Conceptualizing the hydrogeothermal system at Sloquet Hot Springs on unceded St'at'imc territory in southwestern British Columbia

by

Ashley Van Acken
Bachelor of Science, Vancouver Island University, 2017

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Abstract

Geothermal research in the southern Canadian Cordillera has typically focused on hot spring systems and predicting maximum temperatures at depth, estimating fluid circulation depths, and investigating the distribution of hot spring systems and their relation to major geological features that often control thermal fluid flow. Detailed fieldwork to develop local and regional conceptual models of these systems has rarely been conducted and to our best knowledge, never in partnership with a First Nations. The scope of this project was to work collaboratively with the local First Nation to conduct detailed structural, hydrologic and hydrogeologic fieldwork to develop local and regional conceptual models of Sloquet Hot Springs, on unceded St'at'imc territory. To motivate our research and provide a successful example of geoscience research in the era of reconciliation and Indigenous resurgence, we review how resource regulation, research, reconciliation, and resurgence interact in British Columbia and detail our approach to community engagement.

Detailed studies resulted in the development of a working conceptual model for the hydrogeothermal system at Sloquet Hot Springs. The conceptual model synthesizes local and regional groundwater flow, observed geothermal gradients, advective and conductive heat flow, as well as permeability contrasts in the subsurface to understand thermal fluid flow at the study site. Well monitoring, development, and pumping tests revealed numerous soft zones in the subsurface as well as bulk values for high transmissivity and hydraulic conductivity. Findings from subsurface investigations suggest bedrock in the area has significant permeability and that groundwater flow is controlled by steep hydraulic gradients caused by rugged topography in the region. The annual spring flux was calculated for Sloquet Hot Springs and used to approximate the recharge area that is required to drive the system. Although the study did not identify the primary fault that conveys high-temperature fluids, the potential locations of buried fault structures are hypothesized based on zones with observably high temperatures and flow along Sloquet Creek.

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Acknowledgments

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Further gratitude is extended to my supervisory committee - Kathryn Gillis, Dante Canil, and Catherine Hickson. Without experienced personnel on my advisory committee, I would not have been able to complete the works required for my thesis. I would also like to thank Alistair McCrone from Trails and Recreation Sites of British Columbia for his support to pursue field investigations at the co-managed recreation site, Sloquet Hot Springs.

CHAPTER 1. Introduction

Global patterns of geothermal resources are correlated to their proximity to plate boundaries or active tectonics and volcanism (Boden, 2016; Acharya, 1983; Sykes, 2019) and their proximity to crustal-scale fault structures (Scibek et al., 2016; Grasby and Hutcheon, 2001). More specifically, geothermal systems occur along divergent, convergent, and transform plate boundaries with few intraplate exceptions (e.g., Yellowstone National Park). Each of these zones undergoes different crustal-scale processes and result in the formation and/or deformation of various rock types that can act to enhance or reduce subsurface permeability. Several characteristics of fault zones influence their role in conveying fluids, including their structure, age, amount of seismic activity (Curewitz and Karson, 1997), kinematics (Meixner et al., 2016), and subsurface geometry (Moreno et al., 2018). Understanding these parameters and how they interact with different hydrogeologic environments, specifically in areas of high crustal heat flow, are critical to improving our understanding of geothermal systems around the world.

In 2019, the Government of Canada committed to strengthening greenhouse gas reduction measures and developed a legally binding reduction plan to achieve net-zero emissions by the year 2050 (Bush and Lemmen, 2019). The commitment from the government requires further development of new alternative energy resources such as geothermal. When compared to other renewables, geothermal energy is the most advantageous as it can provide a stable baseload-power supply without the need for energy storage solutions (Grasby et al., 2012). Canada has significant geothermal resource potential, however, there are many constraints regarding the ability to produce energy including societal, geological, technical, and regulatory issues (Grasby et al., 2012). Further constraints are related to upfront investments for extensive drilling to determine hot aquifer locations, permeability, and reservoir potential (Grasby et al., 2012). There are three main geological regions of interest when considering exploration and development of geothermal resources in Canada: (1) the Canadian Cordillera in western Canada; (2) sedimentary basins that represent broad regions of the country that are underlain by sedimentary rock; and (3) the Canadian Shield that extends through central and northern Canada. Geothermal resource potential is highest in the Canadian Cordillera due to high crustal heat flow and steep geothermal gradients (Grasby and Hutcheon, 2001). Most studies have focused on the southern Canadian Cordillera due to elevated crustal heat flow (40 to 130 mW/m^2) with local anomalies that exceed 200 mW/m^2 (Finley et al., 2019; Jessop, 2008). Over

100 thermal springs are scattered across the region (Grasby and Hutcheon, 2001), and each of these systems outcrop on the traditional territory of British Columbia's First Peoples. The most detailed study in the southern Cordillera was focused along the southern flank of Mount Meager where exploration wells were drilled and defined resources that exceed 250 °C (Jessop, 2008). Although successful in terms of exploration and identification of resources, development was economically limited by low permeability rocks at depth limiting the ability to extract energy at a cost-effective price. Next, the relevant social and scientific issues in British Columbia will be reviewed to further develop thesis motivation, purpose, and objectives.

Socially, there remains a tumultuous relationship between the natural resource sector (e.g., government, corporations, research institutions, etc.) and Indigenous communities in Canada. These relationships have been shaped by colonization, seizure of lands and resources, historical oppression as well as discriminatory legal frameworks at the federal level (Truth and Reconciliation Commission, 2015; United Nations Declaration on the Rights of Indigenous Peoples, 2007). As a result, there is significant distrust between government, scientific institutions, and Indigenous communities which have reduced the number of collaborative research initiatives that take place across Canada and more specifically, British Columbia (Curran, 2019; Eckart et al., 2020), although these numbers are beginning to increase in recent years. Chapter 2 aims to synthesize these issues to provide context for thesis motivation. Scientifically, there is a lack of data that constrains the physical characteristics of localized geothermal resources leading to significant exploration and development risks. Further, geothermal research and development have been previously underfunded by the federal government as most investments for the energy sector go to the fossil fuel industry (Grasby et al., 2012). To reduce risks for geothermal development, it is therefore critical to review the geological setting, heat flow, and geothermal indicators in the southern Canadian Cordillera at a local scale to understand the opportunities that exist for research, exploration, and collaboration. To address both social and scientific challenges, earth science researchers can develop collaborative projects that seek to contribute to both reconciliation and novel geothermal research. This thesis research integrates western science with collaborative research approaches to pursue a local investigation of geothermal resources at Sloquet Hot Springs in British Columbia, Canada.

Sloquet Hot Springs is one of the many thermal systems in southwestern British Columbia (Figure 1) and is located within the Western Coast Belt (Journeay and Csontos, 1989; Brown et al., 2000) on unceded St'at'imc territory. The region has been identified as an area with moderate to high geothermal potential (Kerr Wood Liedel, 2015). Although feasibility assessments suggest the potential for resource exploration and development, there has been limited local research that characterizes the local geothermal gradient, hydraulic properties of the subsurface, and groundwater flow system. This thesis will focus on the collaborative approaches that were taken to pursue a local investigation of Sloquet Hot Springs and provide insight on the characteristics of geothermal and groundwater resources; herein referred to as the hydrogeothermal system.

The research was motivated by some of the following questions from the University of Victoria and Xa'xtsa First Nations' TTQ Economic Development Corporation: (1) Is there local interest in pursuing scientific investigations of Sloquet Hot Springs? (2) What baseline data exists and what do we know about the hydrogeothermal system? (3) What potential exists to use thermal waters at Sloquet to develop alternative soaking pools to reduce pressure on the culturally sacred springs? and (4) Is there potential to build greenhouses that harness the elevated subsurface temperatures to create sustainable food systems for the remote community?

The scope of this thesis is to derive conceptual models of the regional and local scale hydrogeothermal system based on detailed surface and subsurface investigations around Sloquet Hot Springs. A major component of this thesis included collaborating with Xa'xtsa First Nations' TTQ Economic Development Corporation to ensure research aligned with community values and interests. Through this process, it was possible to develop a transparent and open working relationship with TTQ Economic Development Corporation and Recreation and Recreation Sites and Trails BC to investigate the hydrogeothermal system at Sloquet Hot Springs and to answer the following research questions which also outline the overall thesis organization and contributions:

1. How does the geological environment contribute to the occurrence of geothermal resources in the southern Canadian Cordillera? How are resources, regulation, research, resurgence, and reconciliation connected to geothermal exploration and development in British Columbia, Canada?

Near the start of this thesis, Chapter 2 reviews the literature of the relationship between regional geothermal resources (i.e. thermal springs), geological setting (i.e. structural geology, location with subduction arc region, crustal heat flow), and hydrogeology. This section also provides an integrated approach to understanding the fundamental processes that contribute to the formation of thermal springs. This chapter also considers the societal and scientific background of geothermal and water resources in the province.

Near the end of the thesis, Chapter 4 aims to synthesize thesis research and present the next steps. More specifically, it is a summary and review of how research can contribute to decolonizing the western science processes by being inclusive of Indigenous communities through transparency and authenticity.

2. What are the characteristics of both the local and regional hydrogeothermal system at Sloquet Hot Springs?

The core of the thesis is Chapter 3 which contains scientific methods, results, and interpretations and will form the core of an academic publication. Parts of Chapter 3 were published as a Geoscience BC report (van Acken and Gleeson, 2020). Chapter 3 culminates in the first local and regional conceptual models developed for the system at Sloquet Hot Springs that show the inferred relationship between local and regional distributions of bedrock, faults, and joint structures and the first-ever glimpse into the bulk hydraulic properties and temperature of the subsurface at Sloquet Hot Springs.

For all chapters and the Geoscience BC report, AV completed the analysis and writing while TG provided direction, discussed methods and results, and edited text. Darryl Peters from TTQ Economic Development Corporation will be considered a co-author of the academic publication once completed.

CHAPTER 2. Literature review

2.1 GEOLOGICAL SETTING

The Canadian Cordillera formed in response to the accretion of oceanic arc and sea floor terranes, generation, upward transfer, and intrusive emplacement of batholiths, as well as extensive metamorphism (Brown et al., 2000; Nelson et al., 2013) and resulted in the formation of five morphogeological belts defined as the Insular, Coast, Intermontane, Omineca and Foreland belts (Journeay and Monger, 1994) (Figure 1). Accretionary processes slowed during the Late Paleocene and were followed by further tectonic processes distinct to each belt (Souther and Yorath, 1991; Journeay and Monger, 1994; Nelson et al., 2013). The Coast Belt contains a significant amount of mid- to Late Cretaceous arc magmatic rocks with minor Neogene and Quaternary igneous rocks that are located along two principal volcano-tectonic belts (Souther and Yorath, 1991; Journeay and Friedman, 1993; Lynch, 1990). Granitic bodies in the area intruded through stratified volcanic and sedimentary sequences that range in age from the Middle Triassic through the Early Cretaceous (Monger and Price, 2000). The Pemberton and Garibaldi Volcanic Belts are volcanic fronts that are related to the eastward subduction of the Juan de Fuca Plate (Souther and Yorath, 1991). Sloquet Hot Springs is situated to the east of the Garibaldi Volcanic Belt and just within the Pemberton Volcanic Belt- both of which are within the volcanic arc region of the Cascade subduction zone. This southern section of the Coast Belt is structurally characterized by Late Paleocene crustal-scale extensional faults that trend northwest (Grasby and Hutcheon, 2001) and faults that are Neogene age (Souther and Yorath, 1991; Lynch, 1990; Monger and Brown, 2016). More specifically, deformation in the region consists of shear zones that are spaced ± 10 km apart and are associated with steeply dipping fault planes. The region is characterized by north-northwest trending structures that reflect Cretaceous orogen-normal compression with southwest or northeast dips (Monger and Brown, 2016). The other primary structures in the region include Cenozoic northeast striking transcurrent faults (Journeay, 1990) that record right-lateral strike-slip and oblique-slip displacement (Journeay and Csontos, 1989; Lynch, 1990). Emplacement of Miocene aged intrusive breccias and related volcanic complexes associated with the Pemberton Volcanic Belt was controlled by Cenozoic faults. Northeast striking faults were identified as the primary controls for both Sloquet Hot Springs and Skookumchuck Hot Springs (Journeay and Csontos, 1989; Lynch, 1990). Typically, the northeast faulting is rarely exposed and are marked by marked by physiographic depressions, but largest exposure is the Glacier Lake Fault (Lynch, 1990). Fault timing and kinematics suggest that these structures are apart of a regional system that formed in response to northeast-southwest shortening (Lynch, 1990).

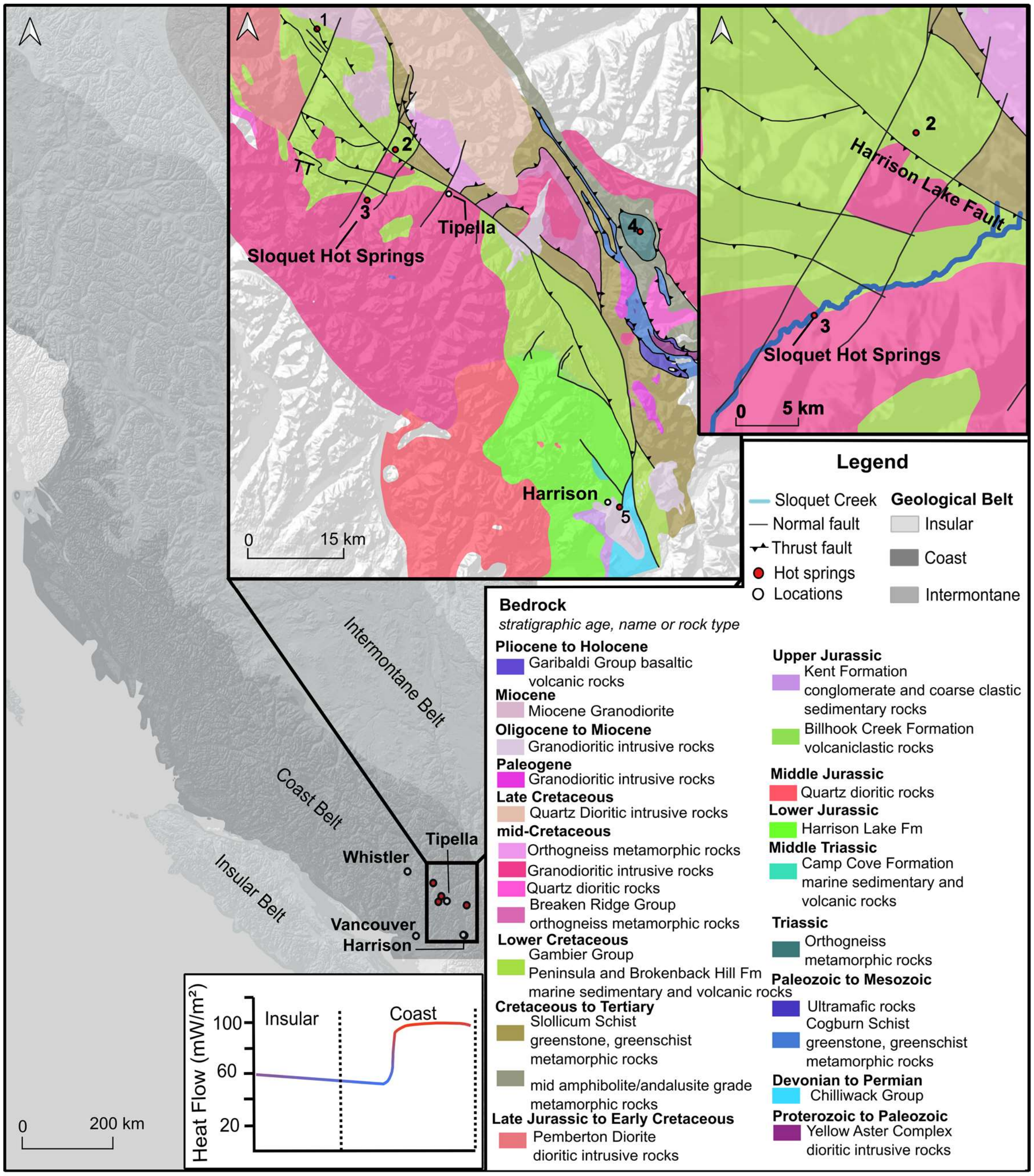

Figure 1. Regional geological and geothermal setting of Sloquet Hot Springs. (1) Skookumchuck Hot Springs; (2) August Jacob's Hot Springs ; (3) Sloquet Hot Springs; (4) Clear Creek Hot Springs; and (5) Harrison Hot Springs. Bedrock mapping from Journeay and Monger (1994) and heat flow as recreated from Grasby and Hutcheon (2001).

Bedrock surrounding Sloquet Hot Springs is primarily Middle Jurassic to Miocene age magmatic suites that have been intruded by Cenozoic dykes and plutons (Lynch, 1990; Monger, 1986; Journeay and Monger, 1994). Igneous sequences surrounding Sloquet are mapped as undifferentiated units of the Gambier-Fire Lake Group which are subdivided into the older Peninsula and younger Brokenback-Hill Formation (Journeay and Monger, 1994). The Peninsula Formation is primarily conglomerate and arkose sandstone and has been juxtaposed on top of the younger Brokenback Hill Formation due to accretionary processes (Lynch, 1990). Further, younger Brokenback Hill units are made up of four volcanic members (Journeay and Monger, 1994; Lynch, 1990). The springs at Sloquet Hot Spring are bound by two north-east striking faults that are related to the Neogene (Lynch, 1990) (Figure 1). Grasby and Hutcheon (2001) suggest that most thermal springs in the Canadian Cordillera are associated with major regional fault zones. However, detailed investigations of the hydrogeological properties of many of these springs or fault systems have not been previously pursued, further suggesting the need for local investigations of thermal springs.

2.2 HEAT FLOW AND GEOTHERMAL SETTING

There are three main geological regions of interest when considering exploration and development of geothermal resources in Canada but for this thesis, we will specifically focus on the southern Canadian Cordillera and the hydrogeothermal system at Sloquet Hot Springs (Figure 1). Regionally, there are over 130 thermal springs that have temperatures ranging from ~ 20 to 80 °C (Grasby and Hutcheon, 2001) indicating heat flow in the Cordillera may be sufficient for geothermal energy exploration and extraction (Finley et al., 2019). Although the distribution is widespread, these thermal springs do not guarantee geothermal energy can be extracted and only indicate that there is resource potential for regions with limited data availability (Finley et al., 2019). Geothermometry studies conducted by Grasby and Hutcheon (2001) suggest maximum fluid temperature for some springs exceeds 180°C between 2 - 5 km depth. Thermal springs across the southern Canadian Cordillera are understood to be controlled by brittle fault structures in the region (Grasby and Hutcheon, 2001; Journeay and Csontos, 1989; Lynch, 1990). The area is characterized by elevated heat flow in the upper 10 km of the crust (Grasby et al., 2012; R. Hyndman, 2010; R. D. Hyndman, 2005; T. J. Lewis et al., 2003). High heat flow in the crust is controlled by thin lithospheric conditions within the arc to back-arc region of the Juan de Fuca subduction zone as well as active and recent (6-18 mya) volcanism in the Pemberton and Garibaldi Volcanic Belt (Lewis et al., 1992, Souther, 1991; Hyndman, 2005). The geothermal gradient in the Canadian Cordillera ranges from 20°C/km to 50 °C/km (Lewis et al., 1992; Grasby and Hutcheon, 2001; Hyndman, 2010) with crustal heat flow ranging between 40 to 130 mW/m^2 with local anomalies that exceed 200 mW/m^2 (Finley, 2019; Grasby and Hutcheon, 2001; Jessop, 2008; Lewis et al., 1992; Lewis et al., 2003). Regionally, geothermal research has focused on crustal heat flow, distribution of thermal springs, and kinematic structure of regional faults with few studies that have constrained localized hot spring systems. The most detailed study in the southern Cordillera was focused along the southern flank of Mount Meager where exploration wells defined resources that exceed 250 °C (Jessop, 2008). Development at the site was economically limited by low permeability rocks at depth limiting the viability of cost-effective energy. The Mount Meager example provides incentive for more localized investigations on spring systems to understand the hydrogeological and geothermal conditions.

2.3 GROUNDWATER FLOW, FAULT ZONES, AND THERMAL SPRINGS

Groundwater flow in geothermal environments is often complex and poorly constrained particularly within regions of high relief mountainous terrain. Research conducted by Grasby and Hutcheon (2001) compared several parameters including heat flow, permeability, topography, refined infiltration rate, as well as the presence of fault zones with regards to their influence on controlling the location of thermal springs in the southern Canadian Cordillera. Findings suggest that fault zones in many areas of the Canadian Cordillera act as the primary control on the physical locations of thermal springs, whereas the other factors have a negligible influence (Grasby and Hutcheon, 2001; Kerr Wood Liedel, 2015; Hickson et al. (a), 2016). In the case of Sloquet Hot Springs and surrounding springs, Grasby and Hutcheon (2001) suggest that the northwest-trending Harrison Lake fault, located over 7 km from the study site, is the hydrogeological control of thermal fluid flow (Figure 1). The Harrison Lake Fault is considered a major dextral strike-slip fault that has undergone complex ductile and brittle deformation (Journeay and Monger, 1998; Monger, 1986; Journeay and Csontos, 1989; Talbot, 1989; Brown et al., 2000). The fault zone extends north into a series of faults that define a major valley system that contains the Meager Creek springs (Grasby and Hutcheon, 2001).

Regional fault zones, such as the Harrison Lake Fault, are typically lithologically heterogenous and structurally anisotropic, having the potential to act as conduits, barriers, or combined systems that promote or impede crustal fluid flow (Caine et al., 1996; Bense et al., 2013). Fault zones are composed of two main areas including the fault core, where most of the displacement has occurred, and the damage zone which is mechanically related to the expansion of the fault zone (Caine et al., 1996; Bense et al., 2013). More specifically, fault cores can include various zones that are single-slip surfaces, unconsolidated and clay-rich, brecciated and geochemically altered, cataclastic, and highly indurated (Caine et al., 1996; Finley et al., 2019). Field-based investigations by Caine et al (1996) suggest that thickness variations of these zones, down-dip and along the strike, coupled with internal structure and composition, play an integral role in controlling the fluid flow properties of fault core zones. Fault cores with lower porosity and permeability are considered to act as barriers to fluid flow as they are characterized by reduced grain size distribution and/or mineral precipitation (Caine et al., 1996; Bense et al., 2013; Finley et al., 2019). In contrast, core zones with higher porosity and permeability act as conduits due to increased grain size distribution within these zones. The damage zone contains a network of subsidiary structures that bound either side of the fault core and can act to enhance fault zone permeability relative to the original zone of deformation (Caine et al., 1996; Bense et al., 2013). Structures related to damage zones can include cleavage, fractures, joints, small faults, veins, and folds that created heterogeneity and anisotropy in the permeability structure of the fault zone (Caine et al., 1996). Research suggests that wide damage zones may indicate successive episodes of deformation over the geologic record (Caine et al., 1996). The geometry and magnitude of permeability contrasts between the fault core and damage zone act as primary controls on barrier-conduit systematics of fault zones (Caine et al., 1996; Bense et al., 2013). Permeability of the fault core reflects fracture density and connectivity which is typically less than in the damage zone, suggesting permeability would be dominated by the grain-scale permeability of the fault rocks (Caine et al., 1996). In contrast, hydraulic properties of the fracture network would control permeability in the damage zone (Caine et al., 1996). Typically, fluid flow across the fault is impeded in the clay-rich core materials while along-fault flow is facilitated by the permeable damaged zone. Intrinsic structural controls on the permeability of fault zones, porosity, and storativity include lithology, fault displacement, fault zone geometry (3D), deformation conditions, fluid-rock interactions, types of subsidiary structures, and the spatial and temporal variability of these parameters (Caine et al., 1996). In summary, it is possible to have thermal fluid flow at land surface when hydraulic properties permit flow from depths where groundwater has been heated by elevated crustal temperatures.

Grasby and Hutcheon (2001) suggest that groundwater recharge for thermal spring systems proximal to the Harrison Lake Fault is meteoric in origin and vertically percolates through the vadose zone into either into the zone of saturation or until water encounters a shallowly dipping fault plane that penetrates the crust. The meteoric water is then heated at depth and forced back up to land surface through the damaged zone conduit(s) (Grasby and Hutcheon, 2001). Groundwater flow through fractured rock still has many uncertainties as researchers have yet to determine why particular faults host thermal springs while others do not. Integrating existing literature on fluid flow in fractured rock with subsurface data from our study site will help understand the relationship between groundwater flow in high relief environments with complex thermal and hydraulic gradients.

2.4 REGULATIONS, RESOURCES, RECONCILIATION, RESURGENCE, AND RESEARCH

In addition to the foundational earth science perspective of this chapter thus far, it is also important to briefly overview regulation, resources, reconciliation, resurgence, and research through the lens of an earth science researcher to understand the complex landscape of these topics and ground the motivation of thesis research. Without commitment and exploration of these topics, thesis research likely would not have received free, prior, and informed consent from Xa'xtsa First Nation and our research would have been redirected to another location. As a literature review, this section does not aim to present novel or new ideas but seeks to present a framework for considering how regulation, resources, reconciliation, resurgence, and research (five R's) operate in British Columbia.

Water and energy resources are often considered to be abundant and reliable in British Columbia yet many Indigenous communities disproportionately experience energy poverty (Ecotrust Canada, 2020; Hoicka et al., 2021; Rezaei, 2017; Rezaei and Dowlatabadi, 2016) as well as reduced water quality and availability (First Nations Health Authority, 2020; Simms, 2014; Simms et al., 2016). Over 200 Indigenous communities in Canada are not connected to the electricity grid and rely on diesel generators (80%) and hydro-electricity (18%) to meet their energy demands (Lovekin, 2017; Rezaei, 2017). These communities often experience lengthy blackouts, field spills, and a shortage of capacity (Konstantinos, 2018). Electricity in these remote communities is approximately three times more expensive than in communities on the grid (Rezaei, 2017). If there is no year-round road access to these remote locations, diesel delivery costs can be ten times higher than normal. Heating needs in these communities are usually met using propane and wood (Rezaei, 2017). Due to these challenges, many remote Indigenous communities are interested in exploring renewable energy, such as geothermal resources, to meet their energy needs (Hoicka et al., 2021; Lovekin, 2017; Narine, 2021; Richter, 2021; Scott, 2020). Geothermal resources can be used to meet basic heating demands and where viable can also produce electricity. In British Columbia, the right, title, and interest in all geothermal resources are owned by the government (Government of Canada, 1966) and the

Geothermal Resources Act (2008) does not mention Indigenous peoples or their inherent rights to the lands where these resources manifest. Although a broad regulatory scope exists at the federal and provincial levels for energy resources, many First Nations are using Indigenous laws and procedures to review projects in their traditional territories (Curran, 2019). Further, Indigenous communities are beginning to evaluate large-scale natural resource projects through their own process rather than the administrative process set up by the federal government (Curran, 2019). Through the lens of free, prior, and informed consent these communities are exercising their own Indigenous environmental governance (Curran, 2019). Decision-making processes between Indigenous and non-Indigenous Canadians are based on vastly differing world views and fundamental procedures (Bozhkov et al., 2020). These differences create an opportunity for enhancing environmental management and decision-making tools, particularly when regarding access to clean and sustainable energy and water resources (Curran, 2019; Bozhkov, 2020; Asselin and Basile, 2018; Nosek, 2019; Eckart et al., 2020).

In Canada, one million residents are estimated to consume groundwater and hundreds of groundwater aquifers provide water for industries, municipalities, and rural homeowners. In 2019, the province of British Columbia suggested 15% of the 121 observation wells were experiencing a moderate to large rate of decline in water levels (Province of British Columbia, 2019). In 2020, there were nine boil water advisories and 8 do not consume advisories across 15 Indigenous communities in British Columbia (First Nations Health Authority, 2020). These advisories affected more than 1,300 Indigenous peoples and were often in effect for more than one year (First Nations Health Authority, 2020). Contamination and depletion of water on First Nation traditional territories is another pervasive issue and is often caused by large-scale resource exploration projects (Human Rights Watch, 2016; Parfit, 2017). First Nations across British Columbia have repeatedly identified that water and decision-making are a priority (Union of British Columbia Indian Chiefs, 2010). Curran (2019) suggests that the state depoliticizes decisions about water by directing them into administrative processes while many Indigenous communities are repoliticizing water governance by creating evaluation processes that are reflective of their own legal traditions and standards. Throughout literature, many Indigenous communities have described water as a sacred resource and lifeblood of the environment that must be cared for (Blackstock 2001; LaBoucane-Benson et al. 2012; McGregor 2012, 2013; Sanderson 2008; Walkem 2004; Wilson 2014). Curran (2019) goes on to state that consultation is not consent and that there is no court identified nor proactive statutory acknowledgment of Indigenous water rights in Canada.

Earth scientists may consider their research objective and unrelated to the (ongoing) legacy of colonialism and the current effort towards reconciliation. But all researchers have a worldview shaped by their experiences and training that leads to subjectivity in all research. And all field-based earth science research occurs in a specific place (on the land) which in Canada often has contested rights. The United Nations Declaration on the Rights of Indigenous Peoples was adopted by the UN general assembly in 2007 after more than 20 years of negotiations (Bain et al., 2018). The declaration provided a framework for justice and reconciliation, applying existing human rights standards to the historical, cultural, and social circumstances of Indigenous peoples, who have - and continue to face- historical and ongoing violations because of colonialism (Bain et al., 2018). Initially, the Government of Canada voted against the declaration (Bain et al., 2018) until the Truth and Reconciliation Commission (2015) released 94 calls to action one of which called on federal, provincial, territorial, and municipal governments to adopt and implement the United Nations Declaration on the Rights of Indigenous Peoples as a framework for reconciliation (Bain et al., 2018). Collectively, the Calls to Action and UN Declaration work to address the historical and ongoing damage caused by colonization, the residential school system, and social oppression (Truth and Reconciliation Commission, 2015) while also creating legislation that covers all facets of human rights of Indigenous peoples such as culture, identity, language, health, education, and community (United Nations Declaration on Rights of Indigenous Peoples, 2007). In 2019, the Government of BC passed the legislation to implement the UN Declaration which is considered the framework for reconciliation by the Truth and Reconciliation Commission. The B.C. Declaration on the Rights of Indigenous Peoples Act aims to develop a united path forward that respects and acknowledges the human rights of Indigenous peoples while increasing transparency and representation of decision-making across communities. Although these are monumental steps toward a united future, Wong et al (2020) suggest many Canadians fail to grasp the complexity of these issues, resulting in a lack of personal connection to Indigenous communities and reconciliation.

Corntassel (2012) suggests that “politics of distraction” such as rights, reconciliation, and resources, divert attention away from decolonizing movements that lead to Indigenous resurgence. These politics of distraction continue to push toward a state agenda of assimilation. Corntassel (2012) recognizes that reconciliation without meaningful restitution perpetuates the injustices Indigenous communities face. Further, many Indigenous nations do not have traditional words for reconciliation, reaffirming the lack of relevance to these communities (Corntassel, 2012). Coleman (2016) proposes that an alternative to state-centered processes is through Indigenous resurgence which aims to revitalize Indigenous peoples’ cultural practices, beliefs, spiritual sense of responsibility to protect their lands, sovereignty, and the right to live without pressure of assimilation. Through the mechanism of resurgence, it would be possible to facilitate a renewal of roles and responsibilities while reconnecting Indigenous communities with their homelands, cultures, and communities (Corntassel, 2012). How do reconciliation and resurgence pertain to researchers in the resource sector? Smith (2013) suggests that for many Indigenous communities, research has become a "dirty" word due to the reality that research on them or in their territory has caused more harm than good in many circumstances. As a fundamental human right, Indigenous peoples have the right to self-determination (Bain et al., 2018; United Nations Declaration on Rights of Indigenous Peoples, 2007). Including the right to determine their own priorities and control how their lands and resources will be accessed, used, and for what purposes (Bain et al., 2018; United Nations Declaration on Rights of Indigenous Peoples, 2007). Indigenous peoples must have access to all relevant information to make their decisions which may also include access to independent assessments (Bain et al., 2018; United Nations Declaration on Rights of Indigenous Peoples, 2007). The process must be free of intimidation, threat of retaliation, or other forms of duress (Bain et al., 2018). Scientific research has remained on the periphery of reconciliation yet is not considered removed or immune from the process (Kovach, 2009; McGregor, 2018, Wong et al., 2020). Debassige (2013) clearly states that Indigenous peoples are the original researchers of their territories. Yet, many researchers treat their knowledge as out of place or are only committed to consultation for individual benefit (Asselin and Basile, 2018). In 2020, Wong et al., published 10 Calls to Action for natural scientists to enable reconciliation to spark engagement and help researchers build a foundation of mutual respect and understanding with Indigenous Peoples. Wong et al. (2020) argue that natural scientists and Indigenous communities both have vested interests in understanding landscapes and how they are changing with human influence, which should lead to more collaborative research. For years, three federal agencies in Canada - the Tri-Council: Social Sciences and Humanities Research Council (SSHRC), Canadian Institutes of Health Research (CIHR), and Natural Sciences and Engineering Research Council (NSERC), have guided ethical conduct for research involving humans through the Ethical Conduct for Research Involving Humans Policy (Wong et al., 2020). Within this policy, there is a chapter on working with Indigenous Communities (Canadian Institutes of Health Research et al., 2018). Wong et al. (2020) further argues that although NSERC is part of the tri-council, there are very few natural science researchers that are aware of the guidance given to work with Indigenous communities, nor does it appear that natural scientists see their work being linked to Indigenous communities if people are not directly interviewed or sampled. From a place of frustration, Wong et al. (2020)

developed 10 calls to action to natural scientists working in Canada to address the need for participatory action.

Natural science researchers can use these calls to action as metrics of success in engaging with Indigenous communities (Wong et al., 2020). Johnson et al. (2016) reaffirms many of these calls in a previous publication by suggesting that scholars working with Indigenous communities must recognize the challenges and “learn to see their own privilege and deep colonizing” while Von der Porten (2013) warns against engaging and using Indigenous knowledge systems in a superficial or secondary sense as it does not address the root problem – one that was born from colonial structures (Curran, 2019). Further Curran (2019) and Schilling-Vacaflor (2017) suggest limited participation of Indigenous peoples in such decision-making and project development would only serve the interest of those already in power by creating an image of legitimacy like the concept of greenwashing - where communication misleads people into forming positive beliefs about an organization’s practices (Lyon and Montgomery, 2015). By authentically participating, engaging, and receiving free, prior, and informed consent it is possible to participate in reconciliation in action and Indigenous resurgence (Johnson et al., 2016). Further, using Wong et al. (2020) to hold natural scientists accountable it is possible to work toward tangible goals when engaging with Indigenous communities.

As an earth scientist, I view thesis research at Sloquet Hot Springs as being amidst the five R’s as we begin to create a more inclusive and collaborative working environment. Although Wong et al. (2020) was published during, rather than before this thesis research, the ten calls to action are used to evaluate our collaboration methods that aimed to conduct inclusive and transparent research on the land of Xa’xtsa First Nation (Chapter 3) and provide further recommendations in Chapter 4.

CHAPTER 3. Evaluating the characteristics of geothermal and groundwater resources at Sloquet Hot Springs in British Columbia, Canada

3.1 INTRODUCTION

Sloquet Hot Springs is in the Coast Mountain physiographic region on the edge of two biogeoclimatic zones. The coastal western hemlock zone receives 2,893 mm of mean annual precipitation and has a mean annual temperature of 6.7 °C. Where as, the mountain hemlock zone receives 3,119 mm of mean annual precipitation and has a mean annual temperature of 2.8 °C (Moore et al., 2010). Biogeoclimatic zones and their associated climatic regime will be used as reference due to limited local meteorological data. The thermal system is situated adjacent to Sloquet Creek at a topographic low of approximately 200 meters above sea level (masl) and is amidst steep terrain that rises to over 1500 masl. The area is further characterized by undulating slopes that are covered by dense vegetation and unconsolidated materials (Figure 2). Bedrock outcrops are localized along forest service roads and along Sloquet Creek, where numerous cold, warm, and hot springs discharge from well-developed joint structures near the creek.

There have been few scientific and economic studies in the region surrounding Sloquet Hot Springs. Exploration projects have sought to identify high-grade gold deposits that are associated with the complex history of deformation, metamorphism, and igneous intrusions (Kerr Wood Liedal, 2015; Shearer, 2010). Shearer (2010) investigated mineral claims land that surrounds Sloquet Hot Springs and did not evaluate geothermal resources that exist in the area. However, the work of Hickson et al. (2016a) and Kerr Wood and Liedel (2015) included analyses of geothermal resources at Sloquet Hot Springs. Other independent studies have carried out field investigations of Sloquet Hot Springs to gain insight into the thermal fluid temperatures at land surface and depth. Data collected from these studies have provided temperature ranges for thermal springs at Sloquet as well as estimates for maximum reservoir temperature and fluid circulation depth. Spring temperatures recorded through these studies show a temperature range from 60.8 to 71 °C (Grasby and Hutcheon, 2001; Hickson et al. (a) 2016). Varying geothermometry methods were used to estimate the maximum reservoir temperature at depth using Na-K-Ca and SiO_2 indicators and have suggested temperature at depth ranges between 110 to 135 °C (Grasby et al., 2000; Hickson et al. (b), Inc. 2016). Circulation depths of 2.3 km depth (Grasby and Hutcheon, 2001) were calculated based on spring temperatures, maximum reservoir temperature, and an assumed regional geothermal gradient of 50 °C/km (Grasby and Hutcheon, 2001). Preliminary geothermal feasibility assessments were also completed and suggest that Sloquet Hot Springs has moderate potential for harnessing thermal resources and could produce up to 10-20 MW of energy (Kerr Wood Liedal, 2015). Although informative, in-situ conditions were not characterized, thus opening the question – what are the characteristics of the hydrogeothermal system at Sloquet Hot Springs, and what are the fundamental controls of fluid flow? This question presented the University of Victoria with an opportunity to explore whether the community of Xa'xtsa First Nation would be interested in pursuing a collaborative investigation of Sloquet Hot Springs. With curiosity, sustainability, and preservation of the land in common, Xa'xtsa First Nation's TTQ Economic Development Corporation and the University of Victoria found common ground in pursuing local scientific investigations of Sloquet Hot Springs to address the lack of data that constrains the hydrogeothermal system.

The five main objectives of this chapter include: (1) review of methodological approaches to developing a collaborative research project with Xa'xtsa First Nations TTQ Economic Development Corporation and Parks and Trails and Recreation Sites British Columba; (2) review methods used for conducting a detailed geological and hydrogeological study of geothermal and groundwater resources at Sloquet Hot Springs; (3) present and discuss the distribution of thermal springs, rock, and joint structures in the hundreds of meters surrounding the study site; (4) present and discuss the results from drilling and testing an observation well;

Figure 2: Sloquet Creek in the foreground and steam can be seen rising from thermal springs above creek bed. Person in photograph for scale. Image taken September 2019.

and (5) present a novel conceptual model that summarizes the lithologic, structural, and hydrogeological framework of the regional and local setting of Sloquet Hot Springs.

3.2 METHODS

3.2.1 COMMUNITY COLLABORATION

The objective of this subsection is to review collaborative research approaches that were taken to work in partnership with Xa’xtsa First Nations’ TTQ Economic Development Corporation. The purpose of highlighting our methods for consultation and collaboration is to showcase how earth scientists can begin to collaborate with Indigenous communities in British Columbia and is by no means a one-size-fits-all solution. Further, it should be explicitly stated that engaging with Indigenous communities could look vastly different and may not result in approval for scientific investigations (Wong et al., 2020). When we first started developing thesis project ideas there had been preliminary talks with Xa’xtsa First Nation, but no verbal or written approval had been received to pursue scientific investigations. If we were unable to receive free, prior, and informed consent from Xa’xtsa First Nation, we would have respected the community’s decision and pursued another project. As presented by Wong et al. (2020), academic researchers have a tremendous opportunity to create a united pathway forward while conducting natural scientific research.

Community consultation was conducted through a series of gatherings that took place over two years and included management from TTQ Economic Development Corporation as well as members of the community. Interactive community gatherings aimed to build a relationship between researchers, TTQ Economic Development Corporation, and the community. Gatherings consisted of a feast hosted in the village of Tipella that I had prepared for the community. The purpose of these gatherings was to open the floor for questions and general discussion about potential project development. Each gathering was opened with acknowledgment of traditional territory, followed by a ceremonial gift exchange to provide gratitude to each elder in attendance. Gifts were made up of medicinal plants most of which were harvested by researchers from Vancouver Island, British Columbia (Figure 3). Elders also received dried tobacco leaves grown by Coast Salish Elders that were wrapped in red cloth. Plant species chosen were based on suggestions from Coast Salish Elders as each offering presents an opportunity to collaborate and work together collectively. Community gatherings provided partners with an opportunity to build relationships amongst one another while also gaining perspective on the cultural significance of Sloquet Hot Springs.

Through these gatherings, it became evident that the community was interested in pursuing local investigations of the study site. A letter of intent was developed and signed in conjunction with the University of Victoria and TTQ Economic Development Corporation. The letter of intent marked approval to conduct visual surveys, mapping, drilling, and reporting into the location and availability of the resource. The letter of intent also clarified the responsibility researchers had if they encountered any artifacts when surveying and/or drilling.

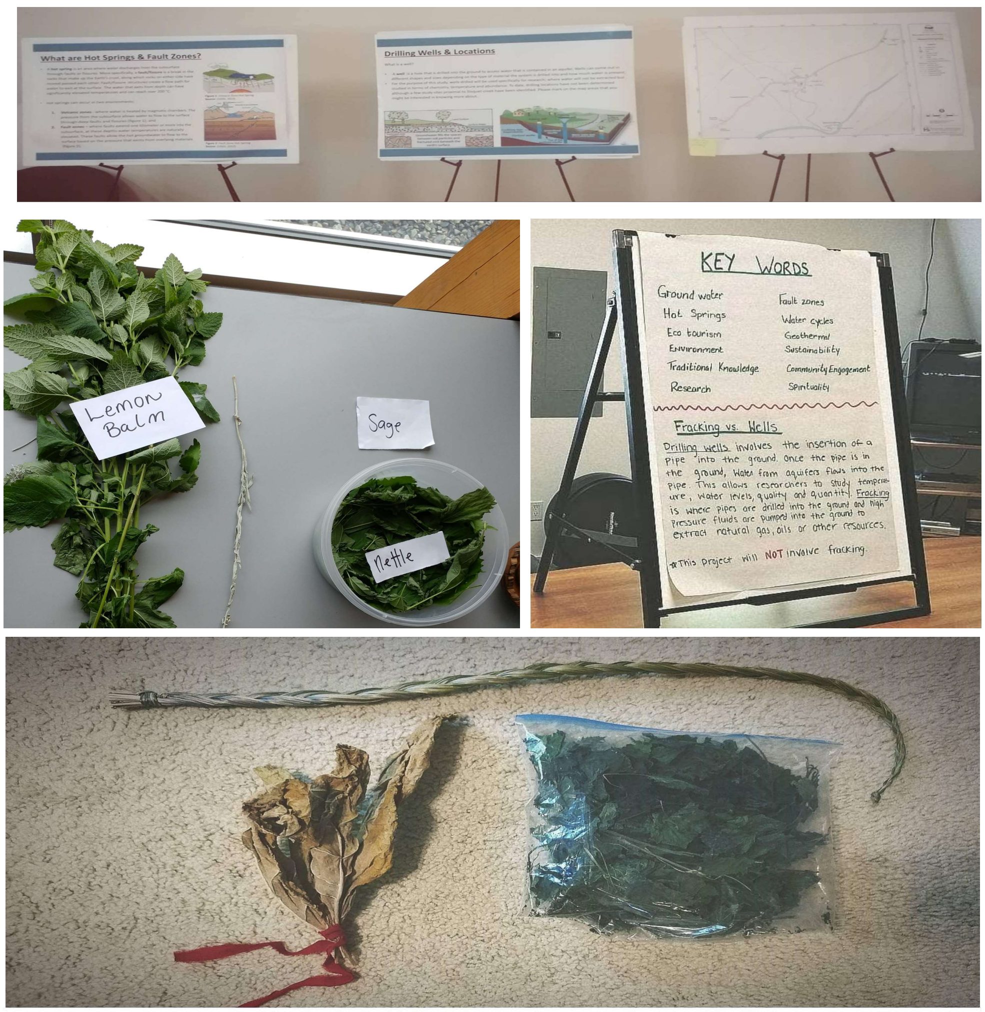

Figure 3: Photographs of some of the medicinal plants that were used as ceremonial gifts to the community and Elders. Upper and top right photograph shows discussion posters for community events.

3.2.2 LITERATURE REVIEW AND FIELD RECONNAISSANCE

Research initially focused on reviewing and synthesizing literature on the local (hundreds of meters) and regional (kilometers) setting of Sloquet Hot Springs to understand the tectonic history, distribution of bedrock, geologic structures, unconsolidated materials, physiography, and thermal springs. The literature review summarized data from the Geological Survey of Canada, mineral exploration reports, and other independent studies conducted on thermal springs across the Province. Once enough preliminary data was gathered, a field reconnaissance was conducted at Sloquet Hot Springs to compare field observations against documented literature. Field reconnaissance focused on investigating the distribution of bedrock, thermal springs, geological structures, and general physiographic setting in the hundreds of meters surrounding Sloquet. The literature review and field reconnaissance provided enough information on the study site to begin planning for the first field season in 2019.

3.2.3 BEDROCK, STRUCTURAL, AND SPRING MAPPING

Figure 4: Spring flow rate being measured using bucket testing. All measurements were collected during September 2019.

Geological mapping was focused along the north and south margins of Sloquet Creek due to extensive sediment and vegetation cover that limited exposures of bedrock and thermal. The north and south margins of Sloquet Creek were investigated along a transect line to collect data on bedrock exposures (outcrop size, lithologic descriptions), thermal springs (temperature, conductivity, flow rates, discharge location in relation to bedrock), and structural measurements (strike and dip). Note, the location of transect lines and newly identified springs are not included in mapping as an agreement between University of Victoria and TTQ Economic Development Corporation. In total, 49 springs were identified and mapped, as well as 98 structural features were measured (joints, faults, and bedding planes). Where possible, water temperature and conductivity data were collected with a Hach HQ40D Portable Multi Meter. Flow rates were assessed with “bucket tests” where containers with known volumes collected water over timed intervals or where this was not possible, semi-quantitatively with visual estimates. During bucket tests, spring flow rates were measured ten times and averaged to get an estimate that likely represents a minimum since it was not always possible to consistently collect all the water due to irregular rock surfaces. Flow rates were measured at the beginning of September 2019 from morning to afternoon.

3.2.4 SPRING MONITORING

Select thermal springs were monitored over the 2019-2020 season to understand how water level and temperature change over time. DS1922L-F5 Thermochron iButton’s and Solinst leveloggers were installed at areas of interest to record water fluctuations and temperature over time. Thermochron iButton’s are designed to only record temperature to an accuracy of ±1°C when within the optimal temperature range of -40 °C to 85 °C. They were chosen based on their size and ability to be placed in discrete locations. Solinst leveloggers record pressure and temperature to interpret water level changes through time and were utilized to calculate discharge rates at one of the major source springs for the soaking pools (HS138). Pressure and temperature data on the Solinst leveloggers recorded data every thirty minutes with an accuracy of 0.05%. A low-impact v-notch weir was also installed within the creek that discharges thermal water from HS138 (Figure 5). The weir was constructed from a sheet of aluminum that was cut to the dimensions of the creek and the v-notch angle (θ) was determined through trial and error to minimize site disturbance. The weir was installed ten separate times with θ values ranging from 30°- 50°. Angles under 50° led to excessive pooling in the creek that did not represent the natural system that existed before installation. To minimize seepage, pond liner was bolted and fastened to the sheet of aluminum with silicon sealant to fill small openings on the weir. Once

Figure 5: V-notch weir installed on HS138. Dense cover of poison ivy surrounding the weir.

finalized, the weir was installed into the creek with one Solinst levelogger and Thermochron iButton at the base of the aluminum. The theoretical principles from the Kindsvater-shen equation were used to calculate flow as the angle of our v-notch was between 25° to 100°. Therefore, it was possible to calculate discharge in an open channel using:

$$Q = 4.28C \tan\frac{\theta}{2}\ (h+k)^{5/2} \qquad \text{(Eq 1)}$$

Where:

C = discharge coefficient

θ =notch angle

h = head (ft)

k = head correction factor (ft)

Further, C and k values are obtained from curve matching for the angles between 25° to 100°. The weir will be removed once public health orders allow non-essential travel to remote communities.

3.2.5 WELL DRILLING AND TESTING

The observation well (OBW1) was drilled in August 2019 using dual rotary methods to drill a 6-inch diameter well (Well Tag Number: 118320). Drill chips were collected every 5 ft to observe changes in lithology during drilling. OBW1 is cased from 0 to 40.5 meters and is secured into bedrock using cement grout and is uncased from 40.5 meters to 152 meters. The uncased open hole well underwent two pumping tests in the fall of 2020 including a 3-hour step drawdown test and a 12-hour constant rate test. Step drawdown tests are used for single wells to collect drawdown data under controlled variable discharge conditions. The well was pumped at 0.17 m^3/minute, 0.20 m^3/minute, and 0.24 m^3/minute for one hour at each pumping rate to help determine an appropriate pumping rate for the constant rate test. A constant rate pumping of 0.24 m^3/minute over 12 hours was used to determine hydraulic properties of transmissivity, hydraulic conductivity, and storage coefficient of the aquifer using Theis (1935) and Cooper-Jacob solutions. The Theis solution was performed by matching the type-curve to drawdown data plotted as a function of time on a log-log plot (Theis, 1935). It is assumed that the aquifer is confined, homogenous, isotropic, uniform in thickness, pumping never effects the exterior boundary, no recharge, well discharge is derived from storage, pumping rate is constant, pumping well fully penetrates the aquifer, 100% well efficiency with no well losses, radius is infinitely small and that the initial potentiometric surface is horizontal (Theis, 1935). The Cooper-Jacob solution (1946) is a late-time approximation that was derived from Theis type-curve method with similar assumptions. The method involves matching a straight line to drawdown data plotted as a function of the logarithm of time since pumping was initiated. The solution assumes the aquifer has infinite areal extent, is homogenous, isotropic and of uniform thickness, control well is fully penetrating, flow is horizontal and unsteady, the aquifer is nonleaky confined, water is released instantaneously from storage with a decline of hydraulic head, the diameter of pumping well is exceedingly small so that storage in the well can be neglected, values of μ are small. There are many uncertainties in interpreting pumping tests based on these assumptions. The classical Theis and Cooper-Jacob methods are often used even when the theoretical assumptions are not met as often there is limited available data about the system. Theis solution requires curve matching of drawdown time series data and if the time series data does match the curve, then the methods would not be sufficient for determining values for transmissivity, hydraulic conductivity, and storage (Figure B2). Further, the drawdown data in Appendix B from OBW1 does not show any anomalies suggesting the assumptions from the Theis solution are reasonable given conditions at Sloquet Hot Springs (Meier et al., 1998). The Cooper-Jacob method is premised on the Theis well function plotting as a straight line on semilogarithmic paper (Meier et al., 1998). The method is considered a valid approximation if it is possible to match the straight line from data points with μ being smaller than 0.03 for which the approximation error is less than 1% (Meier et al., 1998). These methods still give reliable results despite major assumptions if time series drawdown data appears to meet these assumptions. Lastly, the well was completed with two 2-inch nested piezometers that were screened at different depths. Piezometer screen depths were between 67 - 85 meters and 96 - 116 meters. These screens were to be isolated with bentonite at depths of 54 - 64 meters and 85 - 94 meters. The purpose of having two isolated piezometers within the single well was to monitor the upper and lower portions of OBW1 and identify any possible thermal inflows (Figure B5). During completion, bridging occurred at approximately 70 meters and the well was not able to be finalized as planned. The nested piezometers were not isolated because of bridging and require future remediation efforts to work toward well completion.

3.3 RESULTS

3.3.1 LITHOLOGY AND STRUCTURAL MAPPING

Five lithological units were identified in the hundreds of meters surrounding Sloquet Hot Springs recreational site including unconsolidated materials, clast supported conglomerate, an intrusive porphyry, undifferentiated Gambier Group, and granodiorite (Figure 6). Appendix A Figures A1-A6 show more detailed photos of each unit.

Updated mapping in Figure 7 shows that Sloquet Hot Springs is bound by granodiorite, likely from the mid- to Late Cretaceous as well as undifferentiated Gambier Group volcanics based on field interpretations compared to mapping completed by Journeay and Monger (1994). The felsic granodiorite was phaneritic with 2-4 mm hornblende minerals, and the groundmass appeared to be quartz. The undifferentiated Gambier Group unit appeared to be mostly aphanitic with lustrous minerals that were less than 1mm in size. The unit appeared metamorphosed as seen in Appendix A (Figure A6) and had white mineralization where springs were discharging. Certain samples of the rock bubbled when conducting an acid test while others did not. Both units appeared to have well developed joint structures that were oriented to the northwest.

The southern edge of Sloquet Creek is intrusive porphyry (Figure 6 and Appendix A Figure A4-A5). The intrusive porphyry was intermediate, grey/blue, with aphanitic groundmass and well-developed quartz phenocrysts ranging from 2-10 mm in size. The unit had a relatively smooth surface and contained distinct conjugate joint sets that were oriented northwest to southeast, north to south, as well as northeast.

Along the northern side of Sloquet Creek, a clast supported and lithified conglomerate unit unconformably drapes over the intrusive porphyry and was the primary unit observed (Figure 8). Clast lithology within the conglomerate was primarily granitic with few mafic volcanics. Overall, the sorting of clasts was poor to moderate with sand to boulder sized inclusions. The contact between the intrusive porphyry and clast supported conglomerate is depositional (Figure 8). In several locations the conglomerate drapes over the porphyry in a depositional pattern that is consistent in geometry and grain size distribution (fining upwards from boulders at bottom) with fluvial or glaciofluvial deposition in a paleochannel coincident with the modern riverbed geometry. Journeay and Monger (1994) suggest that conglomerate strata associated with the Peninsula Formation contain clasts of andesite, rhyolite, and feldspar porphyry with minor chert, quartz, and granite (Journeay and Monger, 1994). Based on our data, it is proposed that the conglomerate unit is not part of the Peninsula formation as the observed geological contact appears depositional and matrix lithology being primarily granitic inclusions. The only observable structures present within the unit were anastomosing fractures that formed around clasts within the unit (Appendix A, Figure A2).

Unconsolidated materials were the youngest lithological unit identified in the hundreds of meters surrounding Sloquet Hot Springs. The unit was matrix supported and appeared fluvial or glaciofluvial in origin. Unconsolidated materials concealed most bedrock in the area and were poorly sorted with cobble to boulder size inclusions that were surrounded by a silty clay matrix (Figure 6).

Structural joint measurements were collected from the intrusive porphyry, granodiorite and undifferentiated Gambier Group units have a strong northwest to southeast and north to south orientation as presented in Figure 7 a-b. Northwest trending joints are composed of two clusters, one that is sub-vertical (blue) and the other that dips to the southwest (orange) (Figure 7a.). Plotting structural data as poles (Figure 7c.) statistically reiterates the strong northwest clustering of joint structures with a smaller northeast subset. These results are consistent with the regional fault orientations presented in Figure 1. There were no obvious controlling fault structures mapped in the field, but the presence of joint structures and thermal springs suggest that larger fault structures are likely present in the area and may be concealed by unconsolidated materials and the clast supported conglomerate.

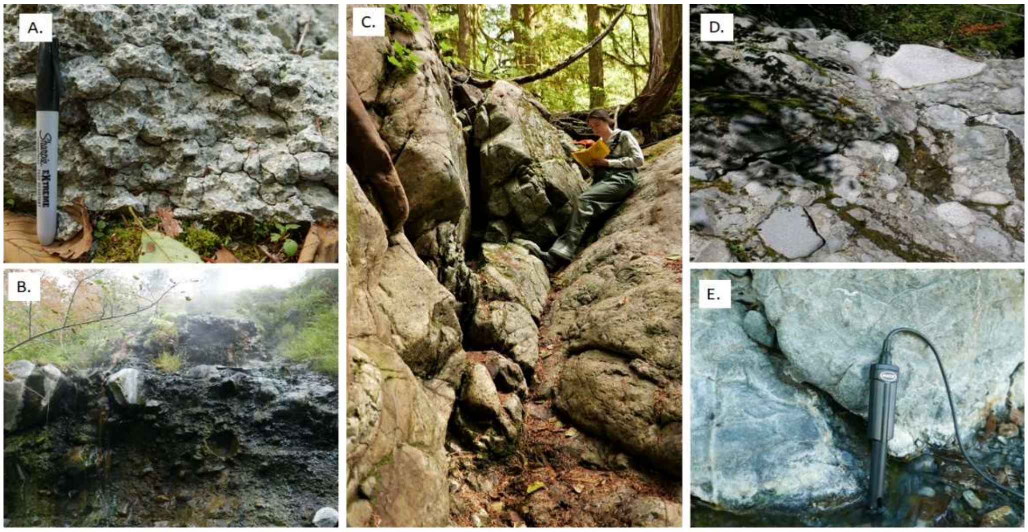

Figure 6. Main lithological units observed in the hundreds of meters surrounding Sloquet Hot Springs. (A) Intrusive porphyry with well developed quartz phenocrysts ranging from 2 to 10 mm in size. (B) Glaciofluvial unconsolidated sediments with cobble to boulder sized clasts. (C) Granodiorite that outcrops near the edges of Sloquet Hot Springs. (D) Clast supported conglomerate that has boulder to sand size fragments in the matrix, poorly to moderately sorted, subrounded inclusions. (E) Undifferentiated Gambier Group appeared highly lustrous and metamorphosed.

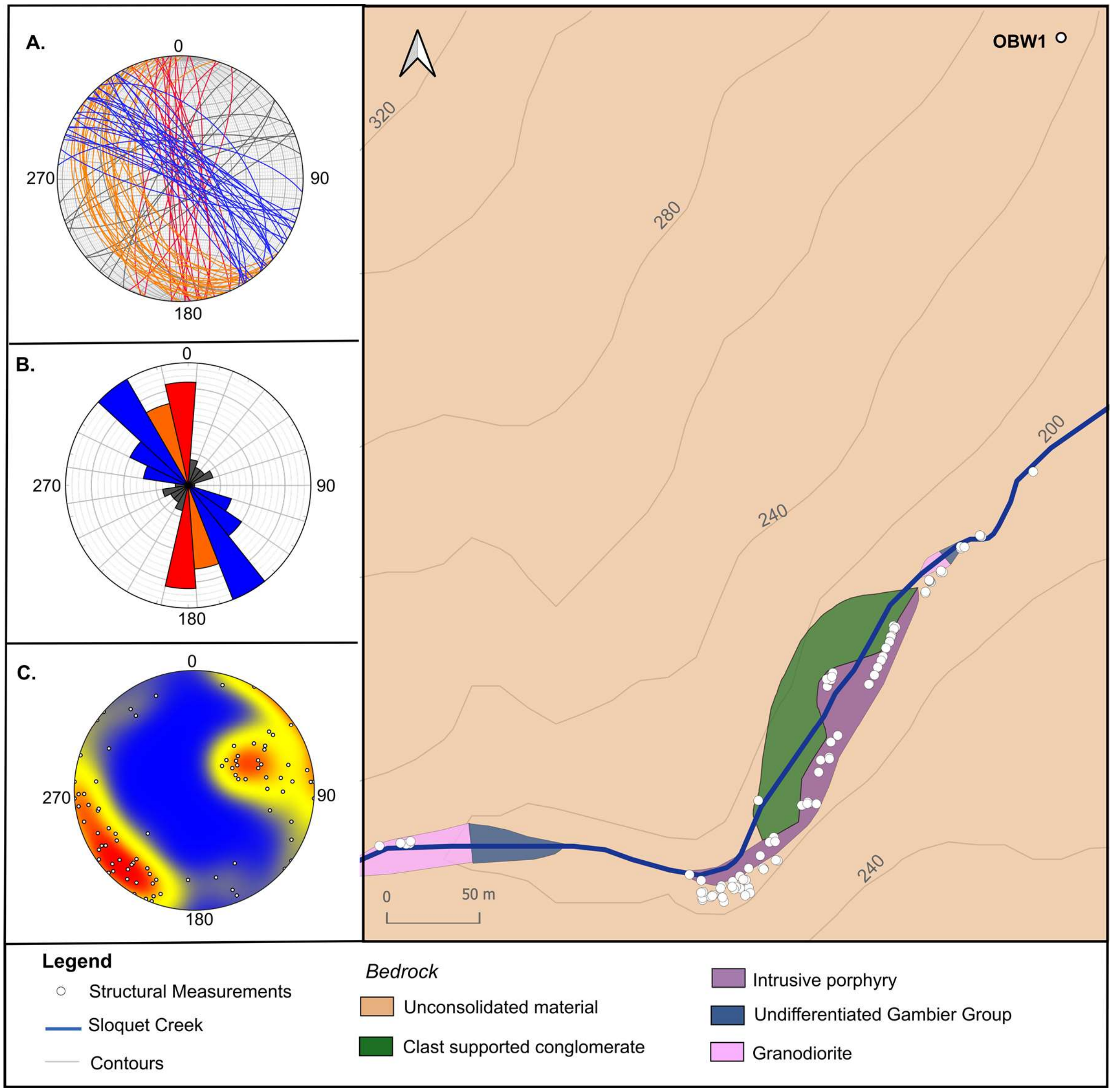

Figure 7: Updated bedrock and joint mapping surrounding Sloquet Hot Springs. Lithological units in map were observed in the hundreds of meters surrounding the main recreation site and their extent was covered by dense vegetation and sediment load. (A) Spherical equal area projection of joint measurements. Lower hemisphere with contour intervals of 2. (B) Circular histogram using equal distance for the strike plane bin count 21. (C) Strike planes plotted as poles using weighted gradient, contour interval of 2 using Kernel density gridding methods. Bedrock mapping representative of field observations that were compared against regional mapping by Journeay and Monger (1994).

Figure 8: Panoramic image of the northern edge of Sloquet creek showing the stratigraphic relationship between conglomerate (green) and the intrusive porphyry (purple). Depositional contact suggests porphyry was already exhumed when unit was deposited. Photograph taken end of August 2019 and person in photo for scale.

3.3.2 SPRING DISTRIBUTION AND MONITORING

Thermal springs discharge along a 500-meter stretch of north and south Sloquet Creek from unconsolidated materials, clast supported conglomerate, intrusive porphyry, and undifferentiated Gambier Group. Newly identified spring locations are not disclosed since they are of cultural importance. Spring temperature and conductivity varied significantly from 22 °C to 68.8 °C and 31 µs/cm to 1200 µs/cm, respectively. Figure 9 shows the spring temperature data for thermal springs located at the main recreation site. Only one spring, HS138, had data collected on flow rates and water level during the 2019-2020 field season (Figure 9a) due to a challenging physiographic setting that made it difficult to install equipment to record flow data. HS138 was chosen due to accessibility, suitability for v-notch weir installation, and because it is the main spring for the recreation area. Flow rates and temperature ranged between ~25 L/s to 80 L/s and ~65 °C to 67 °C and show seasonal variation while electrical conductivity ranged between 950 µs/cm to 980 µs/cm. Figure 9b also shows time series data collected for a few select springs at the recreation site (HS136 to 142) which had highly variable temperatures between ~25 °C to 60 °C with no seasonal patterns. Monitored springs were directly adjacent to Sloquet Creek and may have been exposed to mixing of thermal waters with the cooler water table. Figure 10 shows the distribution of spring temperature in relation to flow rate and lithology. Most springs that exceeded 60 °C discharged from the intrusive porphyry and had flows less than 5 L/minute. Two high temperature and high flow springs were observed along the north side of Sloquet Creek and included the main recreation spring, HS138, possibly discharging from unconsolidated material and HS100 which was discharging from anastomosing fractures in the clast supported conglomerate. Springs discharging from the clast supported conglomerate had the greatest range for temperature and average flow. Overall, most thermal springs appeared to discharge from the conglomerate and porphyry units with fewer springs discharging from unconsolidated sediments and undifferentiated Gambier Group volcanics.

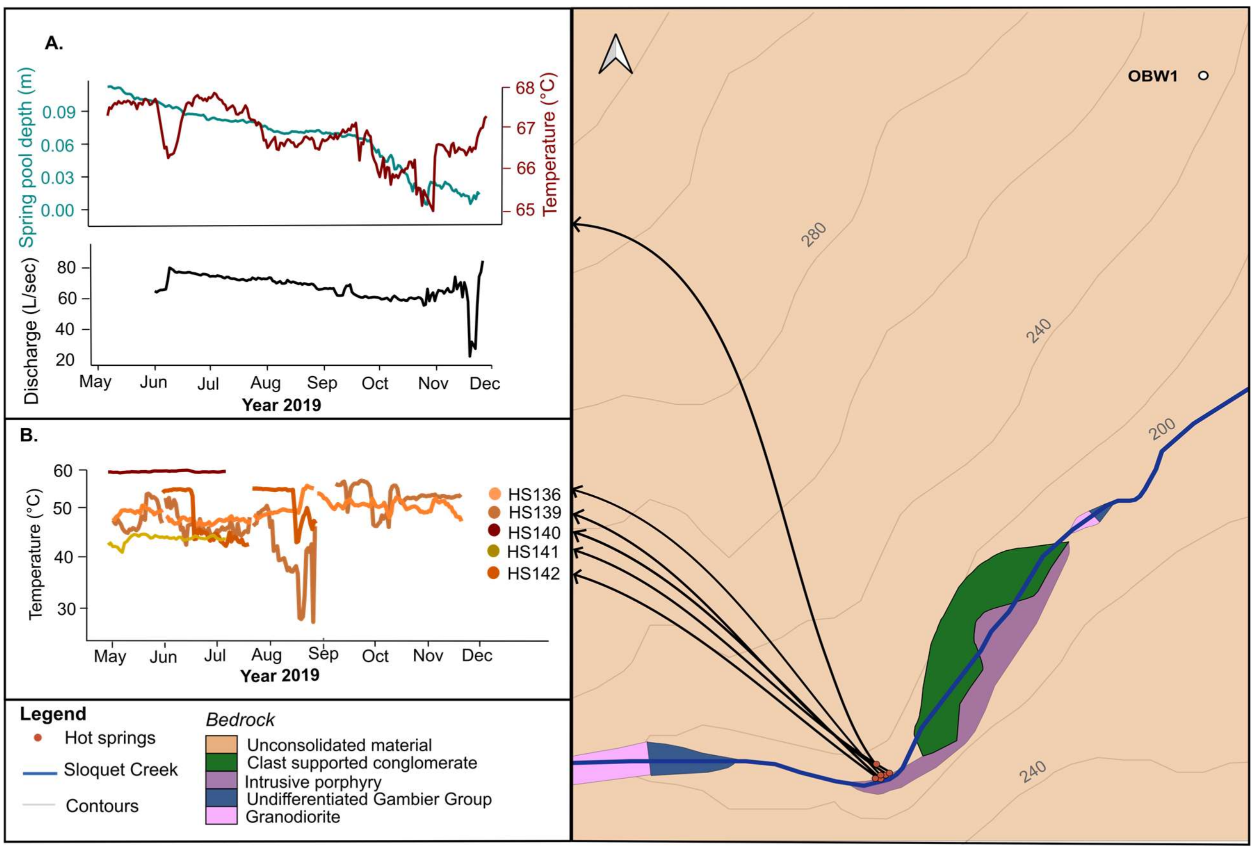

Figure 9: Temperature time series for thermal springs surrounding the recreational soaking area. (A) Spring pool depth (blue), temperature (red), and discharge (black) values for HS138. The main spring had relatively stable temperature between 65 °C to 67 °C. Flow rates ranged between 30 – 80 L/s. (B) Temperature time series data for HS136, 139, 140, 141, 142 showed temperature ranges between 20 °C to 60 °C. Bedrock mapping in the figure is inferred from thesis field investigations along north and south sides of Sloquet Creek and was interpreted based on previous mapping from Journeay and Monger (1994).

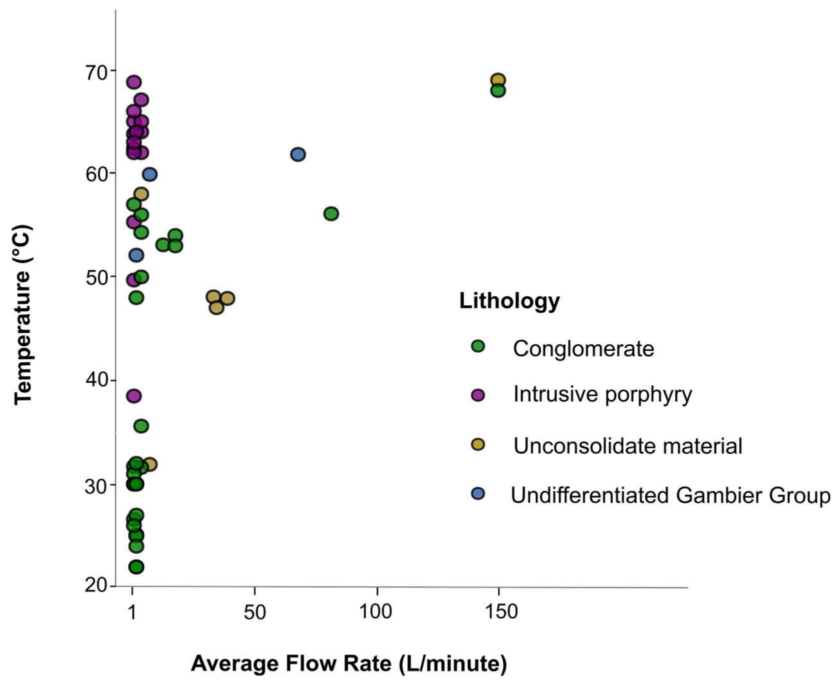

Figure 10: Spring temperature and flow rate observed along transect lines in the hundreds of meters surrounding Sloquet Hot Spring. Each circle is color coordinated based on the lithological unit the spring was discharging from. Graph shows that the highest temperature springs were discharging from the intrusive porphyry while the clast supported conglomerate had variable flow and temperature values.

3.3.3 WELL DRILLING, GROUNDWATER MONITORING, AND PUMPING TESTS

The subsurface environment at Sloquet Hot Springs has never been investigated in-situ apart from geothermometry studies. Figures 11-13 present a first ever glimpse of subsurface conditions at the study site. OBW1 is a 152-meter open hole well that has numerous soft zones in the subsurface which were described by the drilling team as zones of rock that allowed drilling to move faster likely due to compromised rock integrity. Drillers drilled through 38 meters of unconsolidated materials before encountering bedrock at ~39 meters. Water was encountered at ~32 meters with flow rates ~4 L/min at 36 meters depth. Upon contact with bedrock, fragments appeared mafic, angular, bluish and had white materials that did not react during an acid test. The first soft zone was from ~47 to 55 meters and drill chip fragments appeared lighter grey with goldish minerals. The second soft zone was from ~70 to 73 meters and had rock fragments that were blue to grey in color. At ~73 meters it smelled like sulphur and conductivity was measured to be 794 µs/cm with a temperature of 24.2 °C. Flow in this zone was ~190 L/min which was determined from air lifting methods. Another soft zone was recorded between ~82 to

83 meters and drill chip fragments were exceptionally fine with a greyish white appearance suggesting potential hydrothermal alteration. At ~95 to 97 meters, drill chip fragments were highly pulverized appearing grey to blue suggesting another fracture zone at these depths. The last observable soft zone was encountered between ~109 to 112 meters and fragments appeared mafic with a reddish/pink hue and smelled like sulphur. There was mineral build up on cobble suggesting a potential fault or fracture zone. Final in-situ temperature and conductivity values were measured at 120 meters (27 °C and 970 μs/cm), 137 meters (25.8 °C and 940 μs/cm), and 152 meters (26.8 °C and 989 μs/cm). Although the temperature of subsurface fluids did not exceed 30 °C during drilling, conductivity values were similar to HS138 (~945 μs/cm) at 137 meters and 152 meters. Overall, the lithology was interpreted to be a meta-volcanic unit that was intermediate to mafic with veins of quartz throughout. From the drill chips, there was no obvious change in lithology other than transitioning from unconsolidated materials to bedrock (Figure 11).

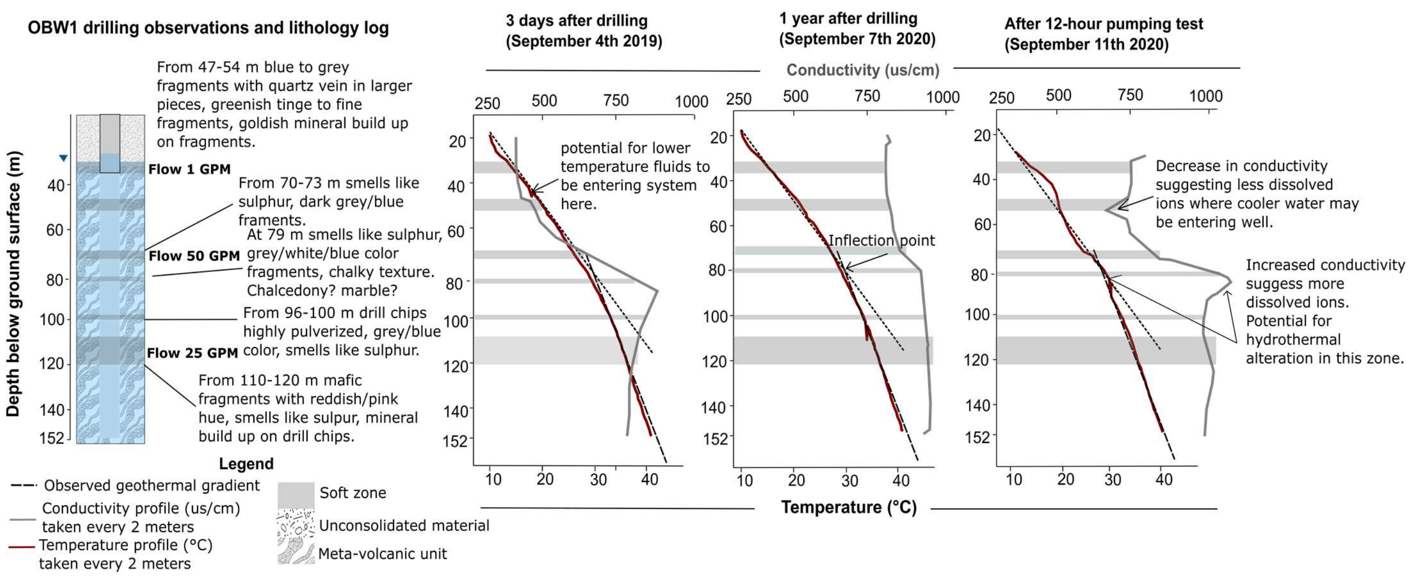

Figure 11: OBW1 drilling observations and lithology log compared with temperature-conductivity profiles from September 4th 2019, September 7th 2020, and September 11th 2020. Consistent inflection point ~80 m in all data profiles which appears to roughly align with a soft zone that has considerable flow in the subsurface. Potential for warmer more conductive water to be entering the system at this site.

Groundwater monitoring was initiated in the fall of 2019 and recorded nearly a full year of water level records (Figure 12). OBW1 experiences seasonal water table fluctuations but generally remains stable. During 2019-2020, water levels only fluctuated a maximum of 1 meter which occurred between December and February (Figure 12). A general trend of increasing water levels and the few events of higher water levels between December to February likely represent winter recharge events from rainfall and/or snowmelt. From April to June there is a slight increase (not as event-based) in groundwater levels possibly due to snowmelt. Groundwater levels are in recession in the late winter-early spring (February to April) and summer (June to September). Figure 12 also shows drawdown and temperature data collected from the step test and constant rate test. During these tests, the top of the pump was at ~70 meters below ground surface and the levelogger was situated ~75 meters. During the step test, the well was pumped for one hour time intervals at 0.17 m^3/minute, 0.20 m^3/minute, and 0.24 m^3/minute, respectively. During the test water temperatures increased from ~23 °C to 26 °C and once the pump was turned off there was an immediate temperature increase to ~28.5 °C. During the constant rate test, OBW1 was pumped for 12 hours at 0.24 m^3/minute and had a temperature increase from ~22.5 °C to 26. °C. Once the pump was turned off there was a sharp increase in temperature to ~29 °C. Drawdown data from the constant rate test was used to calculate hydraulic conductivity (3.7×10^{-2} to 4.7×10^{-2} m per day), transmissivity (5.6 to 7.2 m^2 per day), and storage coefficient (0.19 and 0.37). These data suggest that bedrock in the upper 152 m of the subsurface has enhanced permeability which conveys groundwater through connected voids. Hydraulic conductivity and transmissivity values are similar to a silty sand geological medium. Further, the hydraulic properties of the well and subsurface allow groundwater in the well to quickly re-equilibrate as seen in Figures 12 and 13 where water levels in the well replenished to 90% recovery within ~6 hours of the pump being turned off. Temperature and conductivity were also able to re-establish relatively similar profiles after major hydrological stress events such as drilling and pumping as seen in Figures 12 and 13.

Water temperature in OBW1 was collected on three different occasions to quantify temperature changes in the water column over time (Figure 13a.). The temperature profile was relatively consistent, increasing from ~9 °C to a maximum of 41 °C at the base of the open hole well (Figure 13a.). An inflection point was consistently recorded at ~80 meters where the geothermal gradient is observed to decrease (Figure 13a.). More specifically, in the upper 80 meters of the well the geothermal gradient is approximately 258 °C/km. Below 80 meters, the geothermal gradient lowers to approximately 193 °C/km. Figure 13b shows the geothermal gradient assumed by Grasby and Hutcheon (50 °C/km) as well as the observed geothermal gradients. Electrical conductivity measurements were also collected from the well (Figure 11) and had more variance compared to temperature. Conductivity values ranged from 350 to 850 μs/cm three days after the well was drilled (September 14th, 2019). One year later and immediately preceding the pumping tests (September 7th, 2020), conductivity had a smaller range between 800-850 μs/cm but had a similar signature as the September 4th, 2019 and September 11th, 2020 data. These results suggest that water within the open hole well is

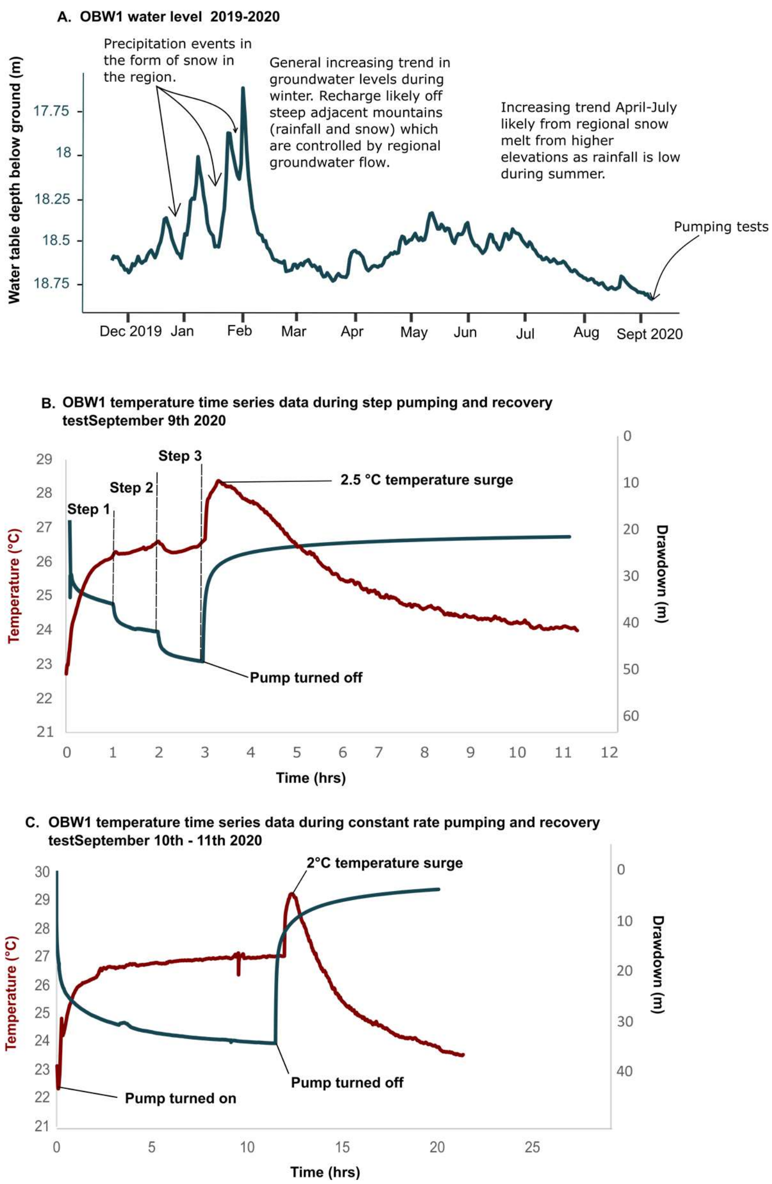

Figure 12: (A) Groundwater levels in OBW1 during 2019-2020. Groundwater levels fluctuate seasonally with minor variation in the water level depth (~1 meter). Water levels appear to be representative of regional groundwater flow rather than local flow conditions. (B) Temperature and drawdown time series data from OBW1 during step pumping test. (C) Temperature and drawdown time series data during constant rate pumping tests. During both pumping water temperature increased ~ 2 °C -3 °C suggesting a warmer inflow is located ~75m where the levelogger was recording data.

relatively stagnant allowing for conductivity values to equilibrate within the water column with limited variance. After the pumping tests (September 11, 2020), the conductivity profile shows a similar pattern as September 2019 but with conductivity ranging between 750 to 1100 μs/cm.

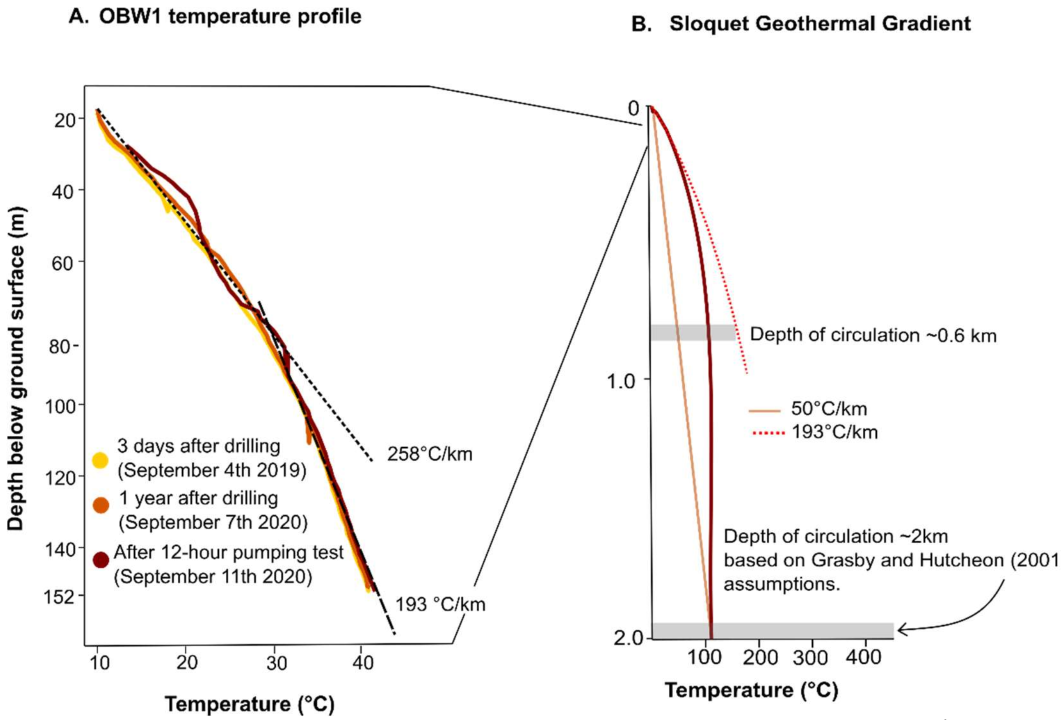

Figure 13: (A) OBW1 temperature profile as measured on September 4th, 2019 (yellow), September 7th, 2020 (orange), and September 11th, 2020 (red). The temperature in the water column ranges from 9 °C to 41 °C. The upper 80 meters of the well has an approximate geothermal gradient of 258 °C /km while the lower portion has a lower gradient of 193 °C /km. (B) Shows assumed geothermal gradient from Grasby and Hutcheon (2001) as well the observed gradients in OBW1 and newly interpreted.

3.4 DISCUSSION

3.4.1 STRUCTURES, LITHOLOGIES, AND SPRINGS AT THE SURFACE

At Sloquet Hot Springs there is evidence of elevated heat flow and permeability contrasts along the north and south sections of Sloquet Creek. There are hundreds of joint structures in the area with only a fraction that transmit thermal fluid flow in the hundreds of meters surrounding the site (Figure 7). The temporal and spatial variability of thermal springs at Sloquet demonstrates the ability of joints to promote fluid flow in the hundreds of meters surrounding the study site. Joint structure orientation at Sloquet is consistent with regional crustal-scale structures that are predominantly oriented in the northwest or northeast direction. Although located several kilometers away from these regional faults (presented in Figures 1 and 14) it is likely that Sloquet Hot Springs is located near unmapped fault(s) with a similar orientation to the mapped regional faults. The source of thermal fluids at Sloquet Hot Springs is likely from one or more larger scale structure(s) concealed at or near land surface. It is hypothesized that the soft zones encountered in OBW1 could be faults especially the high flow zone at ~73 meters which is a permeable conduit that conveys warmer fluids. The thermal fluids moving through this conduit would have been heated by conductive heat flow as seen in Figure 14 before moving toward the groundwater discharge zone at the valley bottom where mixing would occur. It is unlikely that this fault would be the structure supplying high temperature fluids at the hot spring site as the temperature never exceeded 40 °C during drilling or pumping tests. Since the controlling structure was not identified during drilling, it is probable that the buried fault is located proximal to springs that have the highest temperature and flow (HS138 and HS100 - location not disclosed).

Detailed investigations on the structural setting of hydrothermal systems in the southeastern Cordillera have suggested that thermal springs occur where fault zones have sub-vertical shear surfaces, dominant fault kinematics that are dextral, and crosscutting relationships that demonstrate structures were active after the Eocene (Finley et al., 2020). These findings in northeastern BC seem to be broadly consistent with results from Sloquet Hot Springs. Most thermal springs at Sloquet were observed to be discharging from steeply dipping joint structures (between 55° to 90°) that were associated with distinct conjugate sets oriented to the northwest or northeast (although fault kinematics are not resolved). Further, regional northeast striking faults appear to bound Sloquet and were developed in the Neogene (Figure 14) and Lynch (1990) proposed these are the primary controls for thermal fluid flow based on compressional fault kinematics. Locally, fault structures in the shallow crust may promote thermal fluid flow through smaller-scale joint structures at variable temperatures and rates (Figure 14 local model). The distribution in bedrock, thermal conductivity, and associated hydraulic characteristics likely play an integral role in controlling spring location and temperature at Sloquet Hot Spring.

Most high temperature thermal springs (>65°C) discharge from joints within the intrusive porphyry suggesting it is the host unit that thermal springs discharge from before finding preferential flow paths at or near the land surface. More specifically, the variance in spring temperature in the area reflects the geothermal gradient, thermal conductivity of rock units, as well as the duration of time thermal water mixed with non-thermal water before discharging at land surface. Springs that were observed discharging from the clast supported conglomerate and unconsolidated materials had greater flow and temperature variance, suggesting these units may have lower and more variable permeability. Therefore, at these sites, thermal waters would have had more time to mix with the cooler water table before finding preferential flow paths that discharged at the valley bottom. As previously mentioned, thermal springs discharge from anastomosing fractures that surrounded clasts within the conglomerate and there were no observable joint structures within.

Overall, it is estimated that the average total flux through the whole zone is ~4,533 ± 337 L/minute (based on summing the flux from springs in Figure 10 acknowledging that some of the spring flow estimates were semi-quantitative (Table C1). The total flux estimation reflects all cold, warm, and hot springs (~10 °C to 70 °C) that were recorded only in late August 2019 so this is likely an overestimation of the hot water flux in the geothermal system. Grasby and Hutcheon (2001) suggest that the flux at Sloquet Hot Springs is ~6,000 L/minute while other springs in British Columbia have flow rates ranging from 60 L/min at Nakusp Hot Springs to 30,000 L/min at Mount Meager Hot Springs. Harrison Lake Hot Springs, located proximally to Sloquet, has an estimated discharge rate of 15,000 L/min. When compared to these values, Sloquet Hot Springs has moderate flow rates.

3.4.2 GEOTHERMAL GRADIENT

The geothermal gradient was measured in the open hole well (rather than a lined temperature gradient well) at three different times and recorded consistent temperatures and inflection in the geothermal gradient at ~80 m depth below ground surface (Figures 11 and 13). The high geothermal gradient is likely due to less dense, warm water entering the system at ~70-80 meters and warming the cooler upper water column. This is further supported by Figure 12 which shows temperature fluctuations during step and constant rate pumping tests. During these tests, the top of the pump was at ~70 meters below ground surface and the levelogger recorded temperature and pressure at ~75 meters. Over the three-hour step-test, water temperatures increased from ~22.5°C to 26.5°C and once the pump was turned off there was an immediate temperature increase to ~28.5 °C. The observed temperature patterns suggest a warmer inflow is located at these depths and controls the advective heat flow in the upper 80 meters. Notably, the inflection point is roughly coincident with the soft zone that had flows 0.19 m^3/minute (as seen in Figure 11). Below the point of inflection, the geothermal gradient decreases as temperature continues to increase. At the same time, there is an increase in electrical conductivity suggesting that fluids entering the well in this zone have more dissolved ions and there is a possibility of hydrothermal alteration at these depths. Drill chips from these depths were highly fractured and had a grey, blue appearance, and looked similar to marble or limestone. Water with higher electrical conductivity would have increased density therefore saline fluids would control the conductivity in the lower portion of the well immediately after hydrologic stress (i.e. drilling and pumping). There were no observable signs of convective heat flow, such as a segment of a vertical thermal gradient and it is unlikely the inflection caused by lithology changes as drill chips indicate a consistent rock unit at all drilled depths, implying a consistent thermal conductivity over the total well depth. Overall, during drilling and pumping tests we did not encounter any high temperature or conductivity water suggesting the primary conduit that conveys high temperature thermal water to Sloquet Hot Springs was not encountered. However, conductivity values did reach similar readings as the main spring, HS138, and OBW1 is likely along the outer margin of the main thermal system where water temperatures are lower because of mixing with the shallow cooler water table. The observed geothermal gradient was significantly higher than the 50°C/km that Grasby and Hutcheon (2001) suggested therefore these differences will be discussed.

Results from the open hole OBW1 indicate the upper 80 meters of the water column has a geothermal gradient of 253°C/km in contrast to 193°C/km in the lower portion of the well (Figures 11 and 13). The high observed gradient could imply a magmatic source or significant geothermal potential. But this gradient is only measured to relatively shallow depths of 152 meters whereas most temperature gradient wells for geothermal exploration are drilled to hundreds or thousands of meters. No previous literature suggests a magmatic source in this area. Similarly, other signs of a magmatic source or significant geothermal potential are absent such as exceedingly high TDS or high heat flow near the surface. Based on these arguments and the temperature and conductivity observations, the high gradients are interpreted to be a function of mixing in the open hole rather than indicative of an unusually high geothermal gradient. Therefore, we follow Grasby and Hutcheon (2001) in assuming 50°C/km based on regional geothermal gradients which is consistent with other arc settings. Circulation depths from both geothermal gradients are shown in Figure 13 to provide a bound on possible circulation depths.

3.4.3 GROUNDWATER FLOW

Bulk hydraulic conductivity and transmissivity values that were collected from constant rate tests reaffirm that there is extensive permeability in the subsurface. Typically, meta-volcanic bedrock units have hydraulic conductivity values that range between 8.6×10^{-9} to 8.6×10^{-6} m per day and do not make for optimal aquifer systems (Freeze and Cherry, 1979). The subsurface conditions at Sloquet have a bulk hydraulic conductivity of 3.7 x 10^{-2} to 4.7 x 10^{-2} m per day and transmissivity values of 5.6 to 7.2 m^2 per day which for reference is similar to hydraulic parameters of silty sand. Connected voids in the subsurface provide enhanced permeability within local bedrock allowing the groundwater system to have elevated heat flow due to deeper circulation of fluids. Storage values presented are higher than anticipated and are reflective of an unconfined system. Calculating storativity using data obtained from one well is ineffective as the output value correlates with well effects and radius (Kruseman and Ridder,1994). Further, when using Theis and Cooper Jacob solutions there are no options for calculating well effects therefore unless the value of r is obtained from a surrounding observation well. More specifically, the storativity value that was calculated will be a gross overestimation as we did not have another well at the site to observe drawdown. Although we did not encounter a high temperature fault when drilling, the well temperature is likely influenced by the nearby thermal springs due to the steep temperature gradient in the well.

In Appendix B, well water levels and spring discharge are compared to identify any seasonal trends. These graphs are from different years because of data loggers malfunctioning in the high temperature spring. Therefore, the general trend is used to interpret seasonal trends. During summer and fall, spring discharge appears to be in recession as would be expected since this is the lower precipitation and recharge time of year. This implies a lower hydraulic gradient driving flow to the springs. Interestingly, spring temperatures also decrease slightly by ~2°C during the summer and fall seasons coincident with decreasing water levels and spring discharge. The trend of decreasing spring temperatures implies an increase in shallow, cooler contribution, or a decrease in deeper, warmer fluid contributions. An increase in shallow, cooler water contribution is unlikely based on the observed trend of decreasing water levels in the well. Therefore, it is most likely spring temperature decreases due to reduced deeper, warmer water contributions driven by a lower regional hydraulic gradient caused by seasonal fluctuations in the water table in the adjacent high topography (see conceptual model Figure 14 cross-section). Finally, the spring temperatures are used to give a rough estimate of contributions from shallow and deeper systems. Assuming hot water does not cool on the way up from max temp of 116°C° and shallow water is 5°C (the difference is 111°C). So roughly springs are ~65% deeper fluids in the winter or ~63% deeper fluids in the summer. This type of calculation assumes temperature is conservative and should be later tested with a similar calculation with dissolved mineral constituents.

3.4.4 CONCEPTUALIZING THE HYDROGEOTHERMAL SYSTEM AT SLOQUET HOT SPRINGS

Conceptualizing the hydrogeothermal system at Sloquet Hot Springs included detailed desktop and field analysis to understand system dynamics at the local and regional scale (Figure 14). The regional model shows the location of Sloquet Hot Springs amidst the Coast belt and structural setting. Sloquet Hot Springs is bound by northeast striking faults and is located approximately 7 kilometers away from the northwest striking Harrison Lake Fault. Grasby and

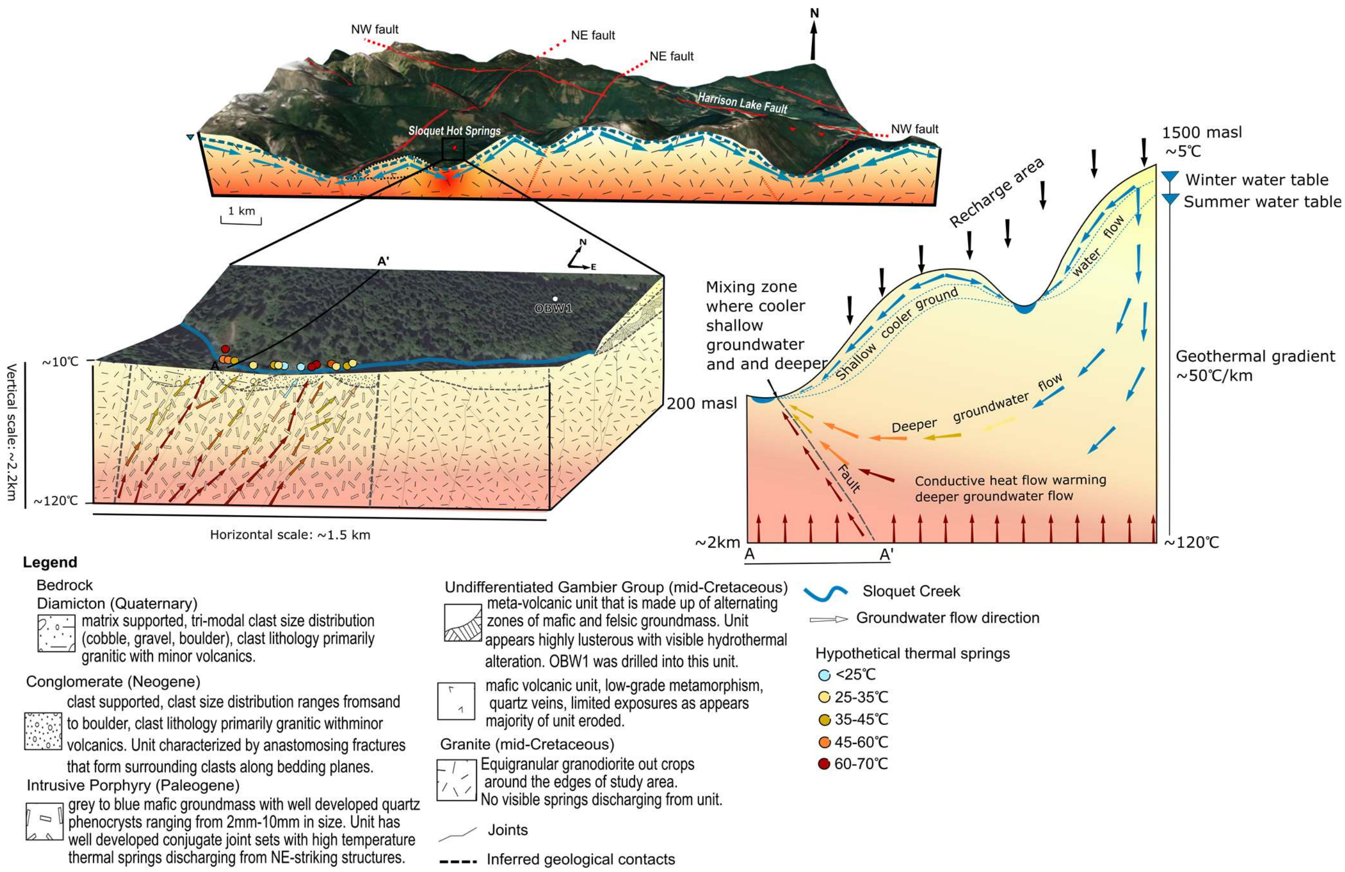

Figure 14: Regional and local conceptual model of the hydrogeothermal system at Sloquet Hot Springs. Regional model shows the location of Sloquet Hot Springs amidst large scale faults. The local conceptual model synthesizes field data hypothesizing the behavior of the system in the hundreds of meters surrounding the main recreation site (i.e., vertical and contact boundaries conceptual). Regional groundwater flow is simplified showing the fundamental processes that occur surrounding Sloquet Hot Springs. The total recharge area is estimated to be 30 km^2 and occurs beyond just the surrounding ridges at Sloquet Hot Springs. This portion of the cross section was simplified for presentation and discussion purposes.

Hutcheon (2001) suggest that the Harrison Lake Fault is the primary control for Sloquet Hot Springs (and other nearby hot springs) on thermal flow whereas the other factors have a negligible impact. However, this study does not address the significant distance between the Harrison Lake fault and Sloquet Hot Spring (~7 km), nor does it discuss northeast striking faults that bound the site. Therefore, we hypothesize that Sloquet Hot Springs is located near unmapped fault(s) with a similar orientation to the mapped regional faults (northeast and northwest). The local conceptual model in Figure 14 shows the relationship between thermal springs, joints, and lithology. In the field, springs had variable temperature ranges because of thermal fluids mixing with the cool water table. Sloquet Hot Springs is located at a topographic low where groundwater flow would be discharging into the adjacent creek (cross-section in Figure 14). Where high temperature springs are observed, the hydraulic gradient and permeability of the host rock are likely high enough to limit the amount of mixing with the shallow cooler water table. In contrast, where permeability and/or hydraulic gradients are lower, spring temperature would be lower as fluid mixing would occur before springs discharged at land surface.

Stable isotope data (Grasby and Hutcheon 2001) indicate that the origin of Sloquet, like other hot springs in British Columbia, is from meteoric water. Based on the thermal observations described above, we argue the meteoric water is a mixture of shallow and deep groundwater flow which is topographically controlled (cross-section in Figure 14). The areal extent of a recharge area can be estimated from the fluxes of the geothermal system or the surface area of the most likely catchment of the hot springs (the ridge immediately north of the hot springs). The recharge area is approximately ~30 km^2 calculated using annual spring flow rates divided by the annual recharge rate for the area (assuming recharge is ~10% of precipitation). This contrasts to a potential recharge area of 2 km^2 assuming the ridge immediately north of Sloquet hot spring is the catchment (QGIS area analysis). The area based on fluxes is significantly larger than based on catchment suggesting the areal extent of the recharge area for the thermal system is likely larger than the ridge north of Sloquet Hot Springs. The source of groundwater at Sloquet Hot Springs is likely both local groundwater flow from the ridge immediately north and regional groundwater flow from neighbouring watersheds. Figure 14 simplifies regional groundwater flow processes in the local context to understand the fundamental processes. Groundwater flow in the upper tens of meters of the subsurface is likely cooler and discharges at valley bottoms in the region, such as Sloquet Creek. Regionally, meteoric water recharges the deeper subsurface through steeply dipping faults and is heated by conductive heat flow before discharging through connected voids in the subsurface. The temperature of springs in the hundreds of meters surrounding Sloquet Hot Springs is controlled by the amount of time hot and cool springs mix as well as lithological hydraulic properties and thermal conductivity.

Through this research, it was evident that interdisciplinary research was necessary to connect hydrogeology, structural geology, and geothermics, and to conceptualize the hydrogeothermal system at Sloquet Hot Springs. Future academic studies could be used as a mechanism to decrease economic risks when moving forward with deep exploration drilling at specific sites. As with any study, there remain many challenges when interpreting the hydrogeothermal setting therefore limitations should also be considered.

3.5 LIMITATIONS

Research conducted at Sloquet Hot Springs provides a conceptual understanding of the relationship between geological structures, bedrock, and thermal fluid flow within the southern Cordillera. It provides baseline data from the local system to provide a first glimpse at the geothermal gradient, hydraulic properties of the subsurface as well as the behavior of the system through time. The region's steep topography, dense vegetation, and extensive distribution of overburden made it difficult to map bedrock and faults in the hundreds of meters surrounding the recreational site. Erosion of sediment and vegetation on the north and south sides of Sloquet Creek focused field investigations on the hundreds of meters surrounding the recreation site. The recreation site experiences seasonal flooding caused by Sloquet Creek therefore high-water levels acted to conceal thermal springs in the valley bottom. Spring mapping was conducted during low flow conditions in September 2019, and it is possible the temperatures and conductivity range through time. As previously mentioned, spring flow rates were collected using semi-quantitative methods therefore could represent an underestimation or overestimation of flow due to seasonality and would be partial to the observer's estimation (Appendix C). In the future, these springs should be directly measured in the field to understand how the flow changes through the seasons and time. Further limitations exist regarding equipment malfunctioning in high temperature springs (Appendix C). Data was irretrievable from Leveloggers at HS138 due to high temperatures damaging the unit. Therefore, there is only a limited amount of information on temperature and flow at HS138. Seasonal flooding also washed away numerous temperature buttons which contained data that extended into the 2020 field season.

Results from OBW1 provide a first glimpse at in-situ conditions within the subsurface at Sloquet Hot Springs. Determining the location of OBW1 was challenging for a multitude of reasons including the steep terrain required for drilling crews to operate safely and efficiently as well as the potential to disrupt and change groundwater flow paths which could cause short- and long-term effects to the natural spring system. Based on these concerns, a location farther away from the spring system was chosen for well development and completion. We do not believe that we drilled into the main “reservoir” but may have encountered a higher temperature structure that controls heat flow in the upper 80 meters for the well. Geothermal gradients that were observed are likely an overestimation as the well is only 152 meters deep making it challenging to predict the deeper geothermal gradient. It is possible that the geothermal gradient assumed by Grasby and Hutcheon (2001) may be an underestimation and that the actual geothermal gradient is somewhere between observed and assumed values. Further, data from pumping tests were used to determine bulk values for hydraulic conductivity, transmissivity, and storativity using the Theis (1935) and Cooper Jacob (1946) method. Ideally, drawdown during pumping is measured in multiple observation wells to provide a detailed understanding of how the system is affected by pumping through time. Due to budgetary and logistical restraints, it was only possible to develop one well at Sloquet therefore drawdown and water levels were measured only within the pumping well. Using these methods to calculate transmissivity and hydraulic conductivity is possible with limited error (Appendix C) but the value of storativity cannot be determined accurately from the data recorded in the pumping well because it correlates with well effects and radius dimensions (Kruseman and Ridder,1994). Typically, the quantity of well effects and radial position of measurement is unknown within the pumping well and depends on water levels within proximal piezometers or observation wells. Using Theis (1935) and Cooper Jacob (1946) does not provide options for single well storage values therefore the value obtained for storativity from these methods would be an overestimation as we used a radius value from the well being pumped (Kruseman and Ridder,1994). This value is effectively small so when dividing the numerator by a decimal we end up with a higher value for storativity which is why we have storage values that are similar to specific yield (i.e., representative of an unconfined system). Equipment limitations also affected the ability to pump the well over .24 m^3/minute as the pump can only operate when water temperatures are less than 30 °C. Due to elevated groundwater temperatures exceeding 30 °C the maximum pumping rate was .24 m^3/minute. We suspect that groundwater temperature and hydraulic properties in the subsurface would increase closer to the main thermal system (HS138) if closer to a buried fault that conveys thermal fluid from depth. Other limitations include the limited availability of geophysical in the hundreds of meters surrounding Sloquet Hot Springs. Geophysical imaging of the subsurface could have aided in interpreting lithologies in the subsurface, potential inflows, buried faults at or near Sloquet while also providing insight into the subsurface geometry of these structures.

Lastly, the conceptual models that were derived only represent a western geoscientific perspective of the regional and local setting of Sloquet Hot Springs. A more holistic model could have been developed as part of a co-creation of knowledge with Xa’xtsa First Nation. Further, our conceptualization lacks cultural interpretations of Sloquet Hot Springs which would have contributed more directly to the resurgence of Indigenous knowledge and world views. Future work should focus on the redevelopment of conceptual models to increase reconciliation in action and resurgence to the community of Xa’xtsa First Nation.

3.6 CONCLUSION

The local setting at Sloquet Hot Springs is geologically diverse with a variety of lithological units present, thermal springs, and joint structures. The area is lithologically characterized by unconsolidated materials, clast supported conglomerate, intrusive porphyry, granodiorite, and undifferentiated Gambier Group. The intrusive porphyry and undifferentiated Gambier Group had well developed joint structures that controlled thermal fluid flow. Joint orientations were consistent with regional faults (NNW to SSE and N to S). Thermal flow from the clast supported conglomerate occurred along anastomosing fractures that surrounded clasts whereas spring from unconsolidated materials occurred as pore flow. There were only two high temperature and flow springs observed and the structure controlling these springs was concealed by sedimentary bedrock or strata. It is probable at these locations there is a buried fault in the upper 100 meters of the subsurface that acts as the primary control for thermal fluid flow in the hundreds of meters surrounding Sloquet Hot Springs. Groundwater levels within OBW1 vary seasonally and appear to represent the regional groundwater flow system with recharge likely being from the surrounding ridges. The temperature of the water column is controlled by advective heat flow and has a consistent inflection point at 80 meters where the geothermal gradient decreases from 253°C/km to 193°C/km. There are no signs of the geothermal gradient being a result of magmatic sources therefore it is likely that the assumed gradient of 50 °C/km (Grasby and Hutcheon, 2001) is reasonable. Bulk hydraulic properties reinforce that bedrock is locally fractured and readily transmits fluids through connected voids in the subsurface. Further, fault plane geometry, kinematics, and age likely play an intrinsic role in thermal fluid flow at Sloquet Hot Springs. Although research provides a first-order glimpse of the conditions at Sloquet, limitations do exist regarding equipment accuracy, methodological limitations, and limited data availability. Other limitations pertain to the challenging terrain surrounding Sloquet Hot Springs is situated and the inability to access thermal springs year-round due to water levels in Sloquet

Creek. Overall, the hydrogeothermal system at Sloquet appears to be relatively stable and future feasibility analysis will be required to refine geothermal potential.

CHAPTER 4. Thesis conclusion

The main objectives of this thesis were to develop a conceptual model that synthesizes the hydrogeothermal system at Sloquet Hot Springs in partnership with the local First Nation. Thesis research presented a first glimpse of the subsurface characteristics at Sloquet which suggests that geothermal gradients and permeability in the shallow crust are increased and that the system at Sloquet Hot Springs is relatively stable.

The first chapter of this thesis illustrates the growing demand for clean and sustainable energy resources in Canada and identifies the geothermal potential of the southern Canadian Cordillera. The largest potential for geothermal exploration and development exists in the Province of British Columbia due to elevated crustal heat flow and complex structural geology. There remain significant challenges when investigating and developing geothermal resources in Canada both socially and scientifically. Government and researchers in British Columbia have a significant opportunity to be leaders in local and regional geothermal investigations by seeking to collaborate with Indigenous communities across the province.

The second chapter synthesizes literature regarding the evolution of the southern Canadian Cordillera to provide relevant contextual support for interpretations and conclusions regarding geothermal resources at Sloquet Hot Springs. Further, the chapter provides a high-level review of the five R’s (regulations, resources, reconciliation, resurgence, and research) to understand the complex social landscape between Indigenous and non-Indigenous Canadians. The five R’s are often considered to be separate, operating at the sectoral level, but the reality is that these topics are intrinsically linked as presented in Figure 15. My view is that this thesis research operated within three spheres – (1) resources and regulations, (2) geoscience, and (3) reconciliation, resurgence, and research (Figure 15) – with overlap between new and old approaches to geoscience and resource development. Our approaches used traditional geoscience approaches with reconciliation in action to work toward new approaches within the field of geoscience. Although thesis research could have developed a more holistic conceptual model that integrated cultural interpretations it was a step toward Indigenous resurgence. By participating in reconciliation and resurgence when conducting scientific works and obtaining free-prior and informed consent it is possible to develop more impactful projects that have a greater influence on social and scientific spheres (Eckart et al., 2020; Curran, 2019; Asselin and Basile, 2018; Wong et al., 2020; Simms et al., 2016). Researchers can implement the 10 calls to action developed by Wong et al. (2020) to create a higher ethical standard when working on

Traditional Territories across the province. Although the Wong et al. (2020) publication was not released when thesis research started, we find it relevant to review our methods and determine where we can enhance practices for future project endeavors (Table 1). Based on the scope of thesis research we found that calls to action 1,2,3,5,6,7 and 10 (Wong et al., 2020) were relevant to our work at Sloquet Hot Springs. We believe that our team was able to meet each of these actions with room for improvement specifically to call 3 and 5. Academics could have put in a greater effort to co-produce conceptual models of Sloquet Hot Springs to expand on the interpretation of the hydrogeothermal system. Further, a monitoring program could have been established earlier into the project that incorporated youth engagement along with members of the community. It would have provided youth and members with the community to participate in fieldwork, implementation of monitoring equipment as well as general experience conducting scientific investigations in the area. Although academics are working to establish a long-term monitoring program, it would have been more productive to have established the initiative early into research rather than at the end.

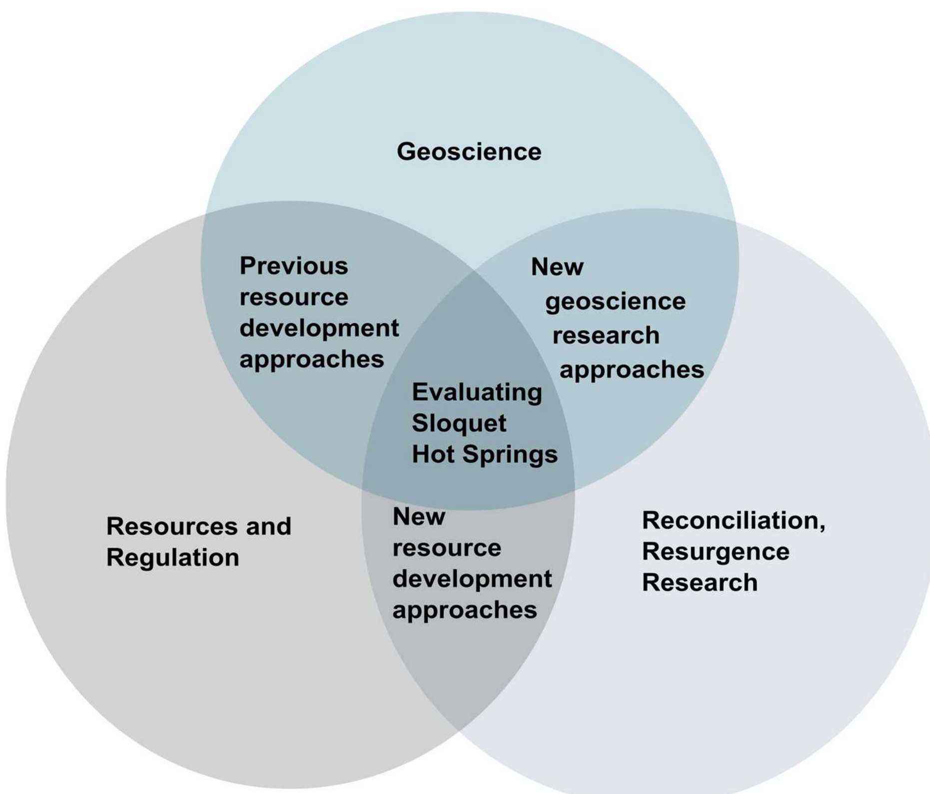

Figure 15: Venn diagram showing the overlap between the five R's and thesis research. Thesis research situation amidst three main spheres: (1) Geoscience, (2) Resources and regulations, (3) Reconciliation, resurgence, and research.

Table 1: Calls to action for natural scientists working towards reconciliation in Canada from Wong et al. (2020). Some calls to action were not directly relevant to research therefore were not included.

Call to Action	Action in project
1. We call on natural scientists to understand the socio-political landscape around their research sites.	Academics worked closely with Xa'xtsa First Nation's TTQ Economic Development Corporation to understand the socio-political landscape in the village of Tipella surrounding region. Research agreements involved both Xa'xtsa First Nations' TTQ Economic Development Corporation as well as Recreation Sites and Trails BC as both groups are responsible for co-managing the recreation site at Sloquet.
2. We call on natural scientists to recognize that generating knowledge about the land is a goal shared with Indigenous peoples and to seek meaningful relationships and possible collaboration for better outcomes for all involved	Initial engagement with TTQ Economic Development Corporation was focused on building a relationship with the organization as well as the broader community. Academics hosted a series of feasts and ceremonial gift exchanges to discuss potential project development and to learn more about the community's values and vision.
3. We call on natural scientists to enable knowledge sharing and knowledge co-production	All knowledge produced was openly shared and discussed to ensure each partner felt the project was reflective of their vision and goals. Knowledge co-production will continue to be facilitated by the option of co-authorship with Darryl Peters when publishing.
5. We call upon natural scientists to provide meaningful opportunities for Indigenous community members, particularly youth, to experience and participate in science.	Indigenous community members will have opportunities to work with academics to develop a long-term well monitoring program that aims to collect data on subsurface conditions at the site.

6. To decolonize the landscape, we call on natural scientists to incorporate Indigenous place names as permitted.	Researchers were sure to include the name of traditional territories on which the study site was located on. The traditional names of the study site were unknown and not able to be included.
7. We call upon natural scientists and their students to take a course on Indigenous history and rights.	The graduate researcher had taken Indigenous studies courses during undergraduate degree.
10. We call on natural scientists and postsecondary research institutions to develop a new vision for conducting natural science: fundamentally mainstreaming reconciliation in all aspects of the scientific endeavor, from formulation to completion.	Academics prioritized developing a strong relationship with Xa'xtsa First Nation and the community from the initial stages of potential project development. We were sure to receive free-prior and informed consent to pursue scientific investigations while also engaging with TTQ Economic Development Corporation during fieldwork trips to ensure they were aware of our works in their traditional territory. All research practices were transparent and inclusive from start to finish with this thesis being approved for publication.

The third chapter of this thesis presents research methods and approaches for conducting collaborative scientific research at Sloquet Hot Springs while also showcasing new data obtained from the hydrogeothermal system. The prioritization of working with Xa'xtsa First Nations' TTQ Economic Development Corporation and community led to a successful project where it was possible to gain insight into the local system at Sloquet Hot Springs. Findings from subsurface investigations identified a geothermal gradient of 258 °C/km in the upper 80 meters of the well and 193 °C/km in the lower portion of the well which is controlled by advective heat flow. There are no signs of the geothermal gradient being a result of magmatic sources therefore it is likely that the assumed gradient of 50 °C/km (Grasby and Hutcheon, 2001) is accurate. Bulk hydraulic properties for hydraulic conductivity (3.7×10^{-2} to 4.7×10^{-2} m per day), transmissivity (5.6 to 7.2 m^2 per day), and storage coefficient (0.19 and 0.37) reinforce that bedrock is locally fractured and readily transmits fluids through connected voids in the subsurface. Further, fault plane geometry, kinematics and age likely play an intrinsic role in thermal fluid flow at Sloquet Hot. Although no obvious faults were identified in the field, there is potential for a buried fault to be present where springs have high temperature and flow values. Sloquet Hot Springs is likely located localized around the northwest and/or northeast trending fault structures that control high temperature fluid flow. These insights into the hydrogeothermal system provide opportunities for further projects to refine the study and target the resource.

In conclusion, this thesis has contributed valuable knowledge on the hydrogeothermal system at Sloquet Hot Springs, and additionally, provides methods that can be further applied when engaging with Indigenous communities. Our team is grateful for the opportunities to have worked in collaboration with Xa’xtsa First Nation and TTQ Economic Development Corporation to provide novel data to the field of geothermal resources in southern British Columbia.

Future studies

This thesis provides a first-order assessment of Sloquet Hot Springs and presents baseline data on the subsurface conditions of the hydrogeothermal system. Therefore, this thesis provides a strong foundation for pursuing an intensive review of the resource when working alongside Xa’xtsa First Nation. Several thought-provoking directions can be pursued that would add value to the field of energy and water resources in British Columbia.

At the social level, thesis research presents literature regarding the complex relationships that exist between the government and Indigenous communities across Canada. The presentation of the five R’s shows how these topics are deeply linked and discuss more collaborative research approaches. Scientifically, thesis research presents local and regional conceptual models that are a starting point for understanding the hydrogeothermal system. Since there was no obvious controlling fault identified in the field, there are significant opportunities for geophysical imaging of the subsurface to constrain the fundamental controls on the system and to appropriately identify resource potential. Further heat budget studies should be conducted if geothermal exploration is to be pursued to understand the thermal capacity of the system. The development of OBW1 presents an opportunity for training community members from Xa’xtsa First Nation to monitor groundwater levels and temperature over time. The value of developing a monitoring program within the community would provide long-term data on the subsurface conditions for future projects and decision making.

Due to the scale and scope of thesis research, constraining the fundamental controls on Sloquet Hot Springs was challenging therefore conceptual models were developed to help guide future studies. In the future, investigations should focus on subsurface imaging and constraining the heat budget of the area to further constrain the potential for geothermal exploration and development.

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APPENDIX A: Bedrock and spring photographs at Sloquet Hot Springs

Figure A1: Unconsolidated glacial materials that are commonly distributed in the area. Photograph taken September 2019.

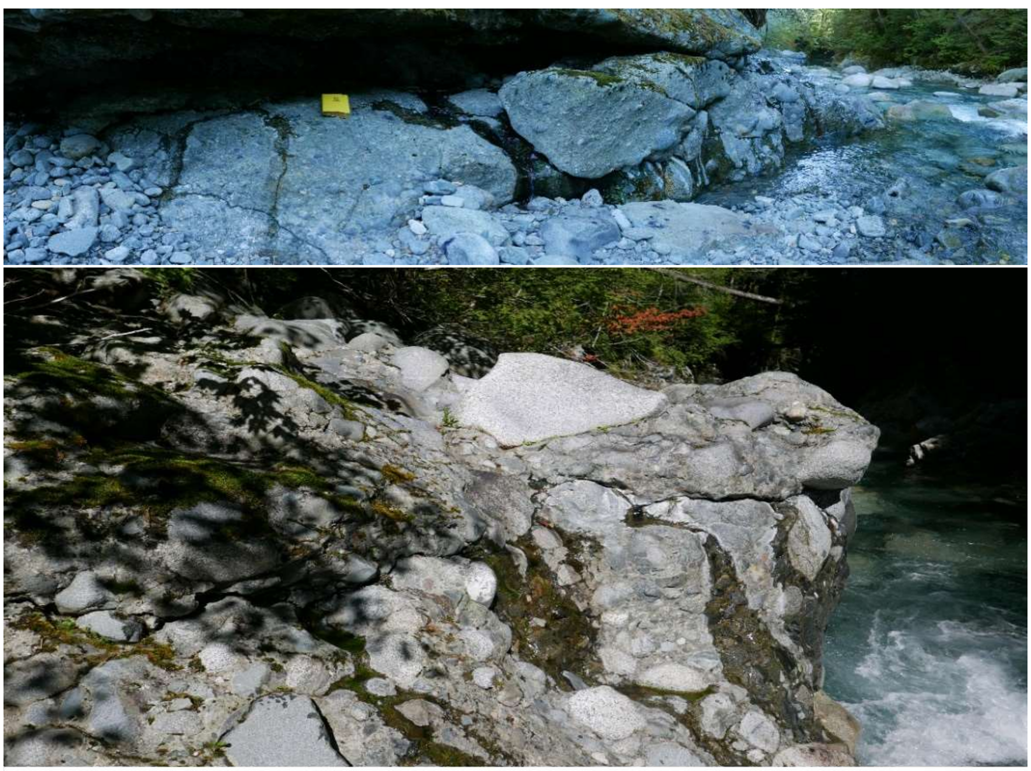

Figure A2: Clast supported conglomerate unit that has thermal springs discharging along anastomosing fractures that surrounding clasts within the matrix. Photograph taken September 2019.

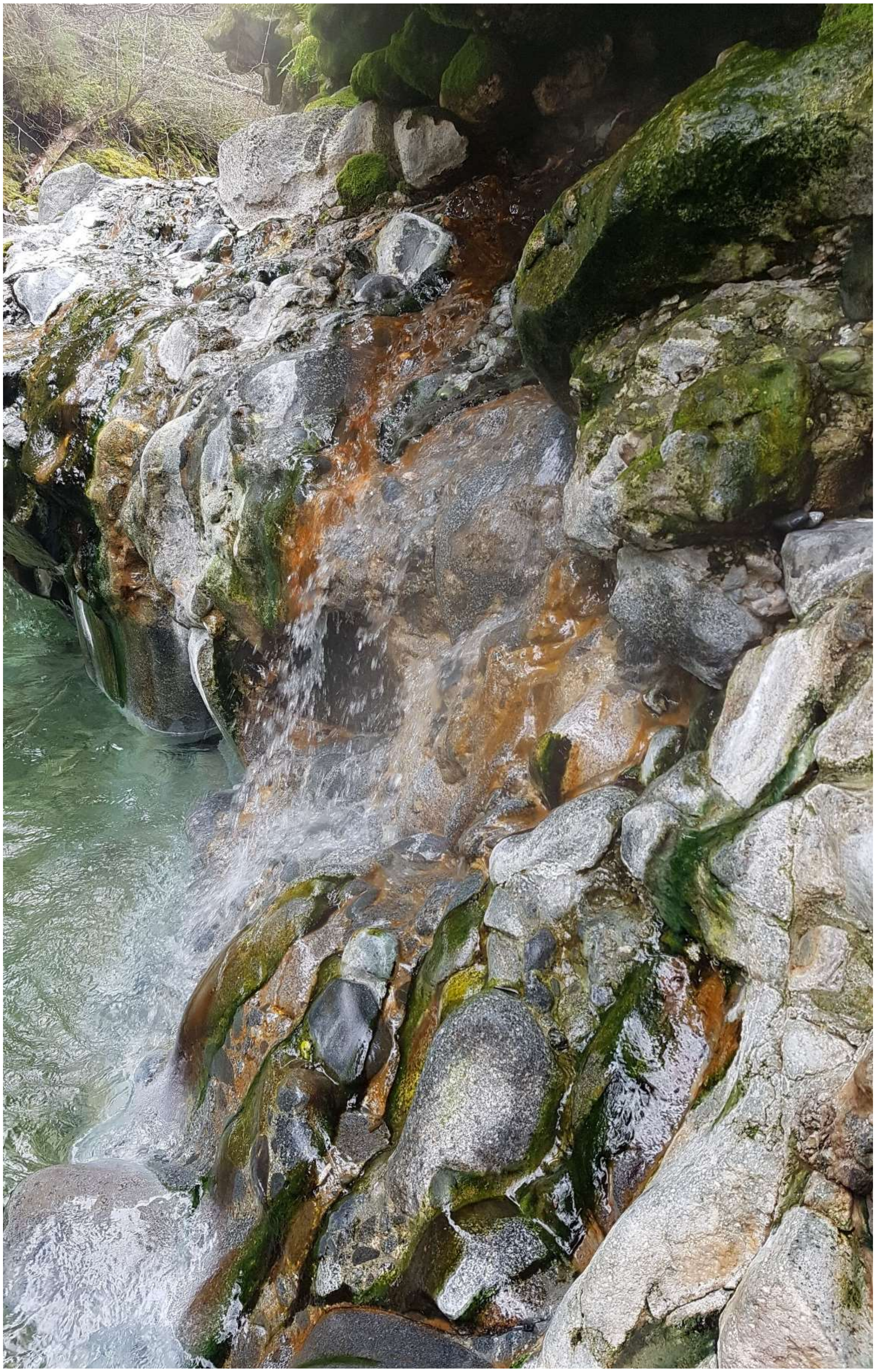

Figure A3: HS100 discharging from clast supported conglomerate. Potential for fault to be at concealed by the unit at this location. Photograph taken May 2019.

Figure A4: Intrusive porphyry weathered and fresh surface. Conjugate structures are visible at the grain scale surrounding quartz phenocrysts and at bulk rock scale. Photograph taken September 2019.

Figure A5: Intrusive porphyry weathered surface with conjugate joint sets. Photograph taken September 2019.

Figure A6: Undifferentiated Gambier Group meta-volcanic unit. Potentially the unit OBW1 drilled into. Photograph taken May 2019. Fresh surface appeared highly lustrous and metamorphosed.

APPENDIX B: Pumping Test Results and Curve Matching & Well Completion

Semptember 2020

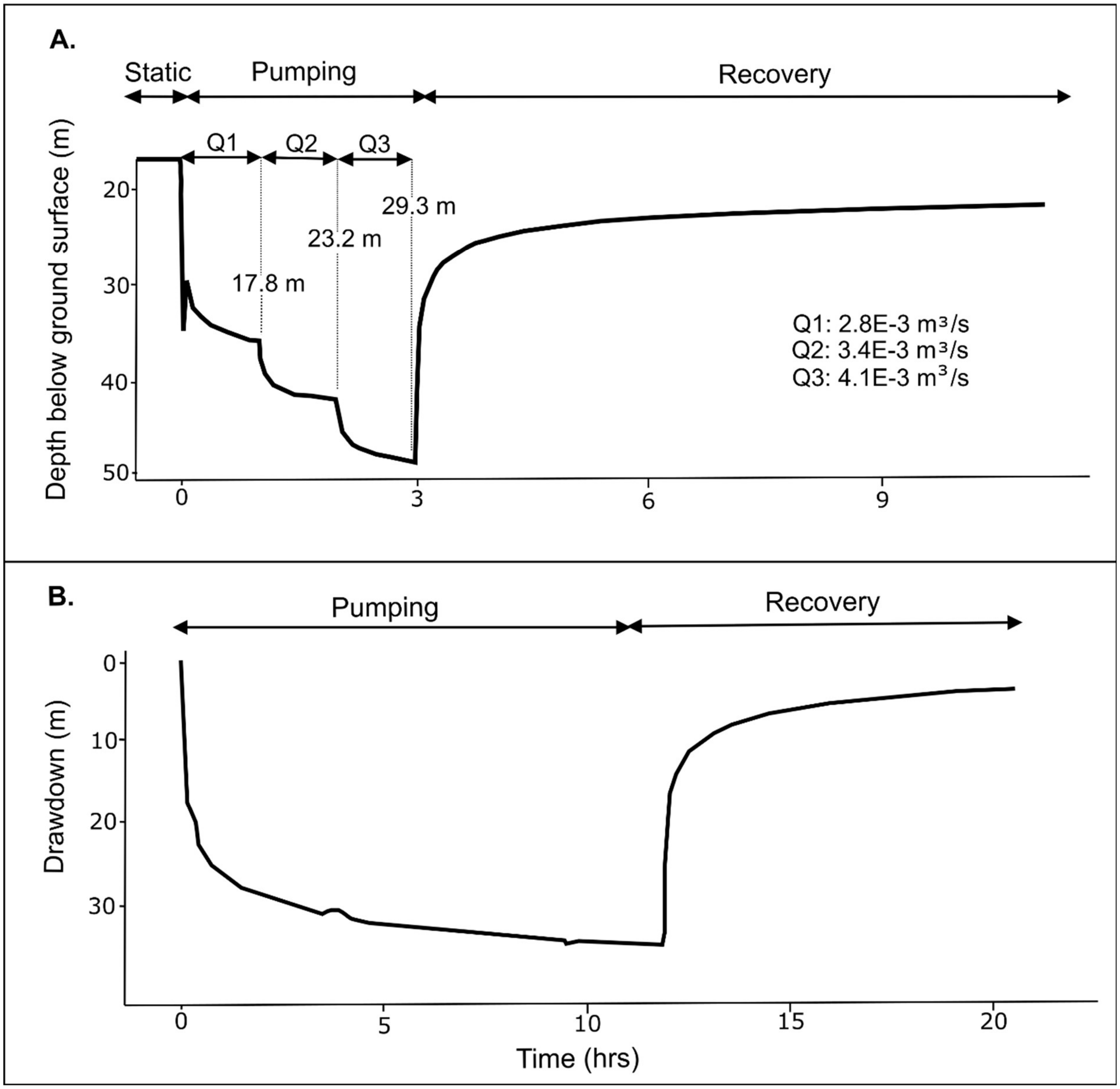

Figure B1: (A) Drawdown data collected during the step pumping test in OBW1. (B) constant rate time series data in OBW1 where well was pumped for 12- hours.

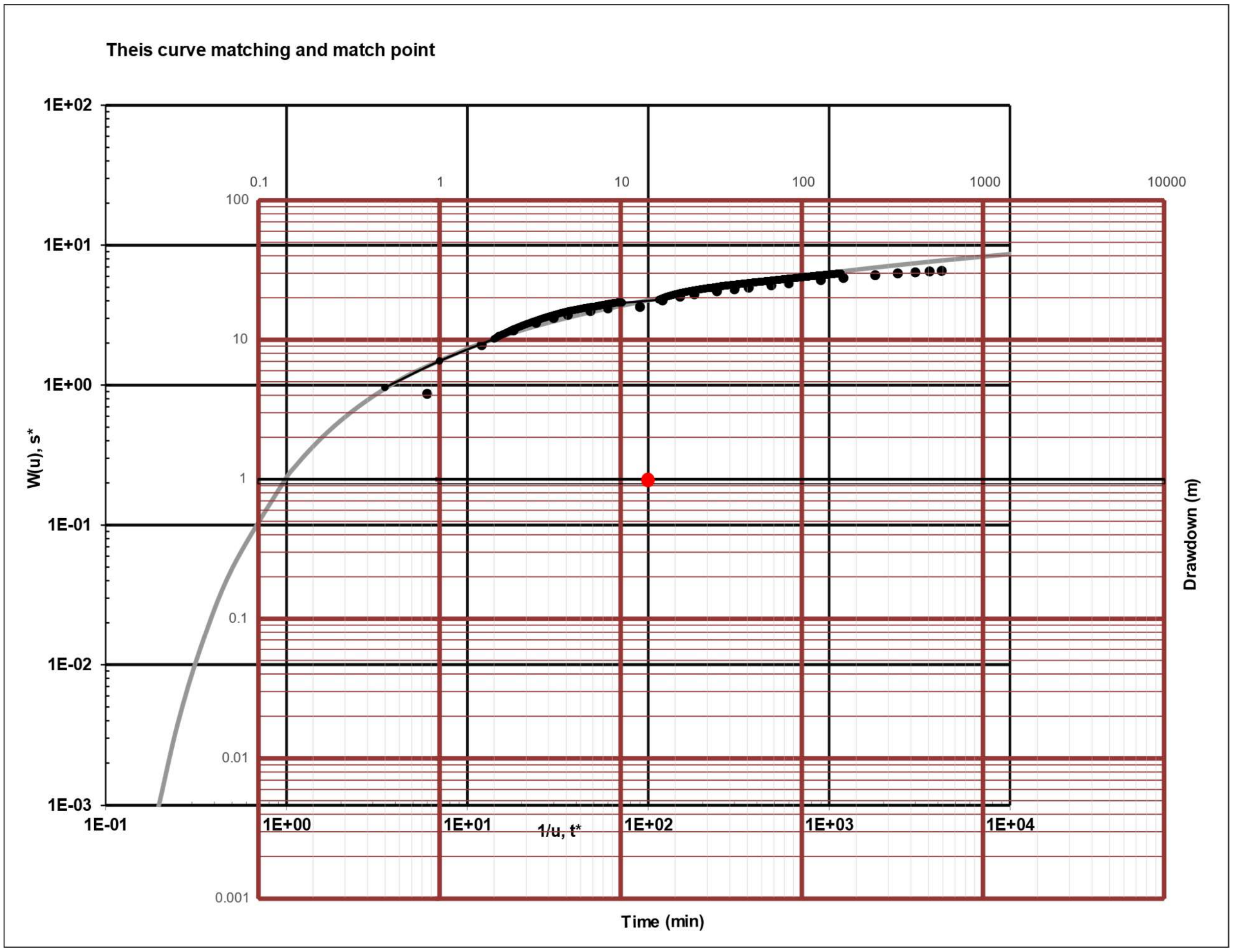

Figure B2: Theis (1935) log-log curve matching for constant rate draw-down data. Black dots are drawdown collected during constant rate pumping test in OBW1 and were used to curve match for values for W(u) to calculate transmissivity, hydraulic conductivity, and storage.

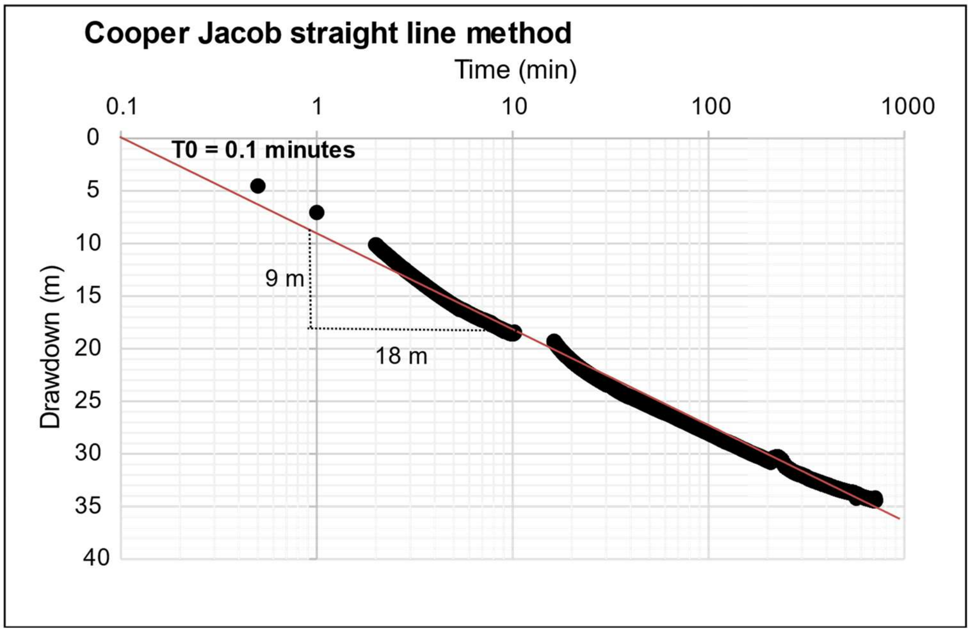

Figure B3: Cooper Jacob (1946) semi-log straight line matching for constant rate drawdown data. Black dots are drawdown collected during constant rate pumping test in OBW1 and were used to line match for calculating transmissivity, hydraulic conductivity, and storage.

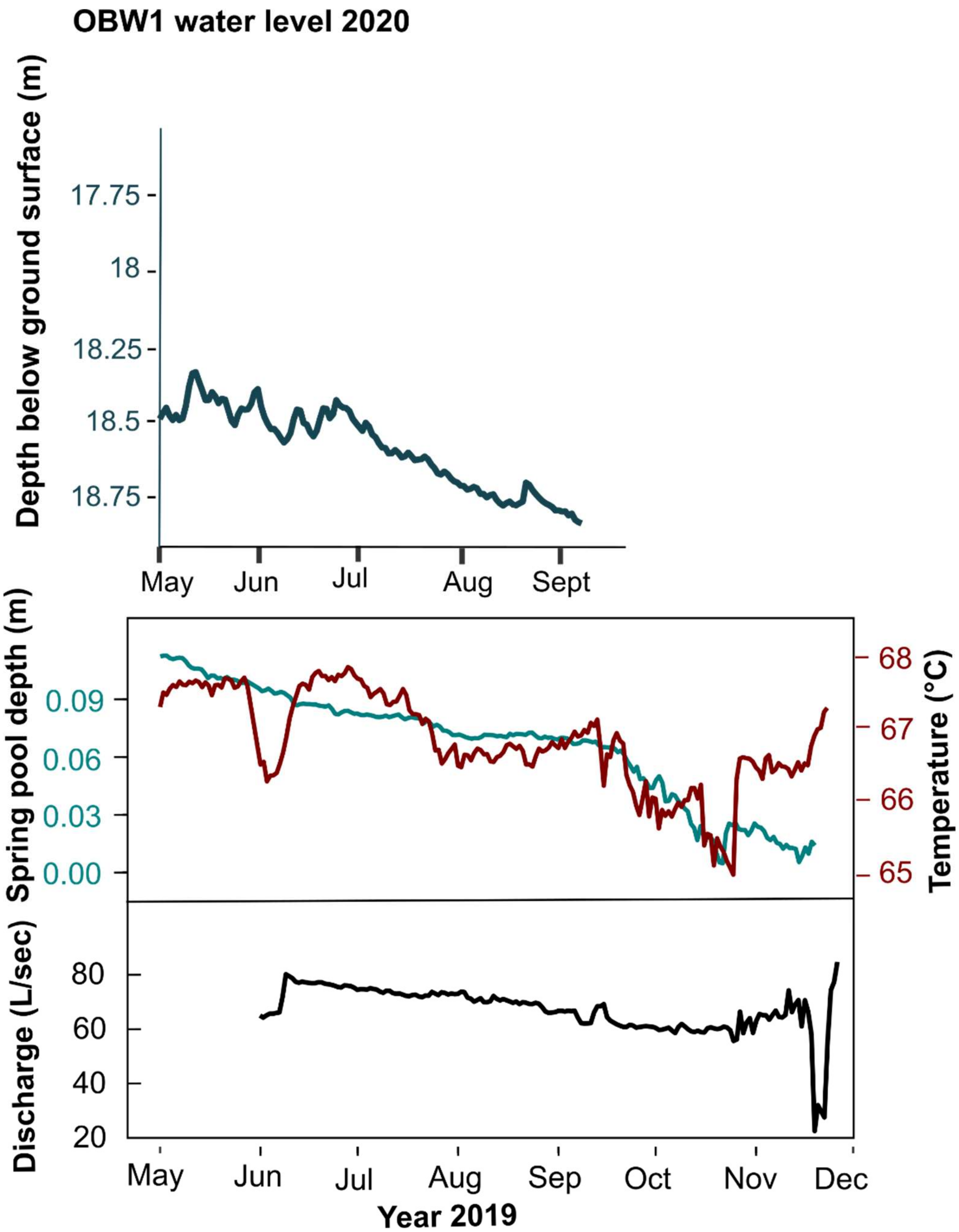

Figure B4: OBW1 water levels from 2020 compared to HS138 spring depth, flow, water levels and temperature from 2019. Visible decrease in water levels observed between both sites suggesting hydraulic gradient controlling seasonal flow to the system. Overall appears to be a relatively stable geothermal system.

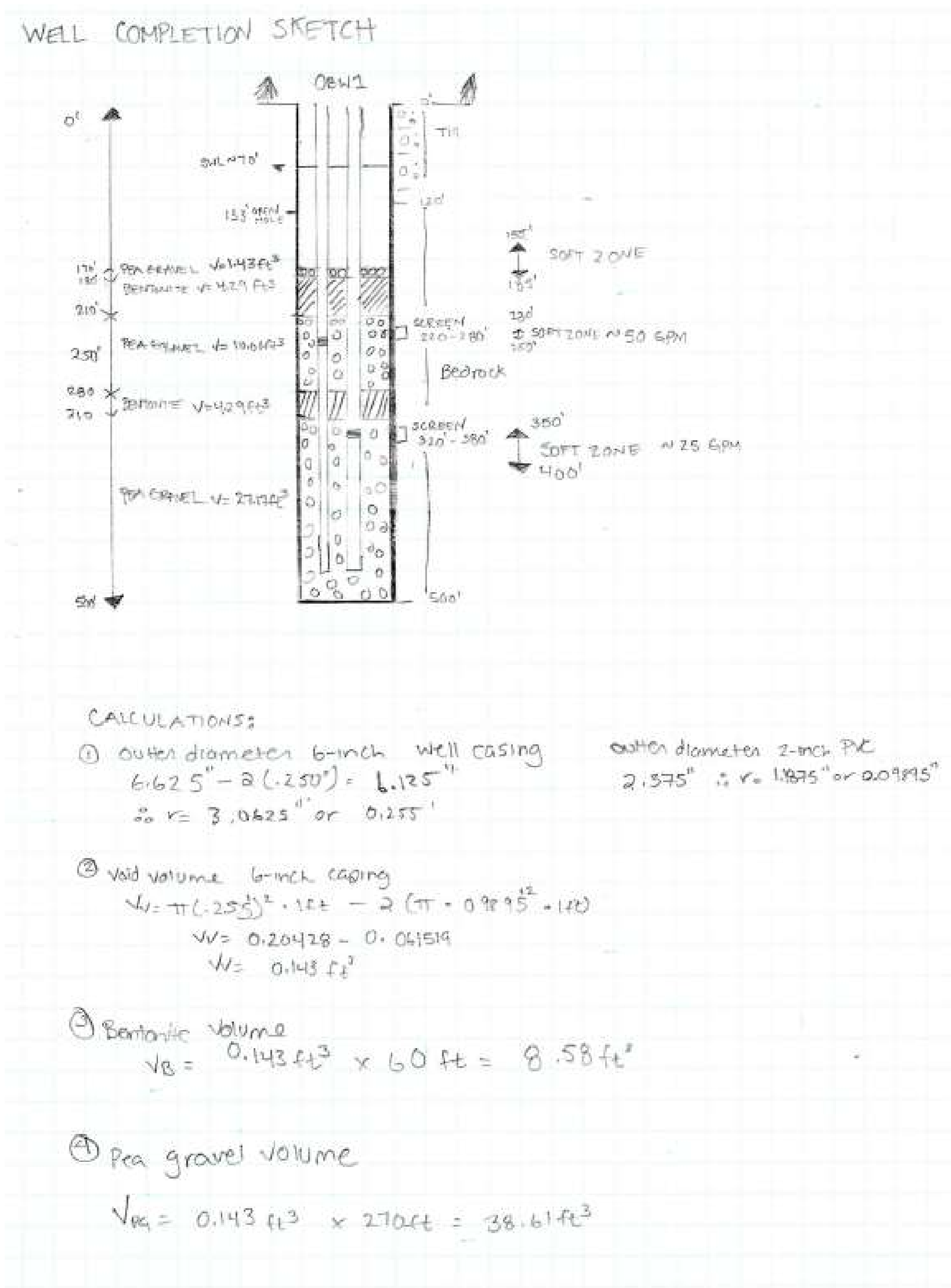

Figure B5: Well completion design for OBW1 as mentioned within the methodology section. Figure shows the intended well completion plan. Bridging occurred at ~70 meters leaving the well unfinished.

APPENDIX C: Limitations and sources of error

Table C1: Limitations and uncertainty of field data.

Field data type	Date source and field notes	Uncertainty	Limitations
Spring pool depth and temperature at H138 (Figure 5a)	Levellogger installed in spring pool above v-notch	Levellogger has an accuracy of 0.05%	Levellogger malfunctioned from 2019-2020.
Spring flow at H138 (Figure 5a)	V-notch weir and pressure transducer (Levellogger XX) installed adjacent to v-notch	V-notch weirs have an uncertainty of +/- 2%	Not located at a discrete site and the equipment was tampered with multiple times.
Spring temperatures (Figure 5b)	DS1922L-F5 temperature buttons	±1°C	Not located at a discreet site and the equipment was tampered with multiple times. Seasonal flooding also displaced numerous buttons.
Spring flow (Figure 6)	Bucket test	Assumed to be+/- 10%	Represents an average and potential for flow to not be entirely captured.
Spring flow (Figure 6)	Visual estimate	Assumed to be +/- 50%	Based on the observer's best guess.
Temperature-conductivity profile	Solinst TLC probe	5% for conductivity +/- 0.2°C	There may be reading inaccuracies based on equipment errors.
Hydraulic properties (T, S, K)	Theis and Cooper-Jacob solutions	Assumed to be ~ 10%	Solutions have significant assumptions about the aquifer that are often not true and can lead to over or underestimation of hydraulic properties. There is also potential for human error when curve matching. Values obtained should be considered estimates of the area that the well was drilled and may not be representative of the entire aquifer system.

Data point locations	Garmin GPS	Accurate within 15 meters	Locations could be slightly off because of dense vegetation and limiting satellite connection. Overall, locations appear relatively accurate when uploaded into QGIS software.
Strike and dip	Bruton Compass	Assumed +/- 5 degrees	Brunton compass typically the most accurate for measuring strike and dip but estimates of error are based on the potential for human error.
Drill chip depths	Dual rotary drilling methods	Assumed +/- 5 meters	Using dual rotary methods convey chips from approximate depths as the drill head is grinding rock down and once chips reach land surface their interpreted depth may be off as we are collecting an intact core log.