Summer 2017

Using Strontium Isotopes in Conjunction with Major, and Trace Elements to Identify Water/Rock Interaction in the Upper Kittitas County, Washington

James Patterson
Central Washington University, pattersonja@cwu.edu

Carey Gazis

Recommended Citation

Patterson, James and Gazis, Carey, "Using Strontium Isotopes in Conjunction with Major, and Trace Elements to Identify Water/Rock Interaction in the Upper Kittitas County, Washington" (2017). *All Master's Theses*. 780.
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USING STRONTIUM ISOTOPES IN CONJUNCTION WITH MAJOR, AND TRACE ELEMENTS TO IDENTIFY WATER/ROCK INTERACTION IN THE UPPER KITTITAS COUNTY, WASHINGTON

A Thesis

Presented to

The Graduate Faculty

Central Washington University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

Geology

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by

James D. Patterson

August 2017

CENTRAL WASHINGTON UNIVERSITY

Graduate Studies

We hereby approve the thesis of

James D. Patterson

Candidate for the degree of Master of Science

APPROVED FOR THE GRADUATE FACULTY

Dr. Carey Gazis, Committee Chair

Dr. Anne Johansen

Dr. Winston Norrish

Dean of Graduate Studies

ABSTRACT

USING STRONTIUM ISOTOPES IN CONJUNCTION WITH MAJOR, AND TRACE ELEMENTS TO IDENTIFY WATER/ROCK INTERACTION IN THE UPPER KITTITAS COUNTY, WASHINGTON

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The complex bedrock lithologies in the Upper Kittitas County provide an ideal setting for developing isotopic methodology to identify groundwater sources and track flow paths through water-rock interaction. A wide range of $^{87}Sr/^{86}Sr$ (0.7040 to 0.7068) in surface waters, springs, and groundwater from wells was found, allowing for identification of the individual signatures of lithologic units. Rock leachates from different lithology were compared to water samples to determine a general $^{87}Sr/^{86}Sr$ signature of the water-rock interaction for that lithology. The signatures identified were systematically lower than their associated waters, but similar enough to identify the expected $^{87}Sr/^{86}Sr$ of water-rock interaction for most of the units. These signatures can then be compared to unknown waters to identify the source and/or mixing between sources. Using this method, many of the water samples in this study were directly correlated to their sources. The greatest limitations of this method were lithologies that were not geochemically homogenous and overlap in ranges of $^{87}Sr/^{86}Sr$ for different lithology.

ACKNOWLEDGMENTS

I would like to extend my immense gratitude to the many people who have supported me during my extended time at Central Washington University (CWU) as a graduate student. Firstly, my academic and research advisor Dr. Carey Gazis. Dr. Gazis not only gave me direction and guidance, but also was very patient with my work schedule which caused me to blow through many deadlines. I would also like to thank my other CWU committee members (Dr. Winston Norrish and Dr. Anne Johansen) for taking the time to review my thesis and provide guidance to help in my success as a master's candidate. Another person who I am truly appreciative of is Dr. Frank Ramos at New Mexico State University (NMSU) for his ample generosity and instruction when I visited NMSU to perform strontium analysis.

Outside of academia I would like to thank my girlfriend and my family for the continued emotional and financial support during my graduate studies as well as the USGS Washington Water Science Center in Tacoma for their encouragement, friendship, and a job that helped to fund most of my research.

Lastly, I am grateful to the Geological Society of America for a $2500 research grant awarded in 2012. This funding was crucial to the initial stages of my research project.

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CHAPTER I

INTRODUCTION

Significance

Geochemistry, and more specifically isotope geochemistry, is useful for characterizing flow paths in fractured bedrock regions (e.g., DePaolo, 2005). Each lithologic unit has a unique elemental, mineralogical, and isotopic composition. Aspects of this geochemical variation, including isotope ratios, are transferred to groundwater during water/rock interactions and can provide geochemical fingerprints of each unit. Using isotopes, it is possible to characterize various water sources, flow paths, and mixing (Uliana et al., 2007, Blum and Erel, 2003, Bain and Bacon, 1994, and DePaolo, 2006). Strontium isotope ratios, specifically $^{87}Sr/^{86}Sr$, are of particular interest because they can vary widely between lithologies and minerals. When water interacts with a rock from a specific unit, partial mineral dissolution may occur imparting the $^{87}Sr/^{86}Sr$ of the rock or the dissolving mineral onto the water. This investigation illustrates the potential of using measurements of $^{87}Sr/^{86}Sr$ and elemental concentrations in the rock leachates to identify potential source aquifers and flow paths of the water samples collected in the surrounding areas.

The northern portion of Kittitas County (known as the Upper Kittitas County) in Washington State was selected as the study area based on the complex bedrock geology, which provides a range of geochemical and Sr isotope compositions in rocks that might produce distinct geochemical signatures in groundwater. Two recent groundwater studies, in this study area, provide some framework for understanding the groundwater geochemistry. In a recent U.S.G.S. study (Gendaszek, et al., 2014), groundwater wells were analyzed for ^{14}C age. Many of these wells, especially the deeper wells, indicate at least some component of older evolved water. In another recent geochemical study (Holt, 2012), the deep sandstone aquifers were seen to have highly evolved water also indicating older water. Both studies indicate that the geochemistry of many of the shallow wells located in the unconsolidated valley fill are strongly influenced by the local surface water. Most of the sampling, in both studies, occurred mostly in valley bottoms or surrounding areas as these were the populated areas. These populated areas only cover approximately 13% of the Upper County (Haugerud and Tabor, 2009). One of the goals of this study is to identify the geochemistry throughout the entire basin (Figure 1) including the fractured bedrock areas of National Forest land. In these regions, springs are the best source for sampling groundwater.

Kinnison and Sceva (1963) stated the mountainous bedrock areas in the Upper Kittitas County have a low capacity for storage or transportation of waters. In the recent U.S.G.S. investigation, the dominant mode of sub-surface water transportation was stated to be through complex fracture flow systems (Gendaszek, et al., 2014). This can result in drastic changes in water level and differing water availabilities over short lateral distances. In a fracture flow system such as this, typical groundwater flow computer models that use 1 km grid squares to simulate hydraulic head pressures are of limited use. With the limitations of standard groundwater models and a complex geology, the Upper Kittitas County provides an ideal setting to refine the geochemical technique of using the water/rock interaction to source water samples.

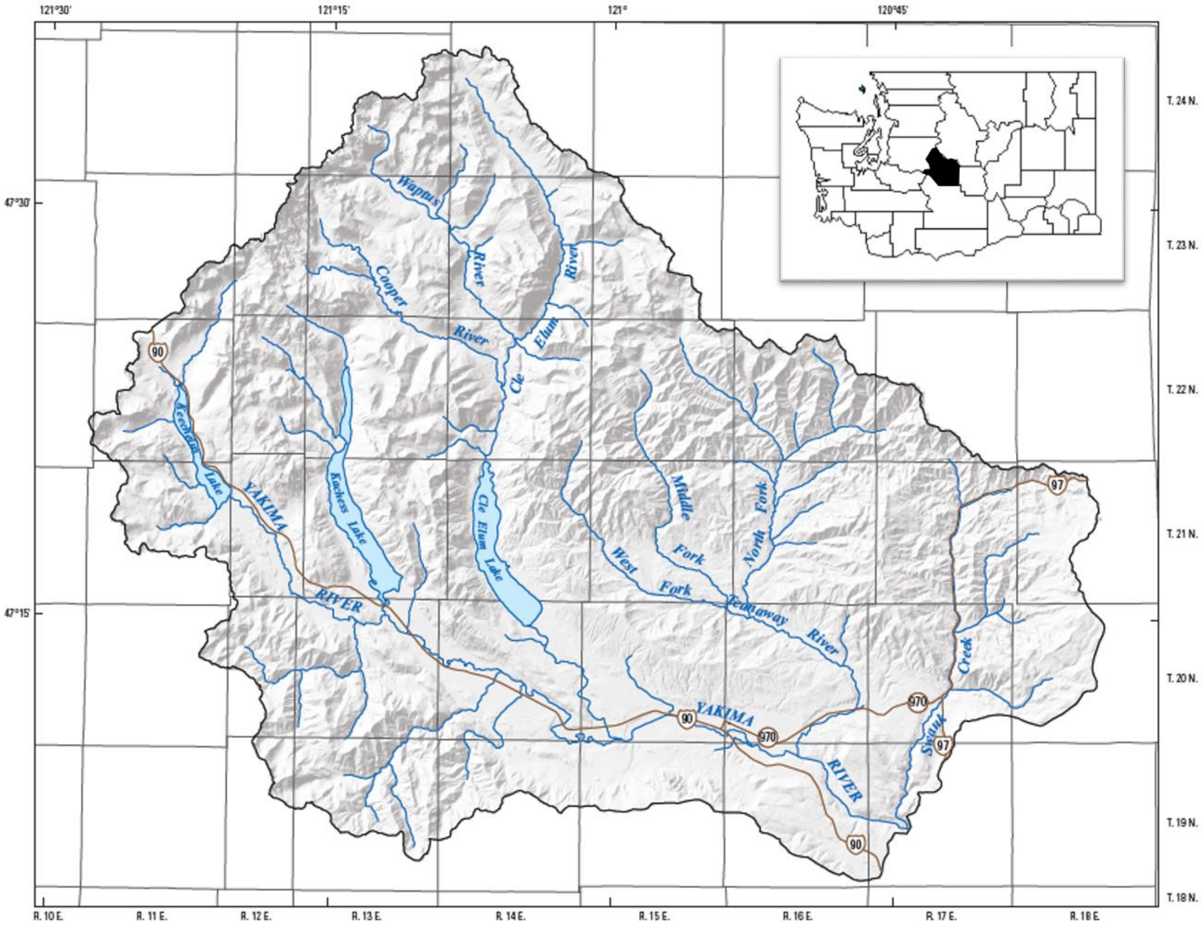

Figure 1 . Shaded relief map of the study area. The Upper Kittitas County, Washington

Rubidium/strontium systematics and variations due to water-rock interaction

A given rock type has a distinct geochemical composition, dependent upon the minerals present and the age of the rock; in some cases, the signature can also be affected by secondary alterations. The primary and secondary minerals control the concentration of major and trace elements present in the rock. These geochemical variations provide a natural "fingerprint" of the rock (Blum and Erel, 2003). When the rock interacts with water, chemical weathering and cation exchange reactions will transfer aspects of this fingerprint to the water.

In this study, the rubidium/strontium (Rb/Sr) system is the primary tool for fingerprinting the various rocks and waters. The trace elements Rb and Sr have the same charge and similar ionic radii to the major elements K and Ca, respectively (Figure 2). Therefore, minerals that readily incorporate the major element tend to incorporate trace amounts of their respective trace elements. This is particularly helpful since most minerals preferentially incorporate one over the other (e.g. K and Rb are preferred in potassium feldspar over Ca and Sr). Therefore, a mineral with a high K/Ca most times will also have a high Rb/Sr.

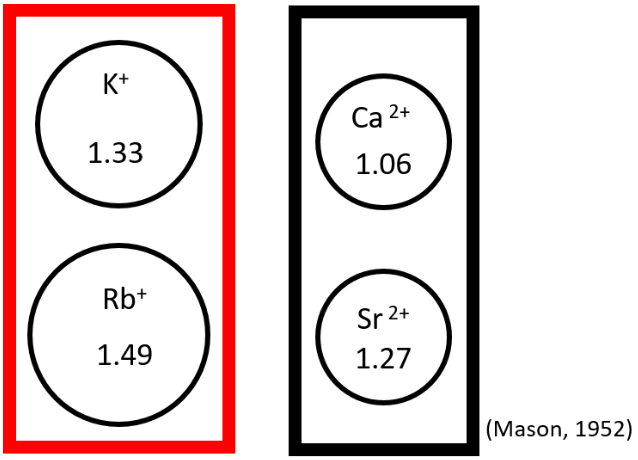

Figure 2. Similar charge and size of K and Ca to Rb and Sr, respectively

Strontium has four naturally occurring isotopes; ^{84}Sr, ^{86}Sr, ^{87}Sr, and ^{88}Sr. All four of these isotopes are non-radioactive and ^{84}Sr, ^{86}Sr, and ^{88}Sr are consistent in their relative abundances in nature. In contrast, ^{87}Sr is radiogenic, the daughter product of the decay of ^{87}Rb, which has a half-life of 48.8 billion years (**Figure 3**).

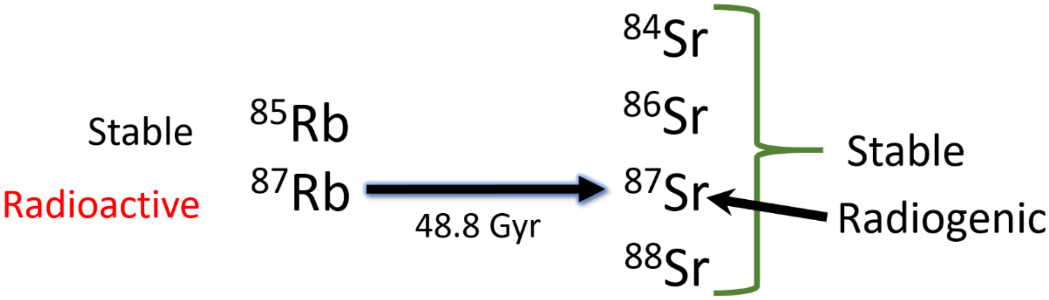

Figure 3. ^{87}Rb decays to ^{87}Sr with 48.8 billion-year half-life

The variability in ^{87}Sr/^{86}Sr in minerals is the result of the initial concentrations of ^{87}Rb decaying over time into ^{87}Sr. A higher starting concentration of Rb and/or more time elapsing results in a higher ^{87}Sr/^{86}Sr value in the mineral (**Figure 4**). Thus, a setting with diverse rock types of varying ages such as the Upper Kittitas County is expected to represent a wide range of strontium isotope ratios. Table 1 identifies typically expected 87Sr/86Sr for various rock types.

TABLE 1. TYPICAL ^{87}SR/^{86}SR IN SOME ROCKS

Mid ocean ridge basalts	0.7025
Columbia River Basalts	0.7040 - 0.7055
Accreted terrain in Washington	>0.7060
Craton	0.7100

(Wolff et al., 2008)

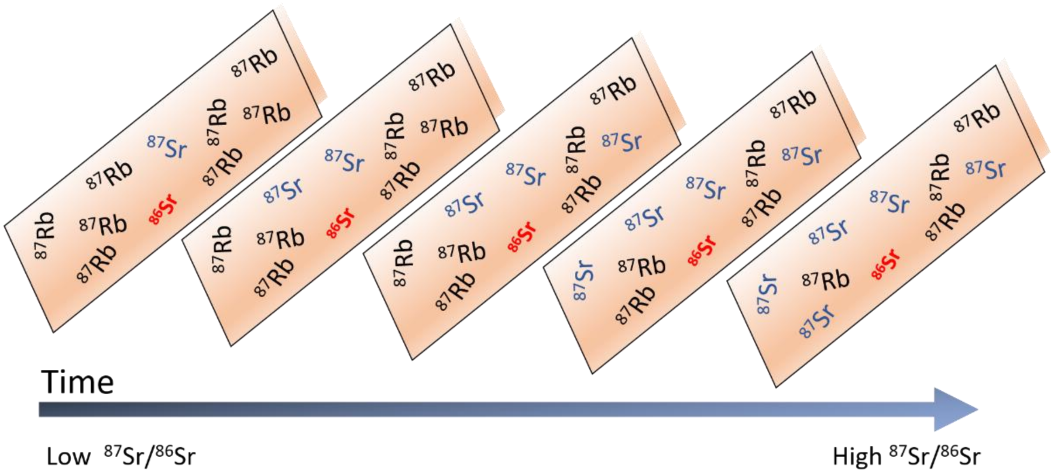

Figure 4. Growth ^{87}Sr over time in a mineral

The chemistry of surface and groundwater can be influenced by many different factors, such as the initial chemistry of the meteoric water, the mineral assemblages present in the rocks, mineral solubility, cation exchange, and mineral precipitation. The ^{87}Sr/^{86}Sr variability in a hydrologic system provides information about the Sr sources sampled by groundwater movement. At near surface conditions, rocks can impart their chemical signatures onto the water through chemical weathering. Chemical weathering is the partial dissolution or alteration of minerals resulting from low-temperature water-rock interaction. Dissolution results in the release of major and trace elements, including strontium into the water (Bain and Bacon, 1994, and Negrel and Aranyossy, 2001). In a recent groundwater study in French Guiana, Negrel and Petelet-Giraud (2010) conclude that the ^{87}Sr/^{86}Sr in the groundwater reflects the rocks that have weathered and influenced their chemistry. They identify a low ^{87}Sr/^{86}Sr signature that is the result of weathering mafic rocks such as basalt and amphibolite and a higher ^{87}Sr/^{86}Sr signature resulting from weathering of altered sediments such as schists and micaschists (Table 2). This results from the mineral assemblages present in each rock type. Mafic rocks typically do not contain minerals that readily incorporate Rb, whereas felsic rocks typically contain more minerals which are K rich minerals and therefore incorporate Rb, including radioactive ^{87}Rb.

TABLE 2. AVERAGE VALUES OF ROCKS FROM STUDY IN FRENCH GUIANA

Water collected from	^{87}Sr/^{86}Sr	Sr ppb	K/Ca
Altered Sediments	0.7147	23	0.36
Basalt	0.7063	141	0.06

(Negrel and Petelet-Giraud, 2010)

There is a very small difference in the ionization potential between ^{87}Sr and ^{86}Sr therefore natural processes near earth’s surface such as physical or chemical weathering will not fractionate the strontium isotopes (Bain and Bacon, 1994, Uliana, et al., 2006). Since natural processes do not fractionate Sr isotopes, the variability in ^{87}Sr/^{86}Sr in groundwaters results from mixing of Sr derived from various sources (Negrel, et al., 2000).

While Sr isotopes are not fractionated, different mineral susceptibility to weathering can result in release of strontium from different minerals at different rates. This preferential dissolution may result in water with a different ^{87}Sr/^{86}Sr ratio than the bulk rock (Bain and Bacon, 1994). Therefore, the chemistry of the water is dependent upon not just the minerals present, but the rates of minerals weathering (Blum and Erel, 2003, and Bullen et al., 1996). Since the strontium isotopes are not readily fractionated by natural processes, the variability in ^{87}Sr/^{86}Sr in the water is a result of the Sr derived from the minerals or a result of water mixing from multiple sources (Negrel, 2000).

Blum and Erel (2003) show that mineral inclusions rich in Sr can heavily impact ^{87}Sr/^{86}Sr during initial weathering, but over time the influence of these inclusions is greatly diminished because the incorporation of Sr is limited to the rate of physical weathering that exposes fresh rocks for chemical weathering. Therefore, the influence of these trace inclusions will be seen mostly in areas where the rocks and minerals are being physically fractured, such as during faulting or physical weathering. In springs that are not following through fracture systems related to active faulting the impact of trace inclusions on the water will be minimal.

Fisher and Stueber (1976) identified that small amounts of carbonate with a different $^{87}Sr/^{86}Sr$ can strongly influence the $^{87}Sr/^{86}Sr$ of waters. Precipitation of Ca rich minerals, such as carbonate, can occur in fracture systems as fluids equilibrate to changing temperatures, pressures, and/or concentrations. These fracture precipitates may have very different signatures than the surrounding lithology. Incorporation of strontium from these precipitates into an aquifer system could overwhelm the $^{87}Sr/^{86}Sr$ signature of waters with low Sr concentration.

In some cases, the water-rock interaction of an area is fairly straight forward. A few different studies (Blum and Erel, 2003; Bain, Bacon 1994; Stillinger and Brantly, 1995) show the $^{87}Sr/^{86}Sr$ of streams and springs to have a similar isotopic composition of the catchment, if a single bedrock lithology underlies the basin. In a study by Innocent et al. (1997) on the Sr isotopic composition of tropical laterites that developed on basalts, the soil was depleted of the parent Sr due to its release during weathering and the $^{87}Sr/^{86}Sr$ of the groundwater was controlled by the $^{87}Sr/^{86}Sr$ of the rain water.

Blum and Erel (2003) conducted a study of a soil chronosequence developed 0.4 kyr – 300 kyr in granitic glacial moraines and alluvial terraces. They found that the initial chemical weathering of freshly ground mineral fragments of biotite into vermiculite is the dominant contributor of radiogenic strontium in the water. During this time biotite is weathering 8 times faster than plagioclase. In the older well-developed soils, the $^{87}Sr/^{86}Sr$ value in the soil water was dominated by the weathering of feldspars. They noted biotite weathered 5 times slower than plagioclase in the oldest soils. A study by Bullen et al. (1997) of partially weathered and sorted alluvial parent material found that biotite was depleted of most of its radiogenic strontium during alluvial transport and deposition.

Bullen et al. (1996) found that plagioclase weathering dominated the chemistry of the water in shallow, dilute systems. However, they noted the composition of the waters in deeper evolved aquifers was dominated by biotite and potassium feldspar weathering.

As seen from these previous studies, there are many factors that can greatly impact the $^{87}Sr/^{86}Sr$ of various waters. Surface waters and short residency springs will typically have less contamination from multiple sources, however deeper groundwaters systems are typically longer lived. The deeper aquifer systems may have a more varied geochemical history as they interact with different $^{87}Sr/^{86}Sr$ sources. An understanding of the possible sources of $^{87}Sr/^{86}Sr$ in a complex geological area is the first step to identifying the $^{87}Sr/^{86}Sr$ signature of the various lithologies and aquifer systems.

Physiographic Boundaries

The Upper Kittitas County study area (Figure 1) encompasses about 2,227 km^2 of the Yakima River basin headwaters and has an annual precipitation ranging from 254 cm in the headwaters to about 51 cm in the eastern lower elevation portion of the basin. The mean elevation of the study area is about 1,100 m and ranges from 527 m to 2,426 m (Gendaszek, et al., 2014). The Upper Kittitas County basin is constrained to the west by the crest of the central Cascades and by the Stuart Range to the North. The southern boundary is the South

Cle Elum Ridge, a NW-SE trending ridge. The north-eastern boundary of the study area is the Wenatchee Range whereas in the southeastern corner of the study area the Yakima River flows out of the basin, to the south of Look Out Mountain, through a narrow canyon cut through basalt (Kinnison and Sceva, 1963).

Geologic Overview

A simplified version of the geologic map of Haugerod and Tabor (2009) is presented in Figure 5. The central portion of the study area is dominantly composed of Tertiary sedimentary bedrock with a roughly E-W trending zone of Tertiary basalt bedrock, known as the Teanaway Basalt and forming topographic ridge commonly identified as the Teanaway Ridge (Figure 7). North of the Teanaway Basalt is the Swauk Formation. The Swauk Formation is located in the central and eastern portion of the basin. In some areas, the Swauk Formation is underlain by nickeliferous iron deposits (Lamey and Holts, 1951). On the western portion of the basin is the Silver Pass member of the Swauk Formation, composed of Eocene andesite flows. To the south of the Teanaway Basalt are the lower, middle and upper members of the Roslyn Formation. All three members are composed mostly of a fine grained, finely laminated sandstone. The upper member of the Roslyn Formation. also contains shale and coal interbeds and was extensively mined during the last century. Throughout the central portion of the basin are intrusive intermediate and felsic flows. Like the Teanaway Basalt, these intrusive rocks are more resistant to erosion, therefore they typically form high topographic features. To the east of the Teanaway basalts is the Swauk valley. It is composed of Swauk sandstone, but unlike the Swauk sandstone to the north and west of the Teanaway basalts, the sandstone in the Swauk Valley also contains gold mines. Quaternary landslides are common throughout the entire area, especially mantling the zones of high relief (Haugerud and Tabor, 2009).

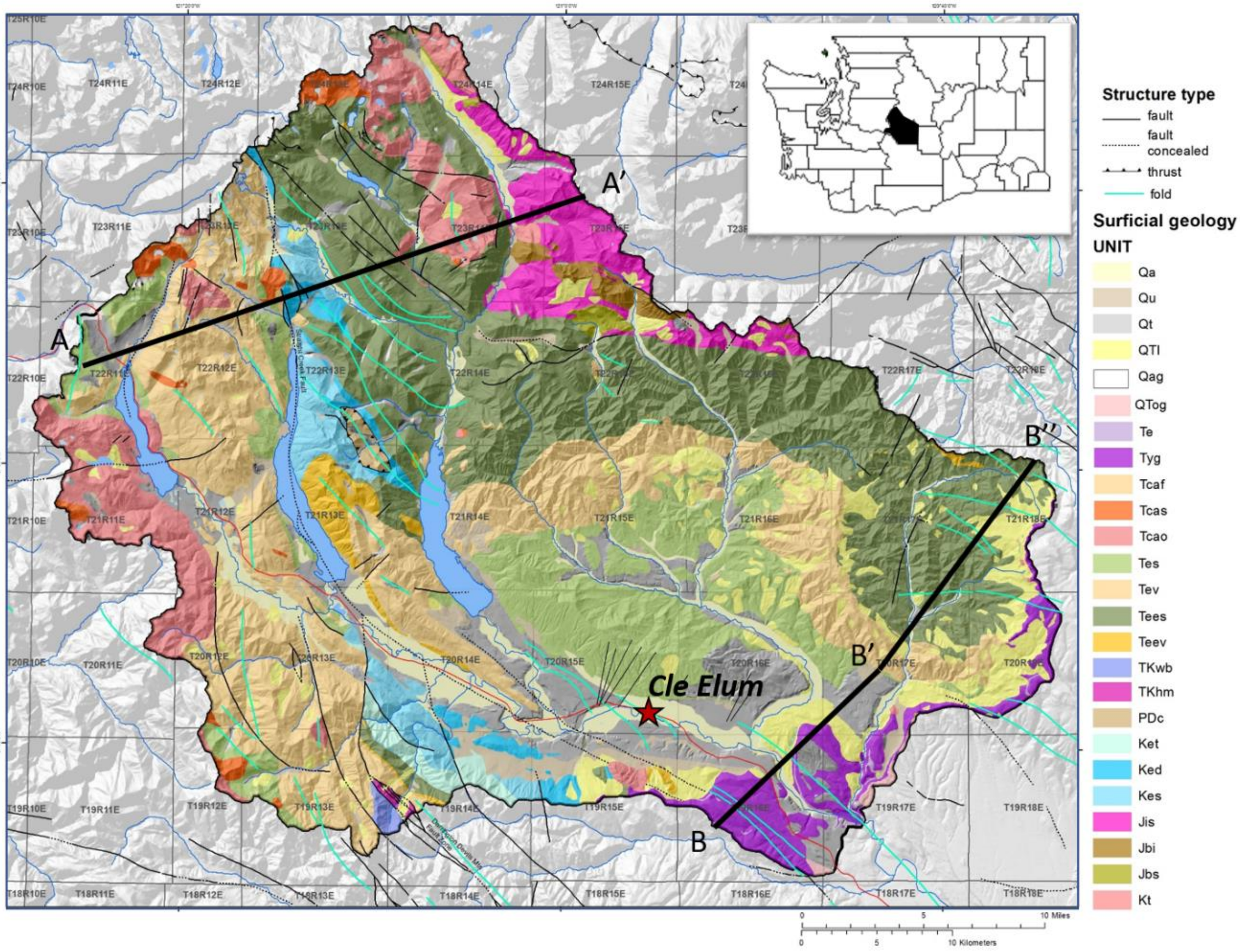

Figure 5. Simplified geologic map and cross section transects.

Explanation:
Qa=Alluvium of valley bottoms (Holocene and Pleistocene)
Qu=Alluvium (Holocene and Pleistocene)
Ql=Talus deposits (Holocene and Pleistocene)
Qtl=Landslide deposits (Holocene, Pleistocene, and Pliocene?)
Qag=Alpine glacial deposits (Holocene and Pleistocene)
QTog=Older gravel (Pleistocene, Pliocene, and Miocene?)
Flood Basalts and associated deposits:
Te=Ellensburg Formation (Miocene)
Tyg=**Grand Ronde Basalt** of the Columbia River Basalt Group
Rocks of Cascade Magmatic Arc:
Tcaf=Volcanic rocks of Fifes Peak episode (Miocene); **Howson Fm**
Tcas=Intrusive rocks of Snoqualmie family (Miocene and Oligocene)
Tcao=Volcanic and sedimentary rocks of **Ohanapecosh** episode (Oligocene)
Rocks of late and post-orogenic transtension:
Tes=Extensional sedimentary rocks (early Oligocene and Eocene); **Roslyn Fm.**
Tev=Volcanic rocks (early Oligocene and Eocene); **Naches Fm. rhyolite and basalt**
Tees=Early extensional sedimentary rocks (middle and early Eocene); **Swauk Fm s.s.**
Teev=Silver Pass Volcanic Member of **Swauk Formation and.**
Orogenic and pre-orogenic rocks:
TKwb=Rocks of western mélange belt (middle Eocene to Late Cretaceous)
TKhm=Serpentinite
PDc=Chilliwack Group of Cairnes (Permian, Carboniferous, and Devonian)
Ket=Tonalite gneiss of Hicks Butte (Early Cretaceous)
Ked=**Darrington Phyllite** (Early Cretaceous)
Kes=**Shuksan Greenschist** (Early Cretaceous)
Jis=**Ingalls terrane** (Jurassic)
Jbi=Resistant blocks of igneous and meta-igneous rocks
Jbs=Resistant blocks of sedimentary rocks
Kt=Tonalitic plutons (Late Cretaceous)

Note: Map and Explanation for geological units modified from Haugerud and Tabor, 2009. Note colors on the map vary as the underlying shaded relief base varies. Unit age in parentheses after the unit name is the age of assemblage or metamorphism for mélange and metamorphic units.

There are many structural features throughout the entire field area, the majority of which are roughly NW-SE trending. The Straight Creek Fault is a large normal fault which follow the Kachess Lake and trends down the main basin valley. The Straight Creek Fault and its splays comprise the dominant fault zone in this basin (Haugerud and Tabor, 2009). Cross sections A-A’ and B-B’-B” provide a simplified view of the structure and lithology (**Figure 6** and Figure 7). Cross section A shows a series of anticlines and synclines that are cut by intrusive units, and faulted. Tertiary sediments and volcanics are seen in the western portion of the cross section cut by several normal faults. In the middle, the Straight Creek Fault is shown cutting through Early Cretaceous metamorphics before being overlain and cut by more Tertiary sediments and volcanics. A Jurassic ultramafic unit is seen in the eastern portion of the section.

Cross section B shows the Tertiary sediments and volcanics overlain by the Grand Ronde Basalt (Columbia River Basalt Group) in the southern portion of the section. The bend in section occurs near the topographic high Teanaway ridgeline. Just north of the ridgeline there is a localized basaltic intrusion as well as a dike swarm cutting the Swauk sandstone. The remainder of the section is a series of anticline and syncline folds.

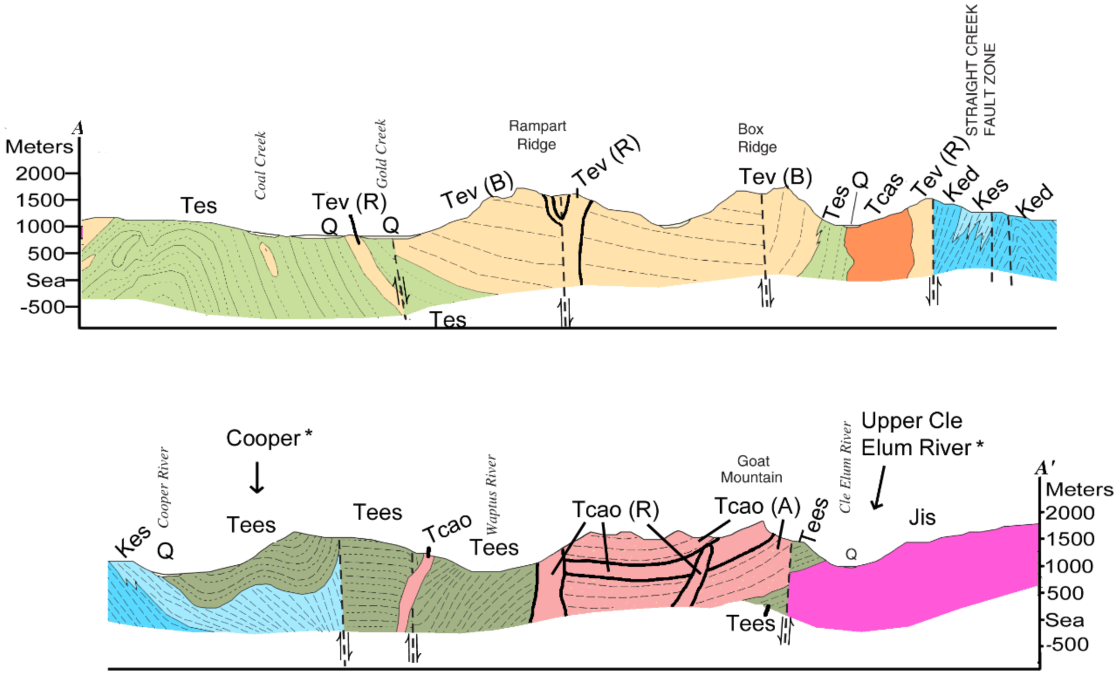

Figure 6. Cross section A, trending ~WSW-ENE located in the NW of study area. *X=sample locations projected onto cross section.

Explanation:
Q=Quaternary deposits
Tcas=Intrusive rocks of Snoqualmie family (Miocene and Oligocene)
Tcao=Ohanapecosh volcanclastic
Tes= Roslyn Fm.
Tev= Naches Fm. rhyolite and basalt
Tees= Swauk Fm sandstone
Ked=Darrington Phyllite
Kes=Shuksan Greenschist
Jis=Ingalls Formation
(Modified from Tabor et al., 2000)

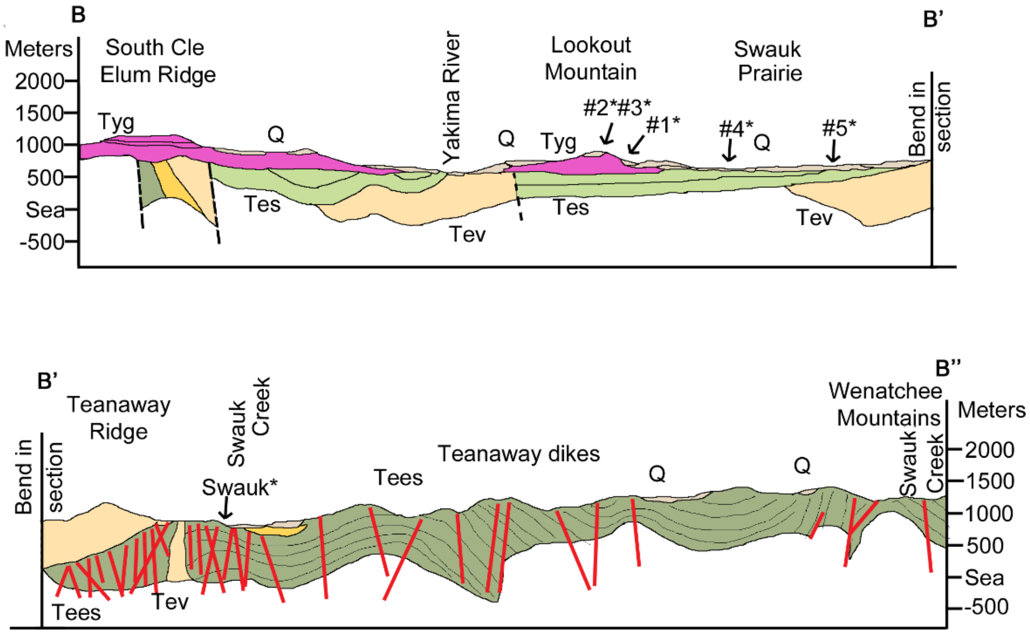

Figure 7. Cross section B, trending ~SW-NE in along the east side of the study area. *X=sample locations projected onto cross section.

Explanation:

Q=Quaternary

Tyg=Grand Ronde Basalt of the Columbia River Basalt Group

Tes= Roslyn Formation

Tev= Naches Formation rhyolite and basalt

Tees=Swauk Fm sandstone

(Modified from Tabor et al., 2000)

CHAPTER II

MATERIALS AND METHODS

Sample Selection

Water and rock samples were collected in the summer and fall of 2012. The four different types of samples collected in this study were spring waters, well waters, surface waters (streams and rivers), and rocks (Figure 8). When possible, rock samples were collected in conjunction with a water sample. In many cases, rock samples were collected from outcrops near groundwater springs. Table 3 is a list of the samples collected. Three of the surface water samples and 10 of the spring water samples were collected at the same locations as samples collected during the USGS investigation of this study area (Gendaszek, et al., 2014).

TABLE 3. SAMPLES TYPE AND LOCATION

Sample Name	Latitude	Longitude	Surface Formation
Well water			
#1	47.1864	120.7292	Q glacial till (depth n/a)
#2	47.1734	120.7407	Q glacial till (88 m deep)
#3	47.1746	120.7408	Q glacial till (depth n/a)
#4	47.1972	120.7131	Q alluvium (21 m deep)
#5	47.1842	120.9555	Q alluvium (23 m deep)
LE#7	47.2439	121.1850	Q glacial till; E ans Creek Drift (29 m deep)
LE#6	47.2539	121.1961	Q glacial till; E ans Creek Drift (38 m deep)
FIRE STATION	47.1757	120.8567	Q alluvium (141 m deep)
NORRISH RXN (S)	47.2144	120.9469	E Shale; Roslyn (upper member) **

TABLE 3 (CONTINUED)

Sample Name	Latitude	Longitude	Surface Formation
Surface Water			
BEVERLY CREEK (S)	47.3742	120.8688	E Sandstone; Swauk Fm. **
YAKIMA RIVER at CLE ELUM	47.1919	120.9491	Mix
LITTLE CREEK*	47.1721	121.0973	J Schist (low grade) Shuksan Greenschist
MEADOW CREEK (S)	47.3122	121.3533	O Volcaniclastic; Ohanapecosh Fm.
NORTH FORK TEANAWAY RIVER*	47.2522	120.8789	Mix (Swauk, Teanaway Basalt, Roslyn)**
SWAUK CREEK*	47.2433	120.6971	E Sandstone; Swauk Fm.**
UPPER CLE ELUM RIVER	47.4644	121.0480	Mix of Cenozic to Mesozoic volcanic rocks
Spring Water			
TEANAWAY SPRING*	47.2640	120.8855	E Sandstone; Roslyn (lower member)**
BEVERLY SPRING* (S,X)	47.3747	120.8753	E Sandstone; Swauk Fm.**
BLOWOUT SPRING*	47.2310	121.3007	E Rhyolite; Naches Fm., Ohanapecosh Fm.?
JUNGLE SPRING*	47.3464	120.8783	Qls; Roslyn (lower) with rhyolite flows interbeded**
COOPER SPRING (S,X)	47.4172	121.1296	E Sandstone; Swauk Fm.**
ELY SPRING* (S,X)	47.2534	121.2419	E Rhyolite; Naches Fm.
ESMERALDA SPRING* (S,X)	47.4267	120.9355	J Mafic intrusive; Ingalls Fm.
GROUSE SPRING*	47.3668	121.0816	E Sandstone; Swauk Fm.**
GUSHER SPRING*	47.3071	121.2183	E Andesite; Swauk Fm. (Silver Pass member)

TABLE 3 (CONTINUED)

Sample Name	Latitude	Longitude	Surface Formation
LITTLE SALMON LA SAC SPRING*	47.3591	121.0586	M Andesite; Howson Fm.
LOVE SPRING* (X)	47.1277	120.9645	K Phyllite, Darrington Phyllite (low grade)
Rock Sample			
OHANAPECOSH ANDESITE	47.2310	121.3223	O Volcaniclastic; Ohanapecosh Fm.
NACHES RHYOLITE	47.2867	121.2919	E Rhyolite; Naches Fm.
INGALLS META-GABBRO	47.4326	120.9363	J Mafic; Ingalls meta-basalt/gabbro
SWAUK ANDESITE	47.3071	121.2183	E Andesite; Swauk Fm.
SWAUK SANDSTONE	47.3634	121.0561	E Sandstone; Swauk Fm.**
ROSLYN SANDSTONE	47.2826	121.0501	E Sandstone; Roslyn (lower member) **

Surface geology identified from (Haugerud and Tabor, 2009) and when possible confirmed during sampling. Sample* identifies samples collected at same location as U.S.G.S. investigation (Gendaszek, et al., 2014); **= formations known to contain calcite (Haugerud and Tabor, 2009); X = Spring samples collected areas of high relief; S = Waters believed to be sourced from single lithologic unit. Well logs in Appendix C. Wells #1 and #3 were collected with the agreement that no personal information be published, including well logs. GSP for wells #1 and #3 are also generalized locations (within 1 km of location).

A total of 11 spring samples were collected (Figure 8). Four of the springs were selected for sampling because it appeared that the water would most likely have interacted with only one rock unit, therefore identifying the hydro-geochemical signature of that unit (identified with an “S” in Table 3).

Uliana et at. (2007) concluded springs in high altitude areas are typically recharged locally. Gendaszek et al. (2014) study of this area demonstrated, based on oxygen isotope data, that the spring waters are all derived from local precipitation. Five of the spring locations sampled in this study were in relatively high elevation areas (identified with an "X" in Table 3). The other springs may represent possible longer flow paths and longer residence times. However, since the dominant method of transportation suggested for this area is through fracture flow (Gendaszek, et al., 2014), and not through rock pore space, even a long flow path may have a short residence time due to very high transmissivity. Thus, the spring waters are anticipated to be modern, shallow waters, not upwelling of deep, old waters.

Stream samples were collected in both single lithology catchments as well as catchments with multiple sources. Stream samples were collected in single lithology catchments, when springs were not available, to define the specific hydro-geochemical signature of that lithology. Other surface waters were collected to specifically define the mixing of two or more hydro-geochemical signatures (Figure 8). A total of 7 surface water samples were collected (Table 3).

Six rock samples were collected to represent each of the major lithologic units in the study area. These samples were collected from outcrops that had minimal weathering or alteration to best characterize the overall geochemical signature of the unit. Sample descriptions were collected at each sampling site. Geology and mineralogy formation descriptions were compiled from published data.

Ground water samples were collected from a total of nine wells whose depths ranged from 21 m to 141 m deep. These samples were collected to further constrain the signatures of the various lithologies. The hydro-geochemical signature identified in each well will be compared to the expected signature. These wells were located both in the valley bottoms and in areas of higher elevation. Prior to sample collection the wells were pumped for at least one borehole volume, when possible.

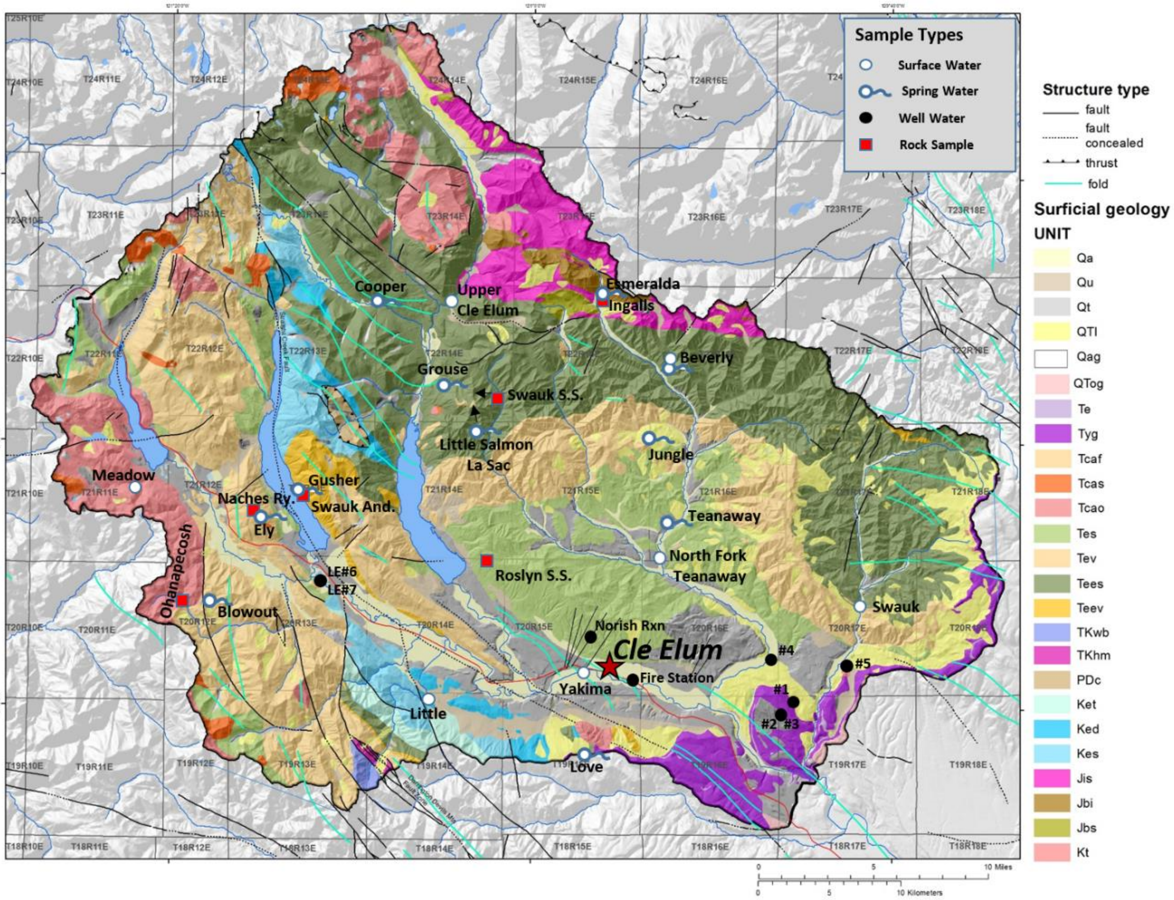

Figure 8. Map of sample types and locations.
See Figure 5 for explanation.

Sample Collection Method for Water and Rock Samples

All water samples were collected in acid-washed polyethylene containers. Detailed sample descriptions were created for each sampling site including but not limited to: sample type, time/date, GPS location, surrounding lithology, surface flow (if applicable), spring size/type (if applicable), and any notes relevant to geochemical analysis. Samples were filtered on the same day upon returning to the clean lab at Central Washington University using a sterile polypropylene syringe and filtered through 0.45 micrometer polypropylene membrane filter. Samples were placed into new acid washed polypropylene bottles for storage at room temperature until analysis preparation.

Rock samples were collected from outcrops that didn’t have any obvious signs of weathering and placed into sterile sealable plastic sample bags until sample preparation.

Sample Preparation and Analysis Summary

All samples were prepared for three different types of analysis. The samples were analyzed on an Inductively Coupled Plasma Mass Spectrometer (ICP-MS) and an Ion Chromatograph (IC) for major and trace element concentrations. Preparation for both the ICP-MS and IC analyses took place in the Geology Clean Laboratory at Central Washington University. For isotope analysis, the samples were analyzed on a Thermal Ionization Mass Spectrometer (TIMS).

ICP-MS Preparation and Analysis

An aliquot of 10 ml of each filtered water sample was loaded into an acid washed centrifuge tube. Each sample was acidified to 2% with the addition of fresh double distilled, concentrated HNO_3.

Leachate preparation took place in the Geology Clean Laboratory at Central Washington University. Each rock sample was crushed and sieved. The 2 mm portion of rock chips for each sample was collected. Two 5-gram aliquots of these chips were then leached in 15 ml 1 molar HCl. One split was leached for 2 minutes (Bohlke and Horan, 2000) the other for 10 minutes. The leachates were then decanted and centrifuged. 10 ml of each leachate was pipetted into 15 ml acid washed Teflon beakers and desiccated on a 60° C hotplate. The samples were then re-dissolved in 0.2 ml of concentrated double distilled HNO_3 and mixed with 10 ml of ultrapure DI water.

The samples were analyzed for major and trace elemental concentrations on the Thermo Elemental X Series Inductively Coupled Plasma Mass Spectrometer (ICP-MS) at Central Washington University in the Geological Sciences department. The measurements began with a calibration block consisting of a blank and nine standards ranging in concentration from 1 ppb to 1000 ppb. The acidified samples were analyzed directly after a calibration block. When necessary, the calibration curves were optimized for the range of values within the samples for a given element. Accuracy of the method was checked by analyzing a standard as an unknown. The uncertainty of this method, based on the known standard values is about ±10%. The detection limits for Mn, Zn, Rb, Sr, and Ba are 0.27, 1.09, 0.48, 0.30, and 0.33 ppb, respectively.

Ion Chromatograph Preparation and Analysis

Filtered, unacidified samples were analyzed on the Dionex DX 500 Ion Chromatograph in the Chemistry Department at Central Washington University. The samples were loaded into one-time use filter-less vials. Analysis was performed by use of an autosampler, which rinsed with milli-q water between each analysis. Samples were calibrated through the use of a cation standard containing Na, K, Mg, and Ca in concentrations ranging from 0μeq/L to 1,000μeq/L. A quality control sample was analyzed after a block of five unknowns. The uncertainty of this method, based on the known standard values was about ±10%. The detection limits for Ca, Mg, Na, and K were 0.181 ppm, 0.087 ppm, 0.107 ppm, 0.142 ppm, respectively.

^{87}Sr/^{86}Sr Preparation and Analysis

Column chromatography was performed in the Geology Clean Laboratory at New Mexico State University. Sr and Rb separations was completed in preparation for TIMS analysis. The 7 ml split of each filtered water sample and the remaining 5 ml rock chip leachate sample were desiccated and re-dissolved in 0.5 ml of 2.5 N HCl. The samples were loaded into individually calibrated glass columns containing (200-400 mesh) cation exchange resin and eluted with 2.5 N HCl. Procedure from Wolff et al. (1999) modified to use 5 ml glass columns.

The purified strontium was desiccated on a 100° C hotplate. The samples were then re-dissolved in 0.025N HNO_3 and loaded onto clean rhenium filaments with a small amount of TaO to stabilize ionization. The filaments were loaded into a VG Sector 54 mass spectrometer in the Geochemistry Department at New Mexico State University. Samples were each analyzed by using a five-collector array in dynamic mode measuring and averaging a total of 150 ratios (Wolff, et al., 1999). Rubidium was monitored continuously throughout the runs to determine if contamination occurred during column chromatography. The in-run errors given in Table 4, are 2 sigma for the ratios measured. A standard from the National Bureau of Standards (NBS) 987 = 0.710248 was analyzed with the sample set to check machine accuracy.

CHAPTER III

RESULTS

Range of $^{87}Sr/^{86}Sr$ and Major & Trace Element Concentrations

The results of the strontium isotope measurements, major (Ca, Mg, Na, and K) and trace element (Rb, and Sr) analysis for surface waters, ground waters, and rock leachates are presented in Table 4 (Mn, Zn, and Ba are listed in Appendix B). There is a wide range of $^{87}Sr/^{86}Sr$ for samples measured. The springs range from 0.7040 (Little Salmon La Sac Spring) to 0.7065 (Cooper Spring), surface waters range from 0.7048 (Upper Cle Elum River) to 0.7068 (Little Creek), and the rock leachate from 0.7042 (Ohanapecosh 2-min) to 0.7063 (Naches Rhyolite 2-min).

The rock leachates concentrations of major and trace elements are significantly higher than the water samples. Of the water samples, the well waters have higher elemental concentrations, on average about five times higher for major elements and about 2 times higher for Rb, and Sr than the spring and surface waters. Wells also have some of the highest Na concentrations.

TABLE 4. STRONTIUM ISOTOPE, MAJOR ELEMENT, AND TRACE ELEMENT DATA

Sample Name	$^{87}Sr/^{86}Sr$	2σ	$\delta^{18}O$	Ca ppm	Mg ppm	Na ppm	K ppm	Rb ppb	Sr ppb
Wells									
#1	0.705258	14	n/a	13.2	16.6	16.8	31.4	6	75
#2	0.704787	18	n/a	17.5	16.0	45.9	5.0	2	87

TABLE 4 (CONTINUED)

Sample Name	$^{87}Sr/^{86}Sr$	2σ	$\delta^{18}O$	Ca ppm	Mg ppm	Na ppm	K ppm	Rb ppb	Sr ppb
#3	0.705565	7	n/a	21.7	19.2	62.3	7.0	n/a	n/a
#4	0.704933	32	n/a	41.9	19.7	16.4	0.3*	bdl	162
#5	0.704677	10	n/a	16.8	12.6	19.1	3.0	1	113
LE#7	0.705596	13	n/a	6.5	2.8	4.0	0.5	bdl	44
LE#6	0.705789	28	n/a	3.8	1.9	3.0	0.5	bdl	35
FIRE STATION	0.704866	25	n/a	5.8	4.6	72.2	1.7	1	151
NORRISH RXN	0.704647	11	n/a	0.3	0.2	63.6	0.3	bdl	186
Surface Waters									
BEVERLY CREEK	0.705250	14	n/a	2.4	12.0	1.1	0.1	bdl	24
LITTLE CREEK	0.706807	13	-14	8.1	3.8	2.7	0.5	bdl	46
MEADOW CREEK	0.704303	8	n/a	3.1	0.7	2.9	0.2	bdl	11
NORTH FORK TEANAWAY RIVER	0.705112	15	-15	10.0*	n/a	n/a	0.3*	bdl	57
SWAUK CREEK	0.705961	25	-15	23.9	7.6	n/a	1.0	bdl	167
UPPER CLE ELUM RIVER	0.704779	10	n/a	3.4	5.5	1.2	0.6	1	11
YAKIMA RIVER AT CLE ELUM	0.705559	15	n/a	4.7	2.5	2.4	0.3	n/a	n/a
Spring Waters									
BEVERLY SPRING	0.705258	22	-15	11.9*	n/a	n/a	0.3*	bdl	32
BLOWOUT SPRING	0.704417	14	-13	3.3	2.2	5.9	0.5	bdl	23
COOPER	0.706467	15	n/a	9.3*	n/a	n/a	0.1*	bdl	45
ELY SPRING	0.706092	18	-13	1.8	0.4	1.8	0.6	1	17
ESMERALDA SPRING	0.704612	11	-15	0.2	7.5	1.0	0.1*	bdl	11
GROUSE SPRING	0.706368	10	-14	4.4	2.4	2.0	0.2	bdl	44
GUSHER SPRING	0.705795	11	-13	11.2	1.5	3.1	0.5	1	115
JUNGLE SPRING	0.704615	10	-14	18.5	4.1	5.8	3.4	1	145
LITTLE SALMON LA SAC SPRING	0.704024	11	-14	5.3	0.8	2.0	1.5	2	53

TABLE 4 (CONTINUED)

Sample Name	$^{87}Sr/^{86}Sr$	2σ	$\delta^{18}O$	Ca ppm	Mg ppm	Na ppm	K ppm	Rb ppb	Sr ppb
LOVE SPRING	0.704287	25	-15	8.4	3.2	7.2	2.2	n/a	n/a
TEANAWAY JUNC	0.704676	11	-15	15.4	13.1	7.0	0.4	bdl	99
Rock Leachates									
OHANAPECOSH 10-min	0.704188	8	n/a	190.9*	n/a	n/a	2.9*	6	197
OHANAPECOSH 2-min	0.704169	14	n/a	134.7*	n/a	n/a	1.9*	5	130
NACHES RHYOLITE 10-min	0.706109	11	n/a	51.0*	n/a	n/a	4.0*	13	553
NACHES RHYOLITE 2-min	0.706303	15	n/a	2.7	1.0	6.0	0.3	9	364
INGALLS MAFIC 10-min	0.704390	11	n/a	73.6*	n/a	n/a	0.5*	3	55
INGALLS MAFIC 2-min	0.704655	10	n/a	84.5*	n/a	n/a	0.5*	3	49
SWAUK ANDESITE 10-min	0.705313	21	n/a	128.6*	n/a	n/a	2.5*	9	198
SWAUK ANDESITE 2-min	0.705435	15	n/a	118.9*	n/a	n/a	2.5*	7	157
SWAUK SANDSTONE 2-min	0.706068	11	n/a	40.5	n/a	n/a	0.4*	2	66
ROSLYN SANDSTONE 10-min	0.704334	11	n/a	399.2*	n/a	n/a	6.9*	27	3724
ROSLYN SANDSTONE 2-min	0.704213	15	n/a	173.1*	n/a	n/a	2.3*	7	1453
$^{87}Sr/^{86}Sr$ Standard									
NBS 987	0.710265	15	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Major element analysis on IC except *values from ICP-MS analysis; bdl = below detection limit; n/a = not analyzed-no data; USGS sample # for $\delta^{18}O$ data listed in Appendix B.

^{87}Sr/^{86}Sr of 2-Minute and 10-Minute Rock Leachates

The Ohanapecosh leachate sample set is the only set that the ^{87}Sr/^{86}Sr values are within analytical error of each other. The 2-minute and 10-minute leachate samples from the Naches Formation are very similar (0.7063 and 0.7061, respectively) as well as the Roslyn 2-minute and 10-minute Leachates (0.7042 and 0.7043). Except for the Ohanapecosh set, the 2-minute leachate strontium values for the other hardrock samples (Naches rhyolite, Swauk andesite and Ingalls mafic) are all higher than their corresponding 10-minute leachate samples (Figure 9). The strontium isotopic ratios of the Roslyn sandstone leachate samples are similarly different; however, the 10-minute leachate has the higher ratio.

Ely spring and Naches rhyolite leachates are very similar with Naches Rhyolite 10-minute and Ely Spring being within error of each other. In the other 4 sets that have both 2-minute and 10-minute measurements, the strontium isotope ratio for the leachates and the water from the respective formation do not have the same signatures. In most samples, the strontium ratios of the waters are higher than the leachates.

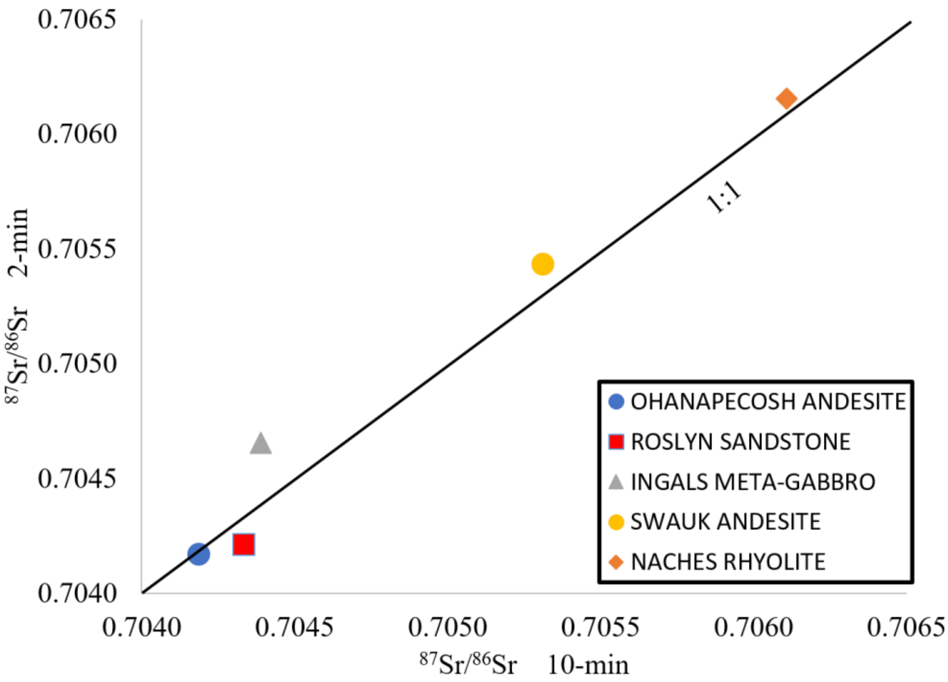

Figure 9. ^{87}Sr/^{86}Sr 2-minute leachate vs. ^{87}Sr/^{86}Sr 10-minute leachate

Major and Trace Element Concentrations

In general, the well waters have the highest major and trace element concentrations (Figure 10, Figure 11).

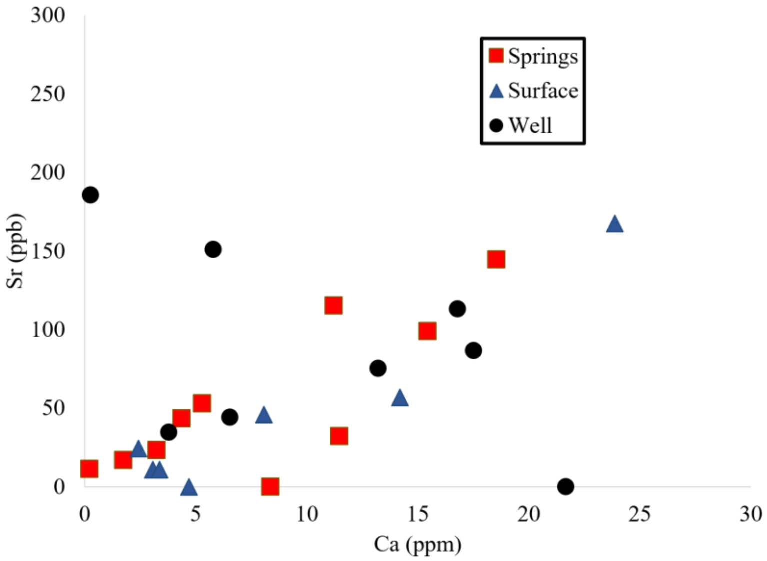

Figure 10. Calcium concentration vs. Strontium concentration

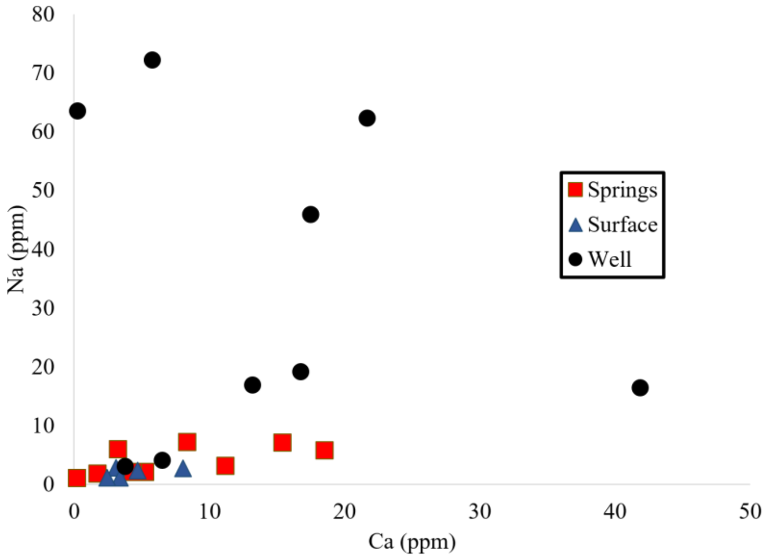

Figure 11. Calcium concentration vs. Sodium concentration

Cation Ratios vs. $^{87}Sr/^{86}Sr$

Figure 12 and Figure 13 show the $^{87}Sr/^{86}Sr$ of each sample plotted against Ca over the sum of the cations and Na over the sum of the cations, respectively.

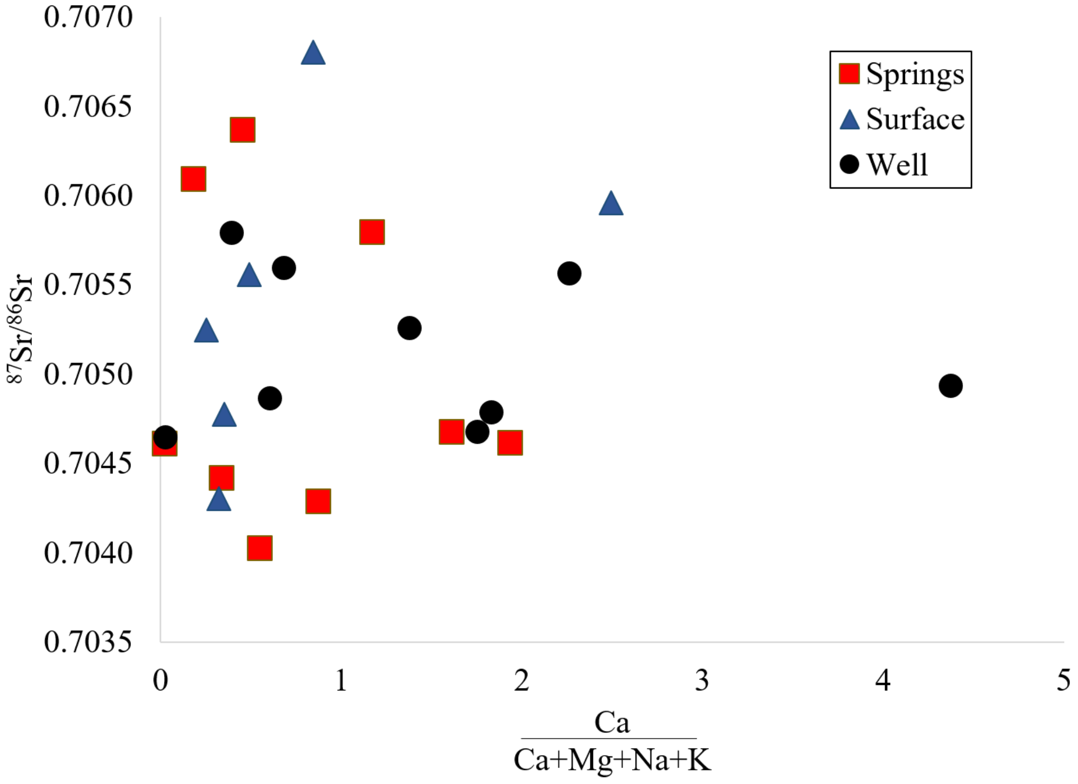

Figure 12. Strontium isotopic ratio vs. Calcium divided by the sum of the cations

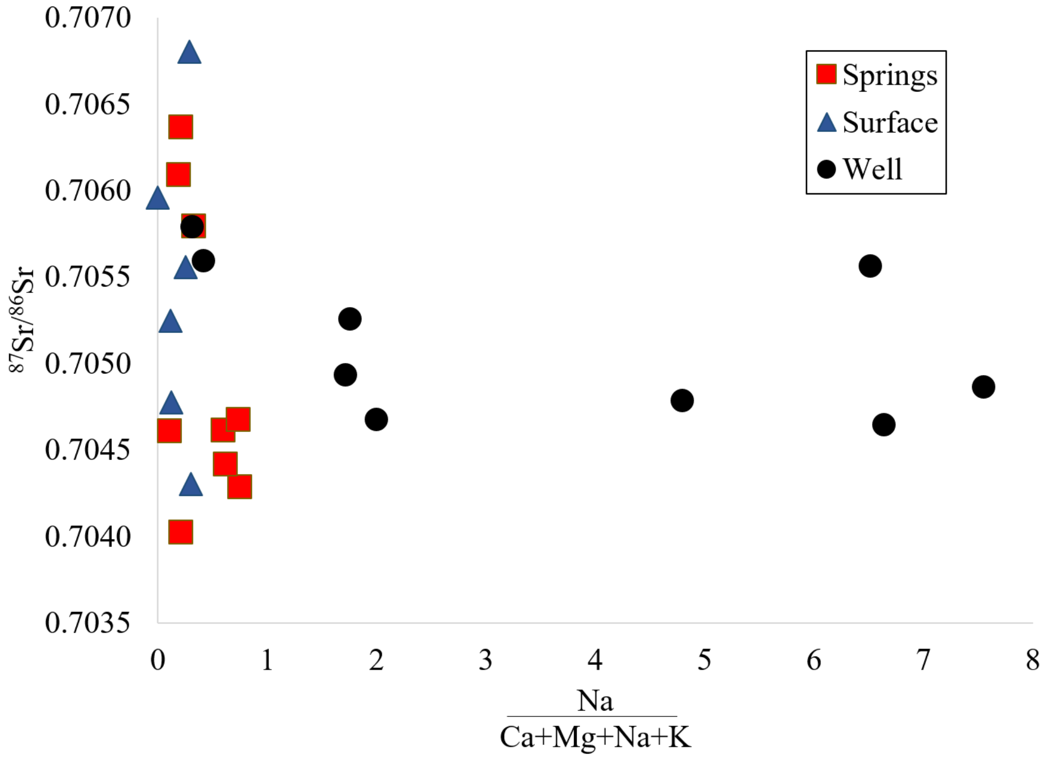

Figure 13. Strontium isotopic ratio vs. Sodium divided by the sum of the cations

CHAPTER IV

DISCUSSION

Variations in $^{87}Sr/^{86}Sr$, Major, and Trace Element Concentrations of Leachates Over Time: Possible Proxy for Weathering

The difference between the strontium isotope ratio of the 2-minute leachate and 10-minute leachate indicates certain minerals are preferentially dissolved during the leaching process. The first minerals to dissolve heavily impact the initial strontium isotope ratio of the leachate. As time elapses, other minerals more resistant to dissolution, will contribute Sr to the leachate (Yu et al., 2015). The variations in $^{87}Sr/^{86}Sr$ as time elapses during dissolution may represent the natural changes in the water as weathering occurs. As the rocks continue to weather the solution is slowly equilibrating with the rocks. The water samples collected, especially in localized systems that have short residence times, are not likely to be in equilibrium with the rocks.

It is also worth noting that the acid leaching process may leach and dissolve more than what would occur in nature. As stated previously, the signature identified from water-rock interaction are that of the minerals weathering. The acid leaching process may partially dissolve minerals that do not readily weather in natural systems. Furthermore, the leaching process may be affected differently by different rocks. Yu et al. (2015) identified the concentration in the leachate is not only impacted by the geochemical and mineralogical factors, but can be dependent upon the grain size. Smaller grain sizes are, typically, directly proportional to higher concentrations. The smaller the grain size, the higher the surface area, therefore the faster the rate of dissolution. Through a series of experiments, Yu et at. (2015) also concluded the solubility of various minerals is affected by the pH of the solution. They found that solutions with higher pH typically resulted in lower solubility. In their study, the volcanic rocks typically had the highest concentrations unless there was secondary mineralization raising the pH.

Figure 14 shows the leachate set from Ohanapecosh is the only rock sample set with no measurable difference between the 2-minute and 10-minute analyses (0.7042). The $^{87}Sr/^{86}Sr$ of the other four leachate sample sets show measurable, but generally small, differences between the 2-minute and 10-minute analysis. The $^{87}Sr/^{86}Sr$ in the Roslyn Sandstone leachate increased from 0.7042 in the 2-minute leachate to 0.7043 in the 10-minute leachate. The $^{87}Sr/^{86}Sr$ for Swauk Andesite, Naches Rhyolite, and Ingalls Formation meta-gabbro dropped between the 2-minute and 10-minute leaches indicating initial dissolution of minerals containing relatively higher $^{87}Sr/^{86}Sr$. The Swauk Andesite leachate started at 0.7054 in the 2-minute and dropped to 0.7053 in the 10-minute. The $^{87}Sr/^{86}Sr$ for Naches Rhyolite dropped from 0.7062 in the 2-minute to 0.7061 in the 10-minute. The Ingalls Mafic leachates had the greatest change starting at 0.7047 in the 2-minute and dropping to 0.7044 in the 10-minute.

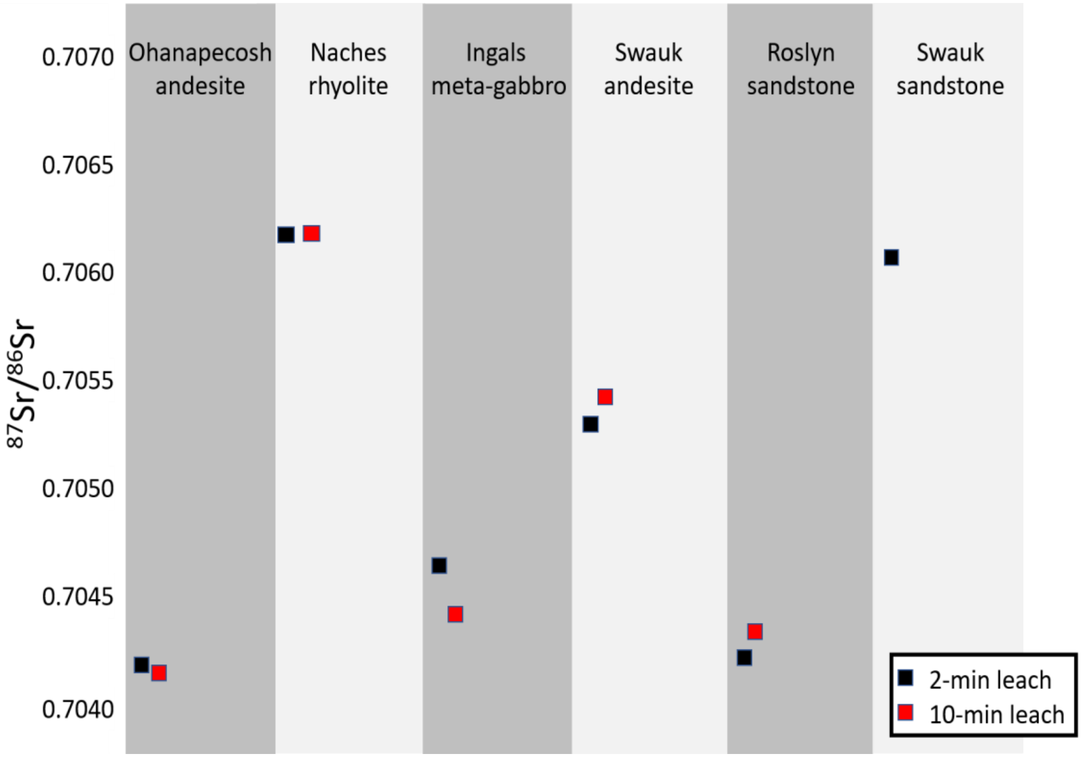

Figure 14. Leachates (2-minute and 10-minute) for each lithology

Analysis was only performed on the 2-minute Swauk Sandstone leachate. However, it is worth noting the Swauk Sandstone 2-minute analysis has a much higher ^{87}Sr/^{86}Sr (0.7061) than the sandstone of the Roslyn Formation (~0.7042).

The similarity of the 2-minute and 10-minute leachate of each set signifies a general trend that may represent the natural water-rock interaction. Even with the geochemical change through time during the leaching process the leachate sets are distinct enough from most of the other sets that a general signature becomes evident. However, the results also suggest overlap between some of the Sr isotope signatures (i.e. Roslyn and Ohanapecosh Formations have similar signatures).

Comparison of Leachates to Associated Waters: Implications for Lithologic Fingerprinting

Eight water samples (Figure 15) were chosen to characterize the water-rock signature of the unit in which they reside. These samples were identified to be waters sourced from monolithic areas and therefore, hopefully, represent the natural water-rock signature with-in each unit. These waters were then compared to their respective leachates. These samples include: Meadow Creek, Ely Spring, Esmeralda Spring, Gusher Spring, Norrish Rxn well, Cooper Spring, Beverly Spring, and Beverly Creek. The surface water sample (Meadow Creek and Beverly Creek) were collected in catchments identified to contain only one lithology. The spring water samples (when available) were collected from locations identified by topography and $\delta^{18}O$ (Gendaszek, et al., 2014) to have short flow paths and to be isolated from other sources. These criteria were established to minimized the possibility of mixing with more than one source. Ideally in these eight samples, the only contributions to the geochemical fingerprint of these waters should be the meteoric water and the constituents imparted during water-rock interaction. Thus, these waters should represent the geochemical fingerprint incurred during water-rock interaction with their associated lithologies. All of these samples are considered to represent only one lithologic unit except the sample collected at Gusher Spring. Water from this spring may contain a small component of water from the neighboring geologic unit. However, since the spring is located 2 km from the contact with the Naches Formation, substantial influence on the water chemistry is not expected.

Comparing the general ^{87}Sr/^{86}Sr general signatures constrained by the leachates to the ^{87}Sr/^{86}Sr signatures identified by each of these waters samples should determine the viability in using leachates to geochemically fingerprint water-rock interaction of each formation. Figure 15 correlates the leachates to the water samples collected in each unit.

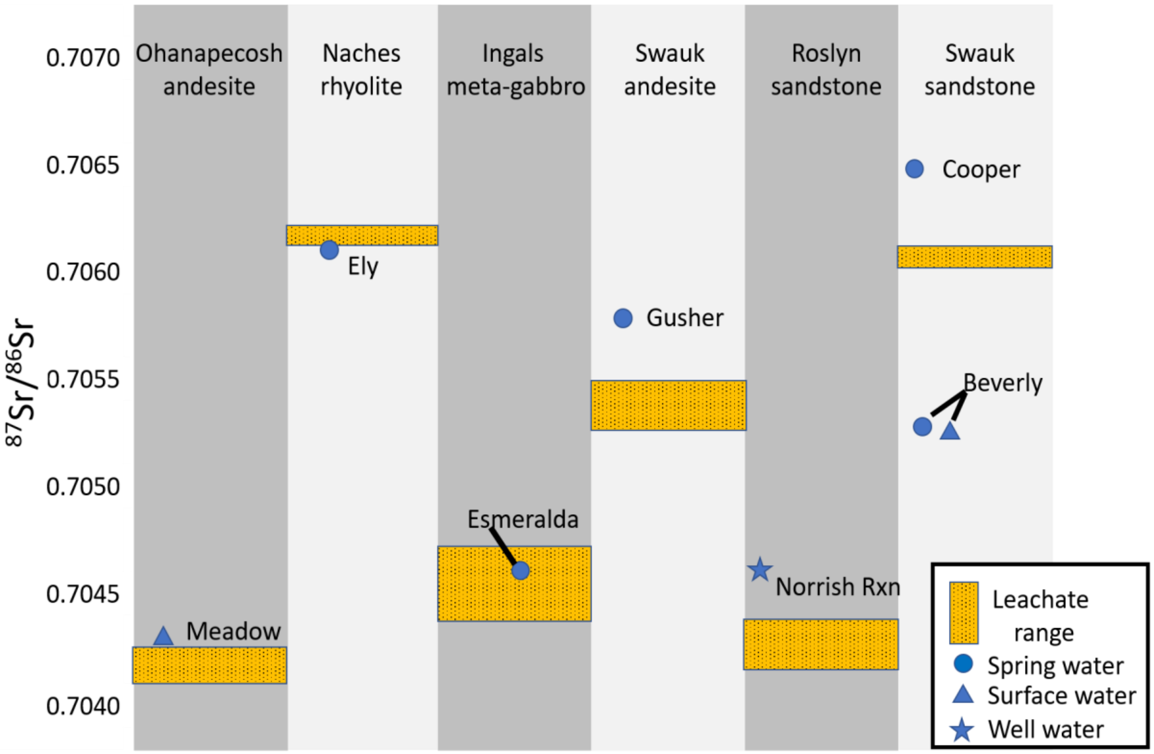

Figure 15. ^{87}Sr/^{86}Sr of leachates and monolithic waters from each unit
Leachate range: ^{87}Sr/^{86}Sr range identified between 2-min leachate and 10-min leachate

Naches Formation rhyolite and Ely Spring

The $^{87}Sr/^{86}Sr$ of Ely spring (Naches rhyolite, Figure 15) directly correlates to the $^{87}Sr/^{86}Sr$ identified in the leaching process. Furthermore, the characteristics of this spring make it ideal to evaluate the signature identified during leaching. Ely Spring is located near the top of Amabilis Mountain. Its proximity to the top of a mountain, composed of a single lithology, suggests it is highly unlikely for there to be any mixing with other lithologies. The water in this spring most likely had a flow path of less than 1 km through rhyolite bedrock of the Naches Formation (identified as Tev in Figure 6). This spring is also ideal for identifying if there is a significant influence on $^{87}Sr/^{86}Sr$ from the meteoric water. The water in this spring has a low (17 ppb) concentration of Sr. Since the $^{87}Sr/^{86}Sr$ in the water directly correlates to the $^{87}Sr/^{86}Sr$ identified in the leachate, the $^{87}Sr/^{86}Sr$ signature of meteoric water must be similar or have minimal influence.

Ingalls Formation meta-gabbro and Esmeralda Spring

The $^{87}Sr/^{86}Sr$ of the water from Esmeralda Spring measures between the two rock leachates of the Ingalls Formation, however it is more similar to the 2-minute leachate. The Ingalls tectonic complex is composed of a highly faulted metamorphic ultramafic and mafic rocks. In this case the initial dissolution, as seen in the 2-minute leachate, seems to better represent the signature seen in the spring, presumed to result from natural water-rock interaction. This initial dissolution could be incorporating Sr from easily weatherable secondary alteration such as the carbonate rocks located near the faults. Assuming the mafic and ultra-mafic signatures of the Ingalls Formation are similar to the low $^{87}Sr/^{86}Sr$ commonly measured in mafic and ultra-mafic rocks from mid ocean ridge basalts; the 10-minute leachate may be incorporating Sr from minerals which are more weathering resistant and therefore trending towards a lower $^{87}Sr/^{86}Sr$ as expected for this type of bulk rock.

The water from Esmeralda Spring has a low Sr concentration of 11 ppb. This low concentration and drastically different $^{87}Sr/^{86}Sr$ signature compared to Ely Spring suggests the influence of the meteoric water signature is negligible. The $^{87}Sr/^{86}Sr$ measured in the springs is dominated by the water-rock interactions.

Ohanapecosh Formation andesite and Meadow Creek

Meadow Creek is a surface water sample collected from a sub-basin that draws dominantly from the Ohanapecosh Formation and is expected to represent water-rock interaction with this unit. The Meadow creek drainage is about 8 km to the northwest of where the rock sample was collected, however it has an $^{87}Sr/^{86}Sr$ similar to the leachate signature.

The Swauk Formation andesite and Gusher Spring.

The water sample from Gusher Spring and rock sample for the Swauk Formation andesite were both collected at the same location. The difference between the leachate grouping and the water could result from the formation being heterogenous, water mixing from another source, or the water interacting with a mineral precipitate. The Sr and Ca concentration for this spring is significantly higher than average for the other springs, however the K and Rb are in the same range. These higher than average concentrations could be a result of the chemical weathering of minerals that contain higher Ca and Sr or interaction of the water with a precipitate like calcium carbonate.

Roslyn Formation sandstone and Norrish Rxn well

The difference between the Roslyn Formation sandstone leachate and the signature measured in the Norrish Rxn well water could result from the leaching process not accurately representing the natural water-rock interaction. The high Na in the water from the Norrish Rxn well indicates this well draws from an older evolved aquifer. This water residing and interacting with the Roslyn Formation sandstone may be incorporating signatures from minerals differently than as measured during the leaching process. This variation could also result from slight heterogeneity in the Roslyn Formation. However, even though these samples were collected approximately 10 km apart and the similarity in signatures (0.7043 – 0.7047) do constrain a general $^{87}Sr/^{86}Sr$ for this unit.

Swauk Formation sandstone, Cooper Spring, Beverly Spring, and Beverly Creek

The sandstone of the Swauk Frmation has the greatest variation between the leachate and the waters. The waters considered to represent the water-rock interaction in this unit were collected from Cooper Spring, Beverly Spring and Beverly Creek. Beverly Spring and Beverly Creek have the same $^{87}Sr/^{86}Sr$ which is very different than the value from Cooper.

The Swauk Creek sample to the far east of the study area has a relatively high $^{87}Sr/^{86}Sr$ (0.7060) which is similar to the Swauk Sandstone leachate. These variations suggest the Swauk Formation is geochemically consistent on a local scale, but is regionally heterogenous.

It is unknown if the Swauk Formation sandstone is derived from the same protolith. The regional $^{87}Sr/^{86}Sr$ variations measured throughout the Swauk Formation sandstone may result from deposition of sediments from different formations. Another factor that could impact the geochemistry in the eastern portion of the Swauk Formation sandstone are the basaltic dikes (Figure 7, B'-B"). These intrusions, along with any hydrothermal alterations resulting from the intrusions, could drastically change the geochemistry of this portion of the Swauk Formation sandstone.

Even with the geochemical change through time during the leaching process and the heterogeneity of the Swauk Formation sandstone, the similarity of each leachate sets to their respective waters does indicates this leaching method identifies a general geochemical signature of the water-rock interaction.

Comparison of Lithologic Signatures to All Associated Waters

In most cases only one monolithic water sample was collected from each lithology; however, in the majority of the geologic units, samples were collected that may have interacted with more than one lithology. The waters from the Upper Cle Elum River and Swauk Creek each sampled more than one lithology, but in both cases one lithology dominates their respective sub-basins. The Swauk Creek sample was collected at the southern extent of the sandstone of the Swauk Formation, representing mostly Swauk Formation. The upper Cle Elum River sample was collected at the southern extent of the Ingalls Terrain (Jis and Jbi on Figure 5 and Figure 8), but the south side of this catchment is dominated by the Ohanapecosh Formation with some Swauk Formation as seen in the A-A' cross section (Figure 6, Upper Cle Elum River and Figure 16).

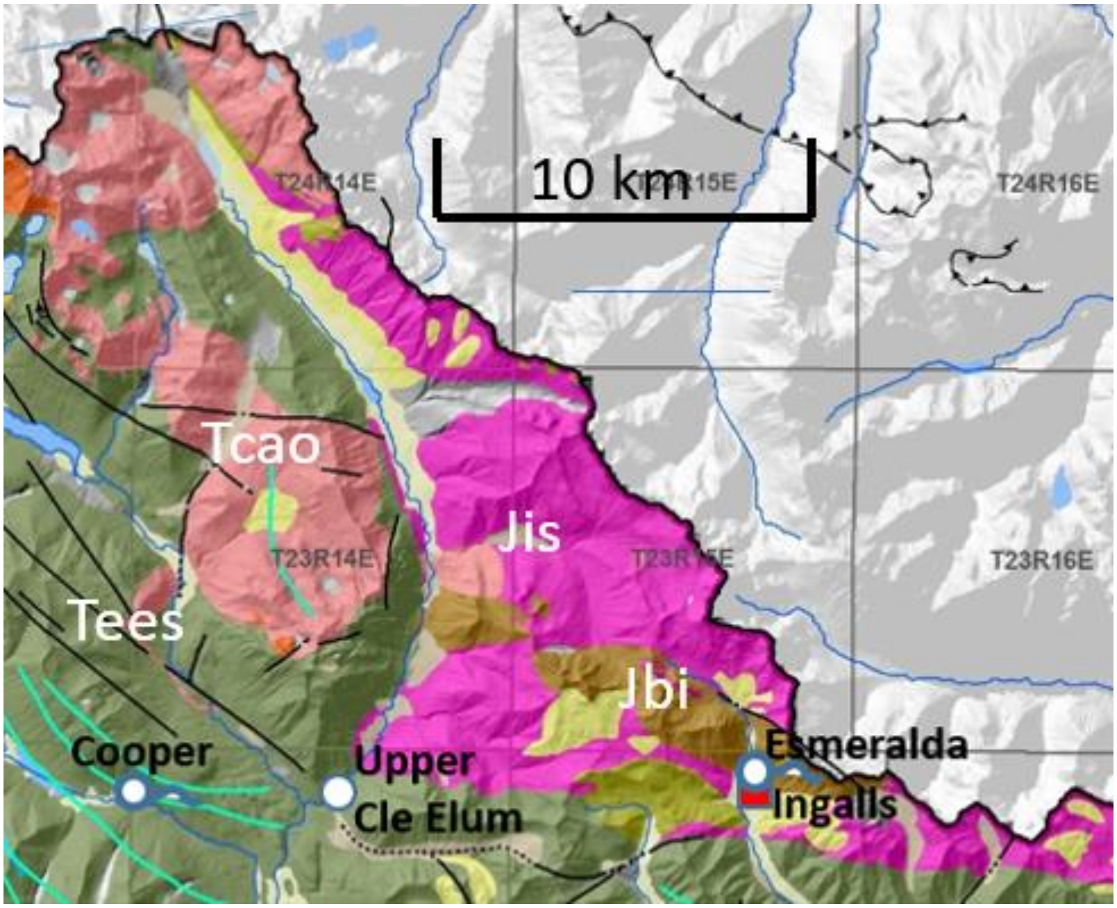

Figure 16. Close-up geologic, sample map of the Upper Cle Elum River catchment. Lithologic symbols identified in white font; Gray is out of study area; See Figure 5 for explanation.

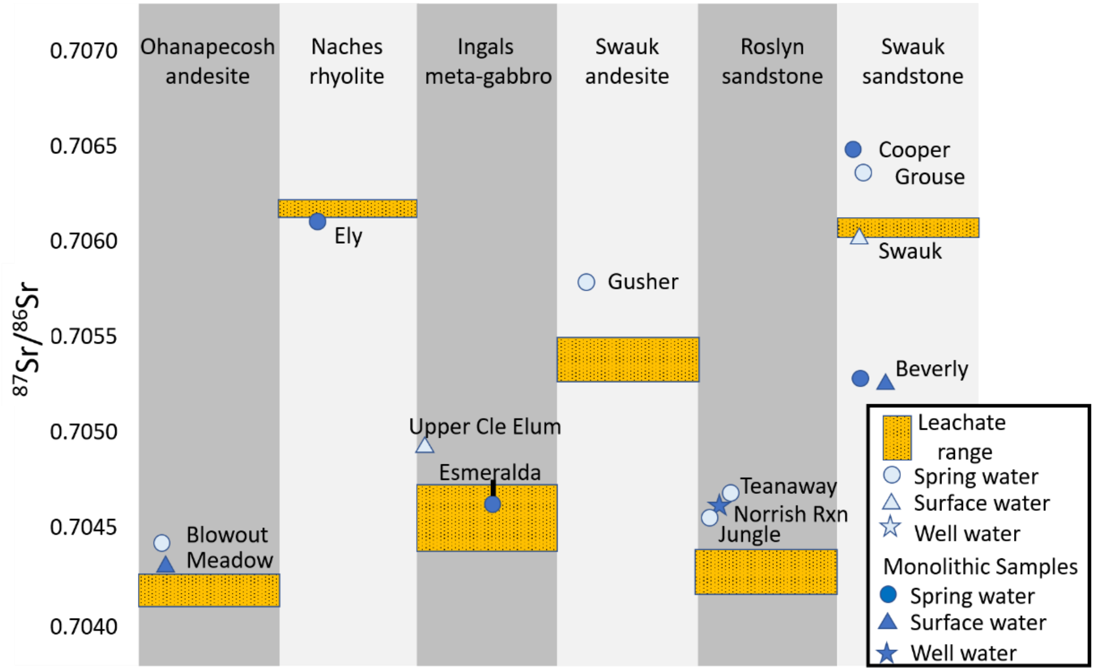

Figure 17. General lithologic signature compared to all associated waters

Samples from Teanaway Spring, Blowout Spring, and Grouse Spring are not classified as monolithic due to the possibility of interaction with more than one lithology/source. The Grouse Spring is located in the Swauk Formation rhyolite but it is down gradient of the contact with the Naches Formation and may have a component of water from both lithologies. Blowout Spring is located in a faulted area in the Naches Formation, but is down gradient from the Ohanapecosh Formation. The Teanaway Spring is in the Teanaway Valley and may include water from the Teanaway River. The $^{87}Sr/^{86}Sr$ of these spring waters, along with the $^{87}Sr/^{86}Sr$ of the waters from Swauk Creek and Upper Cle Elum, are plotted in comparison to general signatures of each unit on Figure 17.

Blowout Spring: Ohanapecosh Formation signature

Blowout spring was collected just down gradient of the Ohanapecosh Formation andesite rock sample. However, the spring is located across a faulted contact with the rhyolite of the Naches Formation. The slightly higher $^{87}Sr/^{86}Sr$ identified in Blowout Spring versus Meadow Creek could be the result of mixing with multiple sources or could be natural geochemical variation throughout the Ohanapecosh Formation. The variation could also result from the water interacting with any secondary mineralization related to the faulted area.

Upper Cle Elum River: Ingalls Formation signature

The water collected from the Upper reach of the Cle Elum River (0.7048) has a slightly higher $^{87}Sr/^{86}Sr$ than the general signature identified for the Ingalls Formation. The catchment for this portion of the river is a mix of mostly Ingalls Formation with some sandstone from the Swauk Formation and a small amount of Ohanapecosh Formation. The $^{87}Sr/^{86}Sr$ value seen in the river is the result of the waters from each lithology mixing. As a result of the higher elevations the majority of water is probably coming from the northern side of the catchment, which is dominated by Ingalls Formation. This water would mix with lesser quantities of water from the Swauk and Ohanapecosh Formations.

Jungle Spring: Possible Roslyn Formation signature

Jungle Spring and Teanaway Spring are both related to the Roslyn Formation. The leachate and the water sample from the Norrish Rxn well (0.7046) are similar enough to define a general signature. Comparing this signature to other samples in the same lithology demonstrates the Roslyn Formation has a regionally consistent geochemical weathering $^{87}Sr/^{86}Sr$ signature of approximately 0.7045.

The Jungle Spring is a high elevation spring and sourced from local water, however the unit in which it resides is unclear. It was expected to be in the Teanaway Basalts, however a landslide covers the area. Close investigation of the area indicates the spring is located near the contact between the Teanaway Basalts and the Roslyn Formation. The $^{87}Sr/^{86}Sr$ of the spring water is consistent with the signature seen in the rest of the Roslyn Formation (Figure 17). Since the signature of the Teanaway Basalts was never constrained, it is inconclusive which formational signature this spring represents.

North Fork of the Teanaway River: Mixing of Swauk and Roslyn Formational waters

The North Fork of the Teanaway River flows from the Swauk Formation sandstone (Figure 6) through the Teanaway Basalts and into the Roslyn Formation. This river (0.7051) is higher than the other signatures identified in the Roslyn Formation. Based on the path of the river, the $^{87}Sr/^{86}Sr$ measured in this river suggests mixing of waters sourced from the Swauk Formation sandstone and waters from the Roslyn Formation sandstone.

Teanaway Spring: Roslyn Formation signature

Initially the water sample collected at the Teanaway Spring (0.7047) was suspected to be heavily influenced or completely sourced by water from the North Fork of the Teanaway River. This does not seem to be the case. The spring is located near the valley bottom, but has a signature more similar to Norrish Rxn water (0.7046) than the water from the North Fork of the Teanaway River (0.7051). In this case the spring may be sourced from the hills to the NW rather than resurfacing the of the North Fork of the Teanaway River (Figure 18).

Figure 18. Close-up geologic, sample map of the Roslyn Formation. Lithologic symbols identified in white font; See Figure 5 for explanation.

Grouse Spring: Swauk Formation signature

The $^{87}Sr/^{86}Sr$ signature identified in the sandstone of the Swauk Formation ranges from 0.7053 to 0.7065. The Swauk Formation sandstone leachate, which was collected near Grouse Spring has an $^{87}Sr/^{86}Sr$ of 0.7061.

The water from Grouse spring, which was collected down gradient of the Little Salmon La Sac Spring (Figure 19) was initially anticipated to be a resurfacing of the Little Salmon La Sac Spring. However, the $^{87}Sr/^{86}Sr$ of Grouse spring (0.7064) is more consistent with the $^{87}Sr/^{86}Sr$ signature identified in the western portion of the Swauk Formation sandstone (0.7061-0.7065) than the signature identified in the waters of the Little Salmon La Sac Spring (0.7040). Furthermore, the Sr/Ba for Grouse Spring is also similar to Cooper Spring, 45 and 44 respectively. The geochemistry identified in the waters from Grouse Spring suggest the source be dominantly Swauk Formation sandstone with no significant mixing waters from Little Salmon La Sac Spring.

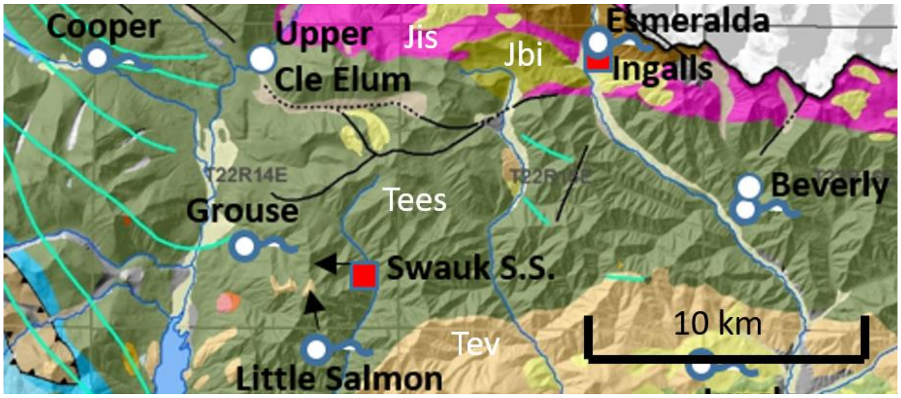

Figure 19. Close-up geologic, sample map of Swauk area.
Lithologic symbols identified in white font; Gray is out of study area. See Figure 5 for explanation.

Comparison of Lithologic Signatures to Wells

By evaluating the geologic and topographic environment of each well, it is possible to identify the various lithologies that may be contributing water to the aquifer from which the well draws. By then comparing these possibilities to the signatures constrained in the previous sections some of the well sources have been identified.

Fire Station well: Roslyn Formation signature not Yakima River water

The Fire Station sample shows an $^{87}Sr/^{86}Sr$ value of 0.7049. The Fire Station well is only about 300 meters from the Yakima River, however this well draws water from the Roslyn Formation sandstone between 128 meters and 140 meters bgs (below ground surface). Based on the well logs, there is a possible confining layer in this area of the Roslyn Formation. A clay layer is logged from 33 meters to 60 meters bgs. Further evidence of a confining layer is that, during drilling, very little water was seen above 128 meters bgs.

The high Na concentrations also suggest this well is dominated by older, evolved water; not a mix of surface water. The slightly higher $^{87}Sr/^{86}Sr$ as compared to the Roslyn Formation signature is probably a result of regional variation.

Well #4: mixing of Roslyn Formation signature and Teanaway River water

The #4 is located at the base of the Teanaway Valley near the Teanaway River. The well water is drawn from the Roslyn Formation gravel and sandstone at 15 m to 21 m below ground surface. Cross section B-B’ (Figure 7) illustrates the Roslyn Formation in this area is unfolded and overlain by alluvium. The $^{87}Sr/^{86}Sr$ ratio of the well water is 0.7049. The signature of the entire Teanaway River is unknown, but using the North Fork as a proxy the well seems to represent mixing between the river and the formation. Gendaszek, et al. (2014) did a thermal stream survey along the North Fork of the Teanaway and found evidence of groundwater seepage in this area. This well water also has relatively moderate Na concentrations suggesting a component of evolved water. The high Ca and Sr concentrations measured could be indicative of interaction with calcium carbonate, a common precipitate in the Roslyn Formation sandstone. The water in this well is most likely a mix between the Teanaway River water and water sourced from the Roslyn Formation.

#5 Well: Roslyn Formation signature + possible Grande Ronde signature

Well #5 is located in the valley bottom near the Swauk Creek. The well is near the contact between the Roslyn Formation to the west, the Grande Ronde Basalts to the east, and the Naches Formation basalts (Figure 7). The water in this well is drawn from the Roslyn Formation sandstone and gravel between 5 m and 23 m below ground surface. The well sample collected has an $^{87}Sr/^{86}Sr$ ratio of 0.7045. The $^{87}Sr/^{86}Sr$ signature identified in the Swauk Creek was much higher (0.7060) than the what is seen in the well. The Grande Ronde Basalts have a whole rock $^{87}Sr/^{86}Sr$ range of 0.7040 to 0.7055 (Wolff et al., 2008). However, a study by Ramos et al. (2005) indicates the plagioclase in the Grande Ronde has an $^{87}Sr/^{86}Sr$ around 0.7060. Most likely the aquifer supplying well #5 has a component of mixing between multiple sources, however the relatively low $^{87}Sr/^{86}Sr$ ratio indicates the water in this aquifer is not dominated by water derived from Swauk Creek.

#1, #2, #3 Wells: Columbia River Basalts aquifer

Wells #1, #2, #3 are all located near the top of Lookout Mountain in the southeastern portion of the study area. Wells #2, and #3 both have relatively high Na concentrations. This suggests older, evolved water. Well #1 has relatively moderate Na suggesting slightly evolved water. All three of these wells are drilled into the Grande Ronde Formation of the Columbia River Basalts. The $^{87}Sr/^{86}Sr$ for these wells range from 0.7048 to 0.7056. This is consistent with the whole rock $^{87}Sr/^{86}Sr$ range (0.7040-0.7055) identified for the Grande Ronde Formation (Wolff et al., 2008).

Well #2 is approximately 100 m deep (depths of #1 and #3 are unknown). The Grande Ronde in this area is mapped to by approximately 250 m deep (Figure 7, B-B’). Therefore, based on the geology and topography of this area, it is unlikely the wells draw from any other unit. The geology in conjunction with the geochemistry suggests these waters are sourced locally and only interact with the Grande Ronde Formation. Well #2 and #3 are most likely older, more evolved waters, whereas well #1 probably has a component of recharge water.

LE#6 and LE#7: Yakima River water + possible Naches Formation rhyolite signature

The wells (located in Easton) LE#6 and LE#7 have strontium ratios of 0.7058 and 0.7056, respectively. Easton is located in the bottom of the valley just downstream of the confluence of the Yakima and the Kachees Rivers. Based on the well logs, both of these wells draw water from the unconsolidated valley fill near the Yakima River. Both samples have relatively high $^{87}Sr/^{86}Sr$ values that are similar to the value identified in the Yakima River (0.7056). The major element concentrations in the waters in these wells is also similar to the Yakima River water sample. The local geology, well logs, and geochemistry all suggest the water in these wells is dominated by Yakima River water. The slightly higher $^{87}Sr/^{86}Sr$ in LE#6 might suggest a component of water mixing from the Naches Formation.

Limitations of Fingerprinting Units in Geologically Complex Areas

Complex geology such as multiple contacts, faulting, and veins, along with variations in weathering rates will all result in variations in the geochemical signatures imparted onto the waters with which the interact. These variations as seen in some of the units and sub-basins in the Upper Kittitas County and can make constraining the signature of one specific unit impossible without more detailed localized mapping and sampling to better characterize the changes. One such sub-basin is the Little Creek catchment in the southern portion of the study area.

Little Creek

Little Creek (0.7068) sample was collected in a small catchment, along the ridge to the west along, which is composed mostly of the Shuksan Greenschist, but the headwaters of this catchment are located in the Darrington Fault zone (Figure 20). This small catchment interacts with six different geological units as well as a fault zone that most like has an abundance of secondary mineralization. All of these variations could make it difficult to constrain the fingerprint of the water-rock interaction for any specific unit unless each unit was characterized.

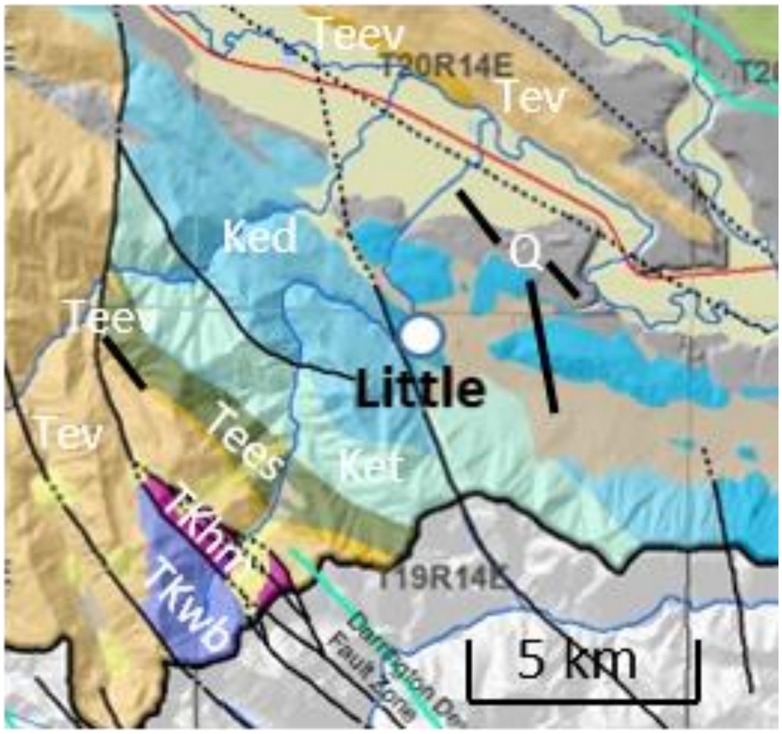

Figure 20. Close-up geologic, sample map of the Little Creek catchment.
Lithologic symbols identified in white font; Gray is out of study area; See Figure 5 for explanation.

Love Spring

Love Spring (0.7043) is another example of the limitations of sampling a single location in hopes of characterizing an entire area. This spring is located near the top of the South Cle Elum Ridge along the southern edge of the study area. This area has substantial weathering and is near the contacts between the Darrington Phyllite Formation (interbedded with Shuksan Greenschist), the Grande Ronde Basalts, and the Ohanapecosh Formation (Figure 21). In addition to the existence of multiple bedrock lithologies, the geochemistry in this spring is likely be influenced by soil weathering and/or cation exchange in the soil because of the extent of chemical weathering. All of these factors make it difficult to source this water or use it as a proxy for the signature of the local area. The $^{87}Sr/^{86}Sr$ is similar to that identified in the Ohanapecosh Formation, however the signature of 3 of the 4 possible sources are unknown.

Figure 21. Close-up geologic, sample map of South Cle Elum Ridge.

Lithologic symbols identified in white font; Gray is out of study area; See Figure 5 for explanation.

CHAPTER V

CONCLUSIONS

Using $^{87}Sr/^{86}Sr$ of Leachates and Waters to Identify Water-Rock Interaction: A Limited but Useful Technique

Leaching of the rocks can in some situations provide a general $^{87}Sr/^{86}Sr$ fingerprint of the natural weathering process. This was found to work best in single lithology areas, if the lithology is geochemically homogenous. Based on the comparison of the monolithic water samples and the leachate sets, 4 of the 6 sets provided a general $^{87}Sr/^{86}Sr$ signature of the natural water-rock interaction. Comparison of these signatures to waters collected in areas that may contain influences from multiple sources identified which sampling locations were dominated by one aquifer and which samples showed signatures resulting from mixing.

The difference between Little Salmon La Sac Spring, located in the Howson Formation, and Grouse Spring, located in the Swauk Formation sandstone, is a perfect example of using the $^{87}Sr/^{86}Sr$ signatures of various lithologies to distinguish waters sourced when the flow path is unknown. The geologic fingerprint was identified for both the local Swauk Formation sandstone and the Howson Formation andesite. Although Grouse Spring is down gradient from the Little Salmon La Sac Spring they have different signatures indicating they are not in communication. Another example of the usefulness of this technique was in sourcing the waters at the Teanaway Spring. The spring is located in close proximity to the river; however, the signature of the spring is consistent with the signature of the Roslyn Formation, not the river. This demonstrated the source of the water in the Teanaway Spring is from the mountainous areas to the northwest of the spring, not the river to the east.

The regional geochemical variations seen in the sandstone of the Swauk Formation identify the limitations of collecting a single sample to characterize the complex water-rock interactions throughout an entire lithologic unit. While this does work in small, homogenous catchments and simple aquifer systems; regional systems should have more sampling to better characterize the possible changes in the geochemical signature.

The Teanaway River basin would be an ideal sub-basin to apply this technique in greater detail. Predominantly, characterization of the chemical changes in the lithology throughout the Swauk sandstone through detailed rock and water sampling would be required. Followed by sampling/characterization of the Teanaway Basalts and more detailed characterization of the Roslyn Formation. With the detailed classification of the various sources, this technique would most likely be able to identify specific flow paths, but could also provide enough information to quantify the extent of influence by each source.

For most of the leachate sets, the 2-minute and 10-minute methods provided a range of mineral dissolution, however in only a couple situations did the associated waters fall in this range. Use of a weaker acid or a water leach may improve the accuracy of the $^{87}Sr/^{86}Sr$ in the leachates and better represent the natural water-rock interaction see in some of the associated waters.

In some cases, the Sr isotopic signature alone was distinct enough to distinguish various sources, but in many cases the $^{87}Sr/^{86}Sr$ range identified in a lithology had overlap with the ranges identified in other lithologies. The major and trace element concentrations were measured in the hope of distinguishing between the units when overlap occurred, but since the concentrations are heavily impacted by residence time they were not helpful in specifically identifying geochemical signatures. However, by identifying the most likely lithologic sources and comparing a water's geochemistry to local signatures, many waters can be sourced. This worked best in simple catchment systems that only have a few possible sources. In more complicated areas the individual signature of each water system would need to be better constrained. This can be accomplished with the aid of measuring another lithologic dependent isotopic system (i.e. U/Pb or Pb/Pb system). Identifying the isotopic signatures of lithologies using various isotopic systems would likely improve our ability to fingerprint water-rock interaction, by allowing us to further distinguish between the lithologies.

The use of this technique combined with the measurements of another lithologically influenced isotopic system could be very useful in identifying flow paths in both simple and complex geologic systems. This study also demonstrated this technique can be used in areas to determine communication between aquifers as well as communication between surface and ground water. An example of the applications for this these techniques would be in areas of water right disputes or identifying possible flow paths of contaminants in bedrock aquifers.

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APPENDIXES

APPENDIX A

GEOLOGIC DESCRIPTIONS

TABLE 5. GEOLOGIC UNITS AND EXPLANATIONS

Map Key	Surface Formation	Description
Tcaf	M Andesite; Howson Fm.	Andesite, basaltic andesite, and basalt flows and flow breccias; subordinate porphyritic hornblende and crystal-lithic tuff; some flows contain both clinopyroxene and orthopyroxene; minor mudflow breccia, dacite, volcanic sandstone, conglomerate, and siltstone.
Tcas	M and O Intrusive rocks of Snoqualmie family	Tonalite, granodiorite, and granite; rare gabbro.
Tcao	O Volcaniclastic; Ohanapecosh Fm.	Greenish to brown and maroon, andesitic to basaltic lithic breccia, tuff, and tuff breccia, and volcanic siltstone, sandstone, and conglomerate; interbedded with basalt and andesite flows and rare dacite to rhyolite flows and tuffs; breccias typically very thickly bedded, poorly sorted.
Tes	E Sandstone; Roslyn (lower member)	Micaceous feldspathic sandstone and lithofeldspathic sandstone interbedded with siltstone, shale, claystone, and coal; locally, interbedded with lava flows, tuffs, volcaniclastic breccias, and pebble conglomerates, and brackish-water deposits
	E Shale; Roslyn (upper member)	Lithofeldspathic to feldspathic sandstone, conglomerate, siltstone, shale, and coal; interbeds of basaltic to rhyolitic tuffaceous and pumiceous sandstone and tuff; conglomerate includes chert and quartz pebbles and cobbles; weakly metamorphosed in part; abundant muscovite, minor biotite.
Tev	E Basalt; Teanaway Basalt	Mostly basalt and rhyolite flows, breccia, and tuff; locally interbedded with feldspathic sandstone, conglomerate, siltstone, shale, and argillite.
	E Rhyolite; Naches Fm.	Rhyolite flows, domes, welded crystallithic ash flow tuffs containing pumice lapilli, and associated flow breccia; minor andesite flows; thin feldspathic sandstones and shales interbedded with tuffs; contains associated plugs and dikes on Teanaway Ridge

TABLE 5 (CONTINUED)

Map Key	Surface Formation	Description
Tyg	Grande Ronde Basalt	Fine- to medium-grained aphyric to slightly plagioclase porphyritic basalt
Tees	E Sandstone; Swauk Fm.	Micaceous-feldspathic and lithofeldspathic sandstone and pebbly sandstone, with carbonaceous siltstone, shale, conglomerate, and coal; locally interbedded with tuff and volcanic breccia.
Teev	E Andesite; Swauk Fm . (Silver Pass member)	Rhyolite, dacite, andesite, and volcaniclastic rocks; locally interbedded with feldspathic sandstone, conglomerate, siltstone, shale, and argillite; local gabbro and diabase; associated plugs and dikes; rare coal
Ked	K Phyllite, Darrington Phyllite (low grade)	Very fine grained, black to gray, graphitic chlorite-sericite-quartz phyllite; commonly highly crenulated; locally interbedded with greenschist and blueschist.
Kes	K Schist (low grade) Shuksan Greenschist	Very fine grained, black to gray, graphitic chlorite-sericite-quartz phyllite; commonly highly crenulated; locally interbedded with greenschist and blueschist.
Jis	J UltraMafic intrusive; Ingalls Fm.	Serpentinite, peridotite, and dunite; locally with layers of chromite; metamorphosed to talc-, tremolite-, or anthophyllitebearing rock near plutons and to silica-carbonate rock near faults; occurs as melange matrix or as dismembered blocks of ophiolite
	J Mafic intrusive; Ingalls Fm.	Metamorphosed diabase, gabbro, and diorite; locally mylonitic; in the Ingalls Tectonic Complex, includes metamorphosed basalt, tuff, and pillow breccia and minor siliceous argillite and chert; includes layered gabbro and interlayered cumulate ultramafic rocks.

(Modified from Haugerod and Tabor, 2009)

APPENDIX B

ALL GEOCHEMICAL DATA

TABLE 6. WELL WATER DATA

Name (USGS Site #)	$^{87}Sr/^{86}Sr$	2σ	$\delta^{18}O$	Ca ppm	Mg ppm	Na ppm	K ppm	Mn ppb	Zn ppb	Rb ppb	Sr ppm	Ba ppb
#1	0.705258	14	N/A	13.2	16.6	16.8	31.4	bdl	139	6	75	8
#2	0.704787	18	N/A	17.5	16.0	45.9	5.0	bdl	1	2	87	3
#3	0.705565	7	N/A	21.7	19.2	62.3	7.0	N/A	N/A	N/A	N/A	N/A
#4	0.704933	32	N/A	41.9	19.7	16.4	0.3*	3	386	bdl	162	13
#5	0.704677	10	N/A	16.8	12.6	19.1	3.0	41	3	1	113	24
LE#6	0.705789	28	N/A	3.8	1.9	3.0	0.5	25	60	bdl	35	1
LE#7	0.705596	13	N/A	6.5	2.8	4.0	0.5	7	10	bdl	44	2
FIRE STATION	0.704866	25	N/A	5.8	4.6	72.2	1.7	13	21	1	151	13
NORRISH RXN	0.704647	11	N/A	0.3	0.2	63.6	0.3	4	22	bdl	186	25

Major element readings from IC analysis, except *ICP-MS; Trace element from ICP-MS; $^{87}Sr/^{86}Sr$ from TIMS; Stable isotope data from (Gendaszek, et al., 2014)

TABLE 7. SURFACE WATER DATA

Name (USGS Site #)	^{87}Sr/^{86}Sr	2σ	δ^{18}O	Ca ppm	Mg ppm	Na ppm	K ppm	Mn ppb	Zn ppb	Rb ppb	Sr ppm	Ba ppb
BEVERLY CREEK	0.705250	14	N/A	2.4	12.0	1.1	0.1	bdl	1	bdl	24	2
LITTLE CREEK (12477340)	0.706807	13	-14.29	8.1	3.8	2.7	0.5	bdl	2	bdl	46	11
MEADOW CREEK	0.704303	8	N/A	3.1	0.7	2.9	0.2	bdl	2	bdl	11	2
NORTH FORK TEANAWAY RIVER (12479690)	0.705112	15	-14.94	10.0*	N/A	N/A	0.3*	bdl	1	bdl	57	13
SWAUK CREEK (12481100)	0.705961	25	-14.67	23.9	7.6	N/A	1.0	bdl	3	bdl	167	13
UPPER CLE ELUM RIVER	0.704779	10	N/A	3.4	5.5	1.2	0.6	bdl	40	1	11	4
YAKIMA RIVER AT CLE ELUM	0.705559	15	N/A	4.7	2.5	2.4	0.3	N/A	N/A	N/A	N/A	N/A

Major element readings from IC analysis, except *ICP-MS; Trace element from ICP-MS; ^{87}Sr/^{86}Sr from TIMS; Stable isotope data from (Gendaszek, et al., 2014)

TABLE 8. SPRING WATER DATA

Name (USGS Site #)	^{87}Sr/^{86}Sr	2σ	δ^{18}O	Ca ppm	Mg ppm	Na ppm	K ppm	Mn ppb	Zn ppb	Rb ppb	Sr ppm	Ba ppb
BEVERLY SPRING (472230120523101)	0.705258	22	-15.01	11.9*	N/A	N/A	0.3*	1	2	bdl	32	1
BLOWOUT SPRING (471220121180201)	0.704417	14	-12.73	3.3	2.2	5.9	0.5	1	bdl	bdl	23	2
COOPER SPRING	0.706467	15	N/A	9.3*	N/A	N/A	0.1*	bdl	bdl	bdl	45	1
ELY SPRING (471712121143801)	0.706092	18	-13.09	1.8	0.4	1.8	0.6	bdl	1	1	17	9
ESMERALDA SPRING (472530120561101)	0.704612	11	-14.78	0.2	7.5	1.0	0.1*	bdl	1	bdl	11	bdl
GROUSE SPRING (472201121045401)	0.706368	10	-14.31	4.4	2.4	2.0	0.2	bdl	2	bdl	44	1
GUSHER SPRING (471826121130601)	0.705795	11	-13.39	11.2	1.5	3.1	0.5	bdl	3	1	115	25
JUNGLE SPRING (472048120524201)	0.704615	10	-14.12	18.5	4.1	5.8	3.4	15	1	1	145	17
LITTLE SALMON LA SAC SPRING (472133121033101)	0.704024	11	-14.31	5.3	0.8	2.0	1.5	1	1	2	53	2
LOVE SPRING (470740120575201)	0.704287	25	-14.86	8.4	3.2	7.2	2.2	N/A	N/A	N/A	N/A	N/A
TEANAWAY SPRING (471551120530801)	0.704676	11	-15.05	15.4	13.1	7.0	0.4	bdl	2	bdl	99	2

Major element readings from IC analysis, except *ICP-MS; Trace element from ICP-MS; ^{87}Sr/^{86}Sr from TIMS; Stable isotope data from (Gendaszek, et al., 2014)

TABLE 9. ROCK LEACHATE DATA

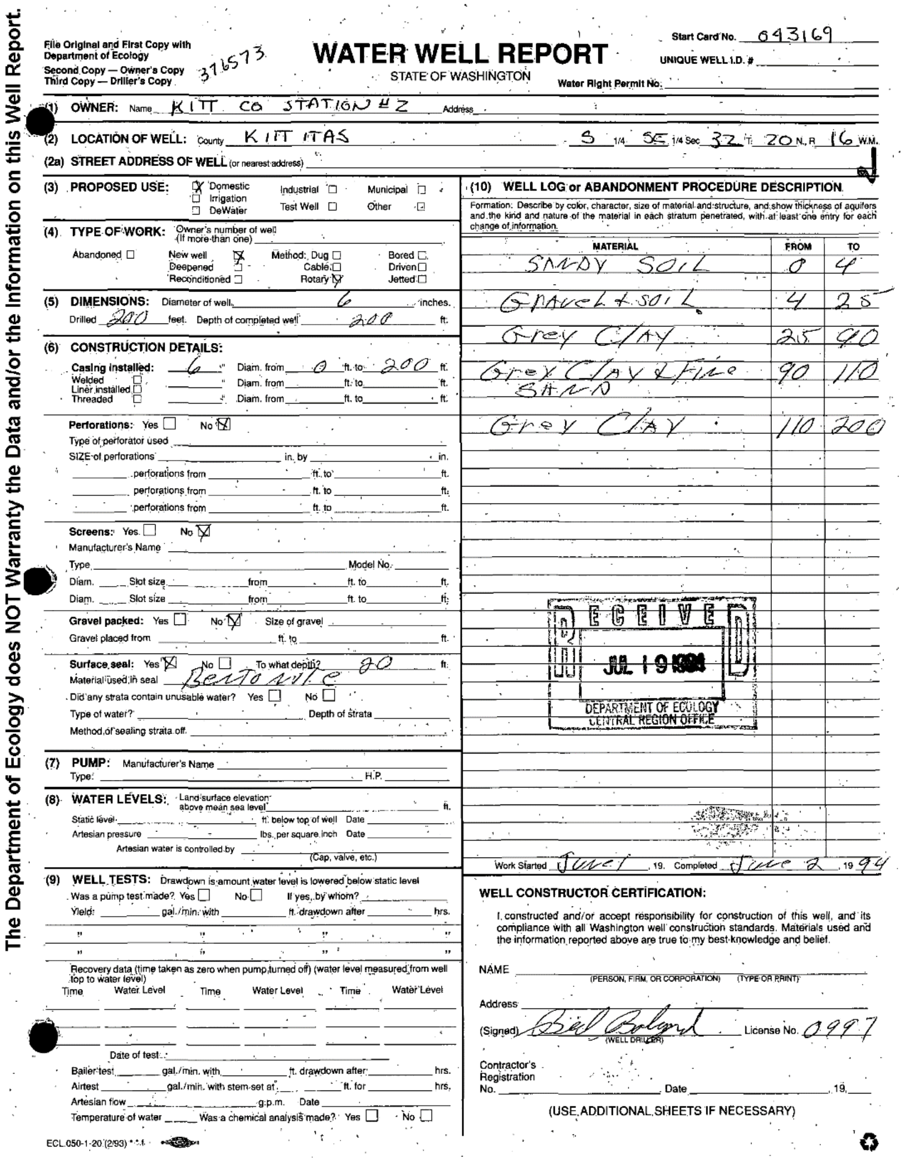
Name (USGS Site #)	^{87}Sr/^{86}Sr	2σ	δ^{18}O	Ca ppm	Mg ppm	Na ppm	K ppm	Mn ppb	Zn ppb	Rb ppb	Sr ppm	Ba ppb
OHANAPECOSH 10-min	0.704188	8	N/A	190.9*	N/A	N/A	2.9*	5758	140	6	197	92
OHANAPECOSH 2-min	0.704169	14	N/A	134.7*	N/A	N/A	1.9*	3347	62	5	130	57
NACHES RHYOLITE 10-min	0.706109	11	N/A	51.0*	N/A	N/A	4.0*	1163	250	13	553	656
NACHES RHYOLITE 2-min	0.706303	15	N/A	2.7	1.0	6.0	0.3	383	178	9	364	372
INGALLS MAFIC 10-min	0.704390	11	N/A	73.6*	N/A	N/A	0.5*	2139	50	3	55	67
INGALLS MAFIC 2-min	0.704655	10	N/A	84.5*	N/A	N/A	0.5*	1967	44	3	49	63
SWAUK ANDESITE 10-min	0.705313	21	N/A	128.6*	N/A	N/A	2.5*	4592	139	9	198	661
SWAUK ANDESITE 2-min	0.705435	15	N/A	118.9*	N/A	N/A	2.5*	4631	134	7	157	487
SWAUK SANDSTONE 2-min	0.706068	11	N/A	40.5	N/A	N/A	0.4*	668	59	2	66	31
ROSLYN SANDSTONE 10-min	0.704334	11	N/A	399.2*	N/A	N/A	6.9*	2086	78	27	3724	2419
ROSLYN SANDSTONE 2-min	0.704213	15	N/A	173.1*	N/A	N/A	2.3*	1139	34	7	1453	1194

Major element readings from IC analysis, except *ICP-MS; Trace element from ICP-MS; ^{87}Sr/^{86}Sr from TIMS

APPENDIX C

WELL LOGS

Fire Station Well Log 0 – 200 feet



The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report.

File Original and First Copy with Department of Ecology
Second Copy — Owner's Copy
Third Copy — Driller's Copy

376573

WATER WELL REPORT
STATE OF WASHINGTON

Start Card No. 643169
UNIQUE WELL I.D. # ______
Water Right Permit No. ______

(1) OWNER: Name KITT CO STATION #2 Address ______

(2) LOCATION OF WELL: County KITTITAS S 1/4 SE 1/4 Sec 32 T. 20 N., R 16 W.M.

(2a) STREET ADDRESS OF WELL (or nearest address) ______

(3) PROPOSED USE: ☒ Domestic ☐ Irrigation ☐ DeWater Industrial ☐ Test Well ☐ Municipal ☐ Other ☐

(4) TYPE OF WORK: Owner's number of well (If more than one) ______
Abandoned ☐ New well ☒ Deepened ☐ Reconditioned ☐
Method: Dug ☐ Cable ☐ Rotary ☒ Bored ☐ Driven ☐ Jetted ☐

(5) DIMENSIONS: Diameter of well 6 inches.
Drilled 200 feet. Depth of completed well 200 ft.

(6) CONSTRUCTION DETAILS:

Casing installed: 6 " Diam. from 0 ft. to 200 ft.
Welded ☐ ______ " Diam. from ______ ft. to ______ ft.
Liner installed ☐
Threaded ☐ ______ " Diam. from ______ ft. to ______ ft.

Perforations: Yes ☐ No ☒
Type of perforator used ______
SIZE of perforations ______ in. by ______ in.
______ perforations from ______ ft. to ______ ft.
______ perforations from ______ ft. to ______ ft.
______ perforations from ______ ft. to ______ ft.

Screens: Yes ☐ No ☒
Manufacturer's Name ______
Type ______ Model No. ______
Diam. ______ Slot size ______ from ______ ft. to ______ ft.
Diam. ______ Slot size ______ from ______ ft. to ______ ft.

Gravel packed: Yes ☐ No ☒ Size of gravel ______
Gravel placed from ______ ft. to ______ ft.

Surface seal: Yes ☒ No ☐ To what depth? 20 ft.
Material used in seal Bentonite
Did any strata contain unusable water? Yes ☐ No ☐
Type of water? ______ Depth of strata ______
Method of sealing strata off ______

(7) PUMP: Manufacturer's Name ______
Type: ______ H.P. ______

(8) WATER LEVELS: Land-surface elevation above mean sea level ______ ft.
Static level ______ ft. below top of well Date ______
Artesian pressure ______ lbs. per square inch Date ______
Artesian water is controlled by ______ (Cap, valve, etc.)

(9) WELL TESTS: Drawdown is amount water level is lowered below static level
Was a pump test made? Yes ☐ No ☐ If yes, by whom? ______
Yield: ______ gal./min. with ______ ft. drawdown after ______ hrs.
" " " "
" " " "

Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level

Date of test ______
Bailer test ______ gal./min. with ______ ft. drawdown after ______ hrs.
Airtest ______ gal./min. with stem set at ______ ft. for ______ hrs.
Artesian flow ______ g.p.m. Date ______
Temperature of water ______ Was a chemical analysis made? Yes ☐ No ☐

(10) WELL LOG or ABANDONMENT PROCEDURE DESCRIPTION

Formation: Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of information.

MATERIAL	FROM	TO
SANDY SOIL	0	4
GRAVEL & SOIL	4	25
Grey CLAY	25	90
Grey CLAY & Fine SAND	90	110
Grey CLAY	110	200

RECEIVED
JUL 19 1994
DEPARTMENT OF ECOLOGY
CENTRAL REGION OFFICE

Work Started June 1, 19. Completed June 2, 1994

WELL CONSTRUCTOR CERTIFICATION:

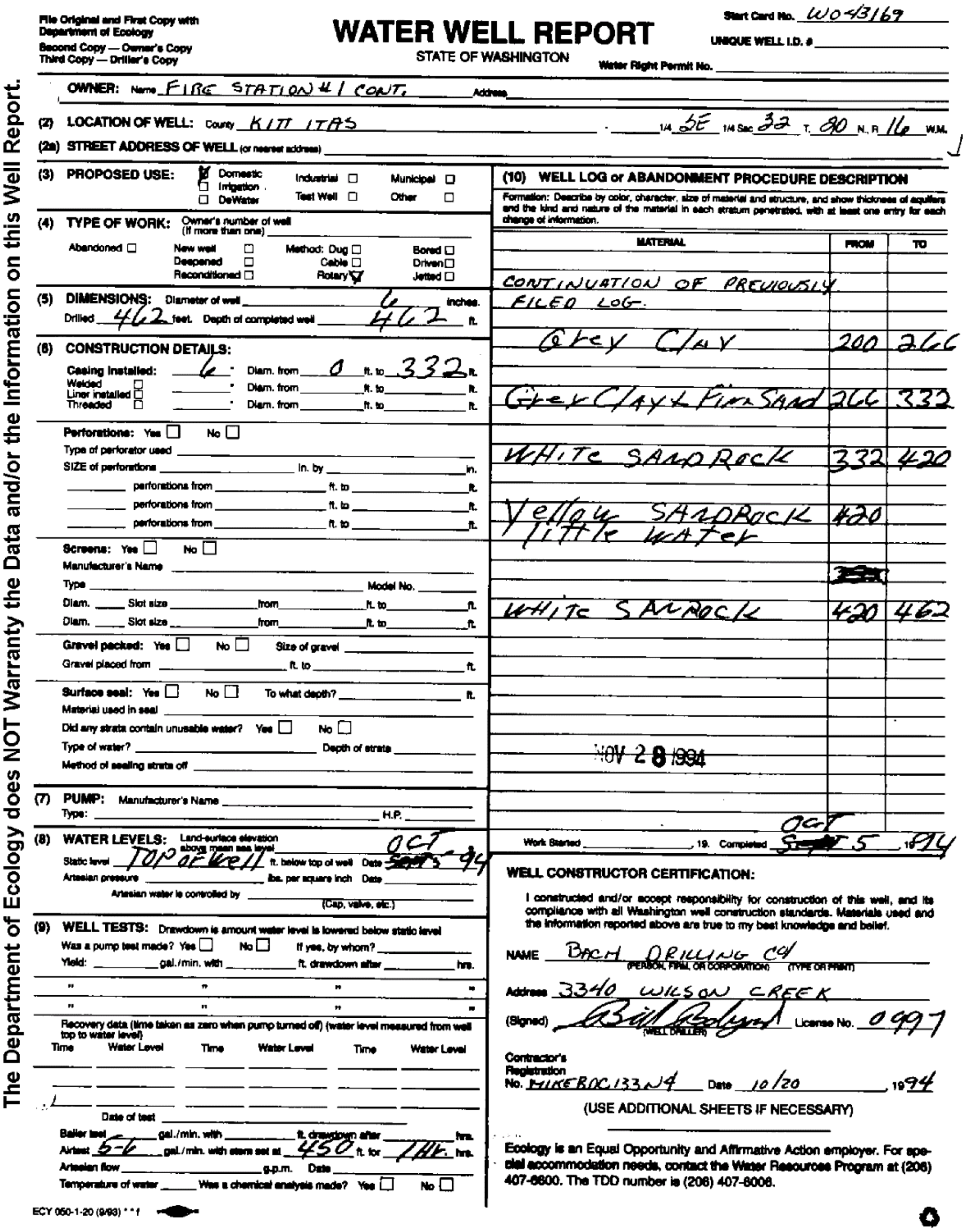
I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported above are true to my best knowledge and belief.

NAME ______ (PERSON, FIRM, OR CORPORATION) (TYPE OR PRINT)
Address ______
(Signed) Bill Bolyard (WELL DRILLER) License No. 0997
Contractor's Registration No. ______ Date ______, 19 ______

(USE ADDITIONAL SHEETS IF NECESSARY)

ECL 050-1-20 (2/93)

Fire Station Well Log 200-462 feet



File Original and First Copy with Department of Ecology
Second Copy — Owner's Copy
Third Copy — Driller's Copy

WATER WELL REPORT

STATE OF WASHINGTON

Start Card No. W043169
UNIQUE WELL I.D. # ______
Water Right Permit No. ______

The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report.

(1) **OWNER:** Name FIRE STATION #1 CONT. Address ______

(2) **LOCATION OF WELL:** County KITTITAS ______ 1/4 SE 1/4 Sec 32 T. 20 N., R 16 W.M.

(2a) **STREET ADDRESS OF WELL** (or nearest address) ______

(3) **PROPOSED USE:** ☒ Domestic ☐ Irrigation ☐ DeWater ☐ Industrial ☐ Test Well ☐ Municipal ☐ Other

(4) **TYPE OF WORK:** Owner's number of well (If more than one) ______
☐ Abandoned ☐ New well ☐ Deepened ☐ Reconditioned
Method: ☐ Dug ☐ Cable ☒ Rotary ☐ Bored ☐ Driven ☐ Jetted

(5) **DIMENSIONS:** Diameter of well 6 inches.
Drilled 462 feet. Depth of completed well 462 ft.

(6) **CONSTRUCTION DETAILS:**
Casing Installed: 6" Diam. from 0 ft. to 332 ft.
☐ Welded ______" Diam. from ______ ft. to ______ ft.
☐ Liner installed ______" Diam. from ______ ft. to ______ ft.
☐ Threaded

Perforations: Yes ☐ No ☐
Type of perforator used ______
SIZE of perforations ______ in. by ______ in.
______ perforations from ______ ft. to ______ ft.
______ perforations from ______ ft. to ______ ft.
______ perforations from ______ ft. to ______ ft.

Screens: Yes ☐ No ☐
Manufacturer's Name ______
Type ______ Model No. ______
Diam. ______ Slot size ______ from ______ ft. to ______ ft.
Diam. ______ Slot size ______ from ______ ft. to ______ ft.

Gravel packed: Yes ☐ No ☐ Size of gravel ______
Gravel placed from ______ ft. to ______ ft.

Surface seal: Yes ☐ No ☐ To what depth? ______ ft.
Material used in seal ______
Did any strata contain unusable water? Yes ☐ No ☐
Type of water? ______ Depth of strata ______
Method of sealing strata off ______

(7) **PUMP:** Manufacturer's Name ______
Type: ______ H.P. ______

(8) **WATER LEVELS:** Land-surface elevation above mean sea level ______
Static level TOP of Well ft. below top of well Date ~~Sept~~ OCT 5 - 94
Artesian pressure ______ lbs. per square inch Date ______
Artesian water is controlled by ______ (Cap, valve, etc.)

(9) **WELL TESTS:** Drawdown is amount water level is lowered below static level
Was a pump test made? Yes ☐ No ☐ If yes, by whom? ______
Yield: ______ gal./min. with ______ ft. drawdown after ______ hrs.
" " " "
" " " "

Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level

Date of test ______
Bailer test ______ gal./min. with ______ ft. drawdown after ______ hrs.
Airtest 5-6 gal./min. with stem set at 450 ft. for 1 Hr. hrs.
Artesian flow ______ g.p.m. Date ______
Temperature of water ______ Was a chemical analysis made? Yes ☐ No ☐

(10) **WELL LOG or ABANDONMENT PROCEDURE DESCRIPTION**

Formation: Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of information.

MATERIAL	FROM	TO
CONTINUATION OF PREVIOUSLY FILED LOG.		
Grey Clay	200	266
Grey Clay & Fine Sand	266	332
WHITE SANDROCK	332	420
Yellow SANDROCK little water	420	
	[illegible]	
WHITE SANROCK	420	462

NOV 28 1994

Work Started ______, 19__. Completed ~~Sept~~ OCT 5, 1994

WELL CONSTRUCTOR CERTIFICATION:

I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported above are true to my best knowledge and belief.

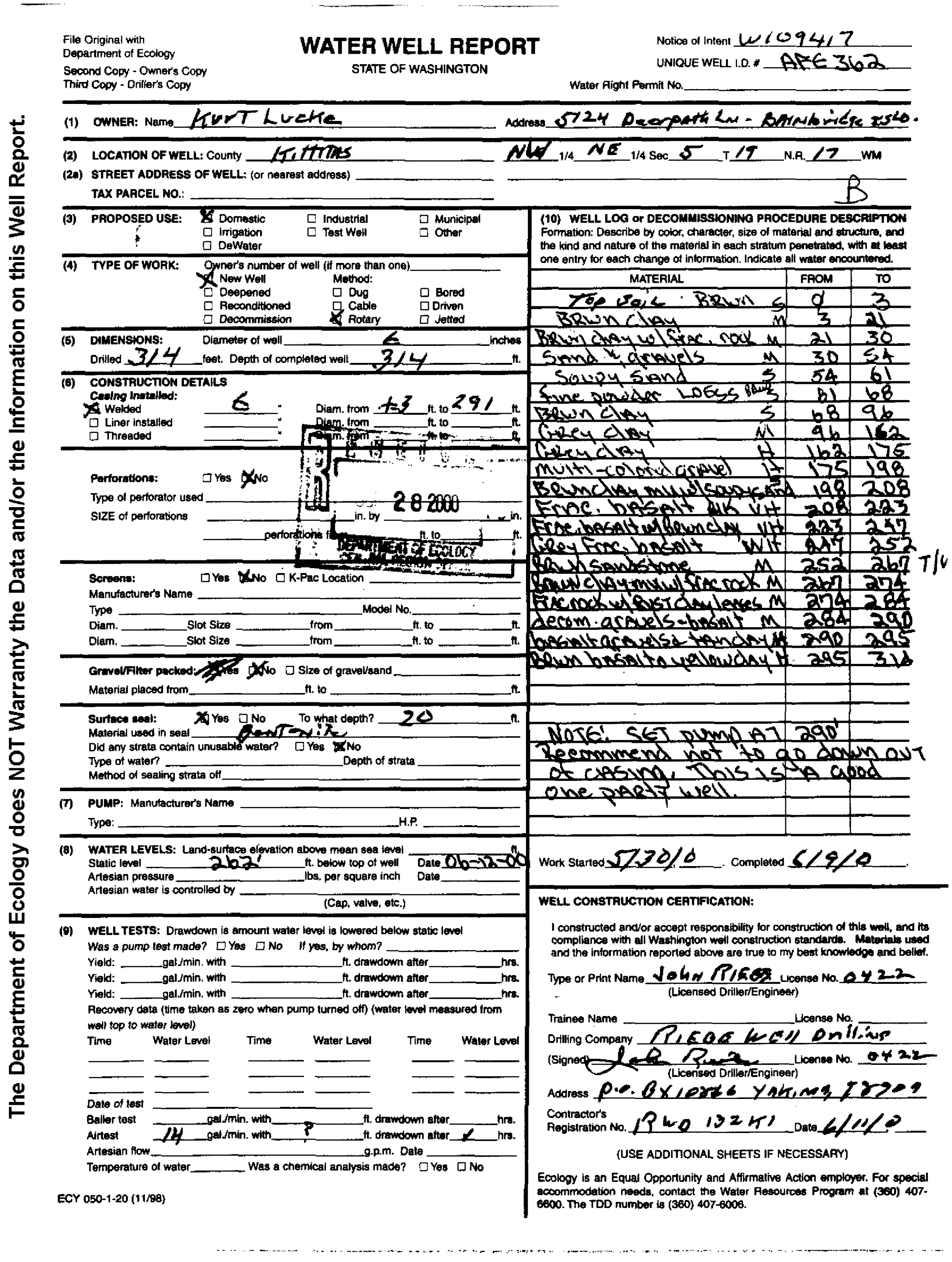
NAME BACH DRILLING CO (PERSON, FIRM, OR CORPORATION) (TYPE OR PRINT)
Address 3340 WILSON CREEK
(Signed) Bill Bolyard (WELL DRILLER) License No. 0997
Contractor's Registration No. MIKEBDC133N4 Date 10/20, 1994

(USE ADDITIONAL SHEETS IF NECESSARY)

Ecology is an Equal Opportunity and Affirmative Action employer. For special accommodation needs, contact the Water Resources Program at (206) 407-6600. The TDD number is (206) 407-6006.

ECY 050-1-20 (9/93)

#2 Well Log



The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report.

File Original with Department of Ecology
Second Copy - Owner's Copy
Third Copy - Driller's Copy

WATER WELL REPORT

STATE OF WASHINGTON

Notice of Intent W109417
UNIQUE WELL I.D. # AFE362
Water Right Permit No.

(1) **OWNER:** Name Kurt Lucke Address 5724 Deerpath Ln - Bainbridge Isl.

(2) **LOCATION OF WELL:** County Kittitas NW 1/4 NE 1/4 Sec 5 T 19 N.R. 17 WM

(2a) **STREET ADDRESS OF WELL:** (or nearest address)

TAX PARCEL NO.:

B

(3) **PROPOSED USE:** ☒ Domestic ☐ Industrial ☐ Municipal ☐ Irrigation ☐ Test Well ☐ Other ☐ DeWater

(4) **TYPE OF WORK:** Owner's number of well (if more than one)
☒ New Well ☐ Deepened ☐ Reconditioned ☐ *Decommission*
Method: ☐ Dug ☐ Cable ☒ Rotary ☐ Bored ☐ Driven ☐ *Jetted*

(5) **DIMENSIONS:** Diameter of well 6 inches
Drilled 314 feet. Depth of completed well 314 ft.

(6) **CONSTRUCTION DETAILS**
Casing Installed:
☒ Welded 6" Diam. from +3 ft. to 291 ft.
☐ Liner installed " Diam. from ft. to ft.
☐ Threaded " Diam. from ft. to ft.

Perforations: ☐ Yes ☒ No
Type of perforator used
SIZE of perforations in. by in.
perforations from ft. to ft.

28 2000
DEPARTMENT OF ECOLOGY

Screens: ☐ Yes ☒ No ☐ K-Pac Location
Manufacturer's Name
Type Model No.
Diam. Slot Size from ft. to ft.
Diam. Slot Size from ft. to ft.

Gravel/Filter packed: ~~Yes~~ ☒ No ☐ Size of gravel/sand
Material placed from ft. to ft.

Surface seal: ☒ Yes ☐ No To what depth? 20 ft.
Material used in seal Bentonite
Did any strata contain unusable water? ☐ Yes ☒ No
Type of water? Depth of strata
Method of sealing strata off

(7) **PUMP:** Manufacturer's Name
Type: H.P.

(8) **WATER LEVELS:** Land-surface elevation above mean sea level ft.
Static level 262' ft. below top of well Date 06-12-00
Artesian pressure lbs. per square inch Date
Artesian water is controlled by (Cap, valve, etc.)

(9) **WELL TESTS:** Drawdown is amount water level is lowered below static level
Was a pump test made? ☐ Yes ☐ No *If yes, by whom?*
Yield: gal./min. with ft. drawdown after hrs.
Yield: gal./min. with ft. drawdown after hrs.
Yield: gal./min. with ft. drawdown after hrs.
Recovery data (time taken as zero when pump turned off) (water level measured from *well top to water level)*

Time	Water Level	Time	Water Level	Time	Water Level

Date of test
Bailer test gal./min. with ft. drawdown after hrs.
Airtest 14 gal./min. with ? ft. drawdown after 1 hrs.
Artesian flow g.p.m. Date
Temperature of water Was a chemical analysis made? ☐ Yes ☐ No

(10) **WELL LOG or DECOMMISSIONING PROCEDURE DESCRIPTION**
Formation: Describe by color, character, size of material and structure, and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of information. Indicate all water encountered.

MATERIAL	FROM	TO
Top Soil · Brwn S	0	3
Brwn Clay M	3	21
Brwn clay w/frac. rock M	21	30
Sand & gravels M	30	54
Soupy Sand S	54	61
Fine powder LOESS Brwn S	61	68
Brwn Clay S	68	96
Grey clay M	96	162
Grey clay H	162	175
multi-colored gravel H	175	198
Brwn clay mix w/soupy sand S	198	208
Frac. basalt blk VH	208	223
Frac. basalt w/brwn clay VH	223	247
Grey frac. basalt VH	247	252
Brwn sandstone M	252	267 T/V
Brwn clay mix w/frac rock M	267	274
Frac rock w/rust clay lenses M	274	284
decom. gravels-basalt M	284	290
basalt gravels & tan clay M	290	295
Brwn basalt to yellow clay H	295	314

NOTE: SET pump AT 290'
Recommend not to go down out of casing. This is a good one party well.

Work Started 5/30/0 Completed 6/9/0

WELL CONSTRUCTION CERTIFICATION:

I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported above are true to my best knowledge and belief.

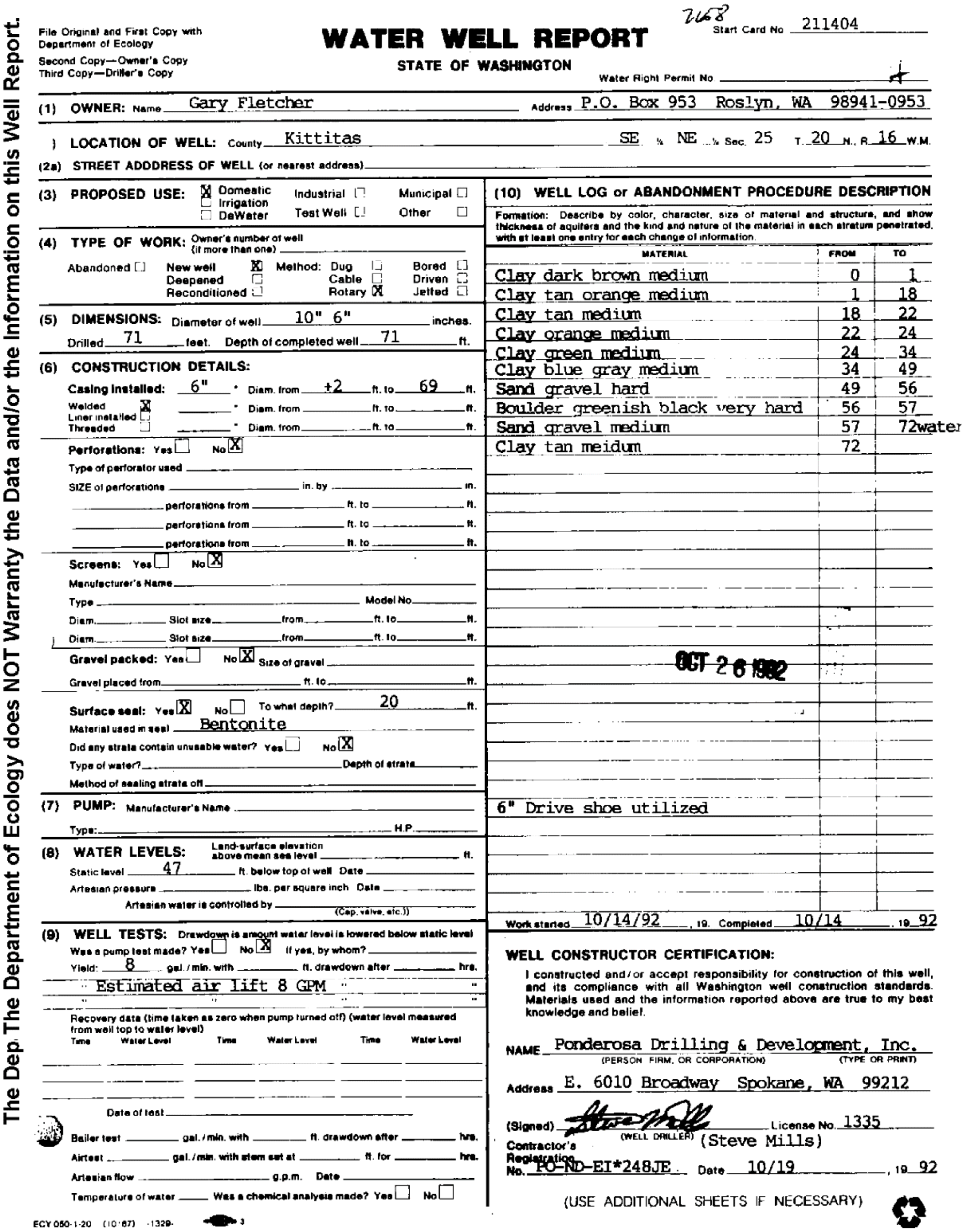
Type or Print Name John Rieger License No. 0422
(Licensed Driller/Engineer)
Trainee Name License No.
Drilling Company Rieger Well Drilling
(Signed) License No. 0422
(Licensed Driller/Engineer)
Address P.O. Bx 10866 Yakima, 98909
Contractor's Registration No. RWD 132KI Date 6/11/0

(USE ADDITIONAL SHEETS IF NECESSARY)

Ecology is an Equal Opportunity and Affirmative Action employer. For special accommodation needs, contact the Water Resources Program at (360) 407-6600. The TDD number is (360) 407-6006.

ECY 050-1-20 (11/98)

#4 Well Log



The Dep. The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report.

File Original and First Copy with Department of Ecology
Second Copy—Owner's Copy
Third Copy—Driller's Copy

WATER WELL REPORT

STATE OF WASHINGTON

2668

Start Card No 211404

Water Right Permit No —

(1) OWNER: Name Gary Fletcher Address P.O. Box 953 Roslyn, WA 98941-0953

) LOCATION OF WELL: County Kittitas SE ¼ NE ¼ Sec. 25 T. 20 N., R. 16 W.M.

(2a) STREET ADDDRESS OF WELL (or nearest address)

(3) PROPOSED USE: ☒ Domestic ☐ Irrigation ☐ DeWater Industrial ☐ Test Well ☐ Municipal ☐ Other ☐

(4) TYPE OF WORK: Owner's number of well (if more than one)

Abandoned ☐ New well ☒ Deepened ☐ Reconditioned ☐

Method: Dug ☐ Cable ☐ Rotary ☒ Bored ☐ Driven ☐ Jetted ☐

(5) DIMENSIONS: Diameter of well 10" 6" inches.

Drilled 71 feet. Depth of completed well 71 ft.

(6) CONSTRUCTION DETAILS:

Casing Installed: 6" " Diam. from +2 ft. to 69 ft.

Welded ☒ " Diam. from ft. to ft.

Liner installed ☐

Threaded ☐ " Diam. from ft. to ft.

Perforations: Yes ☐ No ☒

Type of perforator used

SIZE of perforations in. by in.

perforations from ft. to ft.

perforations from ft. to ft.

perforations from ft. to ft.

Screens: Yes ☐ No ☒

Manufacturer's Name

Type Model No.

Diam. Slot size from ft. to ft.

Diam. Slot size from ft. to ft.

Gravel packed: Yes ☐ No ☒ Size of gravel

Gravel placed from ft. to ft.

Surface seal: Yes ☒ No ☐ To what depth? 20 ft.

Material used in seal Bentonite

Did any strata contain unusable water? Yes ☐ No ☒

Type of water? Depth of strata

Method of sealing strata off

(7) PUMP: Manufacturer's Name

Type: H.P.

(8) WATER LEVELS: Land-surface elevation above mean sea level ft.

Static level 47 ft. below top of well Date

Artesian pressure lbs. per square inch Date

Artesian water is controlled by (Cap, valve, etc.))

(9) WELL TESTS: Drawdown is amount water level is lowered below static level

Was a pump test made? Yes ☐ No ☒ If yes, by whom?

Yield: 8 gal./min. with ft. drawdown after hrs.

" Estimated air lift 8 GPM " "

" " " "

Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level

Date of test

Bailer test gal./min. with ft. drawdown after hrs.

Airtest gal./min. with stem set at ft. for hrs.

Artesian flow g.p.m. Date

Temperature of water Was a chemical analysis made? Yes ☐ No ☐

(10) WELL LOG or ABANDONMENT PROCEDURE DESCRIPTION

Formation: Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of information.

MATERIAL	FROM	TO
Clay dark brown medium	0	1
Clay tan orange medium	1	18
Clay tan medium	18	22
Clay orange medium	22	24
Clay green medium	24	34
Clay blue gray medium	34	49
Sand gravel hard	49	56
Boulder greenish black very hard	56	57
Sand gravel medium	57	72water
Clay tan meidum	72	
6" Drive shoe utilized		

OCT 26 1992

Work started 10/14/92, 19. Completed 10/14, 19 92

WELL CONSTRUCTOR CERTIFICATION:

I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported above are true to my best knowledge and belief.

NAME Ponderosa Drilling & Development, Inc. (PERSON FIRM, OR CORPORATION) (TYPE OR PRINT)

Address E. 6010 Broadway Spokane, WA 99212

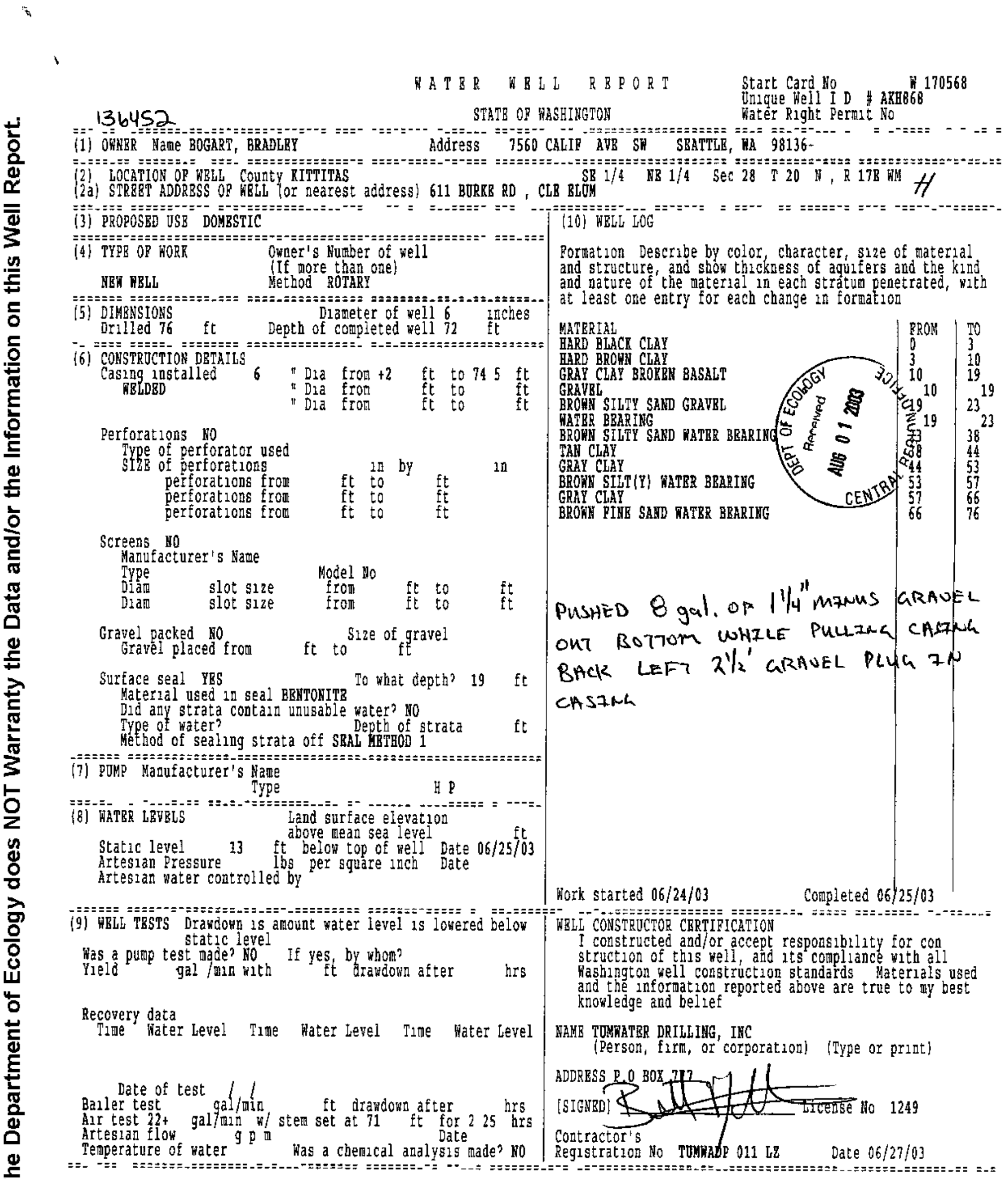
(Signed) (WELL DRILLER) (Steve Mills) License No. 1335

Contractor's Registration No. PO-ND-EI*248JE Date 10/19, 19 92

(USE ADDITIONAL SHEETS IF NECESSARY)

ECY 050-1-20 (10/87) -1329- 3

#5 Well Log



136452

WATER WELL REPORT
STATE OF WASHINGTON

Start Card No W 170568
Unique Well I D # AKH868
Water Right Permit No

(1) OWNER Name BOGART, BRADLEY Address 7560 CALIF AVE SW SEATTLE, WA 98136-

(2) LOCATION OF WELL County KITTITAS SE 1/4 NE 1/4 Sec 28 T 20 N , R 17E WM #
(2a) STREET ADDRESS OF WELL (or nearest address) 611 BURKE RD , CLE ELUM

(3) PROPOSED USE DOMESTIC

(4) TYPE OF WORK Owner's Number of well (If more than one)
NEW WELL Method ROTARY

(5) DIMENSIONS Diameter of well 6 inches
Drilled 76 ft Depth of completed well 72 ft

(6) CONSTRUCTION DETAILS
Casing installed 6 " Dia from +2 ft to 74 5 ft
WELDED " Dia from ft to ft
" Dia from ft to ft

Perforations NO
Type of perforator used
SIZE of perforations in by in
perforations from ft to ft
perforations from ft to ft
perforations from ft to ft

Screens NO
Manufacturer's Name
Type Model No
Diam slot size from ft to ft
Diam slot size from ft to ft

Gravel packed NO Size of gravel
Gravel placed from ft to ft

Surface seal YES To what depth? 19 ft
Material used in seal BENTONITE
Did any strata contain unusable water? NO
Type of water? Depth of strata ft
Method of sealing strata off SEAL METHOD 1

(7) PUMP Manufacturer's Name
Type H P

(8) WATER LEVELS Land surface elevation above mean sea level ft
Static level 13 ft below top of well Date 06/25/03
Artesian Pressure lbs per square inch Date
Artesian water controlled by

(9) WELL TESTS Drawdown is amount water level is lowered below static level
Was a pump test made? NO If yes, by whom?
Yield gal /min with ft drawdown after hrs

Recovery data
Time Water Level Time Water Level Time Water Level

Date of test / /
Bailer test gal/min ft drawdown after hrs
Air test 22+ gal/min w/ stem set at 71 ft for 2 25 hrs
Artesian flow g p m Date
Temperature of water Was a chemical analysis made? NO

(10) WELL LOG

Formation Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change in formation

MATERIAL	FROM	TO
HARD BLACK CLAY	0	3
HARD BROWN CLAY	3	10
GRAY CLAY BROKEN BASALT	10	19
GRAVEL	10	19
BROWN SILTY SAND GRAVEL	19	23
WATER BEARING	19	23
BROWN SILTY SAND WATER BEARING	23	38
TAN CLAY	38	44
GRAY CLAY	44	53
BROWN SILT(Y) WATER BEARING	53	57
GRAY CLAY	57	66
BROWN FINE SAND WATER BEARING	66	76

DEPT OF ECOLOGY Received AUG 01 2003 CENTRAL REGIONAL OFFICE

PUSHED 8 gal. OF 1¼" MINUS GRAVEL OUT BOTTOM WHILE PULLING CASING BACK LEFT 2½' GRAVEL PLUG IN CASING

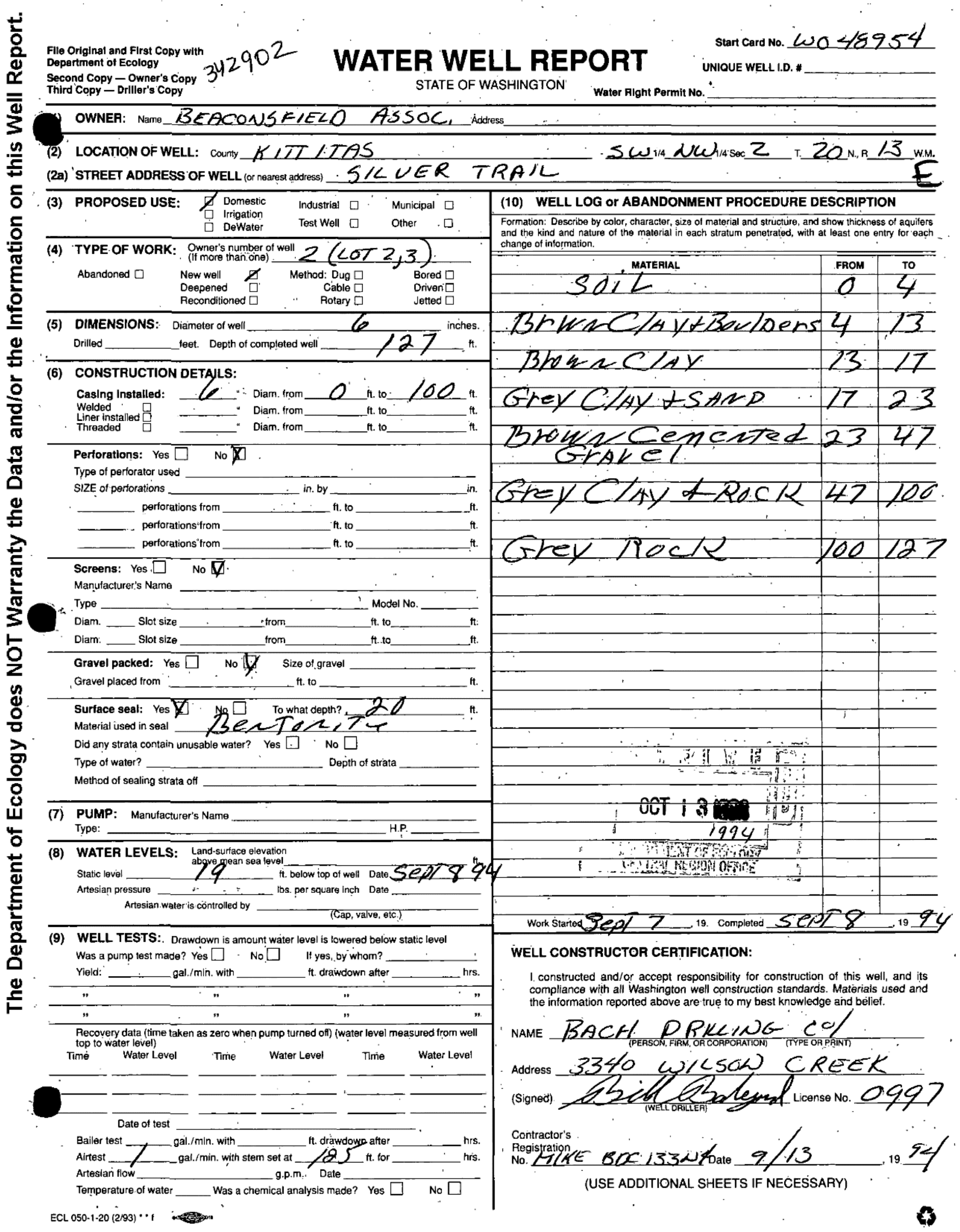
Work started 06/24/03 Completed 06/25/03

WELL CONSTRUCTOR CERTIFICATION
I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards Materials used and the information reported above are true to my best knowledge and belief

NAME TUMWATER DRILLING, INC
(Person, firm, or corporation) (Type or print)

ADDRESS P O BOX 787
[SIGNED] License No 1249
Contractor's Registration No TUMWADP 011 LZ Date 06/27/03

LE#6 Well Log



The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report.

File Original and First Copy with Department of Ecology
Second Copy — Owner's Copy
Third Copy — Driller's Copy

342902

WATER WELL REPORT

STATE OF WASHINGTON

Start Card No. W0 48954
UNIQUE WELL I.D. # ___
Water Right Permit No. ___

OWNER: Name BEACONSFIELD ASSOC. Address ___

(2) **LOCATION OF WELL:** County KITTITAS SW 1/4 NW 1/4 Sec 2 T. 20 N., R 13 W.M. E

(2a) **STREET ADDRESS OF WELL** (or nearest address) SILVER TRAIL

(3) **PROPOSED USE:** ☒ Domestic ☐ Irrigation ☐ DeWater Industrial ☐ Test Well ☐ Municipal ☐ Other ☐

(4) **TYPE OF WORK:** Owner's number of well (If more than one) 2 (LOT 2,3)
Abandoned ☐ New well ☒ Deepened ☐ Reconditioned ☐ Method: Dug ☐ Cable ☐ Rotary ☐ Bored ☐ Driven ☐ Jetted ☐

(5) **DIMENSIONS:** Diameter of well 6 inches.
Drilled ___ feet. Depth of completed well 127 ft.

(6) **CONSTRUCTION DETAILS:**
Casing Installed: 6 " Diam. from 0 ft. to 100 ft.
Welded ☐ ___ " Diam. from ___ ft. to ___ ft.
Liner installed ☐ ___ " Diam. from ___ ft. to ___ ft.
Threaded ☐

Perforations: Yes ☐ No ☒
Type of perforator used ___
SIZE of perforations ___ in. by ___ in.
___ perforations from ___ ft. to ___ ft.
___ perforations from ___ ft. to ___ ft.
___ perforations from ___ ft. to ___ ft.

Screens: Yes ☐ No ☑
Manufacturer's Name ___
Type ___ Model No. ___
Diam. ___ Slot size ___ from ___ ft. to ___ ft.
Diam. ___ Slot size ___ from ___ ft. to ___ ft.

Gravel packed: Yes ☐ No ☑ Size of gravel ___
Gravel placed from ___ ft. to ___ ft.

Surface seal: Yes ☒ No ☐ To what depth? 20 ft.
Material used in seal BENTONITE
Did any strata contain unusable water? Yes ☐ No ☐
Type of water? ___ Depth of strata ___
Method of sealing strata off ___

(7) **PUMP:** Manufacturer's Name ___
Type: ___ H.P. ___

(8) **WATER LEVELS:** Land-surface elevation above mean sea level ___ ft.
Static level 19 ft. below top of well Date Sept 8 94
Artesian pressure ___ lbs. per square inch Date ___
Artesian water is controlled by ___ (Cap, valve, etc.)

(9) **WELL TESTS:** Drawdown is amount water level is lowered below static level
Was a pump test made? Yes ☐ No ☐ If yes, by whom? ___
Yield: ___ gal./min. with ___ ft. drawdown after ___ hrs.
" " " "
" " " "
Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level

Date of test ___
Bailer test ___ gal./min. with ___ ft. drawdown after ___ hrs.
Airtest / gal./min. with stem set at 185 ft. for ___ hrs.
Artesian flow ___ g.p.m. Date ___
Temperature of water ___ Was a chemical analysis made? Yes ☐ No ☐

ECL 050-1-20 (2/93)

(10) **WELL LOG or ABANDONMENT PROCEDURE DESCRIPTION**

Formation: Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of information.

MATERIAL	FROM	TO
SOIL	0	4
Brwn Clay + Boulders	4	13
Brown Clay	13	17
Grey Clay + SAND	17	23
Brown Cemented Gravel	23	47
Grey Clay + ROCK	47	100
Grey Rock	100	127

OCT 1 3 [illegible]
1994
DEPARTMENT OF ECOLOGY
CENTRAL REGION OFFICE

Work Started Sept 7, 19. Completed SEPT 8, 19 94

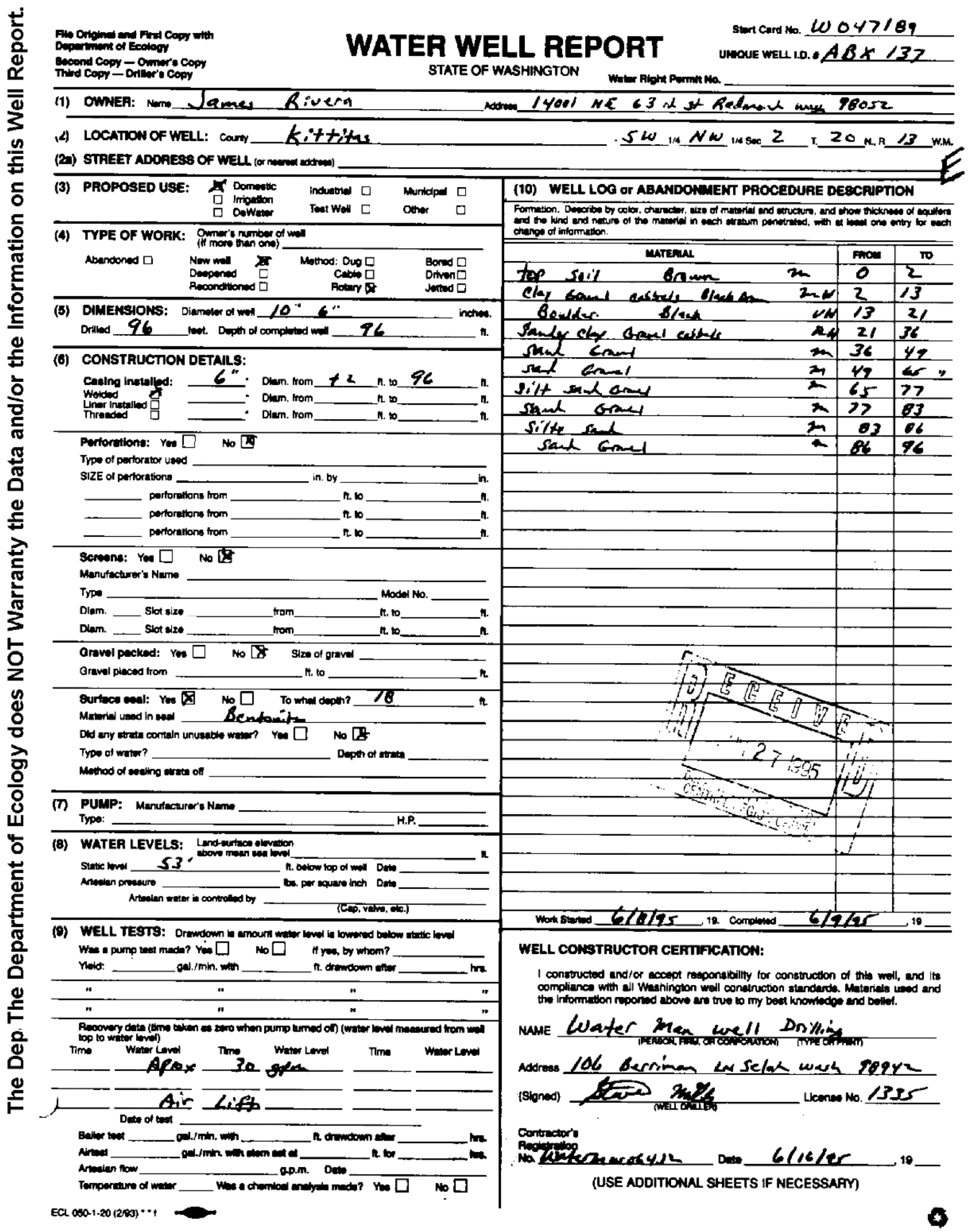
WELL CONSTRUCTOR CERTIFICATION:

I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported above are true to my best knowledge and belief.

NAME BACH DRILLING CO (PERSON, FIRM, OR CORPORATION) (TYPE OR PRINT)
Address 3340 WILSON CREEK
(Signed) Bill Bach (WELL DRILLER) License No. 0997
Contractor's Registration No. MIKE BDC 133NT Date 9/13, 19 94

(USE ADDITIONAL SHEETS IF NECESSARY)

LE#7 Well Log



The Dep. The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report.

File Original and First Copy with Department of Ecology
Second Copy — Owner's Copy
Third Copy — Driller's Copy

WATER WELL REPORT

STATE OF WASHINGTON

Start Card No. W047189
UNIQUE WELL I.D. # ABX 137
Water Right Permit No. ______

(1) **OWNER:** Name James Rivera Address 14001 NE 63rd st Redmond wash 98052

(2) **LOCATION OF WELL:** County Kittitas SW 1/4 NW 1/4 Sec 2 T. 20 N., R 13 W.M.

(2a) **STREET ADDRESS OF WELL** (or nearest address) ______

E

(3) **PROPOSED USE:** ☒ Domestic ☐ Irrigation ☐ DeWater ☐ Industrial ☐ Test Well ☐ Municipal ☐ Other

(4) **TYPE OF WORK:** Owner's number of well (if more than one) ______
Abandoned ☐ New well ☒ Deepened ☐ Reconditioned ☐
Method: Dug ☐ Cable ☐ Rotary ☒ Bored ☐ Driven ☐ Jetted ☐

(5) **DIMENSIONS:** Diameter of well 10" 6" inches.
Drilled 96 feet. Depth of completed well 96 ft.

(6) **CONSTRUCTION DETAILS:**
Casing installed: 6" Diam. from +2 ft. to 96 ft.
Welded ☒ ______ Diam. from ______ ft. to ______ ft.
Liner installed ☐
Threaded ☐ ______ Diam. from ______ ft. to ______ ft.

Perforations: Yes ☐ No ☒
Type of perforator used ______
SIZE of perforations ______ in. by ______ in.
______ perforations from ______ ft. to ______ ft.
______ perforations from ______ ft. to ______ ft.
______ perforations from ______ ft. to ______ ft.

Screens: Yes ☐ No ☒
Manufacturer's Name ______
Type ______ Model No. ______
Diam. ______ Slot size ______ from ______ ft. to ______ ft.
Diam. ______ Slot size ______ from ______ ft. to ______ ft.

Gravel packed: Yes ☐ No ☒ Size of gravel ______
Gravel placed from ______ ft. to ______ ft.

Surface seal: Yes ☒ No ☐ To what depth? 18 ft.
Material used in seal Bentonite
Did any strata contain unusable water? Yes ☐ No ☒
Type of water? ______ Depth of strata ______
Method of sealing strata off ______

(7) **PUMP:** Manufacturer's Name ______
Type: ______ H.P. ______

(8) **WATER LEVELS:** Land-surface elevation above mean sea level ______ ft.
Static level 53' ft. below top of well Date ______
Artesian pressure ______ lbs. per square inch Date ______
Artesian water is controlled by ______ (Cap, valve, etc.)

(9) **WELL TESTS:** Drawdown is amount water level is lowered below static level
Was a pump test made? Yes ☐ No ☐ If yes, by whom? ______
Yield: ______ gal./min. with ______ ft. drawdown after ______ hrs.
" " " "
" " " "
Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level
	Aprox	30 gpm			
	Air	Lift			

Date of test ______
Bailer test ______ gal./min. with ______ ft. drawdown after ______ hrs.
Airtest ______ gal./min. with stem set at ______ ft. for ______ hrs.
Artesian flow ______ g.p.m. Date ______
Temperature of water ______ Was a chemical analysis made? Yes ☐ No ☐

(10) **WELL LOG or ABANDONMENT PROCEDURE DESCRIPTION**

Formation. Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of information.

MATERIAL		FROM	TO
Top Soil Brown	m	0	2
Clay Gravel cobbels Black brown	m W	2	13
Boulder Black	VW	13	21
Sandy clay Gravel cobble	[illegible]	21	36
Sand Gravel	m	36	49
Sand Gravel	m	49	65
Silt sand Gravel	m	65	77
Sand Gravel	m	77	83
Silty sand	m	83	86
Sand Gravel	m	86	96

RECEIVED
27 1995

Work Started 6/8/95, 19. Completed 6/9/95, 19 ______

WELL CONSTRUCTOR CERTIFICATION:

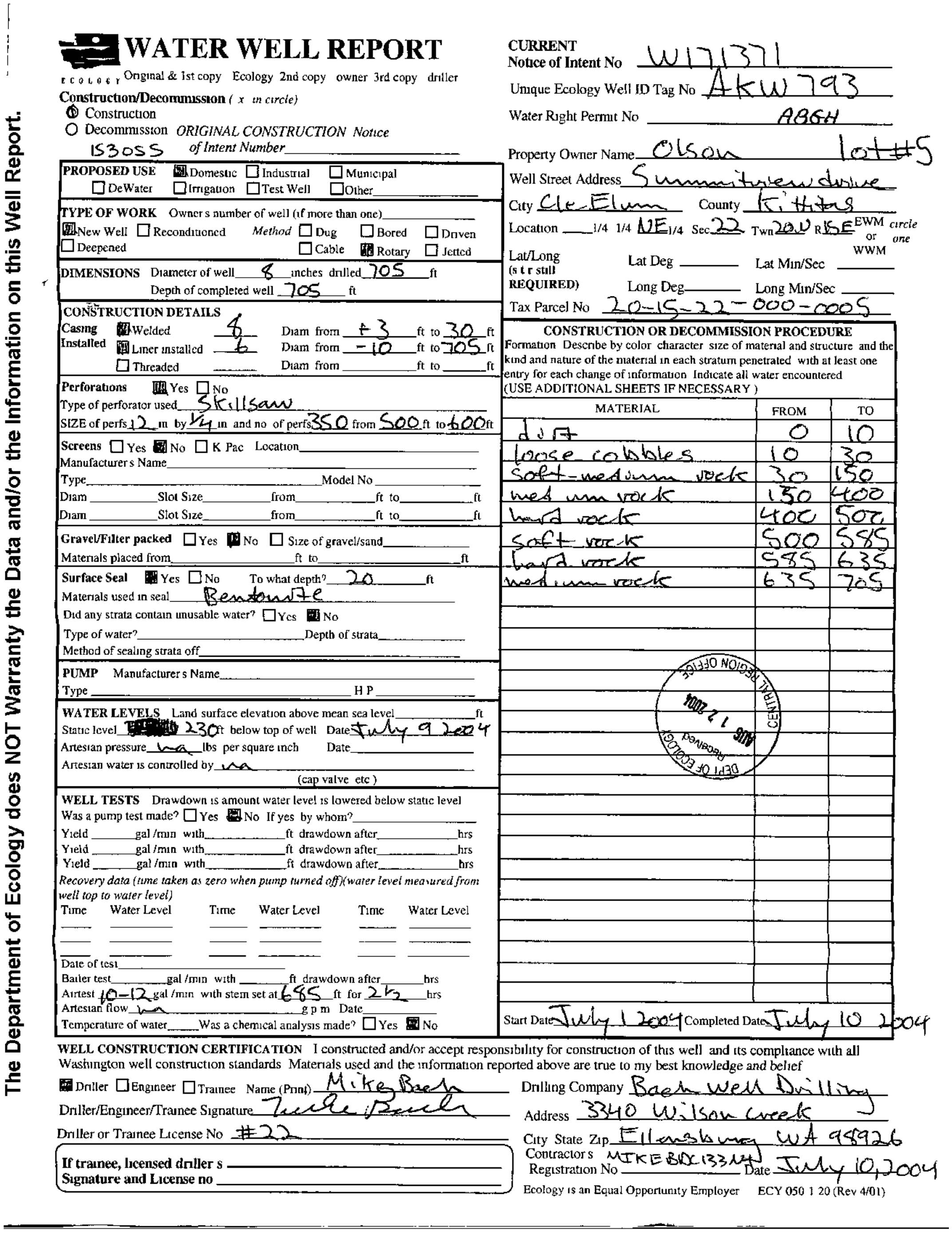
I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported above are true to my best knowledge and belief.

NAME Water Man well Drilling (PERSON, FIRM, OR CORPORATION) (TYPE OR PRINT)
Address 106 Berriman Ln Selah wash 98942
(Signed) ______ (WELL DRILLER) License No. 1335
Contractor's Registration No. Watermw064J2 Date 6/16/95, 19 ______

(USE ADDITIONAL SHEETS IF NECESSARY)

ECL 050-1-20 (2/93)

Norrish Rxn Well Log



The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report.

WATER WELL REPORT

ECOLOGY Original & 1st copy Ecology 2nd copy owner 3rd copy driller

Construction/Decommission *(x in circle)*
● Construction
○ Decommission *ORIGINAL CONSTRUCTION Notice of Intent Number* 153055

CURRENT Notice of Intent No W171371
Unique Ecology Well ID Tag No AKW793
Water Right Permit No ABGH
Property Owner Name Olson lot#5
Well Street Address Summitview drive
City Cle Elum County Kittitas
Location ____1/4 1/4 NE1/4 Sec 22 Twn 20N R 15E EWM or WWM *circle one*
Lat/Long (s t r still REQUIRED) Lat Deg ______ Lat Min/Sec ______ Long Deg______ Long Min/Sec ______
Tax Parcel No 20-15-22-000-0005

PROPOSED USE ☒ Domestic ☐ Industrial ☐ Municipal ☐ DeWater ☐ Irrigation ☐ Test Well ☐ Other______

TYPE OF WORK Owner s number of well (if more than one)______
☒ New Well ☐ Reconditioned *Method* ☐ Dug ☐ Bored ☐ Driven
☐ Deepened ☐ Cable ☒ Rotary ☐ Jetted

DIMENSIONS Diameter of well 8 inches drilled 705 ft
Depth of completed well 705 ft

CONSTRUCTION DETAILS
Casing Installed ☒ Welded 8 Diam from +3 ft to 30 ft
☒ Liner installed 6 Diam from -10 ft to 705 ft
☐ Threaded ____ Diam from ______ ft to ______ ft

Perforations ☒ Yes ☐ No
Type of perforator used Skillsaw
SIZE of perfs 12 in by 1/4 in and no of perfs 350 from 500 ft to 600 ft

Screens ☐ Yes ☒ No ☐ K Pac Location______
Manufacturer s Name______
Type______ Model No______
Diam ______ Slot Size______ from______ ft to______ ft
Diam ______ Slot Size______ from______ ft to______ ft

Gravel/Filter packed ☐ Yes ☒ No ☐ Size of gravel/sand______
Materials placed from______ ft to______ ft

Surface Seal ☒ Yes ☐ No To what depth? 20 ft
Materials used in seal Bentonite
Did any strata contain unusable water? ☐ Yes ☒ No
Type of water?______ Depth of strata______
Method of sealing strata off______

PUMP Manufacturer s Name______
Type ______ H P ______

WATER LEVELS Land surface elevation above mean sea level______ ft
Static level [redacted] 230 ft below top of well Date July 9 2004
Artesian pressure na lbs per square inch Date______
Artesian water is controlled by na (cap valve etc)

WELL TESTS Drawdown is amount water level is lowered below static level
Was a pump test made? ☐ Yes ☒ No If yes by whom?______
Yield ______ gal /min with______ ft drawdown after______ hrs
Yield ______ gal /min with______ ft drawdown after______ hrs
Yield ______ gal /min with______ ft drawdown after______ hrs
Recovery data (time taken as zero when pump turned off)(water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level

Date of test______
Bailer test______ gal /min with ______ ft drawdown after______ hrs
Airtest 10-12 gal /min with stem set at 685 ft for 2½ hrs
Artesian flow na g p m Date______
Temperature of water______ Was a chemical analysis made? ☐ Yes ☒ No

CONSTRUCTION OR DECOMMISSION PROCEDURE
Formation Describe by color character size of material and structure and the kind and nature of the material in each stratum penetrated with at least one entry for each change of information Indicate all water encountered
(USE ADDITIONAL SHEETS IF NECESSARY)

MATERIAL	FROM	TO
dirt	0	10
loose cobbles	10	30
soft-medium rock	30	150
medium rock	150	400
hard rock	400	500
soft rock	500	585
hard rock	585	635
medium rock	635	705

DEPT OF ECOLOGY Received AUG 12 2004 CENTRAL REGION OFFICE

Start Date July 1 2004 Completed Date July 10 2004

WELL CONSTRUCTION CERTIFICATION I constructed and/or accept responsibility for construction of this well and its compliance with all Washington well construction standards Materials used and the information reported above are true to my best knowledge and belief

☒ Driller ☐ Engineer ☐ Trainee Name (Print) Mike Bach
Driller/Engineer/Trainee Signature Mike Bach
Driller or Trainee License No #22

If trainee, licensed driller s Signature and License no ______

Drilling Company Bach Well Drilling
Address 3340 Wilson Creek
City State Zip Ellensburg WA 98926
Contractor s Registration No MIKEBDC133LH Date July 10,2004

Ecology is an Equal Opportunity Employer ECY 050 1 20 (Rev 4/01)