibility of the two thermal water types being unrelated and the product of two separate flow paths is considered unlikely, it cannot be ruled out from the work presented here. Additionally, the results of the mixing portion of the water-rock interaction experiments lead to the assumption that the transition from silicic volcanics to basalt is necessary for re-equilibration to take place. Further work regarding possible flow paths between the Idavada volcanics and overlying basalts is warranted to answer both of these questions. An expansion of the experiment to include the possibility of re-equilibration without mixing, rhyolite exclusive mixing, and temperature decreases in rhyolites and basalts without mixing may also aid in the understanding of the system. Lastly, x-ray powder diffraction (XRD) and scanning electron microscopy (SEM) analysis of post experimental rock samples would aid in both the understanding of alteration mineral assemblages and the exchange or precipitation reactions responsible for re-equilibration.

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APPENDIX A: SAMPLE COLLECTION

Sampling Phase 1: Field Parameters, Filtration, and Collection

A mobile field sampling trailer was constructed to protect equipment and staff from harsh environmental conditions often present in southern Idaho. Sampling took place in a two phase fashion. Phase one includes the measurement of field parameters, rinsing of bottles with sample water, and bottling of samples. If sampling from a thermal spring, a piece of 0.25-inch stainless steel pipe attached to MasterFlex ® peristaltic tubing (both prewashed in 10% trace grade HNO_3) was used as an inlet. The stainless steel tubing often includes a non-reactive Nalgene ® bottle cap acting as a stabilizer to keep the inlet above sediment or algal mats and may be extended to the center of the spring using an extendable swimming pool cleaning rod. The spring water is then pumped from the source using a Geotech ® Geopump Peristaltic Pump (Series II). If measuring from a thermal well, a variety of prewashed spigot fittings and couples can be used to connect to the well head outlet. Thermal water is pumped from the source into a flow through cell (YSI® 6850) where the YSI Professional Plus Multi-parameter Meter is used to record the field parameters. The YSI multimeter is calibrated daily prior to sampling. The calibration procedure and checklist can be found on page 131. If warranted, the sample water may be cooled to $< 60\ ^{o}C$ (YSI sensor limitation) using a coiled stainless steel rod submerged in ice water within a 5-gallon cooler as shown in the picture below. Relevant field parameters include pH, oxidation-reduction potential, dissolved oxygen, temperature, conductivity, and total dissolved solids. Once field parameters are stabilized and logged, sample water travels through an EMD Millipore ® 0.45 µm Groundwater Capsule filter prior to bottling in order to rid the sample of various suspended particles.

Three separate water samples are taken from each source in order to analyze for major cations Ca, K, Mg, Na, and SiO2 (aq)), major anions (F, Cl, SO4, and NO3), and various trace elements (Al, B, Li, Br, Sr, Se, Rb, Ba, and Bi). Bottles are prepared prior any sampling campaign. Cation and anion samples are collected in 250 mL HDPE bottles whereas trace element samples are collected in 1 L HDPE bottles. All bottles are filled with nanopure (18.2 MΩ) deionized water and left to sit for 24 hours. They are subsequently rinsed with this same solution before preparation. Major cation and trace element bottles are partially filled with a 10% trace grade HNO_3 solution and agitated to clean the entirety of the bottle. Anion sample bottles are simply filled with nanopure deionized water once more due to the impending analyses of NO_3 and NO_2. Prior to being filled with sample water in the field, all bottles are emptied of their cleaning solutions (neutralized in waste container with baking soda to a pH of >6). Once emptied bottles are rinsed 3 times with sample water before being capped and preserved.

Figure A1. (A) Sample team comprised of U of I graduate student Cody Cannon (mid left), INL scientist Travis McLing (mid right), Dr. Mark Conrad (foreground) of the LBNL, and Dr. Pat Dobson (background) of the LBNL. (B) Sample equipment set up showing the peristaltic pump and tubing, 0.45µm filter, YSI ® Professional Plus Multimeter and Flow-Through Cell, and three sample bottles. (C) Sampling of Driscoll Spring near Twin Falls, ID. (D) Utilization of a coiled cooling system prior to sampling collection at Worswick Hot Springs, ID.

Sampling Phase 2: Preservation and Titration

A separate 50 mL filtered sample will be collected in an acid-washed graduated cylinder to be used in titration in order to determine the amount of dissolved carbonate (as CO_3 and HCO_3). A Hach ® Digital Titrator (Model 1690001) equipped with either 1.6N or 0.16N sulfuric acid is used to titrate the sample. A pH meter is rinsed with sample water and then used to monitor the samples pH as the acid is applied. The number of titrations it takes for the sample water to be lowered to a pH of 4.5 is recorded from the titrator and subsequently used to calculate the amount of carbonate in the sample. The total alkalinity calculation procedure for a digital titrator can be found in the USGS field manual chapter 6.6 (Rounds and Wilde, 2001). Simultaneously or soon after titration is complete, the major cation and trace element bottles are preserved with 70% optima grade nitric acid until a pH of ≤ 2 is reached. Preservation is done to prevent precipitation of constituents or adsorption onto the bottle walls. Anion samples are not preserved and should be analyzed within approximately 28 days of sample collection as per EPA method 300.1. Cation and trace element samples have a shelf life of 6 months as per EPA Methods SW-846 and 200.8 respectively. After preservation and capping, water samples are sealed with strips of ParaFilm® and refrigerated at 4 ºC until chemical analysis. Upon completion of sampling, all used tubing is cleaned by pumping 10% trace grade nitric acid from one carboy into a baking soda laden waste carboy.

All field parameters for samples utilized in this study are listed below.

Table A1. Field parameters for select ESRP thermal samples collected in 2014.

Timestamp	Date In Lab	Lat	Long	Site	Unit ID	Temperature (C)	pH	Conuctivity (uS/cm)	Dissolved Oxygen (mg/L)	ORP (mV)	TDS (g/L)	Alkalinity (mg/L as HCO3)
3/10/2014 13:30	3/14/2014	43.64283	-111.68768	001	Heise Hot Springs	48.2	6.3	14789	0.43	-269.2	7.0005	986
3/11/2014 8:13	3/14/2014	44.14558	-112.55494	002	Lidy Hot Springs 1	56.1	7.2	836	0.34	-177.5	0.364	132
3/11/2014 9:13	3/14/2014	44.14166	-112.55240	003	Lidy Hot Springs 2	52.3	7.2	815	0.87	-140.9	0.3835	163
3/11/2014 13:12	3/14/2014	43.79211	-111.44009	004	Green Canyon Hot Springs	44	7.2	1152	2.84	96.9	0.585	137
3/11/2014 16:40	3/14/2014	44.09325	-111.43534	005	Sturm Well	31.4	8.7	183	4.5	44.5	0.106	66
3/12/2014 12:15	3/14/2014	43.33278	-113.91790	006	Condie Hot Springs	50.5	7	1075	0.6	-71.8	0.481	315
3/12/2014 15:09	3/14/2014	43.60234	-113.24214	007	Greenhouse Well	36.3	7.1	882	2.89	101.5	0.481	285
3/13/2014 8:53	3/14/2014	42.69940	-114.91040	008	Eckart Office Well	24.7	9.5	610	4.71	39.7	0.3965	81
3/13/2014 10:30	3/14/2014	42.64497	-114.78706	009	Campbell 1	34.5	8	457.7	4.06	64.2	0.2516	144
3/13/2014 11:13	3/14/2014	42.64432	-114.78294	010	Campbell 2	34.4	8	527	4.57	64.6	0.2925	127
3/13/2014 14:34	3/14/2014	42.69457	-114.85592	011	Miracle Hot Springs	58.4	9.5	1002	0.29	-162.1	0.4225	93
3/13/2014 16:19	3/14/2014	42.54479	-114.94855	012	Driscoll Well	37.5	8.6	1070	5.36	-13.8	0.559	95
3/13/2014 16:52	3/14/2014	42.54348	-114.94897	013	Driscoll Spring	36.2	8.7	1027	4.62	27.8	0.5655	98
3/14/2014 8:13	3/14/2014	42.58318	-114.47496	014	CSI Well 2	38.1	8.8	631	3.97	75.5	0.3315	127
6/6/2014 9:14	6/6/2014	43.44244	-111.90484	015	Comore Loma #6	20.9	6.7	828	6.82	176.6	0.585	222
6/6/2014 10:56	6/6/2014	43.43774	-111.93018	016	Comore Loma #5	27.7	6.9	943	6.28	121.5	0.585	251
6/6/2014 12:56	6/6/2014	43.43142	-111.94501	017	Blackhawk #2	26.8	6.6	1249	6.55	114.2	0.83683	271
6/6/2014 12:56	6/6/2014	43.43121	-11.94469	018	Blackhawk #1	25.1	6.8	1176	7.14	109.7	0.7605	268
6/11/2014 11:01	6/11/2014	42.10207	-113.38434	020	Raft River Geothermal # 1	150	7.1	5972	0.06	-217.8	2.3335	34
6/11/2014 11:52	6/11/2014	42.11042	-113.37519	021	Raft River Geothermal # 2	150	6.9	4079	0.07	-218.8	1.846	38
6/11/2014 12:44	6/11/2014	42.08359	-113.35865	022	Raft River Geothermal # 7	150	6.3	11474	0.08	-218.8	5.1805	33
6/11/2014 13:39	6/11/2014	42.09787	-113.38541	023	Raft River Geothermal # 4	150	7.1	4846	0.09	-219.3	2.1775	44
6/17/2014 13:33	6/17/2014	42.72589	-112.87381	024	Indian Hot Springs	32.7	7.2	1452	2.38	-61.2	0.8255	223
6/18/2014 9:57	6/18/2014	42.23667	-113.36971	025	Grush Dairy	54.7	9.2	1196	0.04	-146.5	0.494	283
6/18/2014 11:31	6/18/2014	42.107989	-113.39206	026	Raft River USGS Well	79.6	8.1	5463	1.5	-179.8	2.5805	95
6/18/2014 12:07	6/18/2014	42.10776	-113.39186	027	Raft River Frasier Well	78.6	7.7	4900	0.2	-175.2	2.444	60
6/18/2014 13:18	6/18/2014	42.09656	-113.37800	028	Raft River Crook Well	81	8.3	7297	0.46	-85.5	4.6475	35
6/23/2014 10:18	6/26/2014	43.36414	-113.78943	029	Milford Sweat	38.1	7.3	792	-	69.3	0.416	251
6/23/2014 12:48	6/26/2014	43.32777	-114.39941	030	Magic Hot Springs Landing Runoff	39.1	8.6	2227	-	-24.6	1.1375	710
6/23/2014 15:46	6/26/2014	43.42341	-114.62857	031	Elk Creek 1	50.0	9.1	758	-	-126	0.338	93
6/23/2014 16:15	6/26/2014	43.42322	-114.62865	032	Elk Creek 2	55.5	9.1	812	-	-82.6	0.3445	90
6/24/2014 9:13	6/26/2014	43.29241	-114.91002	033	Barron Well	38.0	8	1195	-	-104.8	0.624	181
6/24/2014 10:24	6/26/2014	43.38290	-114.93224	034	Wardrop Hot Springs (Gonzales' House)	67.5	9	553	-	-130.8	0.2145	193
6/24/2014 13:10	6/26/2014	43.32777	-114.39941	035	Magic Hot Springs Landing Well	75.0	6.8	2951	-	-84	1.183	703

Timestamp	Date In Lab	Lat	Long	Site	Unit ID	Temperature (C)	pH	Conuctivity (uS/cm)	Dissolved Oxygen (mg/L)	ORP (mV)	TDS (g/L)	Alkalinity (mg/L as HCO3)
6/24/2014 16:48	6/26/2014	43.12966	-115.33841	036	Prince Albert Hot Springs	57.7	9.1	472.9	-	-134.6	0.1963	105
6/25/2014 10:44	6/26/2014	42.17334	-113.86163	037	Oakley Warm Spring	46.9	9.3	667	-	-172.7	0.3185	107
6/25/2014 13:30	6/26/2014	42.08533	-113.93984	038	Richard Austin Well 1	45.7	9	733	-	-107.6	0.351	205
6/25/2014 16:28	6/26/2014	42.47663	-113.50770	039	Marsh Creek Well	59.6	8.2	1055	-	-147.7	0.429	124
6/26/2014 10:14	6/26/2014	42.70399	-114.85699	040	1000 Springs (Sliger's Well)	72.0	9.5	1266	-	-127.2	0.494	212
6/26/2014 11:55	6/26/2014	42.68841	-114.82680	041	Banbury Hot Springs Well	58.8	9	798	-	-112.8	0.3315	249
6/26/2014 12:16	6/26/2014	42.68841	-114.82680	042	Banbury Hot Springs	58.5	9	820	-	-115	0.3315	168
7/15/2014 15:01	7/17/2014	42.95543	-115.29997	043	Diamond Laundry	35.0	8.9	829	0.1	-290.2	0.442	315
7/15/2014 18:48	7/17/2014	43.00294	-115.19222	044	Johnston Well	39.0	9.3	499.4	0.2	-212.1	0.2626	117
7/16/2014 12:02	7/17/2014	42.66851	-114.82436	045	Leo Ray Hill	35.0	8.7	414.9	0.1	-24.1	0.2275	140
7/16/2014 12:34	7/17/2014	42.66778	-114.82673	046	Leo Ray Road	35.5	8.4	409.7	0.3	-89.4	0.2217	139
7/16/2014 13:32	7/17/2014	42.65772	-114.79054	047	Kanaka Rapids (Zigler's House)	30.1	8	427.3	3.8	69.3	0.2529	120
7/16/2014 14:29	7/17/2014	42.70501	-114.85701	048	Hensley Well	31.8	9.6	741	0.6	-263.5	0.429	232
7/16/2014 17:38	7/17/2014	43.11025	-115.31258	049	Latty Hot Prings	65.0	9.3	323.1	1.7	-96.2	0.1735	107
7/16/2014 19:50	7/17/2014	42.94632	-115.49423	050	Laib Well	32.5	7.6	1621	0.1	-203.7	0.923	886
7/17/2014 10:03	7/17/2014	42.58050	-114.47089	051	CSI Well 1	37.7	8.8	586	3.3	38.7	0.312	154
7/17/2014 11:25	7/17/2014	42.59755	-114.40018	052	Larry Anderson Well	43.0	9.2	816	0	-205.1	0.3965	188
7/17/2014 12:42	7/17/2014	42.61390	-114.48799	053	Pristine Springs	43.0	9.2	769	0.3	-107.2	0.377	154
7/17/2014 15:16	7/17/2014	42.57256	-114.45175	054	Twin Falls High School	31.0	7.8	660	5.6	-13.7	0.39	161
7/17/2014 16:49	7/17/2014	42.57750	-114.28870	055	Anderson Campground Well	37.0	9.1	786	1.2	-191.1	0.4225	246
7/22/2014 14:00	7/22/2014	43.60827	-113.24432	056	Butte City Well	32.5	7.4	720	4.2	611.2	0.432	386
7/23/2014 14:45	7/23/2014	43.02583	-112.02551	057	Quidop Springs 1	21.0	6.7	1288	2.3	324.4	0.9165	617
7/23/2014 15:49	7/23/2014	43.03717	-112.00427	058	Quidop Springs 2	38.1	6.6	2112	0.5	-139.1	1.0985	710
7/23/2014 18:03	7/23/2014	43.11448	-112.16660	059	YaNDell Warm Springs	22.2	7.3	635	3.2	-22.2	0.4355	266
7/24/2014 12:07	7/24/2014	42.43758	-113.43432	060	Skaggs Ranch	33.3	7.7	396.6	0.4	-28.8	0.2223	181
7/24/2014 14:02	7/24/2014	42.10008	-113.63354	061	Durfee Hot Springs	44.9	8.8	690	4.1	119.3	0.325	107
7/24/2014 18:01	7/24/2014	42.22333	-113.79167	062	Basin Cemetery	30.7	7.9	482	3.3	-15.8	0.2827	122
7/24/2014 19:17	7/24/2014	42.48216	-113.97341	063	Wybenga Dairy	33.9	7.5	331.3	3.7	22	0.1839	115
7/29/2014 12:00	7/29/2014	42.13944	-111.93709	064	David Bosen Well	90.0	6.7	22609	2.56	147	14.5	583
7/30/2014 12:00	7/30/2014	43.87717	-111.55890	065	SchweNDiman Well	28.0	7.6	363	5.9	156	0.3	165
7/30/2014 12:00	7/30/2014	43.88566	-111.55949	066	Clyde Well	32.7	7.5	398	4.11	147	0.3	183
7/30/2014 12:00	7/30/2014	43.90127	-111.50967	067	Cinder Block Well	26.3	7.4	360	3.66	146	0.3	182
7/30/2014 12:00	7/30/2014	43.88308	-111.6186	068	Newdale City Well	30.0	7.3	575	4.45	575	0.3	251
7/30/2014 12:00	7/30/2014	43.85840	-111.67870	069	Spackman Well	14.1	7.2	336	7.15	145	0.2	190
8/15/2014 12:00	8/15/2014	42.97813	-112.41654	070	Fort Hall Thermal Well	21.1	7.9	557	6.6	160.1	0.39	223
6/17/2015 14:10	6/19/2015	43.33723	-115.04430	077	Wolf H.S.	50	9.5	400.5	2.9	-27.3	0.1898	107

YSI® Professional Plus Calibration Procedure

The following contains the order and manner in which the YSI Professional Plus instrument should be calibrated. Tips and troubleshooting not covered in this guide can be found in the YSI Professional Plus Manual and Dissolved Oxygen Handbook.

Temperature:

The YSI temperature sensor does not need to be calibrated as it is accurate to +/- 0.15 ^{o}C and does not drift. However, you should verify that the temperature sensor is reading accurately by comparing it to a traceable thermometer before calibrating any of the other sensors.

Conductivity:

The conductivity calibration should be verified every day the instrument is used. However, the conductivity sensor is very stable and may hold its calibration for several weeks. Whether calibrating in the lab or in the field, you should use a conductivity standard and ensure that you calibrate conductivity and not specific conductance as you will most likely not be in exactly 25.0 ^{o}C water. Never use a calibration fluid that is more than a month old after opening. Rinse the cal cup and all sensors with DI water and then rinse with conductivity calibration solution. Fill the cal cup to where the top vent holes of the conductivity sensor are fully submerged. Input the standard value into the YSI calibration menu. Allow enough time for the temperature and conductivity values to stabilize and accept the calibration. Record the calibration values on the calibration sheet.

pH:

The pH calibration should be verified every day the instrument is used. However, a new pH sensor may be capable of holding its calibration for several days. If you’re absolutely certain that the waters being sampled will all be over or below pH 7, then a 2 point calibration is all that is necessary. Otherwise, it is best to use a 3 point calibration. Rinse the cal cup and all sensors with DI water. Proceed to rinse the cal cup and sensors with a small amount of pH 7 buffer solution. Next, fill the cal cup with enough pH 7 buffer so that the pH sensor tip and temperature sensor are submerged. Input the buffer standard into the pH calibration menu in the YSI. Allow enough time for pH values and temperature values to stabilize. Accept the calibration value. Repeat this process for pH 4 and 10 buffers to complete the calibration. Record the stabilized pH values as well as the pH values in mV. Ensure the mV values fall within the accepted range listed on the calibration sheet.

ORP:

The ORP calibration should be verified every day the instrument is used. However, a new ORP sensor may be capable of holding its calibration for several days. Rinse the cal cup and all sensors with DI water. Proceed to rinse the cal cup and sensors with a small amount of ORP Zobell calibration solution. Fill the cal cup with enough ORP calibration solution so that the ORP sensor is fully submerged. Input the standard value into the YSI handheld. Allow enough time for the temperature and ORP values to stabilize and accept the calibration. Record the pre-calibrated stabilized ORP value and ensure the post-calibrated value matches the standard.

DO:

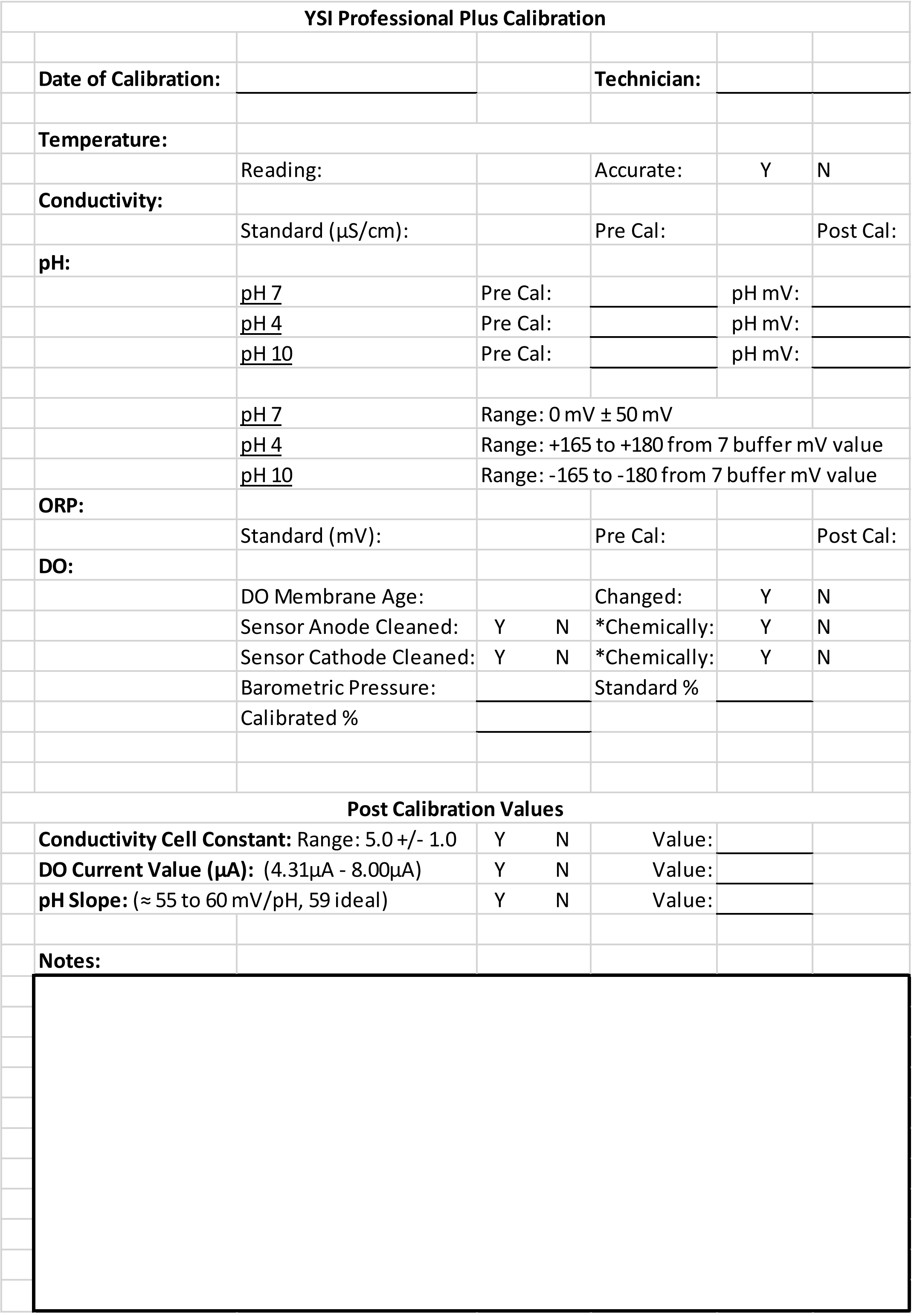
The dissolved oxygen sensor should be calibrated every day the instrument is used. It is not necessary to calibrate in both % and mg/L or ppm. Calibrating in % will simultaneously calibrate mg/L and ppm and vice versa. Before calibrating the DO sensor note the age of the DO membrane from previous calibrations. If it has not been changed within 8 weeks, change it. If any silver chloride has built up on the silver anode, try to simply mechanically clean it with the YSI cleaning brush. If the buildup is too heavy, use wet 400-grit sandpaper to clear away any build up. If you require chemical cleaning, soak the silver anode in a 3% (household ammonium cleaner) for 8-12 hours. Following the soak, rinse thoroughly with DI water and wipe the residue with a paper towel ensuring that no build up is trapped under the membrane. For correct sensor operation, the gold cathode must be textured properly. Use wet 400-grit sandpaper to remove build up and lightly scratch the cathode to allow more surface area for the electrolyte solution under the membrane (2-3 twists of sandpaper is usually sufficient). If any cleaning is required, make sure to record this information in the notes section of the calibration sheet.

The best way to calibrate the DO sensor is by using water saturated air. Fill the cal cup with about 1/8 inches of DI water. Ensure that the DO sensor and temperature sensor are not submerged. Engage 1 or 2 threads to allow for venting into the cal cup. Wait about 10 minutes for the calibration chamber to become completely saturated. While waiting, determine the calibration % value by dividing the true barometric pressure by 760 (cal. value will only be 100% at sea level or 760 mmHg) and multiplying by 100. Allow time for readings to stabilize around calibration value and accept calibration. Record values on calibration sheet.

Note: Chemical cleaning should be performed as infrequently as possible (1 or 2 times per year depending on use).

Post Calibration Values:

After completing calibration record the following values from the .glp file for the day's calibration to ensure the calibration was successful: Conductivity Cal Cell Constant (Range 5.0 +/- 1.0 acceptable), DO Sensor Value (yellow membrane: 4.31µA - 8.00µA), pH Slope (≈ 55 to 60 mV/pH, 59 ideal).



YSI Professional Plus Calibration

Date of Calibration:			**Technician:**		
Temperature:					
	Reading:		Accurate:	Y	N
Conductivity:					
	Standard (µS/cm):		Pre Cal:		Post Cal:
pH:					
	pH 7	Pre Cal:		pH mV:	
	pH 4	Pre Cal:		pH mV:	
	pH 10	Pre Cal:		pH mV:	
	pH 7	Range: 0 mV ± 50 mV			
	pH 4	Range: +165 to +180 from 7 buffer mV value			
	pH 10	Range: -165 to -180 from 7 buffer mV value			
ORP:					
	Standard (mV):		Pre Cal:		Post Cal:
DO:					
	DO Membrane Age:		Changed:	Y	N
	Sensor Anode Cleaned:	Y N	*Chemically:	Y	N
	Sensor Cathode Cleaned:	Y N	*Chemically:	Y	N
	Barometric Pressure:		Standard %		
	Calibrated %				

Post Calibration Values

Conductivity Cell Constant: Range: 5.0 +/- 1.0	Y N	Value:	
DO Current Value (µA): (4.31µA - 8.00µA)	Y N	Value:	
pH Slope: (≈ 55 to 60 mV/pH, 59 ideal)	Y N	Value:	

Notes:

Figure A2. YSI® Professional Plus Calibration Form

APPENDIX B: CHEMICAL ANALYSIS AND QUALITY CONTROL

Chemical analysis was performed by Cody Cannon under the supervision of analytical chemist Debbie Lacroix and the analytical chemistry laboratory lead Joanna Taylor at the Center for Advanced Energy Studies, Idaho Falls, Idaho. Samples were analyzed in accordance with their respective holding times (preserved and non-preserved) and appropriate dilutions were made to each sample when necessary. Calibration standards for each analytical instrument were prepared from various batch solutions provided by Inorganic Ventures ™ in order to obtain valid concentrations in the desired range based upon previous geothermal research (0.1 to 500+ ppm for major cations and anions) and trace elemental needs for multicomponent equilibrium geothermometry calculations (1 ppb to 1ppm) for constituents including aluminum, magnesium, boron, etc. Analyses were conducted using the Dionex ™ ICS-2100 Ion Chromatograph (IC) or major anions, the Thermo iCAP ™ 6500 Inductively-Coupled Plasma Optical Emission Spectrometer (ICP-OES) for major cations, and the Agilent ™ 7500ce Inductively-Coupled Plasma Mass Spectrometer (ICP-MS) for trace elements. The following sections detail the analysis and processing of samples 001-070.

Ion Chromatography for Major Anions

Samples are injected into a stream of eluent, passed through a series of ion exchange columns, and into a conductivity detector. The first column, a guard column, protects the analytical column by removing particulate and organic matter. The analytical column separates anions or cations by their relative affinities for column resins. The suppressor (between the analytical column and the conductivity detector) provides continuous suppression of background conductivity of the eluent and enhances response of the target analytes. The separated anions or cations are measured by conductivity. The compounds are identified based on retention times and quantified by conductivity or absorbance. Control of the instrument is provided by PC-based Chromeleon software

Ion-exchange chromatography is a means of retaining target analytes by separating out the target anions from cations in a separator column. Once separated in the column, the Dionex ™ ICS-2100 IC detects the concentrations of chosen anions by means of measuring conductivity. Calibration standards 1-7 were prepared from an Inorganic Ventures™ stock solution IC-FAS-1A containing the solutes: F^-, Cl^- $NO2^-$, $NO3^-$, Br^-, $SO4^{2-}$, and $PO4^{3-}$. Solutions were prepared by means of dilutions by weight, resulting in seven standards ranging in concentrations from 0 ppm Cl^- (nanopure water) to 100 ppm Cl^-. Standard concentrations are listed below in Table 1. Analysis was carried out using a modified form of the EPA 300.1 Method (Hautman and Munch, 1997). Each run began with the analysis of 3 blank samples (nanopure water) followed by the seven standards in order to establish background levels and a calibration curve. A calibration curve coefficient of determination value of $R^2 = 0.995$ was used for all analyses in accordance with EPA 300.1. A laboratory control standard (LCS) was analyzed following the calibration standards to verify the validity of the calibration curve, followed by a nanopure dilution blank. The dilution blank was analyzed to ensure there was no analyte contamination in the water use to dilute the samples. Every ten samples, a blank sample was analyzed followed by all seven standards analyzed as samples. The blank analysis was used to verify there was no carryover during the run and the reanalysis of standards as samples was used to determine instrument drift and to aid in the LOD calculation for each analyte in the analytical run. Samples were diluted prior to analysis based on any previous water chemistry for specific samples or surrounding areas (diluted for >100 ppm Cl^- and

$SO4^{2-}$). Samples were diluted and re-run after initial analysis if necessary so that the concentrations would fall within the calibration range. Duplicate samples were run at a frequency of one sample per run, modified from the 10% recommended by EPA 300.1. Adherence to the recommended 90-110% recovery and 10% difference values for spikes and duplicates respectively was obtained for adequate quality control. Conductivity peak analysis was performed for each sample to ensure no interference or deviation in baseline provided by the calibration curve influenced sample concentration readings. Quality control information for standard solutions and LOD values for anions are provided in Table 1.

ICP-OES analysis for Major Cations

Samples are pumped through a nebulizer to produce a fine spray. The large droplets are removed by a spray chamber and the small droplets then pass through to the plasma. The plasma is formed by an intense magnetic field produced by radio frequency (RF) passing through a copper coil. The plasma generates photons of light by the excitation of atoms and ions. The emission of light which occurs as discrete lines, are separated according to their wavelength by diffractive optics using an Echelle optical design. The analytical signals are measured using a Charge Injection Device (CID) as the detector. The samples can be analyzed using either the radial or axial plasma views depending on the sensitivity needed. Various interferences must be considered and addressed appropriately. Control of the spectrometer is provided by PC-based iTEVA software.

Inductively-Coupled Plasma Optical Emission Spectrometry is performed by ionizing argon gas in an intense electro-magnetic field and “igniting” the plasma. Water samples are then transported via a peristaltic pump into the analytical nebulizer where the sample is made into an aerosol and forced to collide directly with the plasma flame. The sample is thereby broken down into charged ions after collision with electrons and charged ions of the plasma. The continuous breaking up of molecules into their respective atoms emits signature wavelengths of light that can be read and quantified by the spectrometer (Huang and Hieftje, 1989). In a similar manner to the IC analysis, standards were prepared from an Inorganic Ventures™ stock solution: QCP-CICV-1 containing the cations Ca^{2+}, K^+, Mg^+, Na^+, $Ba^{2+,}$ $Al^{3+,}$ and Fe^{3+}. However, concentrations of aluminum and magnesium proved to be too low in many samples to obtain a reading above the LOD. For this reason, these elements were analyzed separately using the ICP-MS. Standards were prepared in the ranges of 1-25 ppm Ca^{2+}, K^+, Mg^+, Na^+ and 1-20 ppm SiO_2^-. Additional standards were added to account for geothermal waters with high (100+ ppm) SiO_2^- and waters with higher TDS with elevated Na^+ (up to 1500 ppm) concentrations. A calibration curve was established with a 99.5% confidence, $R^2 = 0.995$ in accordance with EPA Method 200.7 (Martin et al., 1994). Analysis began with the running of blanks followed by all calibration standards in order to establish background levels and a calibration curve. Blanks and standards were analyzed again after every 10 samples to determine carryover, instrument drift and LODs. Duplicate and spiked samples were added randomly and run at a frequency of one sample per run, modified from the 10% recommended by EPA 200.7. Adherence to the recommended 70-130% recovery and 10% difference values for spikes and duplicates respectively was obtained for adequate quality control.

Multiple wavelengths of every constituent are read by the ICP-OES for each run as some wavelengths have more interferences than others. In order to pick the appropriate wavelength for each constituent, percent difference deviations from true values were calculated for each standard and the wavelength with the least percent difference (< 10% difference) were chosen and concentrations were reported from each respective wavelength. Quality control information for standard solutions and LOD values for major cations are provided in Table 2.

ICP-MS analysis for Trace Elements

The sample is pumped with a peristaltic pump into a nebulizer where it is converted into a fine aerosol. The fine droplets are separated from the larger droplets by means of a spray chamber. From there, it is transported into the plasma torch. The plasma is formed by an intense magnetic field produced by radio frequency passing through a copper coil. The plasma generates positively charged ions. The ions are directed through the interface region, kept at a vacuum that consists of two metallic cones (sampler and skimmer) that allow the ions to pass through to the electrostatic lenses called the ion optics. These optics stop photons, particulates, and neutral species from reaching the detector. The ions travel through the octapole in the reaction cell which minimizes polyatomic spectral interferences. The ions reach the quadrupole where they are separated according to their mass-to-charge ratio (m/z) by electrostatically steering the ions of a selected mass down the middle of the rods to the detector while ejecting the other unstable ions. The ions are converted into an electronic signal with a detector called an electron multiplier. Control of the spectrometer is provided by PC-based MassHunter® software.

Standards were prepared from Inorganic Ventures™ stock solutions: CCS-4 (alkali, alkaline, non-transition elements) and CCS-5(fluoride soluble elements). CCS-4 was utilized for the constituents: Li, Be, Al, Mg, Se, As, Rb, Sr, Ba, and Bi. CCS-5 was utilized solely for boron. Boron is often regarded as an important conservative tracer in geothermal fluids. Standards utilizing CCS-4 solution were prepared for the range of 1-500 ppb of all elements. CCS-5 standards were prepared for the range 1 ppb to 1 ppm boron based on previous ESRP geothermal studies which included boron. Magnesium and aluminum were analyzed separately for all samples in order to fill in data gaps where concentrations fell below the LOD with the ICP-OES. Magnesium and aluminum standards were prepared in the range of 1 ppb to 1 ppm for both elements.

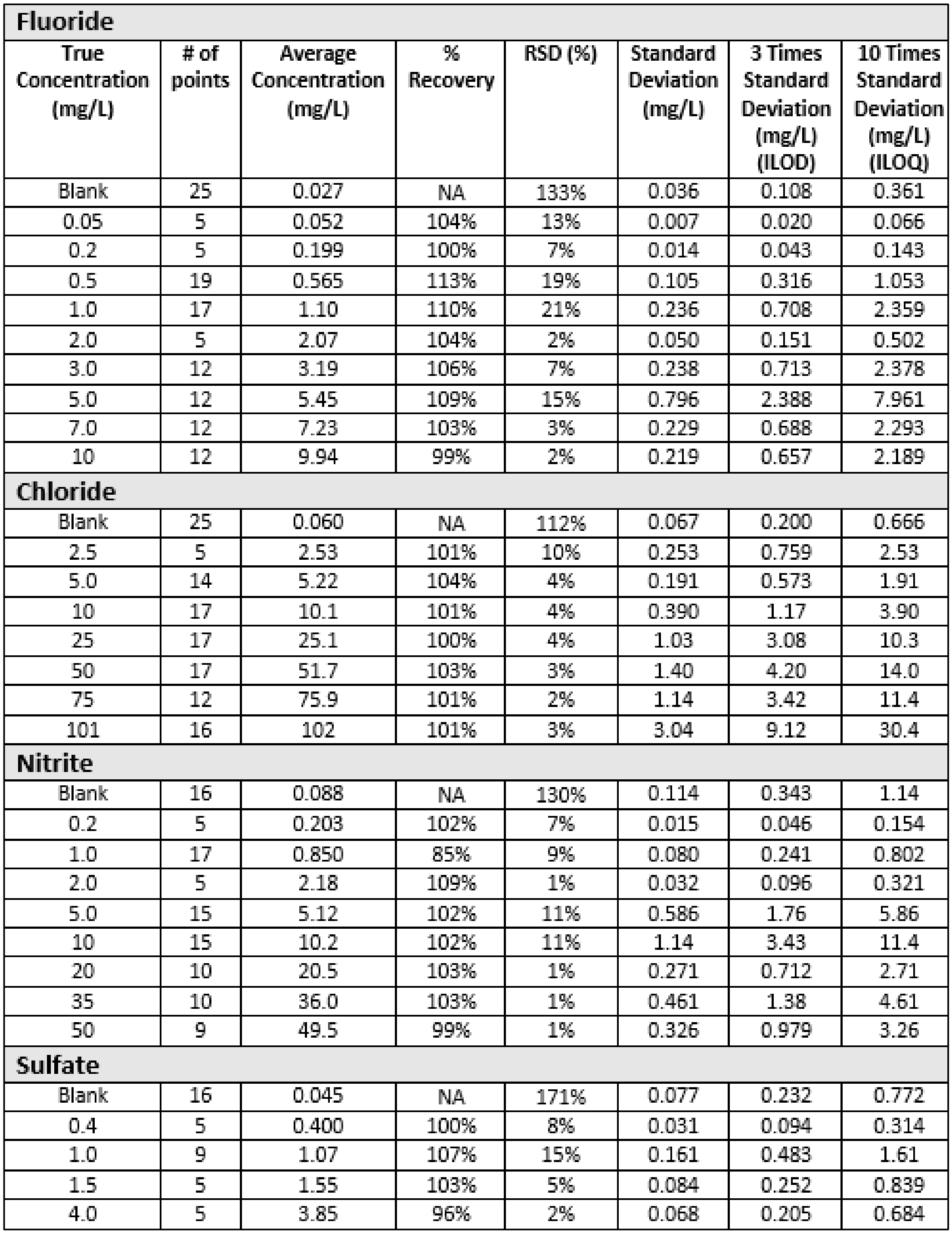
Analysis was accomplished using a modified form of EPA method 200.8 (Creed et al., 1994). Collision cell technology was utilized to eliminate interference from polyatomic ions due to the high TDS nature of geothermal waters. A calibration curve was established with a 99.5% confidence, $R^2 = 0.995$ in accordance with EPA method 200.8. Analysis began with the running of blanks followed by all calibration standards in order to establish background levels and a calibration curve. Blanks and standards were run again after every 10 samples to verify lack any contamination, to determine drift and establish the LOD for the run an internal standard of rhodium (Rh) was analyzed with the samples to correct for any matrix interferences. Duplicate and spiked samples were added randomly and run at a frequency of one sample per run, modified from the 10% recommended by EPA 200.8. Adherence to the recommended 70-130% recovery and 10% difference values for spikes and duplicates respectively was obtained for adequate quality control. Unless a deviation greater than 10% occurred for a particular QC standard, concentration values for samples were reported from raw data. Quality control information for standard solutions and ILOD values for trace elements are provided in Table 3.

Limit of Detection, Precision and Accuracy

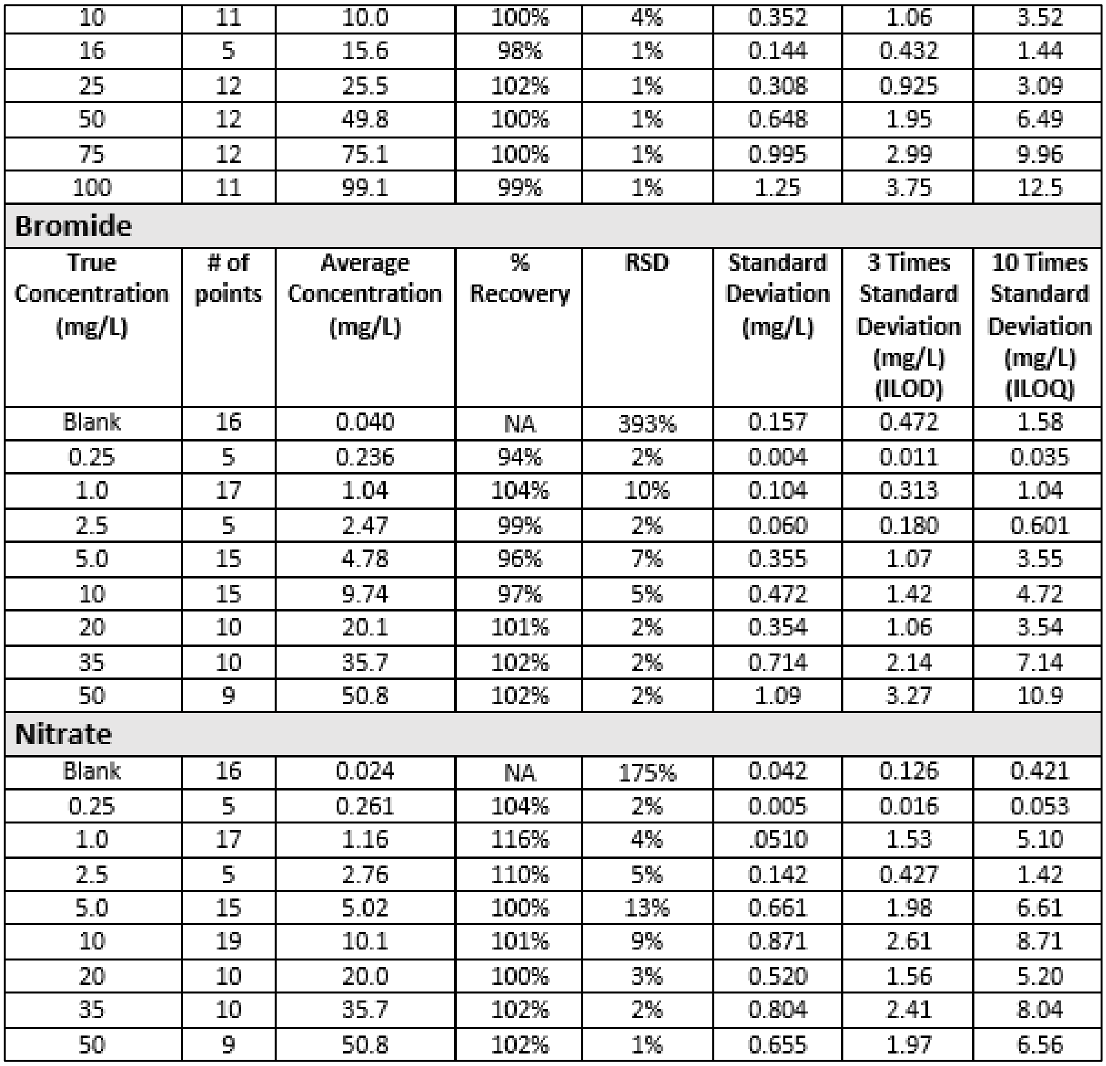
The Limit of detection is the lowest concentration of a given analyte that is likely to be consistently distinguished from analysis (Needleman et al., 1990). Ordinarily, it is calculated from background analyte levels provided by blank samples. In this study, ILOD was calculated using a "limit of blank" approximation where a Gaussian distribution of blank concentrations is assumed. An approximation assuming infinite degrees of freedom would use the student's t distribution value of 1.645 for a 95% confidence interval where LOD = $\text{Average}_{\text{blank}}$ + (1.645 x $\text{Standard Deviation}_{\text{blank}}$). However, in an effort to produce a more conservative approximation due to sample sizes of blanks varying from 4-5 blanks to 20, the standard deviation of blank was multiplied by 3 instead. ILOD values for all chemical constituents in 5% HNO_3 can be seen with the blank values in Tables B1-3.

Tables B1-3 also provides information on average instrument precision and accuracy. Accuracy refers to the closeness of a measured value to a standard or known value. Accuracy can been seen in the % Recovery column in Tables 1-3. Sample data was considered valid if the % recoveries were ± 10% of the known value. Therefore, data not within the 10% acceptable window was not considered valid and the data was not used. Precision refers to the closeness of two or more measurements to each other. Precision was determined by calculating the standard deviation(s) of the standards. The standard deviation provides an indication of the range of variation in the measurements. The relative standard deviation (RSD), expresses the standard deviation as a percentage, with the smaller the relative standard deviation (or standard deviation), the more precise the measurements. The average precision for this sample set can be seen in the %RSD column in tables 1-3 below.

Table B1. Anion QC Table

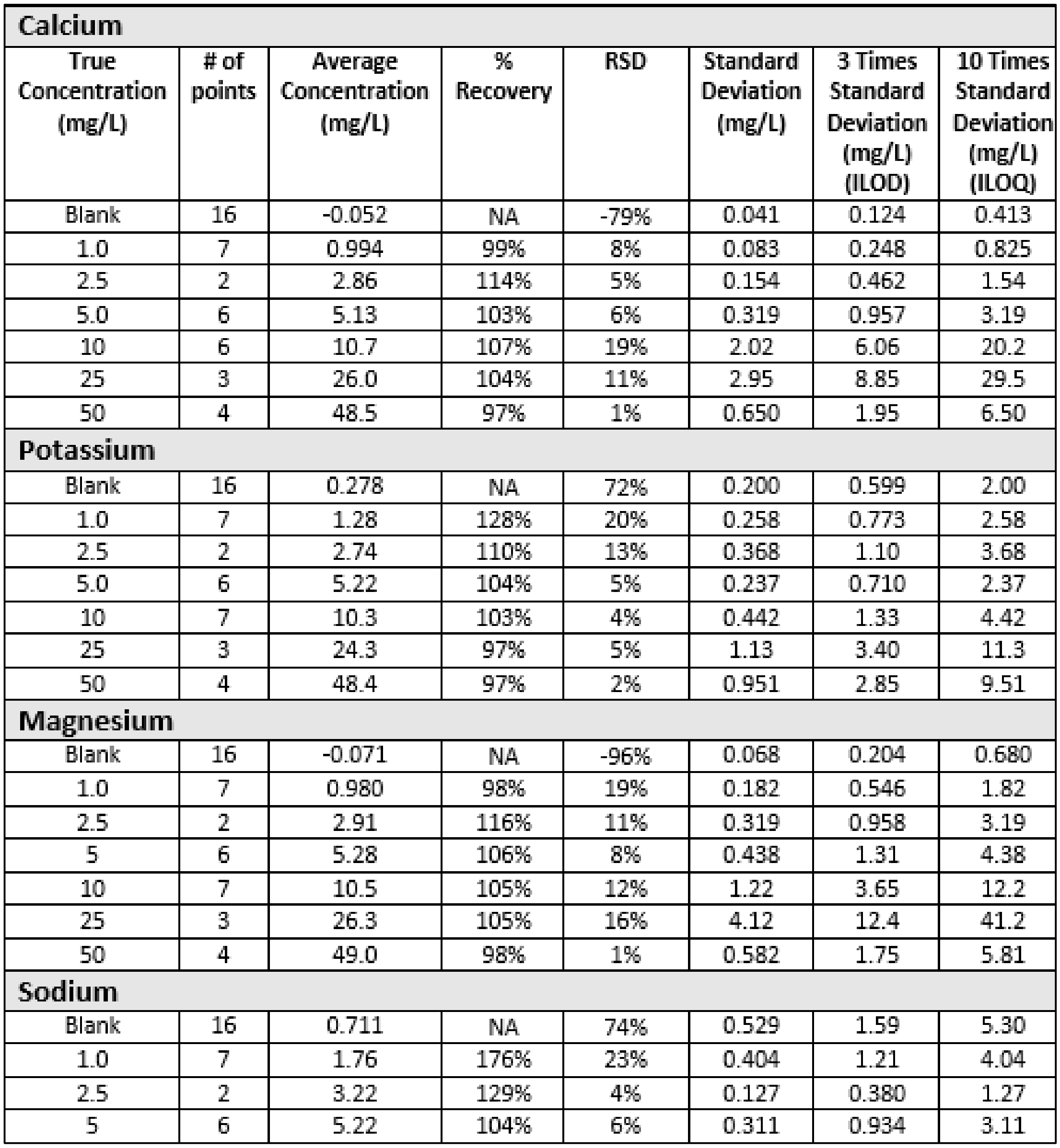


Fluoride							
True Concentration (mg/L)	# of points	Average Concentration (mg/L)	% Recovery	RSD (%)	Standard Deviation (mg/L)	3 Times Standard Deviation (mg/L) (ILOD)	10 Times Standard Deviation (mg/L) (ILOQ)
Blank	25	0.027	NA	133%	0.036	0.108	0.361
0.05	5	0.052	104%	13%	0.007	0.020	0.066
0.2	5	0.199	100%	7%	0.014	0.043	0.143
0.5	19	0.565	113%	19%	0.105	0.316	1.053
1.0	17	1.10	110%	21%	0.236	0.708	2.359
2.0	5	2.07	104%	2%	0.050	0.151	0.502
3.0	12	3.19	106%	7%	0.238	0.713	2.378
5.0	12	5.45	109%	15%	0.796	2.388	7.961
7.0	12	7.23	103%	3%	0.229	0.688	2.293
10	12	9.94	99%	2%	0.219	0.657	2.189
Chloride							
Blank	25	0.060	NA	112%	0.067	0.200	0.666
2.5	5	2.53	101%	10%	0.253	0.759	2.53
5.0	14	5.22	104%	4%	0.191	0.573	1.91
10	17	10.1	101%	4%	0.390	1.17	3.90
25	17	25.1	100%	4%	1.03	3.08	10.3
50	17	51.7	103%	3%	1.40	4.20	14.0
75	12	75.9	101%	2%	1.14	3.42	11.4
101	16	102	101%	3%	3.04	9.12	30.4
Nitrite							
Blank	16	0.088	NA	130%	0.114	0.343	1.14
0.2	5	0.203	102%	7%	0.015	0.046	0.154
1.0	17	0.850	85%	9%	0.080	0.241	0.802
2.0	5	2.18	109%	1%	0.032	0.096	0.321
5.0	15	5.12	102%	11%	0.586	1.76	5.86
10	15	10.2	102%	11%	1.14	3.43	11.4
20	10	20.5	103%	1%	0.271	0.712	2.71
35	10	36.0	103%	1%	0.461	1.38	4.61
50	9	49.5	99%	1%	0.326	0.979	3.26
Sulfate							
Blank	16	0.045	NA	171%	0.077	0.232	0.772
0.4	5	0.400	100%	8%	0.031	0.094	0.314
1.0	9	1.07	107%	15%	0.161	0.483	1.61
1.5	5	1.55	103%	5%	0.084	0.252	0.839
4.0	5	3.85	96%	2%	0.068	0.205	0.684



10	11	10.0	100%	4%	0.352	1.06	3.52
16	5	15.6	98%	1%	0.144	0.432	1.44
25	12	25.5	102%	1%	0.308	0.925	3.09
50	12	49.8	100%	1%	0.648	1.95	6.49
75	12	75.1	100%	1%	0.995	2.99	9.96
100	11	99.1	99%	1%	1.25	3.75	12.5
Bromide							
True Concentration (mg/L)	**# of points**	**Average Concentration (mg/L)**	**% Recovery**	**RSD**	**Standard Deviation (mg/L)**	**3 Times Standard Deviation (mg/L) (ILOD)**	**10 Times Standard Deviation (mg/L) (ILOQ)**
Blank	16	0.040	NA	393%	0.157	0.472	1.58
0.25	5	0.236	94%	2%	0.004	0.011	0.035
1.0	17	1.04	104%	10%	0.104	0.313	1.04
2.5	5	2.47	99%	2%	0.060	0.180	0.601
5.0	15	4.78	96%	7%	0.355	1.07	3.55
10	15	9.74	97%	5%	0.472	1.42	4.72
20	10	20.1	101%	2%	0.354	1.06	3.54
35	10	35.7	102%	2%	0.714	2.14	7.14
50	9	50.8	102%	2%	1.09	3.27	10.9
Nitrate							
Blank	16	0.024	NA	175%	0.042	0.126	0.421
0.25	5	0.261	104%	2%	0.005	0.016	0.053
1.0	17	1.16	116%	4%	.0510	1.53	5.10
2.5	5	2.76	110%	5%	0.142	0.427	1.42
5.0	15	5.02	100%	13%	0.661	1.98	6.61
10	19	10.1	101%	9%	0.871	2.61	8.71
20	10	20.0	100%	3%	0.520	1.56	5.20
35	10	35.7	102%	2%	0.804	2.41	8.04
50	9	50.8	102%	1%	0.655	1.97	6.56

Table B2. Cation QC Table



True Concentration (mg/L)	# of points	Average Concentration (mg/L)	% Recovery	RSD	Standard Deviation (mg/L)	3 Times Standard Deviation (mg/L) (ILOD)	10 Times Standard Deviation (mg/L) (ILOQ)
Calcium							
Blank	16	-0.052	NA	-79%	0.041	0.124	0.413
1.0	7	0.994	99%	8%	0.083	0.248	0.825
2.5	2	2.86	114%	5%	0.154	0.462	1.54
5.0	6	5.13	103%	6%	0.319	0.957	3.19
10	6	10.7	107%	19%	2.02	6.06	20.2
25	3	26.0	104%	11%	2.95	8.85	29.5
50	4	48.5	97%	1%	0.650	1.95	6.50
Potassium							
Blank	16	0.278	NA	72%	0.200	0.599	2.00
1.0	7	1.28	128%	20%	0.258	0.773	2.58
2.5	2	2.74	110%	13%	0.368	1.10	3.68
5.0	6	5.22	104%	5%	0.237	0.710	2.37
10	7	10.3	103%	4%	0.442	1.33	4.42
25	3	24.3	97%	5%	1.13	3.40	11.3
50	4	48.4	97%	2%	0.951	2.85	9.51
Magnesium							
Blank	16	-0.071	NA	-96%	0.068	0.204	0.680
1.0	7	0.980	98%	19%	0.182	0.546	1.82
2.5	2	2.91	116%	11%	0.319	0.958	3.19
5	6	5.28	106%	8%	0.438	1.31	4.38
10	7	10.5	105%	12%	1.22	3.65	12.2
25	3	26.3	105%	16%	4.12	12.4	41.2
50	4	49.0	98%	1%	0.582	1.75	5.81
Sodium							
Blank	16	0.711	NA	74%	0.529	1.59	5.30
1.0	7	1.76	176%	23%	0.404	1.21	4.04
2.5	2	3.22	129%	4%	0.127	0.380	1.27
5	6	5.22	104%	6%	0.311	0.934	3.11

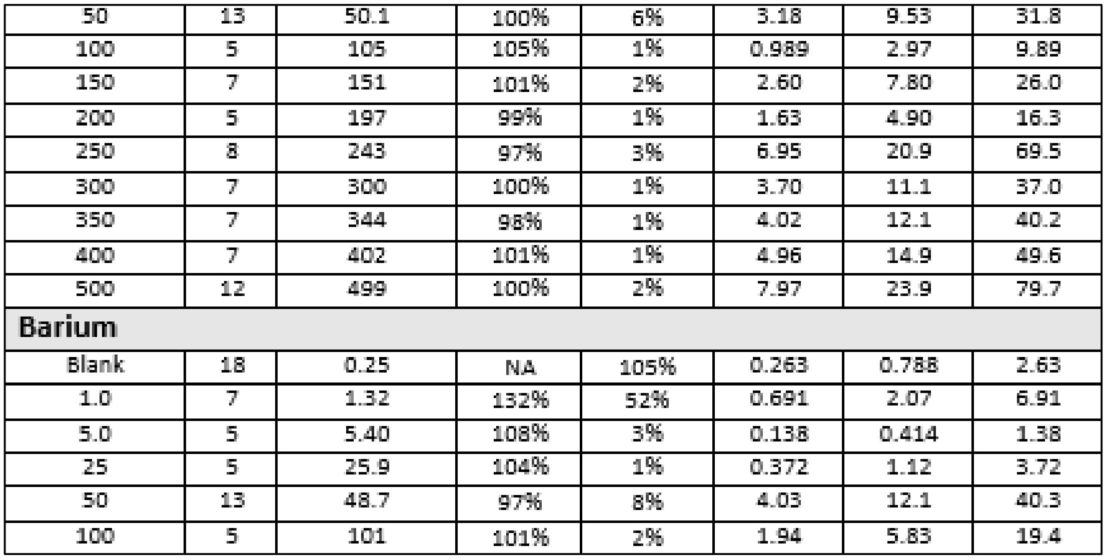
10	7	10.5	105%	4%	0.432	1.30	4.32
25	3	24.7	99%	3%	0.713	2.14	7013
50	4	47.5	95%	2%	0.803	2.41	8.03
Silica							
Blank	16	-0.029	NA	-186%	0.054	0.161	0.536
1.0	6	1.08	108%	11%	0.119	0.358	1.20
5.0	7	5.24	105%	6%	0.317	0.951	3.17
10	7	10.4	104%	5%	0.494	1.48	4.94
20	7	20.9	105%	4%	0.846	2.54	8.47

Table B3. Trace Element QC Table

Boron							
True Concentration (ug/L)	**# of points**	**Average Concentration (ug/L)**	**% Recovery**	**RSD %**	**Standard Deviation (ug/L)**	**3 Times Standard Deviation (ug/L) (ILOD)**	**10 Times Standard Deviation (ug/L) (ILOQ)**
Blank	19	3.98	NA	40%	1.58	4.7	16
1.0	13	3.03	303%	76%	2.29	6.9	23
5.0	13	5.95	119%	26%	1.56	4.7	16
10	13	11.1	111%	13%	1.43	4.3	14
20	13	24.8	124%	7%	1.85	5.6	19
50	13	49.0	98%	7%	3.35	10	33
100	13	108	108%	8%	8.86	27	89
500	13	541	108%	9%	46.9	141	469
1000	13	1022	102%	8%	84.7	254	847
Lithium							
Blank	18	0.392	NA	145%	0.57	1.71	5.70
1.0	7	1.35	135%	97%	1.31	3.93	13.1
5.0	5	5.67	113%	5%	0.257	0.770	2.57
25	5	26.8	107%	4%	1.08	3.25	10.8
50	13	48.1	96%	11%	5.47	16.4	54.7
100	5	105	105%	4%	3.89	11.7	38.9
150	7	144	96%	11%	15.2	45.6	152
200	5	197	99%	3%	4.99	15.0	49.9
250	8	238	95%	9%	21.3	64.0	213
300	7	293	98%	10%	29.2	87.5	292
350	7	338	97%	9%	30.5	91.4	305
400	7	398	100%	7%	26.1	78.4	261
500	12	495	99%	5%	22.7	68.0	227
Beryllium							
Blank	18	0.214	NA	114%	0.244	0.732	2.44

1.0	7	1.33	133%	52%	0.694	2.08	6.94
5.0	5	5.38	108%	4%	0.195	0.584	1.95
25	5	25.9	104%	3%	0.892	2.68	8.92
50	13	49.3	99%	10%	4.98	14.9	49.8
100	5	99.9	100%	2%	2.31	6.92	23.1
150	7	151	101%	2%	3.13	9.39	31.3
200	5	196	98%	2%	3.25	9.74	32.5
250	8	248	99%	4%	9.26	27.8	92.6
300	7	308	103%	4%	11.5	34.4	115
350	7	353	101%	3%	10.2	30.5	102
400	7	410	103%	3%	10.5	31.4	105
500	12	505	101%	3%	15.7	47.0	157
Magnesium							
Blank	17	0.120	NA	233%	0.28	0.839	2.80
1.0	8	5.00	500%	74%	3.72	11.2	37.2
5.0	13	4.53	91%	44%	2.00	6.00	20.0
25	5	27.0	108%	4%	1.01	3.04	10.1
50	13	54.1	108%	14%	7.78	23.3	77.8
100	5	103	103%	3%	2.62	7.85	26.2
150	7	165	110%	3%	4.67	14.0	46.7
200	5	194	97%	2%	3.92	11.8	39.2
250	7	272	109%	1%	4.06	12.2	40.6
350	7	329	94%	2%	5.92	17.7	59.2
400	7	384	96%	1%	3.21	9.64	32.1
450	6	440	98%	1%	4.93	14.8	49.3
500	5	482	96%	2%	10.6	31.7	106
Aluminum							
Blank	25	0.76	NA	NA	0.861	2.58	8.61
1.0	15	2.26	226%	113%	1.23	3.70	12.3
5.0	13	3.53	71%	54%	2.32	6.97	23.2
25	5	27.3	109%	66%	1.20	3.61	12.0
50	20	55.2	110%	4%	5.37	16.1	53.7
100	5	104	104%	10%	3.37	10.1	33.7
150	14	159	106%	3%	6.13	18.4	61.3
200	5	195	98%	4%	5.16	15.5	51.6
250	15	260	104%	3%	12.1	36.2	121
300	7	311	104%	5%	7.11	21.3	71.1
350	21	356	102%	2%	22.5	67.6	225
400	7	417	104%	6%	8.56	25.7	85.6
450	6	440	98%	2%	4.35	13.0	43.5
500	12	504	101%	1%	17.2	51.7	172
Arsenic							
Blank	18	0.35	NA	125%	0.437	1.31	4.37
1.0	7	1.57	157%	40%	0.623	1.87	6.23

5.0	5	5.16	103%	6%	0.311	0.93	3.11
25	5	25.8	103%	2%	0.580	1.74	5.80
50	13	48.6	97%	8%	3.84	11.5	38.4
100	5	99.1	99%	2%	1.53	4.60	15.3
150	7	145	97%	3%	3.84	11.5	38.4
200	5	191	96%	2%	3.67	11.0	36.7
250	7	239	96%	2%	5.75	17.2	57.5
300	7	295	98%	3%	8.27	24.8	82.7
350	7	340	NA	2%	6.99	21.0	69.9
400	7	402	157%	3%	13.4	40.2	134
500	12	496	103%	2%	11.1	33.3	111
Selenium							
Blank	18	0.55	NA	119%	0.654	1.96	6.54
1.0	7	1.93	193%	33%	0.638	1.91	6.38
5.0	5	5.35	107%	9%	0.507	1.52	5.07
25	5	25.7	103%	2%	0.441	1.32	4.41
50	13	49.5	99%	8%	4.06	12.2	40.6
100	5	102	102%	2%	1.76	5.29	17.6
150	7	147	98%	3%	3.77	11.3	37.7
200	5	197	99%	1%	2.85	8.55	28.5
250	8	240	96%	4%	8.42	25.3	84.2
300	7	296	99%	3%	7.53	22.6	75.3
350	7	339	97%	1%	4.35	13.1	43.5
400	7	403	101%	3%	10.8	32.3	108
500	12	494	99%	2%	9.50	28.5	95.0
Rubidium							
Blank	18	0.35	NA	106%	0.371	1.11	3.71
1.0	7	1.40	140%	48%	0.668	2.00	6.68
5.0	5	5.61	112%	2%	0.120	0.36	1.20
25	5	26.9	108%	1%	0.274	0.82	2.74
50	12	50.1	100%	6%	3.21	9.63	32.1
100	5	105	105%	1%	1.03	3.10	10.3
150	7	151	101%	2%	2.54	7.62	25.4
200	5	199	100%	1%	1.86	5.57	18.6
250	8	245	98%	3%	7.16	21.5	71.6
300	7	303	101%	1%	4.20	12.6	42.0
350	7	345	99%	1%	3.90	11.7	39.0
400	7	403	101%	2%	6.09	18.3	60.9
500	12	499	100%	2%	8.90	26.7	89.0
Strontium							
Blank	18	0.22	NA	110%	0.243	0.728	2.43
1.0	7	1.38	138%	46%	0.630	1.89	6.30
5	5	5.62	112%	2%	0.121	0.362	1.21
25	5	26.8	107%	1%	0.267	0.801	2.67



50	13	50.1	100%	6%	3.18	9.53	31.8
100	5	105	105%	1%	0.989	2.97	9.89
150	7	151	101%	2%	2.60	7.80	26.0
200	5	197	99%	1%	1.63	4.90	16.3
250	8	243	97%	3%	6.95	20.9	69.5
300	7	300	100%	1%	3.70	11.1	37.0
350	7	344	98%	1%	4.02	12.1	40.2
400	7	402	101%	1%	4.96	14.9	49.6
500	12	499	100%	2%	7.97	23.9	79.7
Barium							
Blank	18	0.25	NA	105%	0.263	0.788	2.63
1.0	7	1.32	132%	52%	0.691	2.07	6.91
5.0	5	5.40	108%	3%	0.138	0.414	1.38
25	5	25.9	104%	1%	0.372	1.12	3.72
50	13	48.7	97%	8%	4.03	12.1	40.3
100	5	101	101%	2%	1.94	5.83	19.4

Table B4. Chemical concentrations for geothermal samples collected throughout the ESRP in 2014.

Site	Lat	Long	Unit ID	Alkalinity as HCO3	ICP-OES					ICP-MS								IC			
					Ca	Mg	Na	K	SiO2(aq)	Li	Be	Al	As	Rb	Sr	Ba	B	F	Cl	SO4	NO3
001	43.64283	-111.68768	Heise Hot Springs	985.76	487.66	93.79	1539.72	206.21	33.63	2.48	1.17E-03	0.131	0.032	0.652	5.466	0.057	4.550	4.00	2267.48	712.26	ND
002	44.14558	-112.55494	Lidy Hot Springs 1	131.76	66.24	15.58	25.43	13.22	37.76	0.05	<LOD	0.001	0.014	0.019	0.597	0.086	0.093	4.60	7.29	101.91	ND
003	44.14166	-112.55240	Lidy Hot Springs 2	163.48	64.16	16.34	27.65	13.47	34.21	0.05	<LOD	0.001	0.014	0.019	0.611	0.078	0.092	4.68	6.94	98.28	ND
004	43.79211	-111.44009	Green Canyon Hot Springs	136.64	144.20	33.75	4.99	4.46	27.01	0.01	<LOD	<LOD	0.003	0.007	1.172	0.034	0.020	1.46	0.94	314.24	2.12
005	44.09325	-111.43534	Sturm Well	66.12	3.18	0.05	33.25	0.89	63.14	0.05	<LOD	0.005	0.012	0.004	0.005	0.001	0.039	2.09	3.28	5.77	0.63
006	43.33278	-113.91790	Condie Hot Springs	314.76	61.09	11.47	62.40	22.49	29.51	0.09	<LOD	0.003	0.005	0.047	0.932	0.284	0.258	1.58	13.97	33.47	2.69
007	43.60234	-113.24214	Greenhouse Well	285.48	77.81	27.75	33.83	9.36	31.58	0.04	<LOD	<LOD	0.010	0.021	0.723	0.096	0.151	0.74	22.24	57.52	6.59
008	42.69940	-114.91040	Eckart Office Well	80.52	5.74	0.74	112.83	4.16	52.04	0.01	<LOD	0.007	0.046	0.004	0.022	0.001	0.190	12.16	46.46	90.87	1.21
009	42.64497	-114.78706	Campbell 1	143.96	23.47	3.00	57.54	7.69	71.89	0.06	<LOD	0.000	0.008	0.019	0.156	0.004	0.107	2.21	23.09	40.46	5.37
010	42.64432	-114.78294	Campbell 2	126.88	26.66	3.47	55.93	8.04	69.37	0.06	<LOD	0.000	0.007	0.019	0.177	0.002	0.106	2.46	20.03	31.78	4.75
011	42.69457	-114.85592	Miracle Hot Springs	92.72	0.84	0.00	128.20	1.87	99.53	0.05	<LOD	0.022	0.066	0.006	0.001	<LOD	0.332	22.37	31.69	33.72	ND
012	42.54479	-114.94855	Driscoll Well	95.16	11.23	0.36	149.41	1.38	45.54	0.19	<LOD	0.005	0.023	0.005	0.063	0.006	0.117	2.42	53.31	188.04	1.44
013	42.54348	-114.94897	Driscoll Spring	97.60	11.14	0.79	146.61	1.92	48.37	0.19	<LOD	0.016	0.024	0.007	0.065	0.015	0.113	2.45	53.59	186.65	ND
014	42.58318	-114.47496	CSI Well 2	126.88	4.54	0.19	94.90	3.27	64.23	0.01	<LOD	0.001	0.017	0.008	0.019	0.001	0.150	9.64	26.44	46.81	4.89
015	43.44244	-111.90484	Comore Loma #6	222.04	50.80	15.25	96.66	15.97	65.34	0.12	<LOD	0.002	0.003	0.042	0.311	0.163	0.216	0.38	126.11	32.19	5.90
016	43.43774	-111.93018	Comore Loma #5	251.32	51.96	18.54	89.75	15.77	85.12	0.09	<LOD	0.002	0.004	0.042	0.243	0.225	0.215	0.27	120.31	25.60	2.76
017	43.43142	-111.94501	Blackhawk #2	270.84	77.43	22.10	124.43	17.29	83.67	0.13	<LOD	0.002	0.004	0.045	0.405	0.247	0.341	0.23	204.93	36.98	2.84
018	43.43142	-11.94469	Blackhawk #1	268.40	75.34	21.04	122.23	16.74	81.99	0.13	<LOD	0.002	0.004	0.044	0.430	0.229	0.335	0.26	196.52	39.07	3.48
020	42.10207	-113.38434	Raft River Geothermal # 1	34.16	59.89	0.16	567.72	39.89	132.81	1.57	1.31E-03	0.085	0.010	0.420	1.527	0.028	0.269	9.08	956.09	58.43	1.40
021	42.11042	-113.37519	Raft River Geothermal # 2	38.06	52.49	0.10	418.22	37.89	157.34	1.05	5.92E-04	0.086	0.005	0.388	1.224	0.015	0.193	9.49	979.92	63.69	6.30
022	42.08359	-113.35865	Raft River Geothermal # 7	32.94	199.21	0.10	1258.19	150.28	226.84	2.57	9.33E-04	0.069	0.018	1.306	4.931	0.080	0.488	6.05	2197.12	59.30	1.33
023	42.09787	-113.38541	Raft River Geothermal # 4	44.41	59.79	0.14	542.55	38.82	133.60	1.57	6.62E-04	0.066	0.007	0.396	1.413	0.023	0.249	7.15	790.36	59.32	0.06
024	42.72589	-112.87381	Indian Hot Springs	222.53	80.84	19.52	126.03	11.48	20.37	0.08	<LOD	0.002	0.025	0.028	2.115	0.288	0.104	0.50	216.27	19.81	0.36
025	42.23667	-113.36971	Grush Dairy	283.04	0.90	0.09	164.01	2.49	72.97	0.15	<LOD	0.112	0.003	0.011	0.016	0.006	0.093	6.70	68.97	24.02	ND
026	42.108	-113.39206	Raft River USGS Well	95.16	70.72	0.14	621.47	24.85	84.27	1.50	6.77E-04	0.040	0.006	0.287	1.612	0.017	0.274	7.04	976.46	56.47	0.05
027	42.10776	-113.39186	Raft River Frasier Well	59.78	67.22	0.21	598.27	22.61	77.42	1.45	1.08E-03	0.033	0.007	0.280	1.543	0.017	0.264	5.82	857.85	54.42	0.06
028	42.09656	-113.37800	Raft River Crook Well	35.38	157.70	0.31	1186.92	35.88	95.91	2.57	1.45E-03	0.059	0.015	0.430	3.117	0.118	0.480	6.07	1679.69	56.51	0.18
029	43.36414	-113.78943	Milford Sweat	251.32	66.49	13.68	42.95	8.45	24.58	0.04	5.82E-05	0.003	0.073	0.021	0.449	0.092	0.172	1.85	6.61	49.92	0.01
030	43.3278	-114.39941	Magic Hot Springs Runoff	709.59	13.17	1.29	333.02	20.93	109.44	1.17	1.39E-03	0.007	0.006	0.123	0.646	0.147	1.237	10.57	79.07	52.95	ND
031	43.42341	-114.62857	Elk Creek 1	92.72	2.33	0.00	90.18	1.66	65.02	0.21	<LOD	0.022	0.005	0.008	0.109	0.001	0.254	15.13	23.17	42.57	ND
032	43.42322	-114.62865	Elk Creek 2	90.28	2.27	0.00	91.23	1.57	65.30	0.21	<LOD	0.026	0.005	0.008	0.112	0.001	0.252	15.17	23.14	42.60	ND
033	43.29241	-114.91002	Barron Well	180.56	16.90	0.62	156.25	2.97	51.70	0.36	1.83E-04	0.010	0.001	0.020	0.356	0.009	0.173	7.08	9.48	210.93	ND
034	43.38290	-114.93224	Wardrop Hot Springs	192.76	1.18	0.27	56.01	0.88	76.82	0.05	<LOD	0.086	0.003	0.005	0.045	0.000	0.047	3.35	5.06	11.49	0.00
035	43.3278	-114.39941	Magic Hot Springs Well	702.72	22.34	1.39	310.54	19.79	103.74	1.18	2.37E-03	0.009	0.004	0.126	0.931	0.223	1.200	9.95	74.11	50.34	ND

Site	Lat	Long	Unit ID	Alkalinity	ICP-OES					ICP-MS								IC			
				as HCO3	Ca	Mg	Na	K	SiO2(aq)	Li	Be	Al	As	Rb	Sr	Ba	B	F	Cl	SO4	NO3
036	43.12966	-115.33841	Prince Albert Hot Springs	104.92	0.26	0.01	55.28	2.67	110.10	0.01	1.24E-04	0.017	0.009	0.007	0.001	0.001	0.037	6.95	2.55	8.42	ND
037	42.17334	-113.86163	Oakley Warm Spring	107.36	2.23	0.02	85.72	2.18	79.21	0.03	1.26E-04	0.015	0.001	0.015	0.053	0.001	0.052	7.61	52.57	21.40	ND
038	42.08533	-113.93984	Richard Austin Well 1	204.96	2.14	0.06	105.97	1.89	29.71	0.07	1.01E-04	0.025	0.007	0.006	0.038	0.014	0.071	2.42	16.17	22.80	ND
039	42.47663	-113.50770	Marsh Creek Well	124.44	9.08	0.41	107.78	4.28	62.55	0.07	1.69E-04	0.007	0.001	0.029	0.094	0.012	0.063	13.18	51.77	50.26	ND
040	42.70399	-114.85699	1000 Springs (Sliger's Well)	212.28	0.94	0.00	136.44	1.59	93.53	0.05	5.54E-05	0.074	0.061	0.008	0.001	0.000	0.499	24.22	50.45	30.06	ND
041	42.68841	-114.82680	Banbury Hot Springs Well	248.88	0.88	0.00	96.77	1.65	103.40	0.03	8.87E-05	0.014	0.042	0.007	0.001	0.000	0.216	11.39	16.86	23.50	ND
042	42.68841	-114.82680	Banbury Hot Springs	168.36	1.04	0.00	94.90	1.60	102.85	0.03	<LOD	0.015	0.042	0.007	0.001	0.000	0.219	11.36	16.76	23.54	ND
043	42.95543	-115.29997	Diamond Laundry	314.76	1.66	0.18	142.30	1.29	30.13	0.02	<LOD	0.013	0.000	0.002	0.007	0.001	0.890	13.07	23.26	4.30	304.06
044	43.00294	-115.19222	Johnston Well	117.12	2.42	0.05	77.41	1.27	40.93	0.02	<LOD	0.009	0.002	0.002	0.002	0.000	0.329	16.96	5.95	10.29	0.44
045	42.66851	-114.82436	Leo Ray Hill	140.30	5.95	0.19	61.69	3.41	54.05	0.06	5.11E-05	0.002	0.025	0.008	0.010	0.001	0.129	3.42	13.97	31.30	ND
046	42.66778	-114.82673	Leo Ray Road	139.08	7.62	0.45	56.44	4.10	54.47	0.06	<LOD	0.011	0.018	0.010	0.018	0.002	0.132	3.44	11.69	24.77	0.02
048	42.70501	-114.85701	Hensley Well	231.80	1.93	0.01	121.63	1.62	83.31	0.04	<LOD	0.011	0.060	0.002	0.007	0.001	0.579	24.13	51.93	33.13	ND
049	43.11025	-115.31258	Latty Hot Prings	107.36	0.20	0.01	53.91	1.90	103.21	0.02	5.64E-05	0.020	0.009	0.006	0.001	0.000	0.043	6.85	2.73	11.45	0.09
050	42.94632	-115.49423	Laib Well	885.72	9.43	0.55	291.73	9.84	57.73	0.34	4.50E-04	0.176	0.002	0.018	0.093	0.094	2.167	1.74	66.20	10.37	164.00
051	42.58050	-114.47089	CSI Well 1	153.72	3.99	0.22	86.28	2.99	60.92	0.02	8.49E-05	0.003	0.017	0.007	0.017	0.001	0.185	8.61	25.81	45.38	3.50
052	42.59755	-114.40018	Larry Anderson Well	187.88	1.22	0.01	118.11	2.19	69.27	0.03	3.12E-04	0.005	0.014	0.007	0.002	0.001	0.285	15.82	21.13	36.32	36.82
053	42.61390	-114.48799	Pristine Springs	153.72	1.30	0.01	109.33	2.12	71.55	0.01	<LOD	0.004	0.029	0.005	0.004	0.000	0.317	16.47	26.72	30.77	1.09
054	42.5726	-114.4518	Twin Falls High School	161.04	39.91	8.98	55.41	4.92	59.11	0.03	1.04E-04	0.002	0.006	0.012	0.185	0.016	0.107	2.35	37.51	76.03	6.74
055	42.57750	-114.28870	Anderson Campground Well	246.44	1.50	0.02	126.50	3.10	66.02	0.07	<LOD	0.024	0.141	0.009	0.004	0.002	0.495	23.37	34.42	37.39	0.10
056	43.6083	-113.24432	Butte City Well	385.52	51.55	20.88	32.45	7.53	33.17	0.03	<LOD	0.002	0.006	0.016	0.558	0.118	0.164	0.62	19.81	49.43	3.78
057	43.02583	-112.02551	Quidop Springs 1	617.32	165.42	55.84	28.40	22.96	16.05	0.13	2.45E-04	0.005	0.009	0.034	1.824	0.026	0.094	0.81	23.30	223.91	1.97
058	43.0372	-112.0043	Quidop Springs 2	710.04	199.48	68.95	33.80	34.11	19.61	0.21	1.15E-02	0.416	0.027	0.050	2.598	0.125	0.129	0.81	15.16	344.95	8.84
059	43.11448	-112.16660	Yandell Warm Springs	265.96	72.47	26.33	13.55	3.95	16.57	0.02	<LOD	0.000	0.003	0.004	0.489	0.045	0.036	0.60	16.29	90.37	1.97
060	42.4376	-113.4343	Skaggs Ranch	180.56	27.73	1.99	32.62	3.86	44.06	0.02	<LOD	0.000	0.001	0.007	0.134	0.075	0.031	1.52	20.37	14.52	ND
061	42.1001	-113.63354	Durfee Hot Springs	107.36	8.21	0.35	84.27	3.30	67.87	0.09	5.88E-05	0.003	0.002	0.025	0.124	0.012	0.075	6.19	59.19	28.16	0.34
062	42.2233	-113.7917	Basin Cemetery	122.00	18.33	2.42	57.98	1.98	40.20	0.01	1.81E-04	0.001	0.002	0.003	0.168	0.013	0.064	3.58	47.41	21.01	1.40
063	42.4822	-113.97341	Wybenga Dairy	114.68	25.03	1.07	20.90	8.71	69.43	0.01	8.25E-05	0.002	0.002	0.016	0.212	0.129	0.052	0.70	13.13	15.74	0.83
064	42.1394	-111.9371	David Bosen Well	583.16	206.92	18.48	4523.31	794.93	95.12	6.07	6.75E-03	0.078	0.076	4.972	20.351	3.235	5.555	5.21	7128.94	49.19	ND
065	43.8772	-111.55890	Schwendiman Well	164.70	26.86	6.87	39.27	5.49	61.53	0.05	<LOD	0.002	0.007	0.017	0.080	0.022	0.087	2.57	13.67	25.25	4.50
066	43.8857	-111.5595	Clyde Well	183.00	24.67	7.29	45.65	5.32	65.03	0.06	6.09E-05	0.002	0.010	0.018	0.078	0.027	0.119	3.17	15.41	22.97	5.62
067	43.9013	-111.50967	Cinder Block Well	181.78	18.17	3.50	52.25	5.04	70.48	0.07	8.85E-05	0.002	0.013	0.018	0.050	0.021	0.151	4.18	12.18	17.19	1.08
068	43.8831	-111.6186	Newdale City Well	251.32	27.56	4.70	70.89	8.12	70.41	0.12	5.39E-05	0.002	0.012	0.031	0.086	0.052	0.215	5.03	24.86	29.74	7.18
069	43.85840	-111.67870	Spackman Well	190.32	37.16	13.68	11.64	3.00	29.60	<LOD	<LOD	0.001	0.002	0.004	0.108	0.033	0.065	0.46	5.82	12.91	7.71
070	42.9781	-112.4165	Fort Hall Thermal Well	223.26	55.35	21.27	29.30	7.14	49.98	0.03	< 0.0001	< 0.01	0.005	0.311	0.311	0.065	0.054	ND	ND	ND	ND

APPENDIX C: WATER TYPES AND CHARGE BALANCE

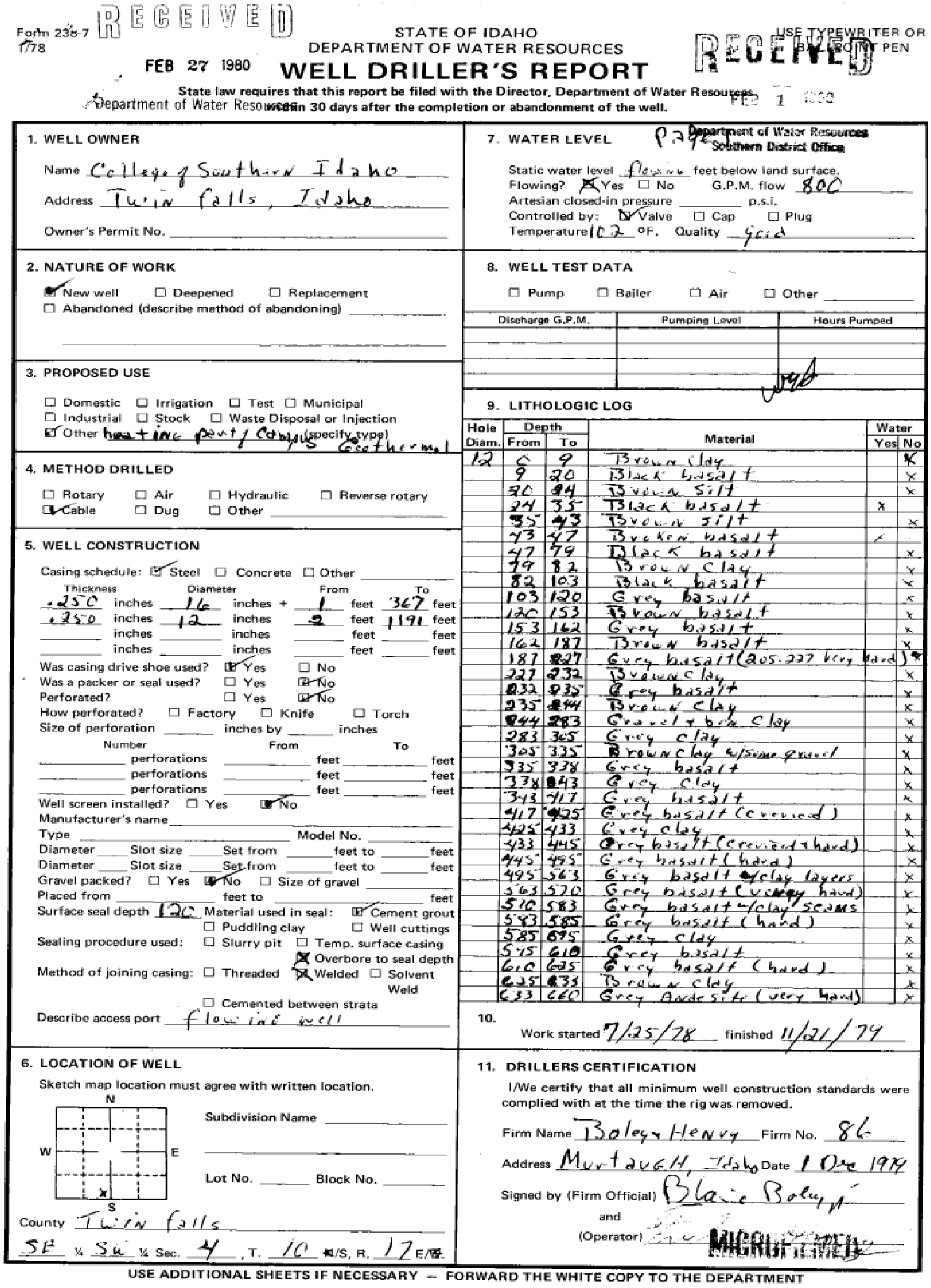
Table C1. Major cations and anions for Na-HCO_3 type thermal waters utilized in this study. Charge balances listed are given as the ratio of cations to anions calculated from meq/L units. Values with more than a 20% difference from a 1:1 balance are highlighted in red.

Site	Lat	Long	T (^{o}C)	pH	Ca	Mg	Na	K	Cl	F	SO4	Alkalinity as HCO3	TDS	Charge Balance
M91-7	42.60316	-114.477722	39	9.3	1.6	0.06	96	2.8	15	11	20	145	331	1.14
M91-8	42.56936	-114.606826	27	8.6	5.1	0.17	61	4.3	11	4	16	134	253	1.00
M91-11	42.58362	-114.48118	30.5	8.6	8.6	0.4	74	6.3	21	11	26	121	267	1.04
M91-13	42.58966	-114.509924	41.5	9	1.7	0.08	130	2.5	36	26	28	195	408	0.94
M91-14	42.57862	-114.287802	42	9.2	1.5	0.01	120	1.9	17	14	32	207	272	1.01
LY89-11	42.63174	-114.597327	30.5	9	2	0.05	82	2.9	11	12	20	110	272	1.18
LY89-12	42.61798	-114.473657	27	9	1.9	0.1	110	3.5	10	22	18	140	341	**1.21**
LY89-13	42.61539	-114.488068	42	8.8	2.5	0.1	110	1.9	16	16	15	140	326	**1.27**
LY89-14	42.59496	-114.481012	39.5	9	1.9	0.1	99	1.9	15	14	25	110	301	**1.28**
LY89-15	42.60581	-114.478121	39	9.3	1.6	0.06	96	2.8	15	11	20	120	299	**1.28**
LY89-22	42.58386	-114.480819	30.5	9	8.6	0.4	74	6.3	21	11	26	110	262	1.09
CC-14	42.58318	-114.47496	38.1	8.79	4.54	0.19	95	3.3	26	10	47	127	332	1.03
CC-51	42.58050	-114.47089	37.7	8.81	3.99	0.22	86	3.0	26	9	45	154	312	0.87
CC-52	42.59755	-114.40018	43.0	9.16	1.22	0.01	118	2.2	21	16	36	188	397	1.00
CC-53	42.61390	-114.48799	43.0	9.18	1.30	0.01	109	2.1	27	16	31	154	377	1.02
CC-55	42.57750	-114.28870	37.0	9.05	1.50	0.02	126	3.1	34	23	37	246	423	0.81
LY82-3	42.70158	-114.856527	62	9.4	0.7	0.1	150	1.4	48	15	35	168	503	1.17
LY82-4	42.70184	-114.854331	71.5	9.5	1.5	0.1	140	1.5	51	27	33	168	505	0.98
LY82-5	42.69133	-114.866789	57	9.4	0.9	0.1	130	1.5	34	21	34	177	485	1.01
LY82-6	42.6881	-114.84012	45.5	9.1	0.9	0.1	100	1.8	30	26	29	163	438	0.81
LY82-7	42.68357	-114.834978	42.5	9.3	1.3	0.1	90	1.7	14	9	28	148	359	1.04
LY82-11	42.68487	-114.829093	44.5	9.4	3.3	0.1	100	1.8	22	12	27	160	414	1.03
LY82-12	42.68251	-114.82902	30	9.3	0.9	0.1	97	1.6	20	13	28	154	379	0.99
LY82-15	42.66904	-114.8236	34	8.7	5.4	0.2	66	2.9	13	4	30	124	302	1.00
LY82-18	42.66149	-114.814894	32	8.4	8	0.2	62	2.8	11	3	26	144	310	0.94
LY82-19	42.66001	-114.81414	31.5	8.6	7.5	0.3	63	2.8	11	3	26	134	299	1.00
LY82-20	42.65886	-114.810791	32.5	8.3	10	0.5	62	3.5	11	3	25	150	316	0.97
LY89-1	42.66191	-114.812514	33	8.4	11	0.5	61	3.9	11	4	24	150	246	0.97
LY89-4	42.63697	-114.754192	26	8.3	7.4	0.2	62	5.6	10	5	21	140	262	0.99
LY89-8	42.65494	-114.650688	44	9	1.5	0.1	96	1.5	14	16	24	78	304	**1.43**
CC-40	42.70399	-114.85699	72.0	9.5	0.94	0.00	136	1.59	50	24	30	212	494	0.89
CC-42	42.68841	-114.82680	58.5	9	1.04	0.00	95	1.60	17	11	24	168	332	0.98
CC-45	42.66851	-114.82436	35.0	8.69	5.95	0.19	62	3.41	14	3	31	140	228	0.87
CC-46	42.66778	-114.82673	35.5	8.41	7.62	0.45	56	4.10	12	3	25	139	222	0.90
CC-48	42.70501	-114.85701	31.8	9.55	1.93	0.01	122	1.62	52	24	33	232	429	0.75
LY89-2	42.66123	-114.791887	37	8.1	13	1.2	58	4.1	12	4	25	140	246	1.01
CC-11	42.69457	-114.85592	58.4	9.53	0.84	0.00	128	1.87	32	22	34	93	423	**1.32**
LY89-9	42.64886	-114.652208	23	9.1	8.9	2.4	73	1.9	20	11	28	95	263	1.18

Table C2: Major cations and anions for Ca-HCO_3 type thermal waters utilized in this study. Charge balances listed are given as the ratio of cations to anions calculated from meq/L units.

Site	Lat	Long	T (^oC)	pH	Ca	Mg	Na	K	Cl	F	SO4	Alkalinity as HCO3	TDS	Charge Balance
LY89-17	42.5759	-114.738609	25	8	35	4.5	63	12	35	2	69	160	371	1.01
LY82-13	42.59993	-114.943824	42	9.2	26	3.9	35	7.9	16	2	35	120	331	1.03
LY89-3	42.65402	-114.795266	28.5	8	16	2.3	55	5.8	13	3	27	150	259	1.00
CC-9	42.64497	-114.78706	34.5	7.98	23.47	3.00	58	7.69	23	2	40	144	252	1.04
CC-10	42.64432	-114.78294	34.4	7.96	26.66	3.47	56	8.04	20	2	32	127	293	1.24
CC-12	42.54479	-114.94855	37.5	8.59	11.23	0.36	149	1.38	53	2	188	95	559	1.00
LY89-10	42.59616	-114.751276	31	8	39	5.6	65	11	38	2	75	160	388	1.03
LY89-5	42.64683	-114.785566	32.5	7.8	18	2.2	54	6	13	3	27	150	268	1.02
LY89-6	42.63448	-114.778469	25	8.1	17	1.1	53	7.5	14	2	22	160	283	0.95
LY89-7	42.5977	-114.760739	29	7.9	36	5.4	61	10	31	2	61	170	356	1.02
M91-12	42.54998	-114.436857	30.5	7.8	37	6.8	31	4.9	31	1	51	100	266	1.07
LY89-18	42.56642	-114.490768	31.5	8	20	3.9	37	7	11	4	17	130	223	1.04
LY89-29	42.39592	-114.691588	18.5	7.8	23	8.4	13	2.9	9	0	11	120	175	1.01
LY89-30	42.34555	-114.509176	37	8	31	13	43	11	6	2	21	270	279	0.93
LY89-32	42.27131	-114.359743	9	6.7	5.4	1.3	6	5	2	0	2	34	95	1.17
LY89-33	42.22239	-114.785594	12	7	7.2	1.2	6	2.6	3	0	5	30	76	1.13
LY89-34	42.20179	-114.664984	32	7.8	21	2	18	6.9	7	1	10	120	200	0.90
LY89-35	42.20114	-114.697878	26	7.5	22	2.6	19	5.8	6	6	12	110	183	0.90
LY89-36	42.15826	-114.66585	32	7.6	18	2.3	18	4.7	7	1	9	100	174	0.97
LY89-37	42.20044	-114.586984	7.5	7.6	34	5.4	19	3.6	16	0	17	120	208	1.10
LY89-38	42.21351	-114.306916	4.5	6	2.6	0.7	3	2.6	1	0	3	20	62	0.91
CC-54	42.57256	-114.45175	31.0	7.77	39.91	8.98	55	4.92	38	2	76	161	390	0.97
CC-8	42.69940	-114.91040	24.7	9.47	5.74	0.74	113	4.16	46	12	91	81	397	1.04
CC-13	42.54348	-114.94897	36.2	8.65	11.14	0.79	147	1.92	54	2	187	98	566	0.99

APPENDIX D: SELECT WELL DRILLER'S LOGS



Form 238-7
1/78

RECEIVED
FEB 27 1980
Department of Water Resources

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

USE TYPEWRITER OR BALLPOINT PEN

RECEIVED
FEB 1 1980

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

1. WELL OWNER

Name College of Southern Idaho
Address Twin Falls, Idaho
Owner's Permit No. ______

2. NATURE OF WORK

☑ New well ☐ Deepened ☐ Replacement
☐ Abandoned (describe method of abandoning) ______

3. PROPOSED USE

☐ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☑ Other heating part / Campus Geothermal (specify type)

4. METHOD DRILLED

☐ Rotary ☐ Air ☐ Hydraulic ☐ Reverse rotary
☑ Cable ☐ Dug ☐ Other ______

5. WELL CONSTRUCTION

Casing schedule: ☑ Steel ☐ Concrete ☐ Other ______

Thickness		Diameter		From		To	
.250	inches	16	inches +	1	feet	367	feet
.250	inches	12	inches	-2	feet	191	feet
	inches		inches		feet		feet
	inches		inches		feet		feet

Was casing drive shoe used? ☑ Yes ☐ No
Was a packer or seal used? ☐ Yes ☑ No
Perforated? ☐ Yes ☑ No
How perforated? ☐ Factory ☐ Knife ☐ Torch
Size of perforation ______ inches by ______ inches

Number		From		To	
	perforations		feet		feet
	perforations		feet		feet
	perforations		feet		feet

Well screen installed? ☐ Yes ☑ No
Manufacturer's name ______
Type ______ Model No. ______
Diameter ______ Slot size ______ Set from ______ feet to ______ feet
Diameter ______ Slot size ______ Set from ______ feet to ______ feet
Gravel packed? ☐ Yes ☑ No ☐ Size of gravel ______
Placed from ______ feet to ______ feet
Surface seal depth 120 Material used in seal: ☑ Cement grout ☐ Puddling clay ☐ Well cuttings
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☒ Overbore to seal depth
Method of joining casing: ☐ Threaded ☒ Welded ☐ Solvent Weld ☐ Cemented between strata
Describe access port flowing well

6. LOCATION OF WELL

Sketch map location must agree with written location.

N
W E
S

Subdivision Name ______
Lot No. ______ Block No. ______
County Twin Falls
SE ¼ SW ¼ Sec. 4, T. 10 N/S, R. 17 E/W.

7. WATER LEVEL P292

Department of Water Resources
Southern District Office

Static water level flowing feet below land surface.
Flowing? ☒ Yes ☐ No G.P.M. flow 800
Artesian closed-in pressure ______ p.s.i.
Controlled by: ☑ Valve ☐ Cap ☐ Plug
Temperature 102 °F. Quality good

8. WELL TEST DATA

☐ Pump ☐ Bailer ☐ Air ☐ Other ______

Discharge G.P.M.	Pumping Level	Hours Pumped

9. LITHOLOGIC LOG

Hole Diam.	Depth From	Depth To	Material	Water Yes	Water No
12	0	9	Brown clay		X
	9	20	Black basalt		x
	20	24	Brown silt		x
	24	35	Black basalt	x	
	35	43	Brown silt		x
	43	47	Broken basalt	✓	
	47	79	Black basalt		x
	79	82	Brown clay		x
	82	103	Black basalt		x
	103	120	Grey basalt		x
	120	153	Brown basalt		x
	153	162	Grey basalt		x
	162	187	Brown basalt		x
	187	227	Grey basalt (205-227 very hard)		x
	227	232	Brown clay		x
	232	235	Grey basalt		x
	235	244	Brown clay		x
	244	283	Gravel + brn clay		x
	283	305	Grey clay		x
	305	335	Brown clay w/some gravel		x
	335	338	Grey basalt		x
	338	343	Grey clay		x
	343	417	Grey basalt		x
	417	425	Grey basalt (creviced)		x
	425	433	Grey clay		x
	433	445	Grey basalt (creviced + hard)		x
	445	495	Grey basalt (hard)		x
	495	563	Grey basalt w/clay layers		x
	563	570	Grey basalt (very hard)		x
	570	583	Grey basalt w/clay seams		x
	583	585	Grey basalt (hard)		x
	585	595	Grey clay		x
	595	610	Grey basalt		x
	610	625	Grey basalt (hard)		x
	625	633	Brown clay		x
	633	660	Grey Andesite (very hard)		x

10.

Work started 7/25/78 finished 11/21/79

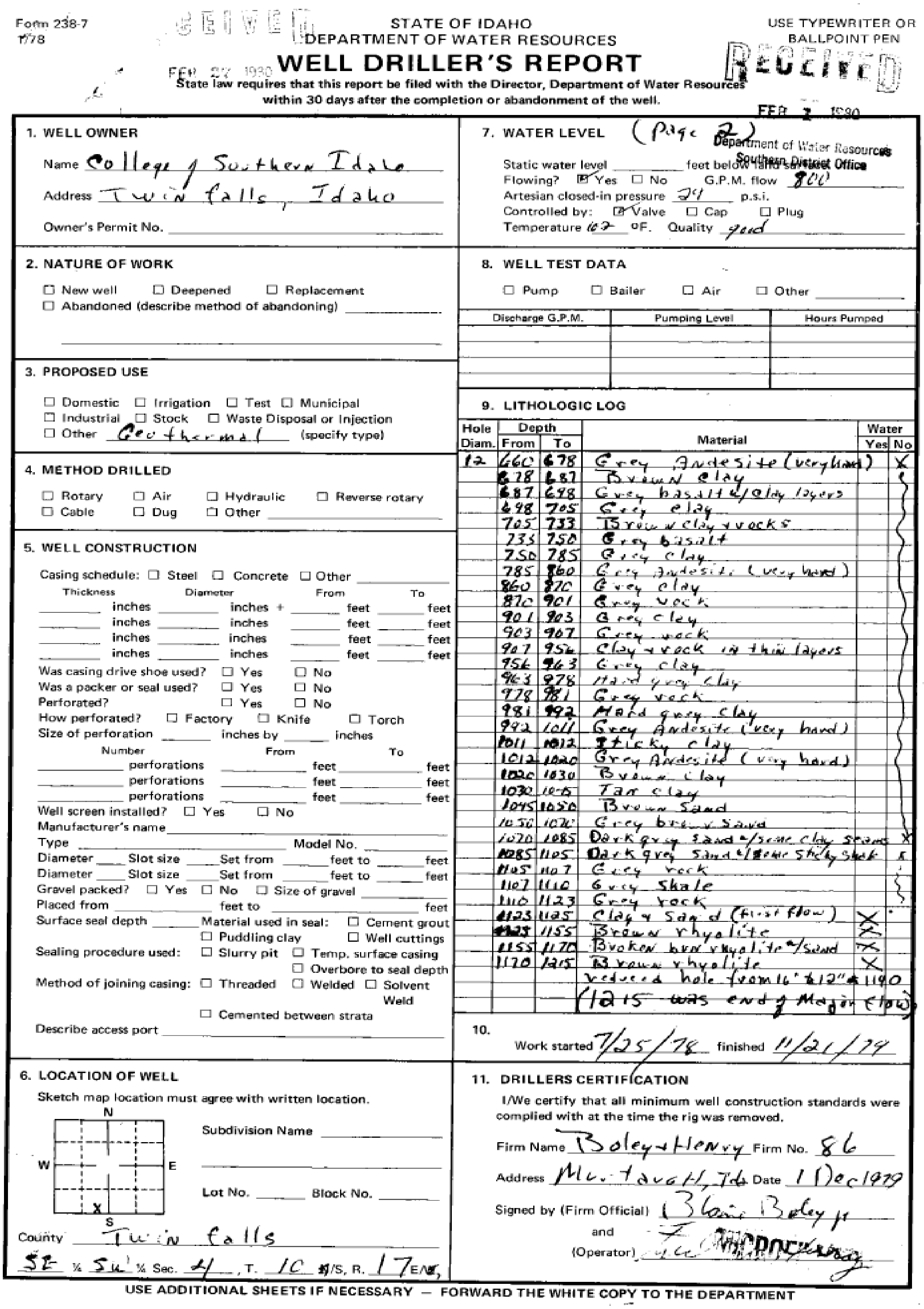
11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Boley Henry Firm No. 86
Address Murtaugh, Idaho Date 1 Dec 1979
Signed by (Firm Official) Blaine Boley
and
(Operator)

MICROFILMED

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT



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STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

USE TYPEWRITER OR
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Southern District Office

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

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Address Twin falls, Idaho
Owner's Permit No. ______

2. NATURE OF WORK

☐ New well ☐ Deepened ☐ Replacement
☐ Abandoned (describe method of abandoning) ______

3. PROPOSED USE

☐ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other Geothermal (specify type)

4. METHOD DRILLED

☐ Rotary ☐ Air ☐ Hydraulic ☐ Reverse rotary
☐ Cable ☐ Dug ☐ Other ______

5. WELL CONSTRUCTION

Casing schedule: ☐ Steel ☐ Concrete ☐ Other ______

Thickness	Diameter	From	To
____ inches	____ inches +	____ feet	____ feet
____ inches	____ inches	____ feet	____ feet
____ inches	____ inches	____ feet	____ feet
____ inches	____ inches	____ feet	____ feet

Was casing drive shoe used? ☐ Yes ☐ No
Was a packer or seal used? ☐ Yes ☐ No
Perforated? ☐ Yes ☐ No
How perforated? ☐ Factory ☐ Knife ☐ Torch
Size of perforation ____ inches by ____ inches

Number	From	To
____ perforations	____ feet	____ feet
____ perforations	____ feet	____ feet
____ perforations	____ feet	____ feet

Well screen installed? ☐ Yes ☐ No
Manufacturer's name ______
Type ______ Model No. ______
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Gravel packed? ☐ Yes ☐ No ☐ Size of gravel ______
Placed from ______ feet to ______ feet
Surface seal depth ____ Material used in seal: ☐ Cement grout ☐ Puddling clay ☐ Well cuttings
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☐ Overbore to seal depth
Method of joining casing: ☐ Threaded ☐ Welded ☐ Solvent Weld ☐ Cemented between strata
Describe access port ______

6. LOCATION OF WELL

Sketch map location must agree with written location.

N
W E
X
S

Subdivision Name ______
Lot No. ____ Block No. ____

County Twin falls
SE ¼ SW ¼ Sec. 4, T. 10 N/S, R. 17 E/W,

7. WATER LEVEL (Page 2)

Static water level ______ feet below land surface
Flowing? ☑ Yes ☐ No G.P.M. flow 800
Artesian closed-in pressure 24 p.s.i.
Controlled by: ☑ Valve ☐ Cap ☐ Plug
Temperature 102 °F. Quality good

8. WELL TEST DATA

☐ Pump ☐ Bailer ☐ Air ☐ Other ______

Discharge G.P.M.	Pumping Level	Hours Pumped

9. LITHOLOGIC LOG

Hole Diam.	Depth From	Depth To	Material	Water Yes	Water No
12	660	678	Grey Andesite (very hard)		X
	678	687	Brown clay		
	687	698	Grey basalt w/clay layers		
	698	705	Grey clay		
	705	733	Brown clay + rocks		
	735	750	Grey basalt		
	750	785	Grey clay		
	785	860	Grey Andesite (very hard)		
	860	870	Grey clay		
	870	901	Grey rock		
	901	903	Grey clay		
	903	907	Grey rock		
	907	956	Clay + rock in thin layers		
	956	963	Grey clay		
	963	978	Hard grey clay		
	978	981	Grey rock		
	981	992	Hard grey clay		
	992	1011	Grey Andesite (very hard)		
	1011	1012	Sticky clay		
	1012	1020	Grey Andesite (very hard)		
	1020	1030	Brown clay		
	1030	1045	Tan clay		
	1045	1050	Brown Sand		
	1050	1070	Grey brn sand		
	1070	1085	Dark grey sand w/some clay stains		X
	1085	1105	Dark grey sand w/some sticky shale		X
	1105	1107	Grey rock		
	1107	1110	Grey Shale		
	1110	1123	Grey rock		
	1123	1125	Clay + Sand (first flow)	X	
	1125	1155	Brown rhyolite	X	
	1155	1170	Broken brn rhyolite w/sand	X	
	1170	1215	Brown rhyolite	X	
			reduced hole from 16" to 12" at 1190		
			(1215 was end of Major flow)		

10.

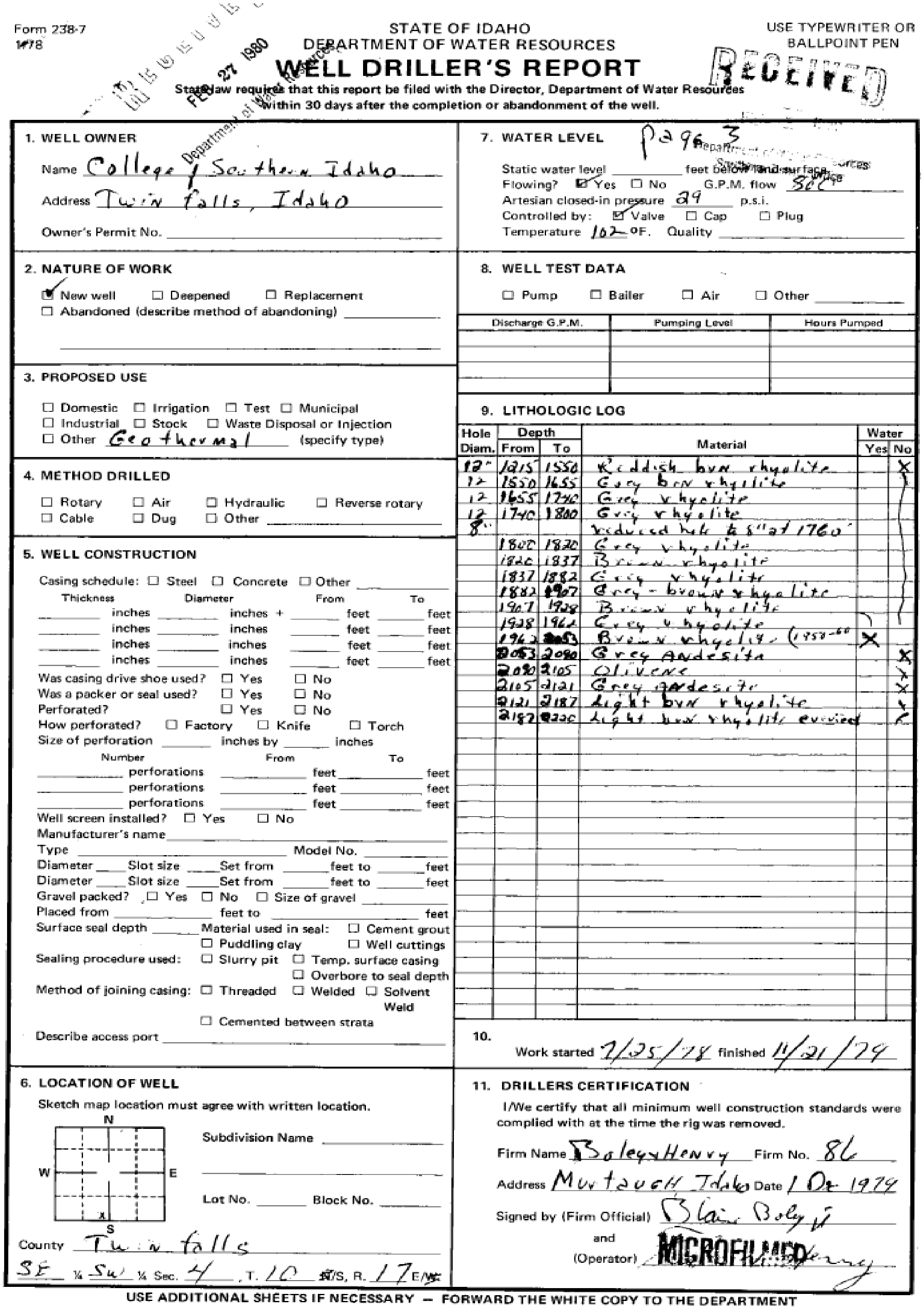
Work started 7/25/78 finished 11/21/79

11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Boley + Henry Firm No. 86
Address Murtaugh, Ida Date 1 Dec 1979
Signed by (Firm Official) Blaine Boley jr
and
(Operator)

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT



Form 238-7
1978

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

USE TYPEWRITER OR
BALLPOINT PEN

RECEIVED

FEB 27 1980
Department of Water Resources

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

1. WELL OWNER

Name College of Southern Idaho
Address Twin falls, Idaho
Owner's Permit No. ____

2. NATURE OF WORK

☑ New well ☐ Deepened ☐ Replacement
☐ Abandoned (describe method of abandoning) ____

3. PROPOSED USE

☐ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other Geothermal (specify type)

4. METHOD DRILLED

☐ Rotary ☐ Air ☐ Hydraulic ☐ Reverse rotary
☐ Cable ☐ Dug ☐ Other ____

5. WELL CONSTRUCTION

Casing schedule: ☐ Steel ☐ Concrete ☐ Other ____

Thickness	Diameter	From	To
____ inches	____ inches +	____ feet	____ feet
____ inches	____ inches	____ feet	____ feet
____ inches	____ inches	____ feet	____ feet
____ inches	____ inches	____ feet	____ feet

Was casing drive shoe used? ☐ Yes ☐ No
Was a packer or seal used? ☐ Yes ☐ No
Perforated? ☐ Yes ☐ No
How perforated? ☐ Factory ☐ Knife ☐ Torch
Size of perforation ____ inches by ____ inches

Number	From	To
____ perforations	____ feet	____ feet
____ perforations	____ feet	____ feet
____ perforations	____ feet	____ feet

Well screen installed? ☐ Yes ☐ No
Manufacturer's name ____
Type ____ Model No. ____
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Gravel packed? ☐ Yes ☐ No ☐ Size of gravel ____
Placed from ____ feet to ____ feet
Surface seal depth ____ Material used in seal: ☐ Cement grout ☐ Puddling clay ☐ Well cuttings
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☐ Overbore to seal depth
Method of joining casing: ☐ Threaded ☐ Welded ☐ Solvent Weld ☐ Cemented between strata
Describe access port ____

6. LOCATION OF WELL

Sketch map location must agree with written location.

N / W / E / S
x

Subdivision Name ____
Lot No. ____ Block No. ____

County Twin falls
SE ¼ SW ¼ Sec. 4, T. 10 N/S, R. 17 E/W

7. WATER LEVEL Page 3

Static water level ____ feet below land surface
Flowing? ☑ Yes ☐ No G.P.M. flow 800
Artesian closed-in pressure 29 p.s.i.
Controlled by: ☑ Valve ☐ Cap ☐ Plug
Temperature 102 °F. Quality ____

8. WELL TEST DATA

☐ Pump ☐ Bailer ☐ Air ☐ Other ____

Discharge G.P.M.	Pumping Level	Hours Pumped

9. LITHOLOGIC LOG

Hole Diam.	Depth From	Depth To	Material	Water Yes	Water No
12"	1215	1550	Reddish brn rhyolite		X
12	1550	1655	Grey brn rhyolite		
12	1655	1740	Grey rhyolite		
12	1740	1800	Grey rhyolite		
8"			reduced hole to 8" at 1760'		
	1800	1820	Grey rhyolite		
	1820	1837	Brown rhyolite		
	1837	1882	Grey rhyolite		
	1882	1907	Grey-brown rhyolite		
	1907	1928	Brown rhyolite		
	1928	1962	Grey rhyolite		
	1962	2053	Brown rhyolite (1958-60	X	
	2053	2090	Grey Andesite		X
	2090	2105	Olivene		X
	2105	2121	Grey andesite		X
	2121	2187	Light brn rhyolite		X
	2187	2220	Light brn rhyolite evoried		X

10. Work started 2/25/78 finished 11/21/79

11. DRILLERS CERTIFICATION

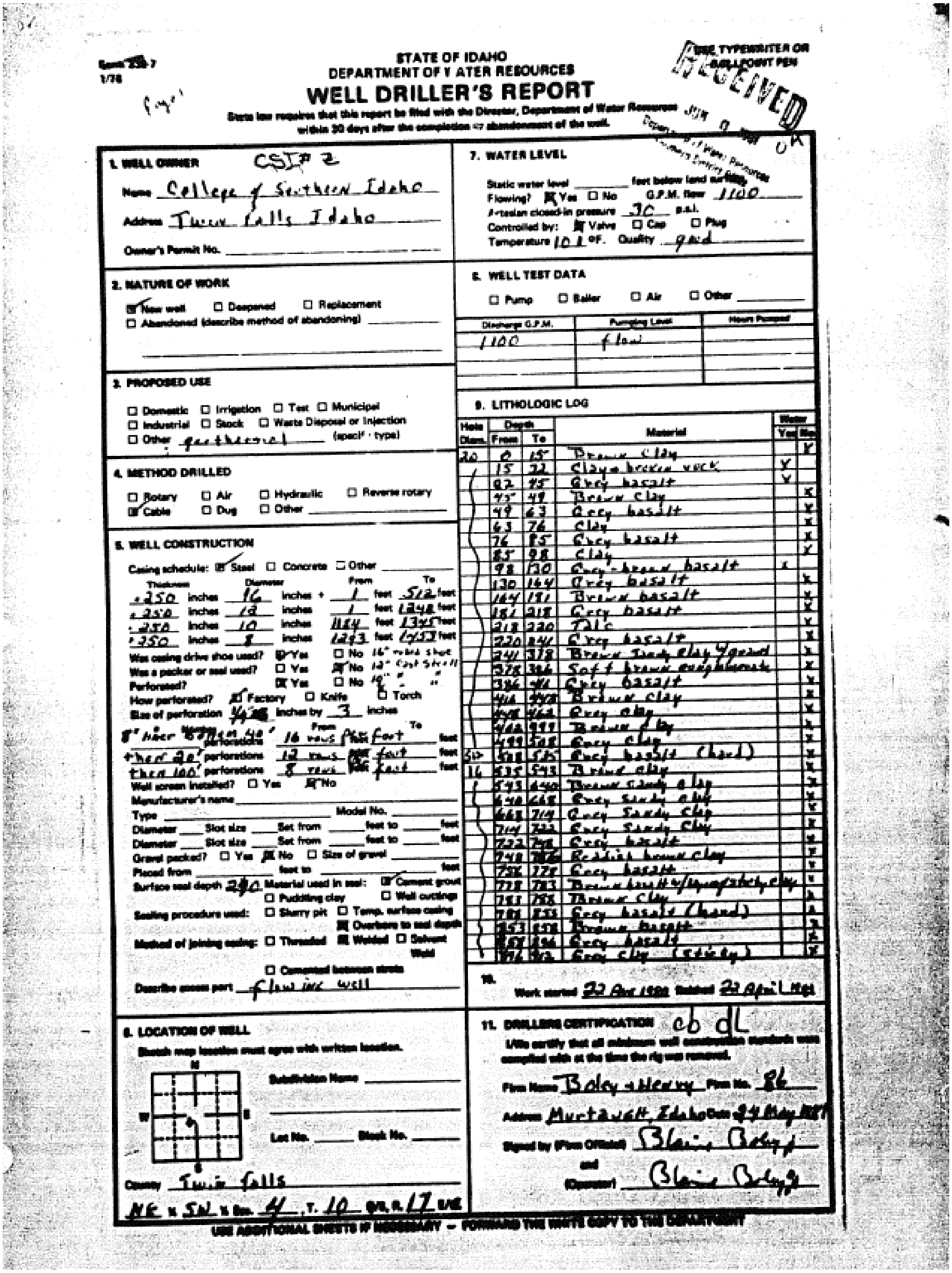
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Boley Henry Firm No. 86
Address Murtaugh Idaho Date 1 Oct 1979
Signed by (Firm Official) Blaine Boley
and
(Operator) Henry

MICROFILMED

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Figure C1. CSI Well 1 Driller's Log



Form 238-7
1/78

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

USE TYPEWRITER OR BALLPOINT PEN

RECEIVED JUN 0 1981 Department of Water Resources OK

1. WELL OWNER CSI # 2

Name College of Southern Idaho

Address Twin Falls Idaho

Owner's Permit No.

2. NATURE OF WORK

☑ New well ☐ Deepened ☐ Replacement

☐ Abandoned (describe method of abandoning)

3. PROPOSED USE

☐ Domestic ☐ Irrigation ☐ Test ☐ Municipal

☐ Industrial ☐ Stock ☐ Waste Disposal or Injection

☐ Other geothermal (specify type)

4. METHOD DRILLED

☐ Rotary ☐ Air ☐ Hydraulic ☐ Reverse rotary

☑ Cable ☐ Dug ☐ Other

5. WELL CONSTRUCTION

Casing schedule: ☑ Steel ☐ Concrete ☐ Other

Thickness		Diameter		From		To	
.250	inches	16	inches +	1	feet	512	feet
.250	inches	12	inches	1	feet	1248	feet
.250	inches	10	inches	1164	feet	1345	feet
.350	inches	8	inches	1293	feet	1453	feet

Was casing drive shoe used? ☑ Yes ☐ No 16" welded shoe

Was a packer or seal used? ☐ Yes ☒ No 12" cast steel

Perforated? ☒ Yes ☐ No 10" " "

8" " "

How perforated? ☑ Factory ☐ Knife ☐ Torch

Size of perforation 1/4 inches by 3 inches

		From	To	
8" liner between 40'	perforations	16 rows per foot		feet
then 20'	perforations	12 rows per foot		feet
then 100'	perforations	8 rows per foot		feet

Well screen installed? ☐ Yes ☒ No

Manufacturer's name

Type Model No.

Diameter Slot size Set from feet to feet

Diameter Slot size Set from feet to feet

Gravel packed? ☐ Yes ☒ No ☐ Size of gravel

Placed from feet to feet

Surface seal depth 240 Material used in seal: ☑ Cement grout ☐ Puddling clay ☐ Well cuttings

Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☒ Overbore to seal depth

Method of joining casing: ☐ Threaded ☒ Welded ☐ Solvent Weld

☐ Cemented between strata

Describe access port flowing well

6. LOCATION OF WELL

Sketch map location must agree with written location.

N W E S

Subdivision Name

Lot No. Block No.

County Twin Falls

NE ¼ SW ¼ Sec. 4, T. 10 N or S, R. 17 E or W

7. WATER LEVEL

Static water level feet below land surface

Flowing? ☒ Yes ☐ No G.P.M. flow 1100

Artesian closed-in pressure 30 p.s.i.

Controlled by: ☒ Valve ☐ Cap ☐ Plug

Temperature 101 °F. Quality good

8. WELL TEST DATA

☐ Pump ☐ Bailer ☐ Air ☐ Other

Discharge G.P.M.	Pumping Level	Hours Pumped
1100	flow	

9. LITHOLOGIC LOG

Hole Diam.	Depth From	Depth To	Material	Water Yes	Water No
20	0	15	Brown clay		X
	15	22	Clay & broken rock	X	
	22	45	Grey basalt	X	
	45	49	Brown clay		X
	49	63	Grey basalt		X
	63	76	Clay		X
	76	85	Grey basalt		X
	85	98	Clay		X
	98	130	Grey-brown basalt	X	
	130	164	Grey basalt		X
	164	181	Brown basalt		X
	181	218	Grey basalt		X
	218	220	Talc		X
	220	241	Grey basalt		X
	241	378	Brown sandy clay & gravel		X
	378	386	Soft brown conglomerate		X
	386	416	Grey basalt		X
	416	448	Brown clay		X
	448	462	Grey clay		X
	462	499	Brown clay		X
	499	508	Grey clay		X
512	508	535	Grey basalt (hard)		X
16	535	543	Brown clay		X
	543	640	Brown sandy clay		X
	640	668	Grey sandy clay		X
	668	714	Grey sandy clay		X
	714	722	Grey sandy clay		X
	722	748	Grey basalt		X
	748	756	Reddish brown clay		X
	756	778	Grey basalt		X
	778	783	Brown basalt w/[illegible] clay		X
	783	788	Brown clay		X
	788	853	Grey basalt (hard)		X
	853	858	Brown basalt		X
	858	896	Grey basalt		X
	896	912	Grey clay (sticky)		X

10. Work started 22 Apr 1980 finished 22 April 1981

11. DRILLERS CERTIFICATION cb dL

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Boley + Henry Firm No. 86

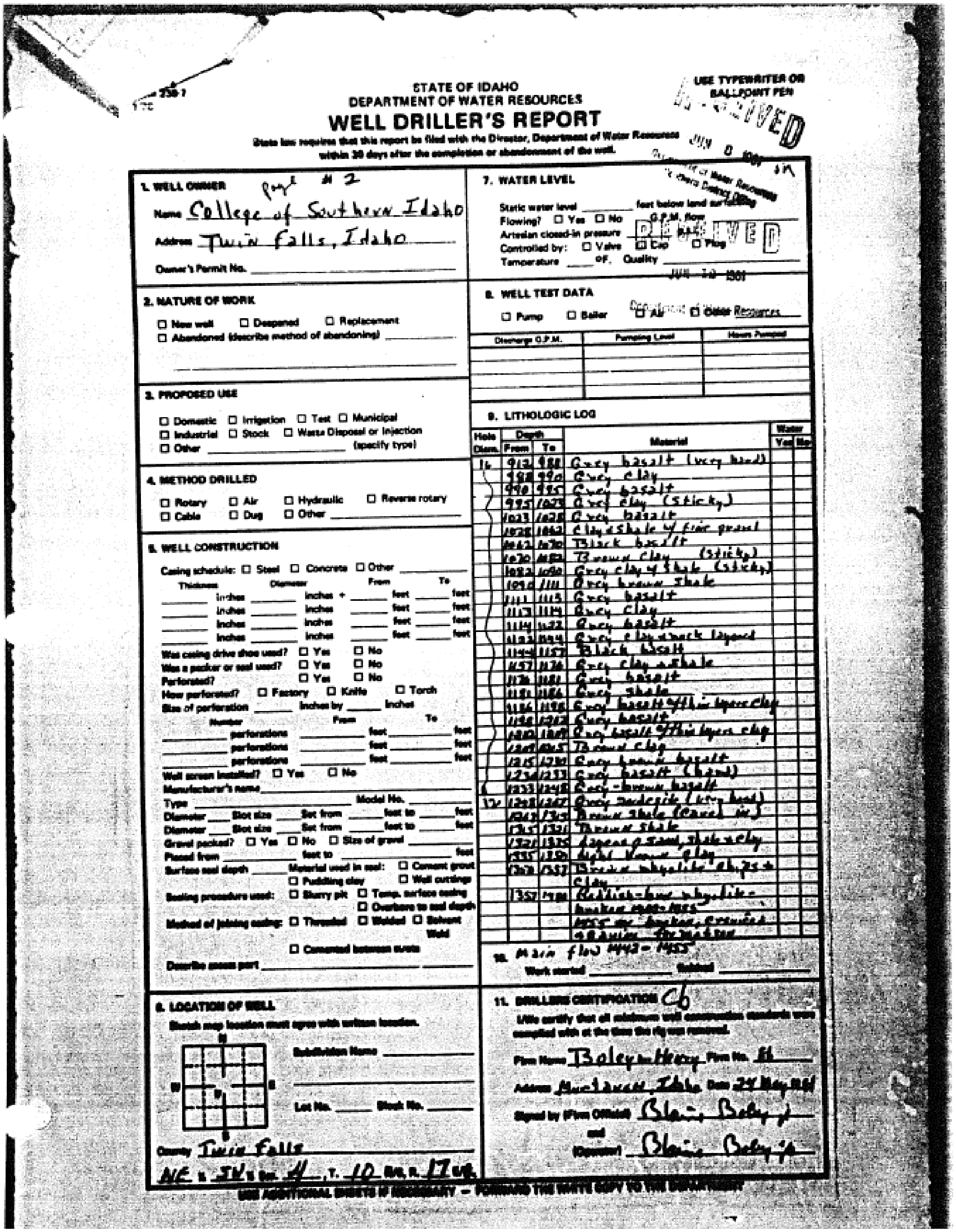
Address Murtaugh, Idaho Date 24 May 1981

Signed by (Firm Official) Blaine Boley

and

(Operator) Blaine Boley

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT



STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

USE TYPEWRITER OR BALLPOINT PEN

RECEIVED JUN 8 1981
Department of Water Resources
Southern District Office

1. WELL OWNER Pg 2 #2

Name College of Southern Idaho

Address Twin Falls, Idaho

Owner's Permit No. ____

2. NATURE OF WORK

☐ New well ☐ Deepened ☐ Replacement
☐ Abandoned (describe method of abandoning) ____

3. PROPOSED USE

☐ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other ____ (specify type)

4. METHOD DRILLED

☐ Rotary ☐ Air ☐ Hydraulic ☐ Reverse rotary
☐ Cable ☐ Dug ☐ Other ____

5. WELL CONSTRUCTION

Casing schedule: ☐ Steel ☐ Concrete ☐ Other ____

Thickness	Diameter	From	To
inches	inches +	feet	feet
inches	inches	feet	feet
inches	inches	feet	feet
inches	inches	feet	feet

Was casing drive shoe used? ☐ Yes ☐ No
Was a packer or seal used? ☐ Yes ☐ No
Perforated? ☐ Yes ☐ No
How perforated? ☐ Factory ☐ Knife ☐ Torch
Size of perforation ____ inches by ____ inches

Number	From	To
perforations	feet	feet
perforations	feet	feet
perforations	feet	feet

Well screen installed? ☐ Yes ☐ No
Manufacturer's name ____
Type ____ Model No. ____
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Gravel packed? ☐ Yes ☐ No ☐ Size of gravel ____
Placed from ____ feet to ____ feet
Surface seal depth ____ Material used in seal: ☐ Cement grout ☐ Puddling clay ☐ Well cuttings
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☐ Overbore to seal depth
Method of joining casing: ☐ Threaded ☐ Welded ☐ Solvent Weld ☐ Cemented between strata
Describe access port ____

6. LOCATION OF WELL

Sketch map location must agree with written location.

N
W E
S

Subdivision Name ____
Lot No. ____ Block No. ____

County Twin Falls

NE ¼ SW ¼ Sec. 14, T. 10 N/S, R. 17 E/W

7. WATER LEVEL

Static water level ____ feet below land surface
Flowing? ☐ Yes ☐ No G.P.M. flow ____
Artesian closed-in pressure ____
Controlled by: ☐ Valve ☒ Cap ☐ Plug
Temperature ____ °F. Quality ____

RECEIVED JUL 10 1981
Department of Water Resources

8. WELL TEST DATA

☐ Pump ☐ Bailer ☐ Air ☐ Other

Discharge G.P.M.	Pumping Level	Hours Pumped

9. LITHOLOGIC LOG

Hole Diam.	Depth From	Depth To	Material	Water Yes	Water No
16	912	988	Grey basalt (very hard)		
	988	990	Grey clay		
	990	995	Grey basalt		
	995	1023	Grey clay (sticky)		
	1023	1028	Grey basalt		
	1028	1062	Clay & shale w/ fine gravel		
	1062	1070	Black basalt		
	1070	1082	Brown clay (sticky)		
	1082	1090	Grey clay & shale (sticky)		
	1090	1111	Grey brown shale		
	1111	1113	Grey basalt		
	1113	1114	Grey clay		
	1114	1122	Grey basalt		
	1122	1144	Grey clay & rock layered		
	1144	1157	Black basalt		
	1157	1176	Grey clay & shale		
	1176	1181	Grey basalt		
	1181	1186	Grey shale		
	1186	1198	Grey basalt w/ thin layers clay		
	1198	1202	Grey basalt		
	1202	1208	Grey basalt w/ thin layers clay		
	1208	1215	Brown clay		
	1215	1230	Grey brown basalt		
	1230	1233	Grey basalt (hard)		
	1233	1248	Grey-brown basalt		
12	1248	1263	Grey andesite (very hard)		
	1263	1305	Brown shale (caved in)		
	1305	1321	Brown shale		
	1321	1335	Layers of sand, shale & clay		
	1335	1350	Light brown clay		
	1350	1357	Brown rhyolite chips &		
			clay		
	1357	1460	Reddish-brown rhyolite -		
			broken 1442-1455		
			1455 on broken, cracked		
			[illegible]		

10. Main flow 1442-1455

Work started ____ finished ____

11. DRILLERS CERTIFICATION Cb

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Boley & Henry Firm No. 86

Address Murtaugh, Idaho Date 24 May 81

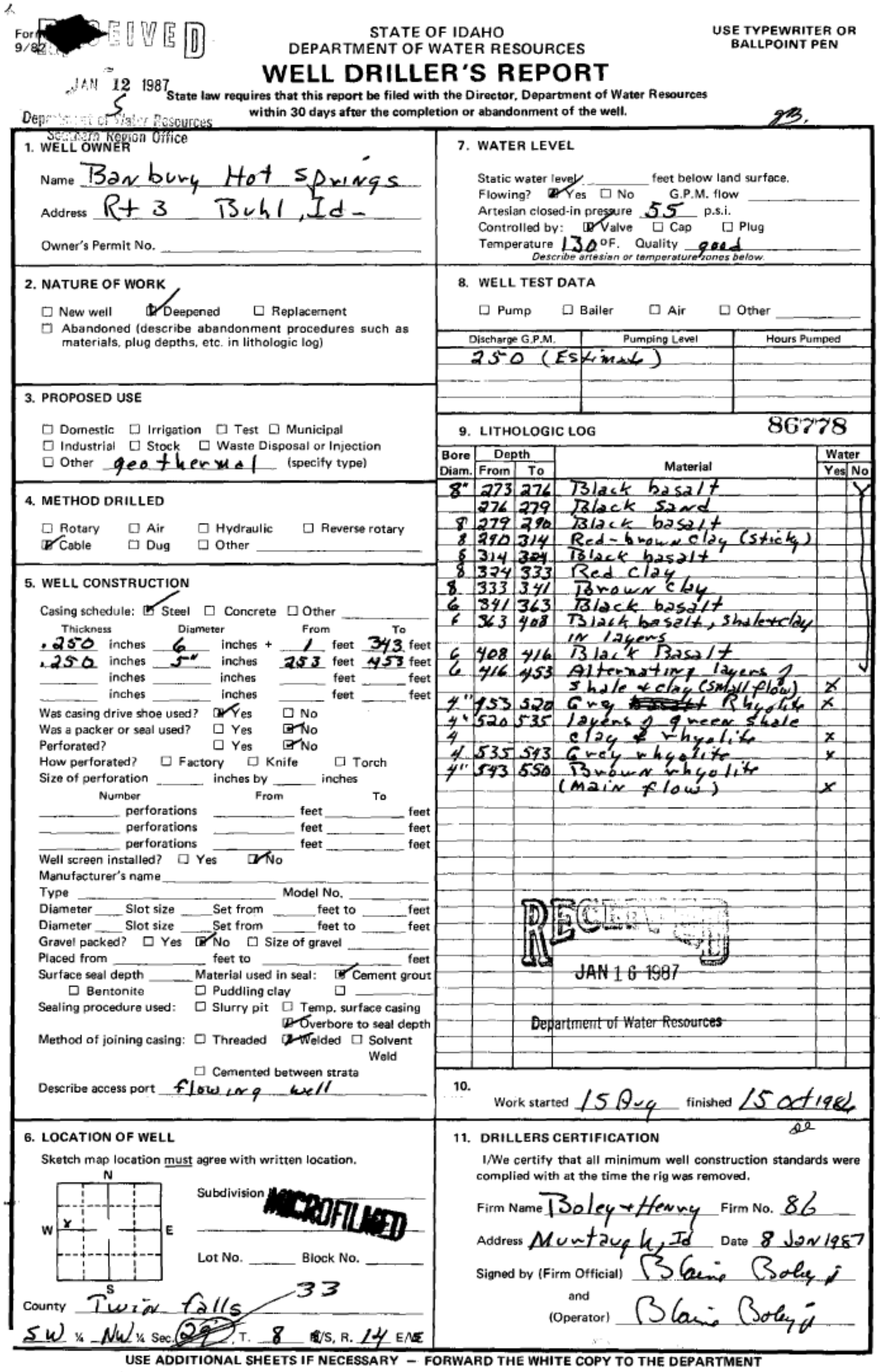
Signed by (Firm Official) Blaine Boley Jr.

and

(Operator) Blaine Boley Jr.

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Figure C2. CSI Well 2 Driller's Log



For[redacted]EIVED
9/8

JAN 12 1987
Department of Water Resources
Southern Region Office

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

USE TYPEWRITER OR BALLPOINT PEN

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

1. WELL OWNER

Name Banbury Hot Springs
Address Rt 3 Buhl, Id.
Owner's Permit No. ____

2. NATURE OF WORK

☐ New well ☑ Deepened ☐ Replacement
☐ Abandoned (describe abandonment procedures such as materials, plug depths, etc. in lithologic log)

3. PROPOSED USE

☐ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other geothermal (specify type)

4. METHOD DRILLED

☐ Rotary ☐ Air ☐ Hydraulic ☐ Reverse rotary
☑ Cable ☐ Dug ☐ Other ____

5. WELL CONSTRUCTION

Casing schedule: ☑ Steel ☐ Concrete ☐ Other ____

Thickness		Diameter		From		To	
.250	inches	6	inches +	1	feet	343	feet
.250	inches	5"	inches	253	feet	453	feet
	inches		inches		feet		feet
	inches		inches		feet		feet

Was casing drive shoe used? ☑ Yes ☐ No
Was a packer or seal used? ☐ Yes ☑ No
Perforated? ☐ Yes ☑ No
How perforated? ☐ Factory ☐ Knife ☐ Torch
Size of perforation ____ inches by ____ inches

Number		From		To	
	perforations		feet		feet
	perforations		feet		feet
	perforations		feet		feet

Well screen installed? ☐ Yes ☑ No
Manufacturer's name ____
Type ____ Model No. ____
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Gravel packed? ☐ Yes ☑ No ☐ Size of gravel ____
Placed from ____ feet to ____ feet
Surface seal depth ____ Material used in seal: ☑ Cement grout ☐ Bentonite ☐ Puddling clay ☐ ____
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☑ Overbore to seal depth
Method of joining casing: ☐ Threaded ☑ Welded ☐ Solvent Weld ☐ Cemented between strata
Describe access port flowing well

6. LOCATION OF WELL

Sketch map location must agree with written location.

N
W x E
S

Subdivision ____
MICROFILMED
Lot No. ____ Block No. ____
County Twin falls
SW ¼ NW ¼ Sec. ~~29~~ 33, T. 8 [✓ N]/S, R. 14 E/[✓ W]

7. WATER LEVEL

Static water level ✓ ____ feet below land surface.
Flowing? ☑ Yes ☐ No G.P.M. flow ____
Artesian closed-in pressure 55 p.s.i.
Controlled by: ☑ Valve ☐ Cap ☐ Plug
Temperature 130 °F. Quality good
Describe artesian or temperature zones below.

8. WELL TEST DATA

☐ Pump ☐ Bailer ☐ Air ☐ Other ____

Discharge G.P.M.	Pumping Level	Hours Pumped
250 (Estimate)		

9. LITHOLOGIC LOG 86778

Bore Diam.	Depth From	Depth To	Material	Water Yes	Water No
8"	273	276	Black basalt		Y
	276	279	Black sand		
8	279	290	Black basalt		
8	290	314	Red-brown clay (sticky)		
8	314	324	Black basalt		
8	324	333	Red clay		
8	333	341	Brown clay		
6	341	363	Black basalt		
6	363	408	Black basalt, shale+clay in layers		
6	408	416	Black Basalt		
6	416	453	Alternating layers of shale + clay (Small flow)	x	
4"	453	520	Grey ~~basalt~~ Rhyolite	x	
4"	520	535	layers of green shale		
4			clay & rhyolite	x	
4	535	543	Grey rhyolite	x	
4"	543	550	Brown rhyolite (Main flow)	x	

RECEIVED
JAN 16 1987
Department of Water Resources

10. Work started 15 Aug finished 15 oct 1986

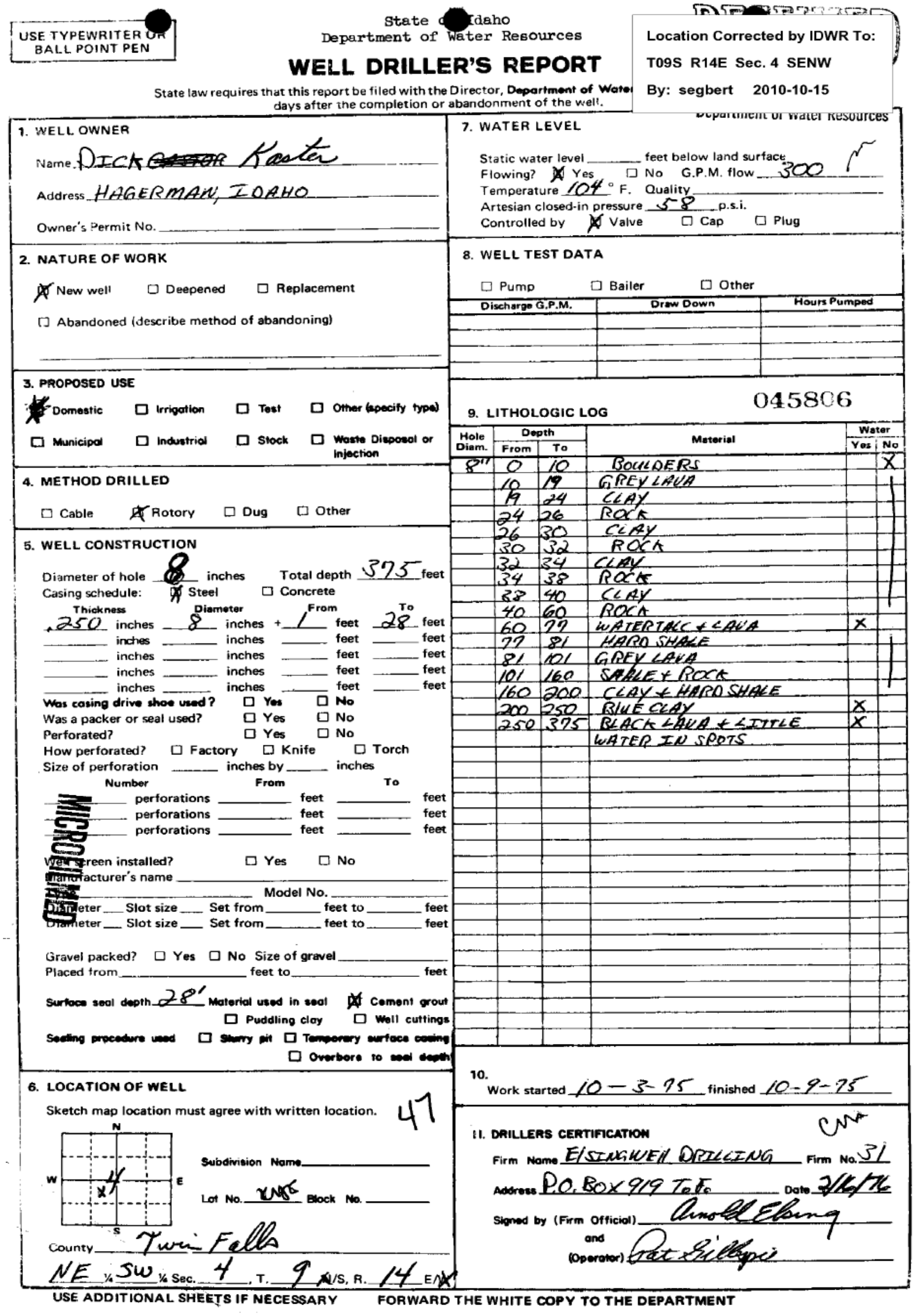
11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Boley + Henry Firm No. 86
Address Murtaugh, Id Date 8 Jan 1987
Signed by (Firm Official) Blaine Boley jr
and
(Operator) Blaine Boley jr

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Figure C3. Banbury Hot Springs Well Driller's Log



USE TYPEWRITER OR BALL POINT PEN

State o[illegible]Idaho
Department of Water Resources

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of Water
days after the completion or abandonment of the well.

Location Corrected by IDWR To:
T09S R14E Sec. 4 SENW
By: segbert 2010-10-15

Department of Water Resources

1. WELL OWNER

Name DICK ~~[illegible]~~ Kaster
Address HAGERMAN, IDAHO
Owner's Permit No.

2. NATURE OF WORK

☒ New well ☐ Deepened ☐ Replacement
☐ Abandoned (describe method of abandoning)

3. PROPOSED USE

☒ Domestic ☐ Irrigation ☐ Test ☐ Other (specify type)
☐ Municipal ☐ Industrial ☐ Stock ☐ Waste Disposal or Injection

4. METHOD DRILLED

☐ Cable ☒ Rotory ☐ Dug ☐ Other

5. WELL CONSTRUCTION

Diameter of hole 8 inches Total depth 375 feet
Casing schedule: ☒ Steel ☐ Concrete

Thickness		Diameter		From		To	
.250	inches	8	inches	+1	feet	28	feet
	inches		inches		feet		feet
	inches		inches		feet		feet
	inches		inches		feet		feet
	inches		inches		feet		feet

Was casing drive shoe used? ☐ Yes ☐ No
Was a packer or seal used? ☐ Yes ☐ No
Perforated? ☐ Yes ☐ No
How perforated? ☐ Factory ☐ Knife ☐ Torch
Size of perforation ______ inches by ______ inches

Number		From		To	
	perforations		feet		feet
	perforations		feet		feet
	perforations		feet		feet

MICROFILMED

Well screen installed? ☐ Yes ☐ No
Manufacturer's name
Type ______ Model No.
Diameter ___ Slot size ___ Set from ______ feet to ______ feet
Diameter ___ Slot size ___ Set from ______ feet to ______ feet

Gravel packed? ☐ Yes ☐ No Size of gravel
Placed from ______ feet to ______ feet

Surface seal depth 28' Material used in seal ☒ Cement grout ☐ Puddling clay ☐ Well cuttings
Sealing procedure used ☐ Slurry pit ☐ Temporary surface casing ☐ Overbore to seal depth

6. LOCATION OF WELL

Sketch map location must agree with written location. 47

N
W 4 x E
S

Subdivision Name
Lot No. [illegible] Block No.
County Twin Falls
NE ¼ SW ¼ Sec. 4, T. 9 N/S, R. 14 E/W

7. WATER LEVEL

Static water level ______ feet below land surface
Flowing? ☒ Yes ☐ No G.P.M. flow 300
Temperature 104 ° F. Quality
Artesian closed-in pressure 58 p.s.i.
Controlled by ☒ Valve ☐ Cap ☐ Plug

8. WELL TEST DATA

☐ Pump ☐ Bailer ☐ Other

Discharge G.P.M.	Draw Down	Hours Pumped

045806

9. LITHOLOGIC LOG

Hole Diam.	Depth From	Depth To	Material	Water Yes	Water No
8"	0	10	BOULDERS		X
	10	19	GREY LAVA		
	19	24	CLAY		
	24	26	ROCK		
	26	30	CLAY		
	30	32	ROCK		
	32	34	CLAY		
	34	38	ROCK		
	38	40	CLAY		
	40	60	ROCK		
	60	77	WATERTALC + LAVA	X	
	77	81	HARD SHALE		
	81	101	GREY LAVA		
	101	160	SHALE + ROCK		
	160	200	CLAY + HARD SHALE		
	200	250	BLUE CLAY	X	
	250	375	BLACK LAVA + LITTLE WATER IN SPOTS	X	

10.

Work started 10-3-75 finished 10-9-75

11. DRILLERS CERTIFICATION CMA

Firm Name ELSINGWEN DRILLING Firm No. 31
Address P.O. BOX 919 T.F. Date 2/16/76
Signed by (Firm Official) Arnold Elsing
and
(Operator) Pat Gillispie

USE ADDITIONAL SHEETS IF NECESSARY FORWARD THE WHITE COPY TO THE DEPARTMENT

Figure C4. Dick Kaster Well 1 Driller's Log

Form 238-7
3/95

MAR 16 1998
Department of Water Resources
Southern Region

IDAHO DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

Use Typewriter or Ballpoint Pen

Office Use Only
Inspected by ______
Twp____ Rge____ Sec ____
____1/4 ____1/4 ____1/4
Lat: : : Long: : :

1. DRILLING PERMIT NO. 47-97-S-0117-000
Other IDWR No. 00002080

2. OWNER:
Name KASTER, EDITH & RICHARD
Address 1224-C E 3675 S
City BUHL State ID Zip 83316

3. LOCATION OF WELL by legal description:

Sketch map location must agree with written location.

	N		
X			

W E S

Twp. 9 North ☐ or South ☒
Rge. 14 East ☒ or West ☐
Sec. 4, ____ 1/4 (10 acres) NW 1/4 (40 acres) NW 1/4 (160 acres)
Gov't Lot ____ County TWIN FALLS
Lat: : : Long: : :
Address of Well Site ______
______ City ______
(Give at least name of road + Distance to Road or Landmark)

Lt. 3 Blk. 2 Sub. Name OREGON TRAIL SUBD.

4. USE:
☒ Domestic ☐ Municipal ☐ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other ______

5. TYPE OF WORK check all that apply (Replacement etc.)
☒ New Well ☐ Modify ☐ Abandonment ☐ Other ______

6. DRILL METHOD
☒ Air Rotary ☐ Cable ☐ Mud Rotary ☐ Other ______

7. SEALING PROCEDURES

SEAL/FILTER PACK			AMOUNT	METHOD
Material	From	To	Sacks or Pounds	
CEMENT	-5	140	75 SACKS	PRESSURE GROUT
CEMENT	0	304	190 SACK	PRESSURE GROUT

Was drive shoe used? ☐ Y ☐ N Shoe Depth(s) ______
Was drive shoe seal tested? ☐ Y ☐ N How? ______

8. CASING/LINER:

Diameter	From	To	Gauge	Material	Casing	Liner	Welded	Threaded
10.75	-.5	139	.250	STEEL	☒	☐	☒	☐
6.625	+1	304	.250	STEEL	☒	☐	☒	☐
					☐	☐	☐	☐

Length of Headpipe ______ Length of Tailpipe ______

9. PERFORATIONS/SCREENS
☐ Perforations Method ______
☐ Screens Screen Type ______

From	To	Slot Size	Number	Diameter	Material	Casing	Liner
						☐	☐
						☐	☐
						☐	☐

10. STATIC WATER LEVEL OR ARTESIAN PRESSURE:
______ ft. below ground Artesian pressure 36 lb.
Depth flow encountered ______ ft. Describe access port or control devices: ______

11. WELL TESTS:
☐ Pump ☐ Bailer ☐ Air ☒ Flowing Artesian

Yield gal./min.	Drawdown	Pumping Level	Time
25			

Water Temp. 104 Bottom hole temp. ______
Water Quality test or comments: ______
______ Depth first Water Encountered ______

12. LITHOLOGIC LOG: (Describe repairs or abandonment)

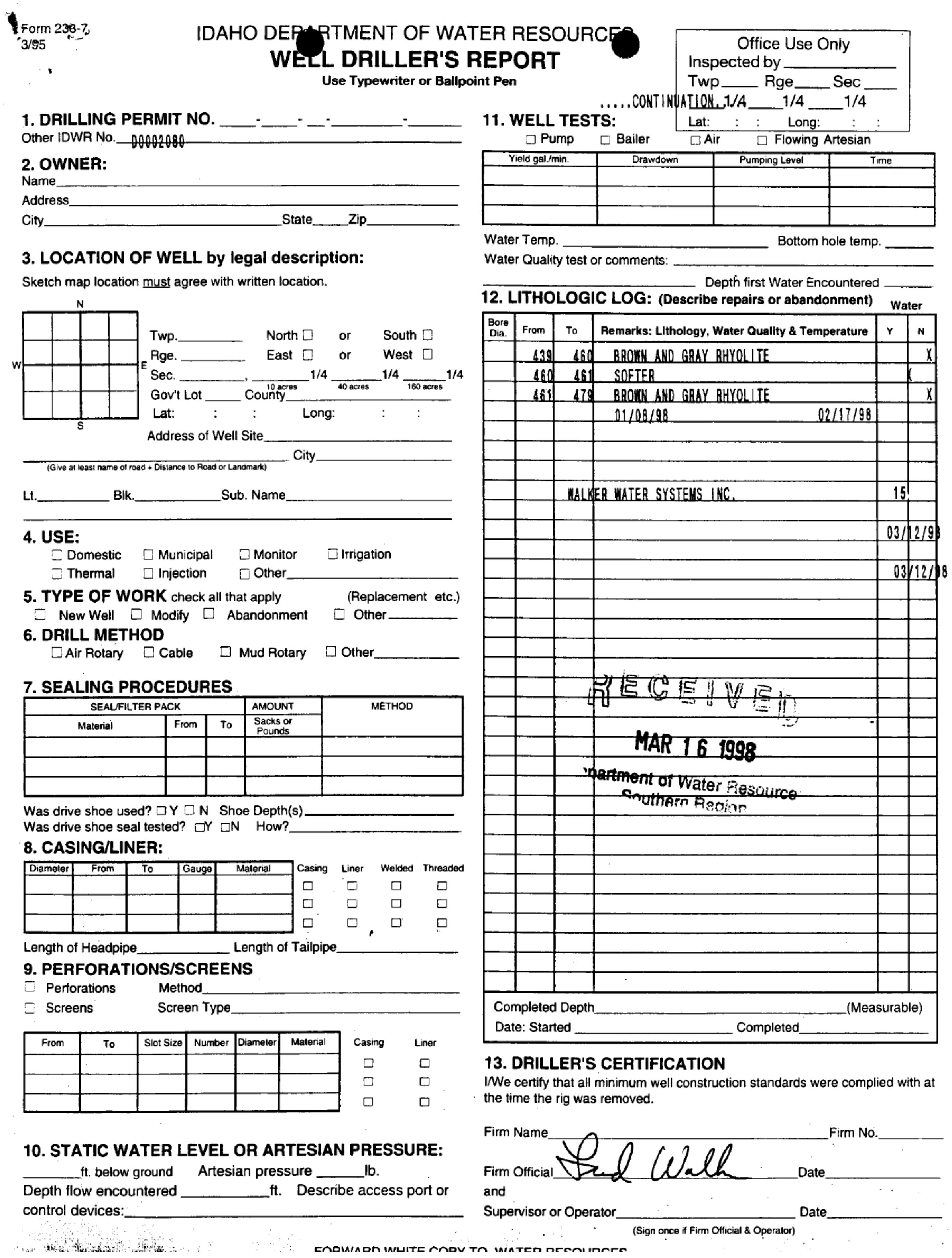
Bore Dia.	From	To	Remarks: Lithology, Water Quality & Temperature	Water Y	Water N
12	250	3	SANDY TOPSOIL		X
	3	51	SAND		X
	51	54	SAND & GRAVEL		X
	54	65	SAND		X
	65	69	BOULDERS		X
	69	85	SAND		X
	85	87	SAND & GRAVEL		X
	87	102	SAND		X
	102	112	SAND & GRAVEL		X
	112	117	BOULDERS		X
	117	120	GRAVEL	X	
	120	140	GREY BASALT SHALE		X
10	140	167	GREY BASALT SHALE		X
	167	170	BROWN GREY BASALT		X
	170	177	GREY BASALT SHALE		X
	177	208	HARD GREY BASALT		X
	208	210	SOFTER		X
	210	215	GREY SHALE	X	
	215	240	GREY BLACK BASALT		X
	240	247	SOFTER BLACK BASALT		X
	247	278	BLACK BASALT		X
	278	282	SOFT BLACK BASALT	X	
	282	309	HARD BROWN AND GRAY RHYOLITE		X
6	309	323	HARD BROWN AND GRAY RHYOLITE		X
	323	324	FRACTURED	X	
	324	346	HARD BROWN AND GRAY RHYOLITE	X	
	346	366	HARD BROWN AND GRAY RHYOLITE		X
	366	369	FRACTURED GREY CLAY		X
	369	420	HARD BROWN AND GRAY RHYOLITE		X
	420	423	SOFT SOFT CLAY	X	
	423	438	BROWN AND GRAY RHYOLITE		X
	438	439	SOFT		X
			TO BE CONTINUED ON NEXT PAGE		

Completed Depth 479' (Measurable)
Date: Started 01/08/98 Completed 02/17/98

13. DRILLER'S CERTIFICATION
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name WALKER WATER SYSTEMS INC. Firm No. 15
Firm Official Fred Walker Date 03/12/98
and
Supervisor or Operator ______ Date 03/12/98
(Sign once if Firm Official & Operator)

FORWARD WHITE COPY TO WATER RESOURCES



Form 238-7
3/95

IDAHO DEPARTMENT OF WATER RESOURCES
WELL DRILLER'S REPORT
Use Typewriter or Ballpoint Pen

Office Use Only
Inspected by ______
Twp____ Rge____ Sec____
.....CONTINUATION. 1/4____1/4____1/4
Lat: : : Long: : :

1. DRILLING PERMIT NO. ____-____-__-________-______
Other IDWR No. D0002080

2. OWNER:
Name______
Address______
City______ State____ Zip______

3. LOCATION OF WELL by legal description:
Sketch map location must agree with written location.

Twp.______ North ☐ or South ☐
Rge.______ East ☐ or West ☐
Sec.______, ______1/4 (10 acres) ______1/4 (40 acres) ______1/4 (160 acres)
Gov't Lot ____ County______
Lat: : : Long: : :
Address of Well Site______
______ City______
(Give at least name of road + Distance to Road or Landmark)
Lt.______ Blk.______ Sub. Name______

4. USE:
☐ Domestic ☐ Municipal ☐ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other______

5. TYPE OF WORK check all that apply (Replacement etc.)
☐ New Well ☐ Modify ☐ Abandonment ☐ Other______

6. DRILL METHOD
☐ Air Rotary ☐ Cable ☐ Mud Rotary ☐ Other______

7. SEALING PROCEDURES

SEAL/FILTER PACK			AMOUNT	METHOD
Material	From	To	Sacks or Pounds	

Was drive shoe used? ☐Y ☐N Shoe Depth(s)______
Was drive shoe seal tested? ☐Y ☐N How?______

8. CASING/LINER:

Diameter	From	To	Gauge	Material	Casing	Liner	Welded	Threaded
					☐	☐	☐	☐
					☐	☐	☐	☐
					☐	☐	☐	☐

Length of Headpipe______ Length of Tailpipe______

9. PERFORATIONS/SCREENS
☐ Perforations Method______
☐ Screens Screen Type______

From	To	Slot Size	Number	Diameter	Material	Casing	Liner
						☐	☐
						☐	☐
						☐	☐

10. STATIC WATER LEVEL OR ARTESIAN PRESSURE:
______ft. below ground Artesian pressure ______lb.
Depth flow encountered ______ft. Describe access port or control devices:______

11. WELL TESTS:
☐ Pump ☐ Bailer ☐ Air ☐ Flowing Artesian

Yield gal./min.	Drawdown	Pumping Level	Time

Water Temp.______ Bottom hole temp.______
Water Quality test or comments:______
______ Depth first Water Encountered______

12. LITHOLOGIC LOG: (Describe repairs or abandonment)

Bore Dia.	From	To	Remarks: Lithology, Water Quality & Temperature	Water Y	Water N
	439	460	BROWN AND GRAY RHYOLITE		X
	460	461	SOFTER		X
	461	479	BROWN AND GRAY RHYOLITE		X
			01/08/98 02/17/98		
		WALKER	WATER SYSTEMS INC.	15	
				03/12/98	
				03/12/98	

RECEIVED
MAR 16 1998
Department of Water Resources
Southern Region

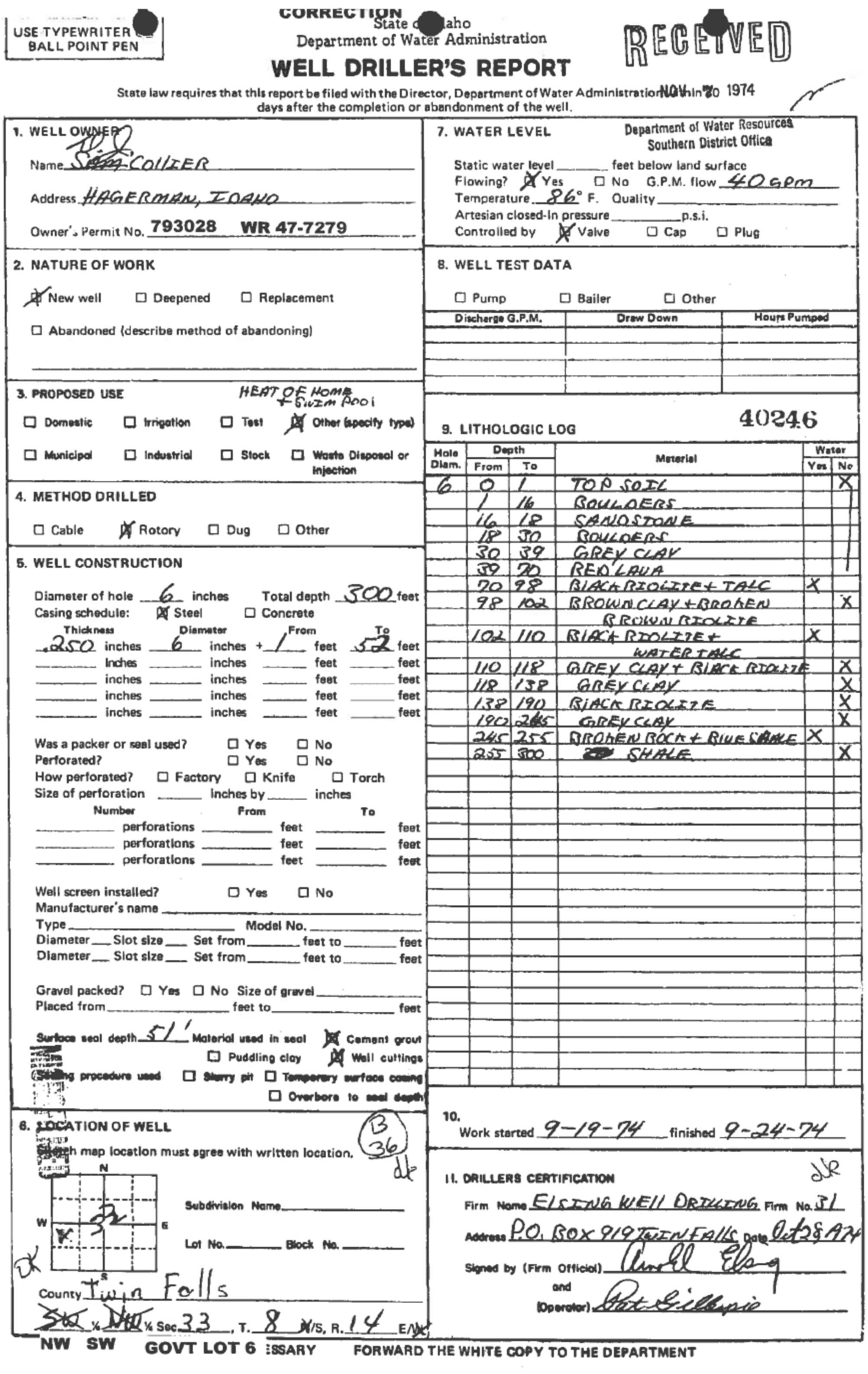
Completed Depth______(Measurable)
Date: Started______ Completed______

13. DRILLER'S CERTIFICATION
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name______ Firm No.______
Firm Official______ Date______
and
Supervisor or Operator______ Date______
(Sign once if Firm Official & Operator)

FORWARD WHITE COPY TO WATER RESOURCES

Figure C5. Dick Kaster Well 2 Driller's Log



USE TYPEWRITER OR
BALL POINT PEN

CORRECTION

State of Idaho
Department of Water Administration

WELL DRILLER'S REPORT

RECEIVED
NOV 20 1974
Department of Water Resources
Southern District Office

State law requires that this report be filed with the Director, Department of Water Administration within 30 days after the completion or abandonment of the well.

1. WELL OWNER

Name ~~Sam~~ D.J. COLLIER

Address HAGERMAN, IDAHO

Owner's Permit No. 793028 WR 47-7279

2. NATURE OF WORK

☒ New well ☐ Deepened ☐ Replacement

☐ Abandoned (describe method of abandoning)

3. PROPOSED USE HEAT OF HOME + SWIM POOL

☐ Domestic ☐ Irrigation ☐ Test ☒ Other (specify type)

☐ Municipal ☐ Industrial ☐ Stock ☐ Waste Disposal or Injection

4. METHOD DRILLED

☐ Cable ☒ Rotary ☐ Dug ☐ Other

5. WELL CONSTRUCTION

Diameter of hole 6 inches Total depth 300 feet

Casing schedule: ☒ Steel ☐ Concrete

Thickness	Diameter	From	To
.250 inches	6 inches	+1 feet	52 feet
inches	inches	feet	feet
inches	inches	feet	feet
inches	inches	feet	feet
inches	inches	feet	feet

Was a packer or seal used? ☐ Yes ☐ No

Perforated? ☐ Yes ☐ No

How perforated? ☐ Factory ☐ Knife ☐ Torch

Size of perforation ______ inches by ______ inches

Number		From	To
	perforations	feet	feet
	perforations	feet	feet
	perforations	feet	feet

Well screen installed? ☐ Yes ☐ No

Manufacturer's name ______

Type ______ Model No. ______

Diameter ___ Slot size ___ Set from ______ feet to ______ feet

Diameter ___ Slot size ___ Set from ______ feet to ______ feet

Gravel packed? ☐ Yes ☐ No Size of gravel ______

Placed from ______ feet to ______ feet

Surface seal depth 51' Material used in seal ☒ Cement grout ☐ Puddling clay ☒ Well cuttings

Sealing procedure used ☐ Slurry pit ☐ Temporary surface casing ☐ Overbore to seal depth

6. LOCATION OF WELL B 36 dk

Sketch map location must agree with written location.

N / W / E / S 32

Subdivision Name ______

Lot No. ______ Block No. ______

County Twin Falls

~~SW~~ ¼ ~~NW~~ ¼ Sec. 33, T. 8 ~~N~~/S, R. 14 E/~~W~~

NW SW GOVT LOT 6 SSARY

7. WATER LEVEL

Static water level ______ feet below land surface

Flowing? ☒ Yes ☐ No G.P.M. flow 40 GPM

Temperature 86° F. Quality ______

Artesian closed-in pressure ______ p.s.i.

Controlled by ☒ Valve ☐ Cap ☐ Plug

8. WELL TEST DATA

☐ Pump ☐ Bailer ☐ Other

Discharge G.P.M.	Draw Down	Hours Pumped

9. LITHOLOGIC LOG 40246

Hole Diam.	Depth From	Depth To	Material	Water Yes	Water No
6	0	1	TOP SOIL		X
	1	16	BOULDERS		
	16	18	SANDSTONE		
	18	30	BOULDERS		
	30	39	GREY CLAY		
	39	70	RED LAVA		
	70	98	BLACK RIOLITE + TALC	X	
	98	102	BROWN CLAY + BROKEN BROWN RIOLITE		X
	102	110	BLACK RIOLITE + WATER TALC	X	
	110	118	GREY CLAY + BLACK RIOLITE		X
	118	138	GREY CLAY		X
	138	190	BLACK RIOLITE		X
	190	245	GREY CLAY		X
	245	255	BROKEN ROCK + BLUE SHALE	X	
	255	300	SHALE		X

10. Work started 9-19-74 finished 9-24-74

11. DRILLERS CERTIFICATION dk

Firm Name EISING WELL DRILLING Firm No. 31

Address P.O. BOX 919 TWIN FALLS Date Oct 28 A74

Signed by (Firm Official) Arnold Eising

and

(Operator) Pat Gillespie

FORWARD THE WHITE COPY TO THE DEPARTMENT

Figure C6. Sam Collier Well Driller's Log

Well Log Form 1
9/59. - 3-M

069569

RECEIVED
AUG 23 1960
Department of Reclamation

WELL LOG AND REPORT OF THE STATE RECLAMATION ENGINEER OF IDAHO

Permit No.____ Well No.____ County Twin Falls

Owner City of Twin Falls

Address Twin Falls, Idaho

Driller Boley, Henry, Weech & Mack Gray

Address Murtaugh & Kimberly, Idaho

SW SW NW 10 10S17E [illegible] 17

Well location Lynwood Addition, City of Twin Falls E/W

Size of drilled hole 20" to 12"

Total depth of well 1530 ft.

Locate well in section

NW¼	NE¼
SW¼	SE¼

Give depth to standing water from the ground flowing Water temp. 87 °Fahr.

On "Pumping Test" delivery was 1000 g.p.m. or 2 c.f.s. Drawdown was 450 feet.

Size of pump and motor used to make test 10" pump, 300 H.P. Diesel, 500 ft. setting.

Length of time of test 15 hours____ minutes.

If flowing well, give flow____ c.f.s. or 120 g.p.m. and of shut off pressure no

If flowing well, described control works none
(TYPE AND SIZE OF VALVE, ETC.)

Water will be used for Municipal Weight of casing per lineal foot____

Thickness of casing ½" Casing material steel
(STEEL, CONCRETE, WOOD, ETC.)

Diameter, length and location of casing 47 ft of 22" OD & 514 ft of 16" OD. Cemented in at bottom.
(CASING 12" IN DIAMETER OR LESS, GIVE INSIDE DIAMETER; CASING OVER 12" IN DIAMETER, GIVE OUTSIDE DIAMETER)

CASING RECORD

Diam. Casing	From Feet	To Feet	Length	Remarks—seals, grouting, etc.
22"	0	47'	47'	Cemented
16"	0	514'	514'	12' of cement grout around the bottom.

Number and size of perforations none located____ feet to____ feet from ground

Date of commencement of well 5/4/1959 Date of completion of well 8/1/1960

10S17E 10 SW SW NW

4-16-70

WELL LOG

From Feet	To Feet	Type of Material	Water-bearing Formation Ans. Yes or No	Casing Perforated Ans. Yes or No
		If more space is required use Sheet No. 2		

WELL DRILLER'S STATEMENT

This well was drilled under my supervision and the above information is true and correct to the best of my knowledge and belief.

Signed Mack Gray

By

License No. 150

Dated 8/14/60, 19

Well Log Form 1
4/59 1 M

069570

SHEET NO. 2

Well Owner

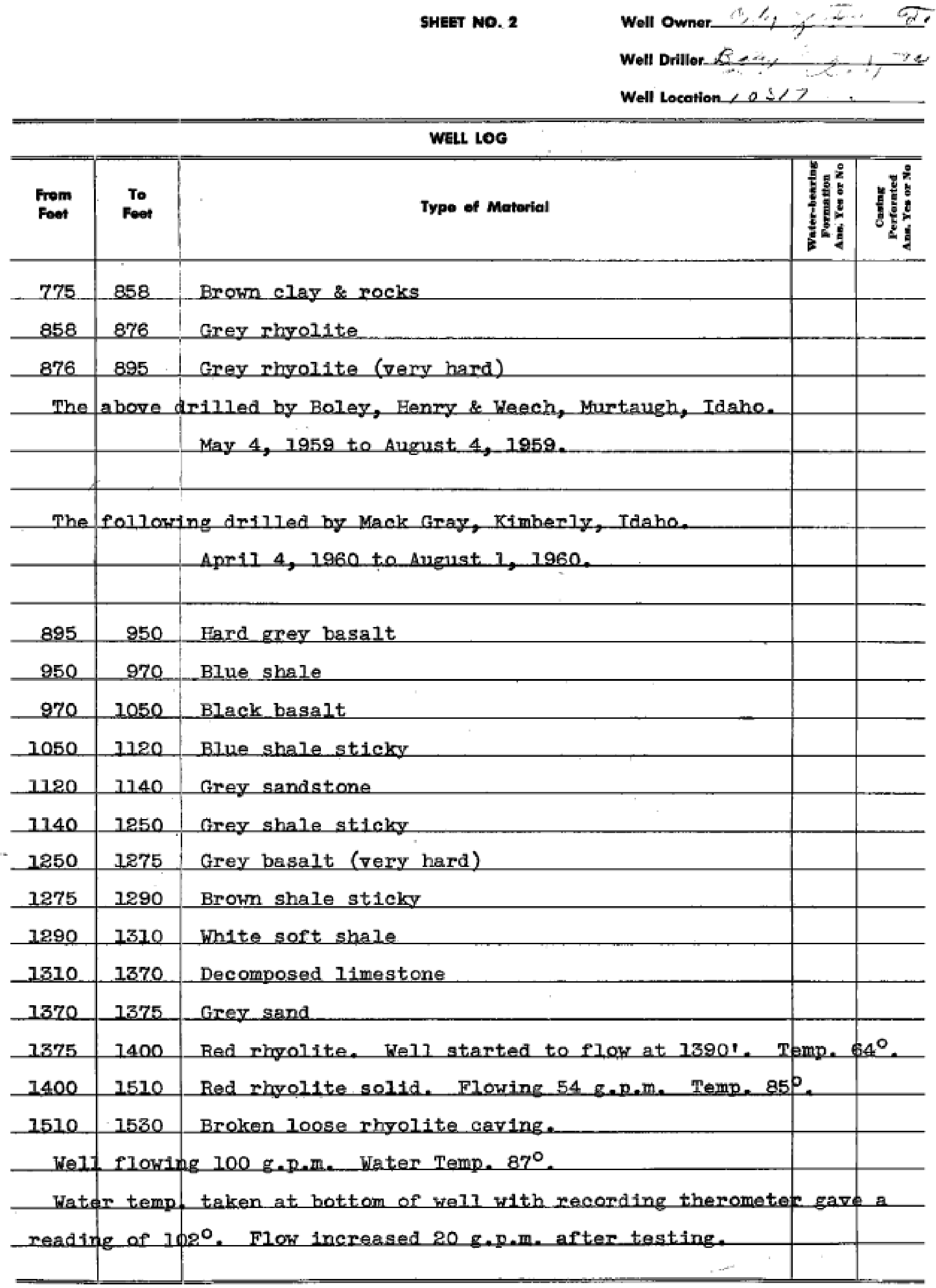
Well Driller

Well Location

WELL LOG

From Feet	To Feet	Type of Material	Water-bearing Formation Ans. Yes or No	Casing Perforated Ans. Yes or No
0	9	Dirt and rock		
9	22	Grey lava		
22	31	Black lava		
31	56	Grey lava		
56	73	Brown clay & rocks		
73	86	Black lava		
86	93	Grey lava		
93	102	Brown clay		
102	113	Grey lava broken		
113	118	Clay		
118	140	Grey lava		
140	153	Brown lava		
153	174	Grey lava		
174	218	Brown lava		
218	258	Grey lava		
258	300	Clay & fine gravel		
300	375	Brown clay		
375	418	Grey clay		
418	458	Tan clay		
458	483	Grey clay & gravel		
483	487	Clay & rhyolite		
487	503	Brown clay		
503	579	Black rhyolite		
579	730	Grey rhyolite		
730	746	Black rhyolite		
746	758	Black rhyolite & clay		
758	775	Grey rhyolite (very hard)		

10S 17E



SHEET NO. 2

Well Owner [illegible]
Well Driller [illegible]
Well Location 10S17

WELL LOG

From Foot	To Foot	Type of Material	Water-bearing Formation Ans. Yes or No	Casing Perforated Ans. Yes or No
775	858	Brown clay & rocks		
858	876	Grey rhyolite		
876	895	Grey rhyolite (very hard)		
The above drilled by Boley, Henry & Weech, Murtaugh, Idaho.				
		May 4, 1959 to August 4, 1959.		
The following drilled by Mack Gray, Kimberly, Idaho.				
		April 4, 1960 to August 1, 1960.		
895	950	Hard grey basalt		
950	970	Blue shale		
970	1050	Black basalt		
1050	1120	Blue shale sticky		
1120	1140	Grey sandstone		
1140	1250	Grey shale sticky		
1250	1275	Grey basalt (very hard)		
1275	1290	Brown shale sticky		
1290	1310	White soft shale		
1310	1370	Decomposed limestone		
1370	1375	Grey sand		
1375	1400	Red rhyolite. Well started to flow at 1390'. Temp. 64°.		
1400	1510	Red rhyolite solid. Flowing 54 g.p.m. Temp. 85°.		
1510	1530	Broken loose rhyolite caving.		
Well flowing 100 g.p.m. Water Temp. 87°.				
Water temp. taken at bottom of well with recording therometer gave a reading of 102°. Flow increased 20 g.p.m. after testing.				

Figure C7. City of Twin Falls Well Driller's Log

Form 238-7
9/82

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

USE TYPEWRITER OR BALLPOINT PEN

WELL DRILLER'S REPORT

5

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

1. WELL OWNER

Name **Twin Falls School District No. 411**
Address **201 Main Avenue West**
Twin Falls, Idaho 83301
Owner's Permit No. 47-7964

2. NATURE OF WORK

☒ New well ☐ Deepened ☐ Replacement
☐ Abandoned (describe abandonment procedures such as materials, plug depths, etc. in lithologic log)

3. PROPOSED USE

☐ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other **Heating** (specify type)

4. METHOD DRILLED

☒ Rotary ☒ Air ☐ Hydraulic ☐ Reverse rotary
☐ Cable ☐ Dug ☐ Other

5. WELL CONSTRUCTION

Casing schedule: ☒ Steel ☐ Concrete ☐ Other

Thickness		Diameter		From		To	
16	inches	.250	inches +	1	feet	23	feet
.250	inches	12	inches	2	feet	900	feet
	inches		inches		feet		feet
	inches		inches		feet		feet

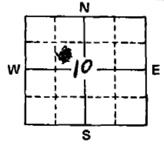
Was casing drive shoe used? ☒ Yes ☐ No
Was a packer or seal used? ☐ Yes ☐ No
Perforated? ☐ Yes ☐ No
How perforated? ☐ Factory ☐ Knife ☐ Torch
Size of perforation ______ inches by ______ inches

Number		From		To	
	perforations		feet		feet
	perforations		feet		feet
	perforations		feet		feet

Well screen installed? ☐ Yes ☒ No
Manufacturer's name
Type ______ Model No.
Diameter ____ Slot size ____ Set from ______ feet to ______ feet
Diameter ____ Slot size ____ Set from ______ feet to ______ feet
Gravel packed? ☐ Yes ☐ No ☐ Size of gravel
Placed from ______ feet to ______ feet
Surface seal depth **900** Material used in seal: ☒ Cement grout ☐ Bentonite ☐ Puddling clay ☐
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☒ Overbore to seal depth
Method of joining casing: ☐ Threaded ☒ Welded ☐ Solvent Weld
☒ Cemented between strata
Describe access port **Valve**

6. LOCATION OF WELL

Sketch map location must agree with written location.



Subdivision Name
Lot No. ______ Block No. ______
County **Twin Falls**
SE ¼ NW ¼ Sec. 10, T. **10** N [✓ S] R. **17** [✓ E] W.

7. WATER LEVEL

Static water level **0** feet below land surface.
Flowing? ☒ Yes ☐ No G.P.M. flow **15 gpm**
Artesian closed-in pressure **0** p.s.i.
Controlled by: ☒ Valve ☒ Cap ☐ Plug
Temperature **96**°F. Quality
Describe artesian or temperature zones below.

8. WELL TEST DATA

☒ Pump ☐ Bailer ☐ Air ☐ Other

Discharge G.P.M.	Pumping Level	Hours Pumped

9. LITHOLOGIC LOG

Pg 1 of 2

052988

Bore Diam.	Depth From	Depth To	Material	Water Yes	Water No
	0	12	Top Soil		
	12	48	Gray Lava		
	48	53	Lava Ash		
	53	130	Gray Lava		
	130	137	Red Lava		
	137	165	Brown Lava		
	165	170	Red Lava		
	170	238	Gray Lava		
	238	258	Brown Lava		
	258	263	Brown Lava		
	263	274	Brown Rhyolite		
	274	315	Gray Rhyolite		
	315	438	Gray Rhyolite		
	438	458	Softer Gr. Rhyolite More Water		
	458	471	Red & Gray Broken Rhy.-Water		
	471	518	" " " Lots of water		
	518	528	Brown Rhyolite		
	528	531	Broken Gray Rhy. Water		
	531	557	Hard Gray Rhyolite		
	557	583	Broken Softer Red Rhyolite		
	583	587	Solid Gray Rhyolite		
	587	606	Very Hard Gray Rhyolite		
	606	612	Brown Broken Rhy. - water		
	612	625	Solid Gray Rhyolite		
	625	638	Broken Gray Rhy. More Water		
	638	698	Hard Gray Rhyolite		
	698	714	Gray Shale Some Black Rock More Water		
	714	797	Black Rhy. Broken - Water		
	797	803	Broken Brown Rock		
	803	809	Brown Clay		
	809	842	Green Clay & Shale		
	842	870	Broken Black Rock		
	870	879	Soft Red Rhyolite		
	879	910	Medium Black Rock		
	910	926	Hard Black Rock		

RECEIVED
JAN 11 1985
Department of Water Resources

MICROFILMED

10.

(See Page 2)

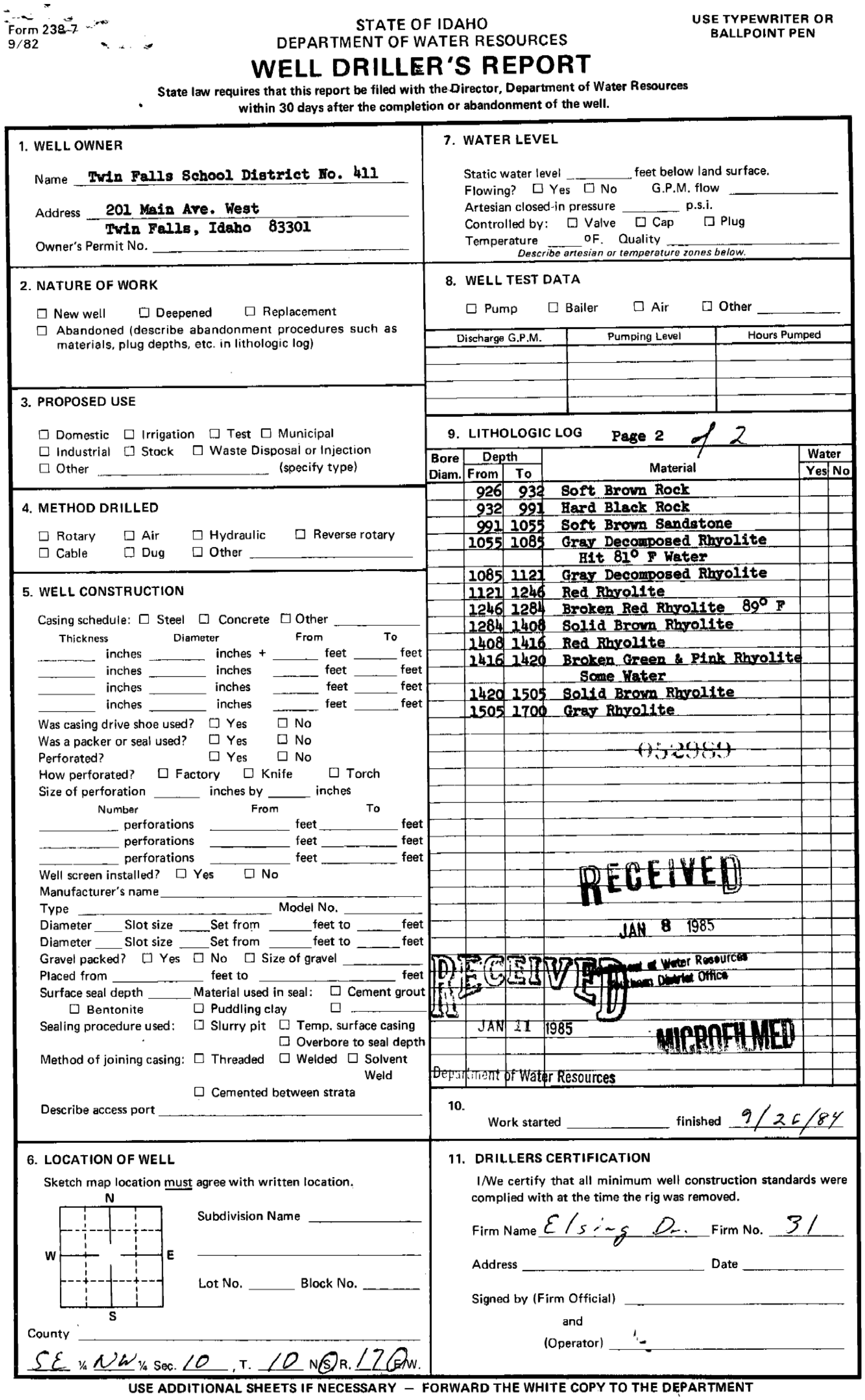
Work started **Aug. 15, 1984** finished **Sept. [illegible], 1984**

11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name **Elsing Drilling** Firm No. **31**
Address **Box 919**
Twin Falls, ID Date **Nov. 6, 1984**
Signed by (Firm Official) Arnold Elsing
and
(Operator) Loyd Kaylor

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT



Form 238-7
9/82

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

USE TYPEWRITER OR
BALLPOINT PEN

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

1. WELL OWNER

Name Twin Falls School District No. 411
Address 201 Main Ave. West
Twin Falls, Idaho 83301
Owner's Permit No. ____

2. NATURE OF WORK

☐ New well ☐ Deepened ☐ Replacement
☐ Abandoned (describe abandonment procedures such as materials, plug depths, etc. in lithologic log)

3. PROPOSED USE

☐ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other ____ (specify type)

4. METHOD DRILLED

☐ Rotary ☐ Air ☐ Hydraulic ☐ Reverse rotary
☐ Cable ☐ Dug ☐ Other ____

5. WELL CONSTRUCTION

Casing schedule: ☐ Steel ☐ Concrete ☐ Other ____

Thickness		Diameter		From		To	
____	inches	____	inches +	____	feet	____	feet
____	inches	____	inches	____	feet	____	feet
____	inches	____	inches	____	feet	____	feet
____	inches	____	inches	____	feet	____	feet

Was casing drive shoe used? ☐ Yes ☐ No
Was a packer or seal used? ☐ Yes ☐ No
Perforated? ☐ Yes ☐ No
How perforated? ☐ Factory ☐ Knife ☐ Torch
Size of perforation ____ inches by ____ inches

Number		From		To	
____	perforations	____	feet	____	feet
____	perforations	____	feet	____	feet
____	perforations	____	feet	____	feet

Well screen installed? ☐ Yes ☐ No
Manufacturer's name ____
Type ____ Model No. ____
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Gravel packed? ☐ Yes ☐ No ☐ Size of gravel ____
Placed from ____ feet to ____ feet
Surface seal depth ____ Material used in seal: ☐ Cement grout ☐ Bentonite ☐ Puddling clay ☐ ____
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☐ Overbore to seal depth
Method of joining casing: ☐ Threaded ☐ Welded ☐ Solvent Weld ☐ Cemented between strata
Describe access port ____

6. LOCATION OF WELL

Sketch map location must agree with written location.

N W E S

Subdivision Name ____
Lot No. ____ Block No. ____
County ____
SE ¼ NW ¼ Sec. 10, T. 10 N/S R. 17 E/W.

7. WATER LEVEL

Static water level ____ feet below land surface.
Flowing? ☐ Yes ☐ No G.P.M. flow ____
Artesian closed-in pressure ____ p.s.i.
Controlled by: ☐ Valve ☐ Cap ☐ Plug
Temperature ____ °F. Quality ____
Describe artesian or temperature zones below.

8. WELL TEST DATA

☐ Pump ☐ Bailer ☐ Air ☐ Other ____

Discharge G.P.M.	Pumping Level	Hours Pumped

9. LITHOLOGIC LOG Page 2 of 2

Bore Diam.	Depth From	Depth To	Material	Water Yes	Water No
	926	932	Soft Brown Rock		
	932	991	Hard Black Rock		
	991	1055	Soft Brown Sandstone		
	1055	1085	Gray Decomposed Rhyolite		
			Hit 81° F Water		
	1085	1121	Gray Decomposed Rhyolite		
	1121	1246	Red Rhyolite		
	1246	1284	Broken Red Rhyolite 89° F		
	1284	1408	Solid Brown Rhyolite		
	1408	1416	Red Rhyolite		
	1416	1420	Broken Green & Pink Rhyolite		
			Some Water		
	1420	1505	Solid Brown Rhyolite		
	1505	1700	Gray Rhyolite		

052989

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Department of Water Resources
Southern District Office

RECEIVED
JAN 11 1985
Department of Water Resources

MICROFILMED

10. Work started ____ finished 9/26/84

11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Elsing Dr. Firm No. 31
Address ____ Date ____
Signed by (Firm Official) ____
and
(Operator) ____

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Figure C8. Twin Falls High School Well Driller's Log

Form 238-7
1/78

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Department of Water Resources

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

USE TYPEWRITER OR BALLPOINT PEN

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JUL 28 1983
Department of Water Resources
Southern District Office

120

1. WELL OWNER

Name Mike Archibald

Address Rt. 3 Buhl,Idaho

Owner's Permit No. 47-7577

2. NATURE OF WORK

☒ New well ☐ Deepened ☐ Replacement

☐ Abandoned (describe method of abandoning) ______

3. PROPOSED USE

☐ Domestic ☐ Irrigation ☐ Test ☐ Municipal

☐ Industrial ☐ Stock ☐ Waste Disposal or Injection

☒ Other Geothermal (specify type)

4. METHOD DRILLED

☐ Rotary ☐ Air ☐ Hydraulic ☐ Reverse rotary

☒ Cable ☐ Dug ☐ Other ______

5. WELL CONSTRUCTION

Casing schedule: ☒ Steel ☐ Concrete ☐ Other ______

Thickness		Diameter		From		To	
.250	inches	12	inches +	1	feet	119	feet
.250	inches	8	inches	1½	feet	278	feet
.188	inches	6	inches	185	feet	470	feet
	inches		inches		feet		feet

on liner top

Was casing drive shoe used? ☒ Yes ☐ No

Was a packer or seal used? ☐ Yes ☒ No

Perforated? ☐ Yes ☒ No

How perforated? ☐ Factory ☐ Knife ☐ Torch

Size of perforation ______ inches by ______ inches

Number		From		To	
	perforations		feet		feet
	perforations		feet		feet
	perforations		feet		feet

Well screen installed? ☐ Yes ☒ No

Manufacturer's name ______

Type ______ Model No. ______

Diameter ____ Slot size ____ Set from ______ feet to ______ feet

Diameter ____ Slot size ____ Set from ______ feet to ______ feet

Gravel packed? ☐ Yes ☒ No ☐ Size of gravel ______

Placed from ______ feet to ______ feet

Surface seal depth 35' Material used in seal: ☐ Cement grout ☒ Puddling clay ☐ Well cuttings

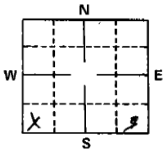
Sealing procedure used: ☐ Slurry pit ☒ Temp. surface casing ☒ Overbore to seal depth

Method of joining casing: ☐ Threaded ☒ Welded ☐ Solvent Weld ☐ Cemented between strata

Describe access port flowing well

6. LOCATION OF WELL

Sketch map location must agree with written location.



Subdivision Name ______

Lot No. 7 Block No. ______

County Twin Falls

SW ¼ SW ¼ Sec. 33, T. 8 ~~N~~/S, R. 14 E/~~W~~.

7. WATER LEVEL

Static water level ______ feet below land surface

Flowing? ☒ Yes ☐ No G.P.M. flow [illegible]20

Artesian closed-in pressure 55 p.s.i.

Controlled by: ☒ Valve ☐ Cap ☐ Plug

Temperature 113 °F. Quality very good

8. WELL TEST DATA

☐ Pump ☐ Bailer ☐ Air ☐ Other ______

Discharge G.P.M.	Pumping Level	Hours Pumped

Pg 1 of 2

88526

9. LITHOLOGIC LOG

Hole Diam.	Depth From	Depth To	Material	Water Yes	Water No
12	0	8	Brown clay		X
	8	35	Brown sand	X	
	35	48	Grey basalt		X
	48	67	Grey-brown clay		
	67	72	Grey basalt		
	72	92	Brown clay		
8	92	137	Grey basalt		
"	137	142	Brown basalt		
"	142	168	Grey basalt		
"	168	175	Dark ~~grey~~brown clay		
	175	209	Grey basalt		
	209	213	Brown clay & brn basalt		
	213	219	Brown basalt		
	219	253	Brown basalt		
	253	257	Green clay		
	257	270	Tan clay w/thin layers of basalt		
6	270	306	Tan clay w/shale layers		
	306	327	Hard grey shale	x	
	327	352	Grey-brn clay w/shale in layers	x	
	352	378	Grey-brown shale w/clay in 1-2' layers		x
	378	409	Grey clay		
	409	416	Light tan clay		
	416	420	Dark green shale		
	420	441	Light green clay		
	441	450	Grey-brn shale		
	450	470	Grey shale		
	470	487	Dark grey shale		
	487	507	Light grey shale		
	507	510	Black rhyolite	x	
	510	556	Brown rhyolite		
	556	578	Black rhyolite		
	578	584	Grey shale		
	584	632	Black rhyolite		

10.

Work started 1 May 1983 finished 1 July 1983

11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Boley & Henry Firm No. 86

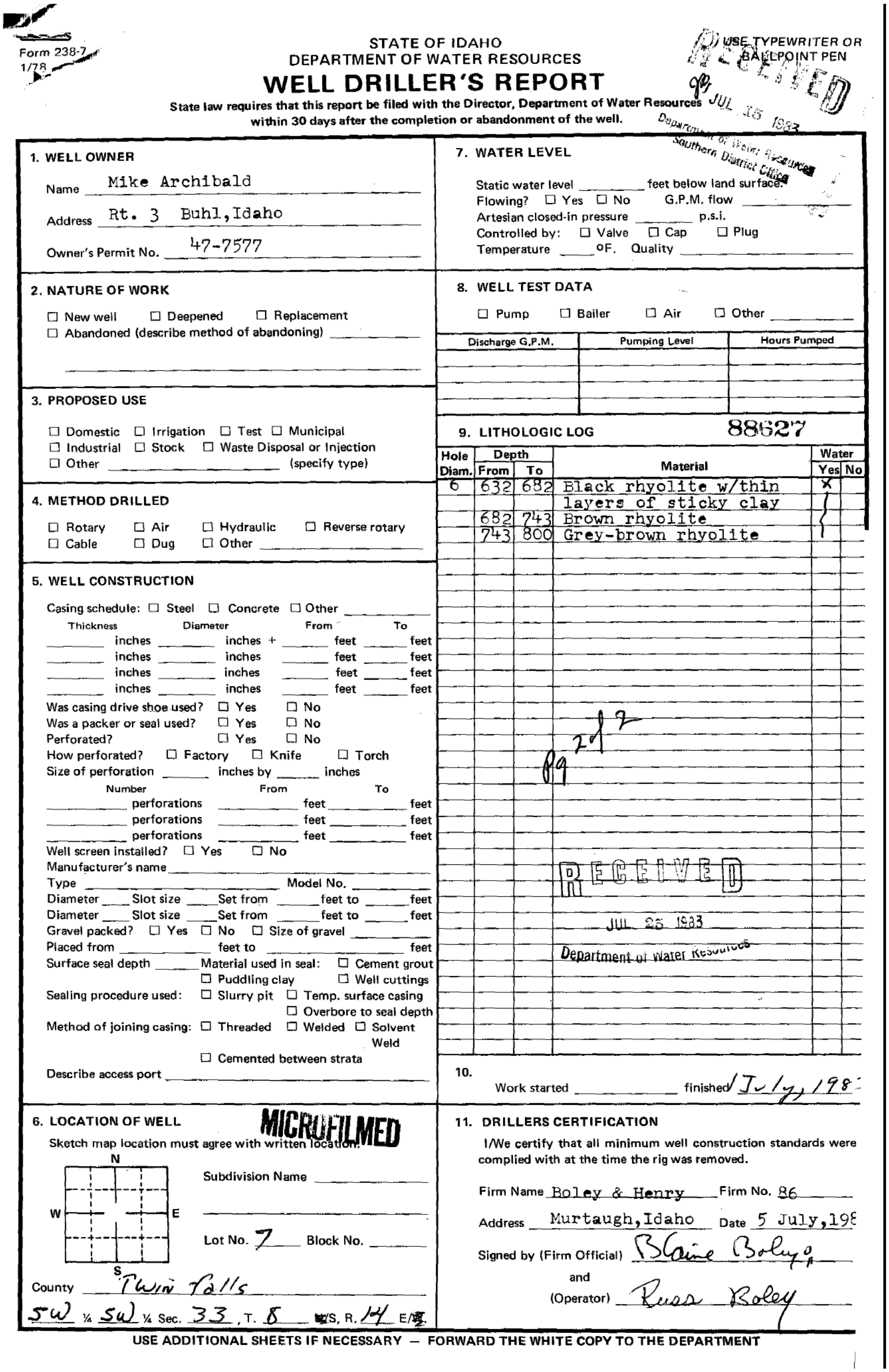
Address Murtaugh,Idaho Date 5 July,198

Signed by (Firm Official) Blaine Boley

and

(Operator) Russ Boley

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT



Form 238-7
1/78

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

USE TYPEWRITER OR BALLPOINT PEN

RECEIVED
JUL 15 1983
Department of Water Resources
Southern District Office

1. WELL OWNER

Name Mike Archibald
Address Rt. 3 Buhl, Idaho
Owner's Permit No. 47-7577

2. NATURE OF WORK

☐ New well ☐ Deepened ☐ Replacement
☐ Abandoned (describe method of abandoning) ____

3. PROPOSED USE

☐ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other ____ (specify type)

4. METHOD DRILLED

☐ Rotary ☐ Air ☐ Hydraulic ☐ Reverse rotary
☐ Cable ☐ Dug ☐ Other ____

5. WELL CONSTRUCTION

Casing schedule: ☐ Steel ☐ Concrete ☐ Other ____

Thickness	Diameter	From	To
____ inches	____ inches +	____ feet	____ feet
____ inches	____ inches	____ feet	____ feet
____ inches	____ inches	____ feet	____ feet
____ inches	____ inches	____ feet	____ feet

Was casing drive shoe used? ☐ Yes ☐ No
Was a packer or seal used? ☐ Yes ☐ No
Perforated? ☐ Yes ☐ No
How perforated? ☐ Factory ☐ Knife ☐ Torch
Size of perforation ____ inches by ____ inches

Number	From	To
____ perforations	____ feet	____ feet
____ perforations	____ feet	____ feet
____ perforations	____ feet	____ feet

Well screen installed? ☐ Yes ☐ No
Manufacturer's name ____
Type ____ Model No. ____
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Gravel packed? ☐ Yes ☐ No ☐ Size of gravel ____
Placed from ____ feet to ____ feet
Surface seal depth ____ Material used in seal: ☐ Cement grout ☐ Puddling clay ☐ Well cuttings
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☐ Overbore to seal depth
Method of joining casing: ☐ Threaded ☐ Welded ☐ Solvent Weld ☐ Cemented between strata
Describe access port ____

6. LOCATION OF WELL

MICROFILMED

Sketch map location must agree with written location.

N
W E
S

Subdivision Name ____
Lot No. 7 Block No. ____

County Twin Falls
SW ¼ SW ¼ Sec. 33, T. 8 ~~N~~/S, R. 14 E/~~W~~

7. WATER LEVEL

Static water level ____ feet below land surface.
Flowing? ☐ Yes ☐ No G.P.M. flow ____
Artesian closed-in pressure ____ p.s.i.
Controlled by: ☐ Valve ☐ Cap ☐ Plug
Temperature ____ °F. Quality ____

8. WELL TEST DATA

☐ Pump ☐ Bailer ☐ Air ☐ Other ____

Discharge G.P.M.	Pumping Level	Hours Pumped

9. LITHOLOGIC LOG 88627

Hole Diam.	Depth From	Depth To	Material	Water Yes	Water No
6	632	682	Black rhyolite w/thin layers of sticky clay	X	
	682	743	Brown rhyolite		
	743	800	Grey-brown rhyolite		

8927

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JUL 25 1983
Department of Water Resources

10.

Work started ____ finished July, 198

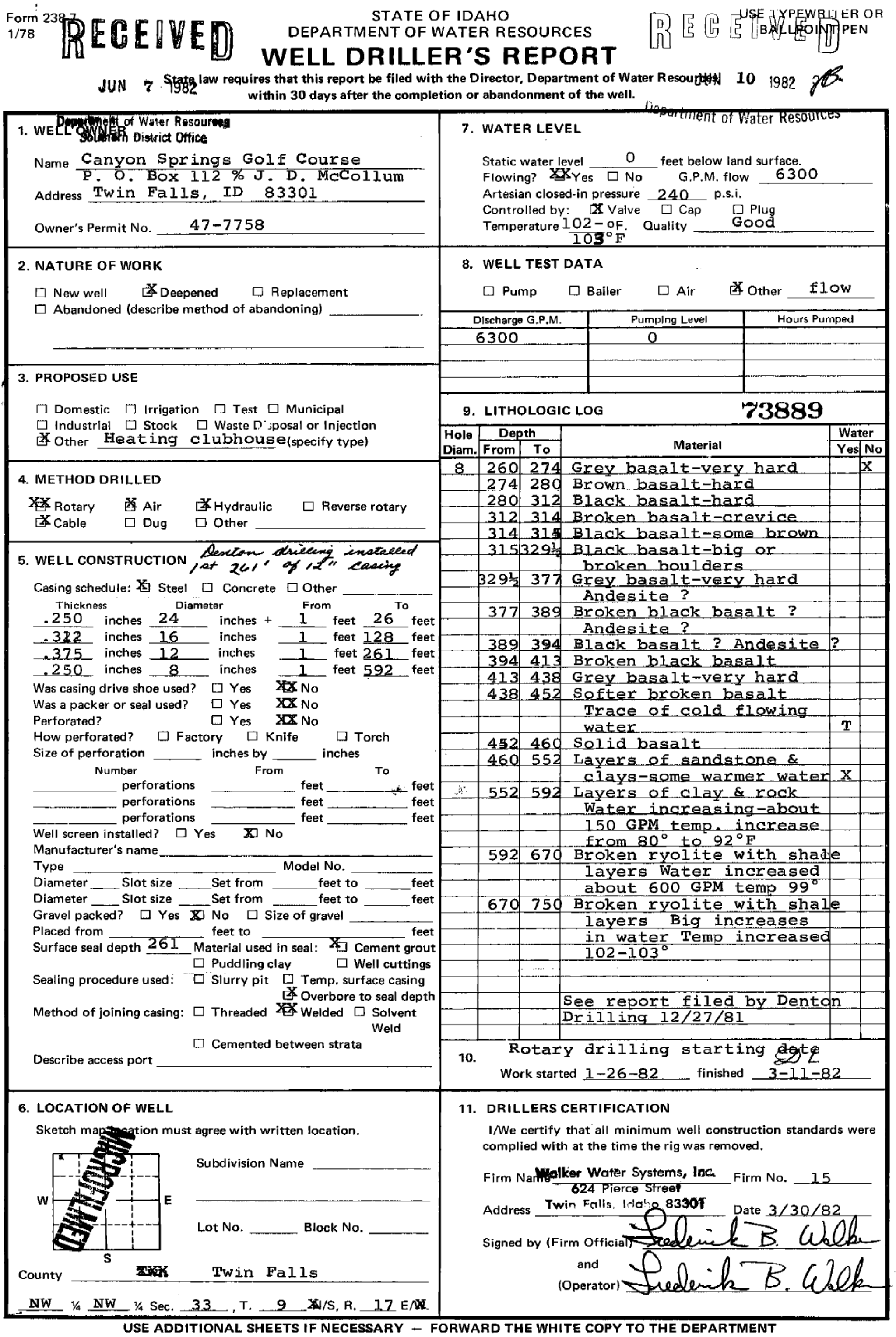
11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Boley & Henry Firm No. 86
Address Murtaugh, Idaho Date 5 July, 198
Signed by (Firm Official) Blaine Boley
and
(Operator) Russ Boley

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Figure C9. Mike Archibald Well Driller's Log



Form 238-7
1/78

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JUN 7 1982
Department of Water Resources
Southern District Office

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

RECEIVED
JUN 10 1982
Department of Water Resources

USE TYPEWRITER OR BALLPOINT PEN

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

1. WELL OWNER

Name Canyon Springs Golf Course
Address P. O. Box 112 % J. D. McCollum
Twin Falls, ID 83301
Owner's Permit No. 47-7758

2. NATURE OF WORK

☐ New well ☒ Deepened ☐ Replacement
☐ Abandoned (describe method of abandoning) ______

3. PROPOSED USE

☐ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☒ Other Heating clubhouse (specify type)

4. METHOD DRILLED

☒ Rotary ☒ Air ☒ Hydraulic ☐ Reverse rotary
☒ Cable ☐ Dug ☐ Other ______

5. WELL CONSTRUCTION Denton drilling installed 1st 261' of 12" casing

Casing schedule: ☒ Steel ☐ Concrete ☐ Other ______

Thickness		Diameter		From		To	
.250	inches	24	inches +	1	feet	26	feet
.322	inches	16	inches	1	feet	128	feet
.375	inches	12	inches	1	feet	261	feet
.250	inches	8	inches	1	feet	592	feet

Was casing drive shoe used? ☐ Yes ☒ No
Was a packer or seal used? ☐ Yes ☒ No
Perforated? ☐ Yes ☒ No
How perforated? ☐ Factory ☐ Knife ☐ Torch
Size of perforation ______ inches by ______ inches

Number		From		To	
	perforations		feet		feet
	perforations		feet		feet
	perforations		feet		feet

Well screen installed? ☐ Yes ☒ No
Manufacturer's name ______
Type ______ Model No. ______
Diameter ____ Slot size ____ Set from ______ feet to ______ feet
Diameter ____ Slot size ____ Set from ______ feet to ______ feet
Gravel packed? ☐ Yes ☒ No ☐ Size of gravel ______
Placed from ______ feet to ______ feet
Surface seal depth 261 Material used in seal: ☒ Cement grout ☐ Puddling clay ☐ Well cuttings
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☒ Overbore to seal depth
Method of joining casing: ☐ Threaded ☒ Welded ☐ Solvent Weld ☐ Cemented between strata
Describe access port ______

6. LOCATION OF WELL

Sketch map location must agree with written location.

W E S

MICROFILMED

Subdivision Name ______
Lot No. ______ Block No. ______
County Twin Falls
NW ¼ NW ¼ Sec. 33, T. 9 N/S, R. 17 E/W.

7. WATER LEVEL

Static water level 0 feet below land surface.
Flowing? ☒ Yes ☐ No G.P.M. flow 6300
Artesian closed-in pressure 240 p.s.i.
Controlled by: ☒ Valve ☐ Cap ☐ Plug
Temperature 102-103°F °F. Quality Good

8. WELL TEST DATA

☐ Pump ☐ Bailer ☐ Air ☒ Other flow

Discharge G.P.M.	Pumping Level	Hours Pumped
6300	0	

9. LITHOLOGIC LOG 73889

Hole Diam.	Depth From	Depth To	Material	Water Yes	Water No
8	260	274	Grey basalt-very hard		X
	274	280	Brown basalt-hard		
	280	312	Black basalt-hard		
	312	314	Broken basalt-crevice		
	314	315	Black basalt-some brown		
	315	329½	Black basalt-big or broken boulders		
	329½	377	Grey basalt-very hard Andesite ?		
	377	389	Broken black basalt ? Andesite ?		
	389	394	Black basalt ? Andesite	?	
	394	413	Broken black basalt		
	413	438	Grey basalt-very hard		
	438	452	Softer broken basalt Trace of cold flowing water	T	
	452	460	Solid basalt		
	460	552	Layers of sandstone & clays-some warmer water	X	
	552	592	Layers of clay & rock Water increasing-about 150 GPM temp. increase from 80° to 92°F		
	592	670	Broken ryolite with shale layers Water increased about 600 GPM temp 99°		
	670	750	Broken ryolite with shale layers Big increases in water Temp increased 102-103°		
			See report filed by Denton Drilling 12/27/81		

10. Rotary drilling starting date
Work started 1-26-82 finished 3-11-82

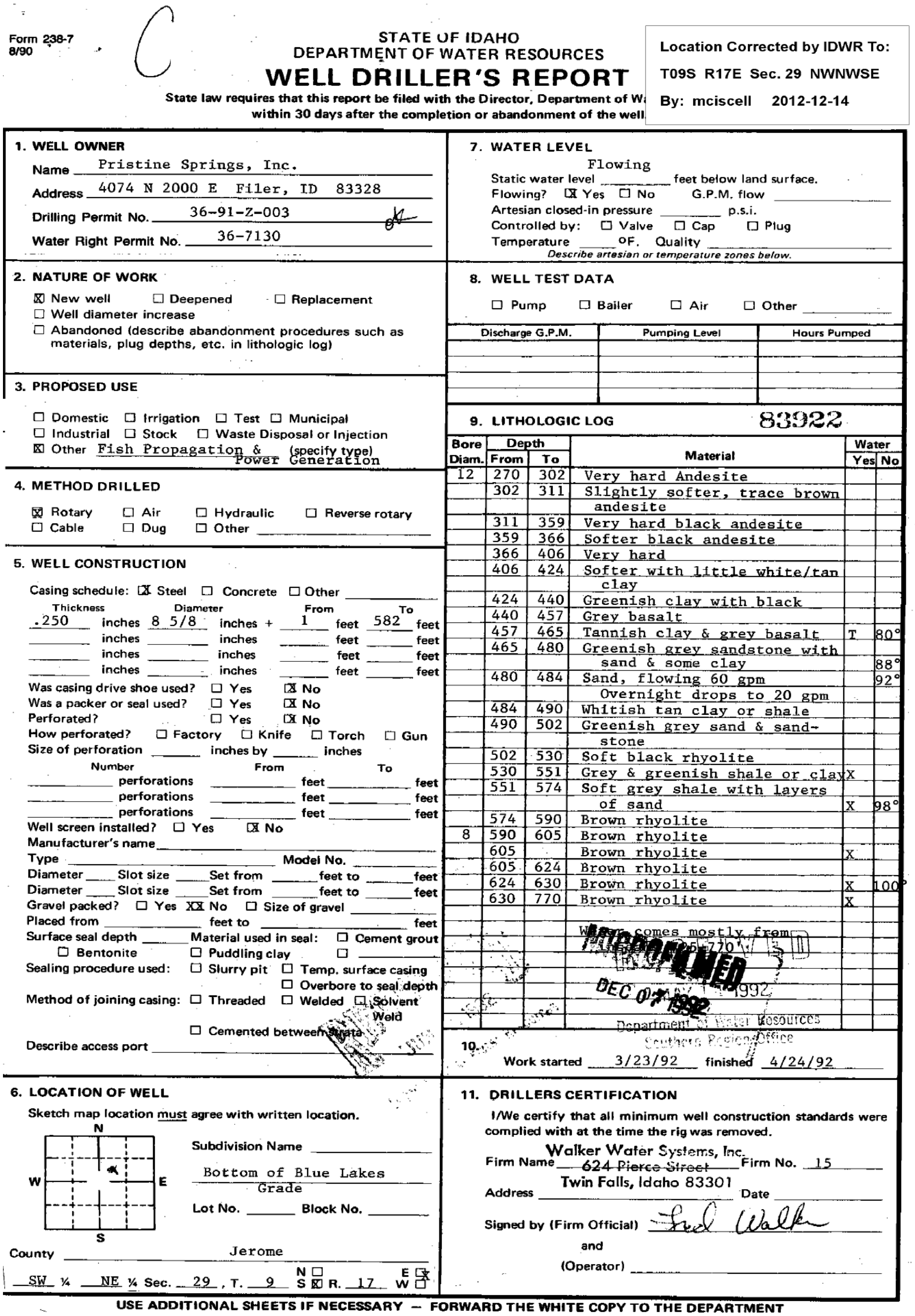
11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Walker Water Systems, Inc. Firm No. 15
Address 624 Pierce Street
Twin Falls, Idaho 83301 Date 3/30/82
Signed by (Firm Official) Frederick B. Walker
and
(Operator) Frederick B. Walker

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Figure C10. Canyon Springs Golf Course Well Driller's Log



Form 238-7
8/90

C

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of W[ater Resources] within 30 days after the completion or abandonment of the well.

Location Corrected by IDWR To:
T09S R17E Sec. 29 NWNWSE
By: mciscell 2012-12-14

1. WELL OWNER

Name Pristine Springs, Inc.
Address 4074 N 2000 E Filer, ID 83328
Drilling Permit No. 36-91-Z-003
Water Right Permit No. 36-7130

2. NATURE OF WORK

☒ New well ☐ Deepened ☐ Replacement
☐ Well diameter increase
☐ Abandoned (describe abandonment procedures such as materials, plug depths, etc. in lithologic log)

3. PROPOSED USE

☐ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☒ Other Fish Propagation & Power Generation (specify type)

4. METHOD DRILLED

☒ Rotary ☐ Air ☐ Hydraulic ☐ Reverse rotary
☐ Cable ☐ Dug ☐ Other

5. WELL CONSTRUCTION

Casing schedule: ☒ Steel ☐ Concrete ☐ Other

Thickness		Diameter		From		To	
.250	inches	8 5/8	inches +	1	feet	582	feet
	inches		inches		feet		feet
	inches		inches		feet		feet
	inches		inches		feet		feet

Was casing drive shoe used? ☐ Yes ☒ No
Was a packer or seal used? ☐ Yes ☒ No
Perforated? ☐ Yes ☒ No
How perforated? ☐ Factory ☐ Knife ☐ Torch ☐ Gun
Size of perforation ____ inches by ____ inches

Number		From		To	
	perforations		feet		feet
	perforations		feet		feet
	perforations		feet		feet

Well screen installed? ☐ Yes ☒ No
Manufacturer's name
Type ____ Model No. ____
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Gravel packed? ☐ Yes XX No ☐ Size of gravel
Placed from ____ feet to ____ feet
Surface seal depth ____ Material used in seal: ☐ Cement grout ☐ Bentonite ☐ Puddling clay ☐
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☐ Overbore to seal depth
Method of joining casing: ☐ Threaded ☐ Welded ☐ Solvent Weld ☐ Cemented between strata
Describe access port

6. LOCATION OF WELL

Sketch map location must agree with written location.

N
W E
S

Subdivision Name Bottom of Blue Lakes Grade
Lot No. ____ Block No. ____

County Jerome

SW ¼ NE ¼ Sec. 29 , T. 9 N ☐ S ☒ R. 17 E ☒ W ☐

7. WATER LEVEL

Static water level Flowing feet below land surface.
Flowing? ☒ Yes ☐ No G.P.M. flow
Artesian closed-in pressure ____ p.s.i.
Controlled by: ☐ Valve ☐ Cap ☐ Plug
Temperature ____ °F. Quality
Describe artesian or temperature zones below.

8. WELL TEST DATA

☐ Pump ☐ Bailer ☐ Air ☐ Other

Discharge G.P.M.	Pumping Level	Hours Pumped

9. LITHOLOGIC LOG 83922

Bore Diam.	Depth From	Depth To	Material	Water Yes	Water No
12	270	302	Very hard Andesite		
	302	311	Slightly softer, trace brown andesite		
	311	359	Very hard black andesite		
	359	366	Softer black andesite		
	366	406	Very hard		
	406	424	Softer with little white/tan clay		
	424	440	Greenish clay with black		
	440	457	Grey basalt		
	457	465	Tannish clay & grey basalt	T	80°
	465	480	Greenish grey sandstone with sand & some clay		88°
	480	484	Sand, flowing 60 gpm Overnight drops to 20 gpm		92°
	484	490	Whitish tan clay or shale		
	490	502	Greenish grey sand & sandstone		
	502	530	Soft black rhyolite		
	530	551	Grey & greenish shale or clay	X	
	551	574	Soft grey shale with layers of sand	X	98°
	574	590	Brown rhyolite		
8	590	605	Brown rhyolite		
	605		Brown rhyolite	X	
	605	624	Brown rhyolite		
	624	630	Brown rhyolite	X	100°
	630	770	Brown rhyolite	X	
			Water comes mostly from [illegible] 25-770'		

MICROFILMED
DEC 07 1992

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1992
Department of Water Resources
Southern Region Office

10. Work started 3/23/92 finished 4/24/92

11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Walker Water Systems, Inc. Firm No. 15
Address 624 Pierce Street Twin Falls, Idaho 83301 Date
Signed by (Firm Official) Fred Walker
and
(Operator)

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Figure C11. Pristine Springs Well Driller's Log