Conceptualizing the hydrogeothermal setting of Sloquet Hot Springs in the Canadian Cordillera on unceded St'at'imc Territory: an example of a reconciliation-based approach to field geoscience

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Abstract:
Field geoscience has made important scientific advances but has not consistently considered the impact of these geoscience results on communities where the fieldwork is conducted. A reconciliation-based approach calls for critical thought about who defines, participates in, owns, and uses geoscience research, particularly in light of unresolved aboriginal rights and title claims and treaty rights throughout all of Canada. Geothermal research in the 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 Nation. The scope of this project was working collaboratively with Xa'xtsa 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 a reconciliation-based approach to field geoscience, we review how resource regulation, research, relationships, and reconciliation interact in British Columbia and consider our community partnership relative to Wong et al (2020)'s 10 Calls for Action for Natural Scientists.

Well drilling, testing and monitoring revealed numerous soft zones in the subsurface as well as high transmissivity suggesting bedrock in the area has significant permeability. The annual flux calculated for Sloquet Hot Springs suggests a regional flow contribution from nearby watersheds. Although surface and subsurface observations 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. These results and interpretations are synthesized into a conceptual model of a localized hydrogeothermal system with local and regional groundwater flow along permeable pathways in the subsurface and mixing with cooler water before discharging in some of the springs.

Keywords: groundwater, geothermal resources, reconciliation, faults, community-based research

Motivation and purpose

Field geoscience is often considered culturally and socio-ecologically acontextual (Mata-Perelló, 2012; Bohle, 2019). Although geoscience is often motivated by social or economic interests, and sometimes considers society (e.g. Geological Society of America's Geology and Society Division that advances the concept of "geology working for society"), "most geologists have yet to grasp the wider societal interests and implications of the Anthropocene Epoch debate" (Stewart & Gill, 2017 at 165). Historically, field geoscience has made important scientific advances but has not consistently considered the impact of these geoscience results on communities where the fieldwork is conducted (Baillie et al, 2020). In Canada the widespread commitment by all levels of government and both settler and Indigenous communities to reconciliation between Indigenous and settler societies challenges this traditional approach to geoscience. Rather than simply being about knowledge creation relating to what is on or under the landscape, a reconciliation-based approach calls for critical thought about who defines, participates in, owns, and uses geoscience research, particularly in light of unresolved aboriginal rights and title claims and treaty rights throughout all of Canada. Geoscience is not neutral but is an expression of the tension between unsettled colonial authority over natural resources, Indigenous responsibility for territories, access to and benefit from natural resources, and who has decision-making authority. This unsettling is seen most clearly in the conflict between state regulation of geoscience and the research that supports the development of geoscience resources on the one hand and Indigenous communities' responsibilities towards their territories on the other (Borrows, 2018). Particularly in the mining context (Stk'emlúpsemc te Secwépemc Nation, 2017; Canadian Press, 2021), but increasingly relating to groundwater use and management (Hernandez, 2021), Indigenous communities often oppose state-approved exploration and development of geologic resources (William, 2019; Gilpin, 2021). In many cases the Indigenous communities whose Indigenous legal orders operate throughout their territories have not consented to state regulation or research and, in

keeping with other government-to-government arrangements for collaborative Indigenous-state governance, the geoscience community is being called to adapt research practices that respect Indigenous authority (Wong et al. 2020).

Our field geoscience focused on Sloquet Hot Springs on the traditional territory of St'at'imc people and near the Xa'xtsa First Nation community of Tipella, in southwestern British Columbia. The Xa'xtsa First Nation were strong and consistent partners in this research through the TTQ Economic Development Corporation which co-manages the Sloquet Hot Springs with the Province of British Columbia. Tipella is a small community and relatively remote with concerns about economic development as well as food security due to the long distance to groceries. The community was interested in exploring the science of the hot springs to better understand the potential for the economic development of alternative soaking pools and/or potential for a sustainable food system with heated greenhouses, and more broadly to understand resources on their territory to enable self-determination. Although not motivated by geothermal energy resource development, our reconciliation-based approach to field geoscience could be adapted to geothermal and broader geoscientific fields.

Across Canada and internationally, field geoscience research for geothermal is motivated by geothermal's stable baseload-power supply which could help meet greenhouse gas reduction measures (Grasby et al., 2012). 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. Researchers have rarely conducted detailed fieldwork to develop local and regional conceptual models of these systems and, to the best of our knowledge, never in partnership with a First Nation.

The purpose of this article is to: (1) share a research process that centered Indigenous interests related to geothermal resources in the southern Canadian Cordillera; and (2) describe detailed fieldwork and develop conceptual models of an under studied hot springs. Working collaboratively with Xa'xtsa First Nation, we conducted detailed structural, hydrologic and hydrogeologic fieldwork to develop local and regional conceptual models of Sloquet Hot Springs. The novel contribution of this research to the field is twofold. First, we explain the relationship-based approach we used in co-creating the research in the context of generating knowledge that can further our partner First Nation's goals. Second, the detailed fieldwork leading to the conceptual models of these systems is rare and offers instructive insight into the subsurface geothermal conditions in a remote area.

Approaching this research as a case study in both community-based research in partnership with an Indigenous community and novel geoscience, we first explore the continued disconnection between reconciliation and geoscience. Recognizing the outdated approach of natural science research to Indigenous authority, Wong et al published *10 Calls to Action for Natural Scientists* (2020) (Table 1) to challenge scientists to embrace reconciliation in their work. Geoscience researchers can adapt and adopt this framework to explain a community-based research approach that centers on reconciliation and advances the goals of the Indigenous community on whose territory the research occurs. Pointing to Wong et al's *10 Calls to Action for Natural Scientists* as an organizing framework, we explain the process undertaken by geoscience researchers in collaboration with the Xa'xtsa First Nation. From

community gatherings to a letter of intent, the Indigenous community partners directed the research and ensured that it would be both scientifically robust and meet their needs. Keeping those two objectives of robustness and usefulness at the forefront, we describe the geologic context, methodology, and findings. The discussion and conclusions describe first, the geologic structures, lithologies, and springs at the surface, geothermal gradient, groundwater flow which together lead to a conceptual model of the hydrogeothermal system at Sloquet Hot Springs. Second, we assess how our community-based geoscience research approach reflected Wong et al's *10 Calls to Action* and consider how the reorientation of geoscience research can more fully meet the interests of the Indigenous communities on whose territory the research takes place to support the self-determination goals of those First Nations. The purpose of highlighting our methods for community partnership is to showcase how earth scientists can begin to collaborate with Indigenous communities and by no means suggests 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).

Reconciliation and Geoscience

To situate our research as an example of this collaborative research in the era of reconciliation, we use the concept of the five Rs: Resources, Regulations, Research, Reconciliation, and Relationships from the perspective of earth scientists and community members to guide our research and contrast it with previous approaches (Figure 1). Previously research and teaching in an Indigenous context have used Rs to organize concepts. Kirkness and Barnhardt (1991) and later Allen et al. (2018) described four R's (Respect, Relevance, Reciprocal relationships, Responsibility) as an ethical practice relating to Indigenous knowledge and pedagogy, while Castleden et al. (2017) suggested two additional R's are important: Relationality and Reconciliation, which are highlighted in the 'Reconciliation and Relationships' circle of Figure 1. We also acknowledge the decolonization-focused R of Resurgence, the locus of which is outside of state-sanctioned aboriginal rights (described below). Resurgence refers to Indigenous communities revitalizing cultural practices, beliefs, responsibility to protect their land- and water-scapes, and sovereignty without pressure of assimilation (Coleman, 2016), which includes attention to restitution (Corntassel, 2012). Finally, we acknowledge Tuck & Yang (2018) who use the R words 'Refusing Research' to suggests that researchers or research subjects can refuse to do research in whole or part which which importantly can enable communities to direct or define research questions, process and approaches.

Figure 1 builds on these previous descriptions of Rs to visualize the overlapping concepts in our research process. So 'Evaluating Sloquet Hot Springs' is at the center of the Venn diagram. 'Previous resource development approaches' have often been in the overlap of 'Resources and regulation' and 'Geoscience' such as mineral and petroleum geoscience research for resource evaluation and development. More recently, there are 'New resource development approaches' emerging at the interface of 'Resources and regulation' and 'Reconciliation and relationships' such as the Indigenous-led or co-owned resource developments. 'Geoscience research' is any fundamental or applied geoscience research not

directly related to resource development. 'Community-based research' and other related approaches can be at the interface between 'Reconciliation and relationships' and 'Research'. We have found the Venn diagram and language of '5 R's' useful for describing and situating our work relative to traditional geoscience work and may be useful to other studies as an example. However, this approach is not intended to be a new framework.

Since 1982 state governments in Canada have "recognized and affirmed" aboriginal and treaty rights pursuant to section 35 of the *Constitution Act, 1982*, which leads to a duty of the state-federal and provincial governments - to consult about proposed activities within traditional territories that may have an impact on those rights (*Haida Nation*, 2004). The term reconciliation flows from this constitutional placement of Indigenous authority as Canadian courts have noted that the purpose of section 35 is the reconciliation between the state and Indigenous societies in Canada (*Van der Peet*, 1996*).*

Since that legal recognition, both domestic and international processes have further defined reconciliation. In 2007 after several decades of work the United Nations General Assembly adopted the United Nations Declaration on the Rights of Indigenous Peoples (UN Declaration) to provide a framework for justice and reconciliation for Indigenous peoples (Bain et al., 2018). The UN Declaration applies human rights standards to the historical, cultural, and social circumstances of Indigenous peoples, who face ongoing violations because of colonialism (Bain et al., 2018). A key provision of the UN Declaration that Indigenous communities have widely adopted is Article 32 that identifies a right of Indigenous peoples to give their "free, prior and informed consent" for state-sanctioned activities that occur within their traditional territories. The text of that article is broader than just seeking consent; it identifies a right to determine and develop priorities for the use of their territories and resources, as well as state governments participating through Indigenous processes and institutions to obtain consent (UN, 2007, Art. 32).

In Canada, the federal government did not sign on to the UN Declaration until after the Truth and Reconciliation Commission of Canada (2015) released 94 calls to action to redress the violent colonial legacy of dispossession perpetrated through the residential school system. Call to action 43 calls on federal, provincial, territorial, and municipal governments to adopt and implement the UN Declaration as a framework for reconciliation. Collectively, the Calls to Action and UN Declaration identify the historic and ongoing damage caused by colonization and the residential school system and establish specific actions for state governments, institutions, and society. In the past two years, both the state governments of British Columbia and Canada have enacted legislation to align state laws with the UN Declaration (*Declaration on the Rights of Indigenous Peoples Act*, 2019; *United National Declaration on the Rights of Indigenous Peoples Act*, 2021).

Earth scientists may consider their research objective and unrelated to the ongoing legacy of colonialism and the current effort towards reconciliation. However, all researchers have a worldview shaped by their experiences and training, most often within colonial society, that leads to subjectivity (Curtis, 2012) and oppressive practices (Chaudhury 2021). Indeed, one group of scholars notes that "racism thrives in geoscience" (Ali et al, 2021).

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 (Tuck & Yang 2018). Scientific research has remained on the

periphery of reconciliation yet is not considered removed nor immune from the process (Kovach, 2009; McGregor, 2018, Wong et al., 2020). While Indigenous peoples are the original researchers of their territories (Debassige, 2013), many researchers treat their knowledge as out of place or are only committed to consultation for individual benefit (Asselin and Basile, 2018).

Over this same period, the importance of Indigenous knowledge for environmental research and management has received considerable attention and acceptance (Artelle et al, 2018; Arsenault et al, 2019; Thompson et al, 2019; Schang et al, 2020). The requirement to consider Indigenous knowledge is now embedded in many state environmental laws in Canada such as the federal *Species At Risk Act* (2002) and the British Columbia *Environmental Impact Assessment Act* (2018). A key part of this approach is the integration of Indigenous knowledge systems and western science into research (Henri et al 2021; Luby 2021). Often discussed in the context of reconciliation and free, prior and informed consent, researcher-Indigenous or state-Indigenous collaborations have the dual purpose of generating new knowledge that also furthers Indigenous self-determination priorities (Adams et al, 2014; Hemming et al, 2017).

Noticeably absent from this work are community-based or collaborative approaches to geoscience with Indigenous partners (Marshall et al, 2018). Geoscience researchers and teachers are exploring how geoscience practice in the field and classroom can be integrated with Indigenous knowledge and a place-based approach to improve earth science education (Riggs and Riggs, 2003; Semken, 2005; Palmer et al, 2009; Johnson et al, 2014; Ward et al, 2014; Semken et al, 2017; Ricci and Riggs, 2019). One study addressed Indigenous community vulnerability to volcanic activity by embedding geoscience research in the specific socio-ecological context (Pardo et al, 2015). These studies are significantly advancing the field, however, it is important to note that the scholarly attention to date is more about teaching culturally appropriate approaches to geoscience than doing collaborative community-based research with Indigenous communities. Few natural science researchers are aware of the guidance given to researchers for work with Indigenous communities (Wong et al, 2020), even with extensive direction from major research funding agencies (Government of Canada, 2018) and Indigenous-developed principles about ownership, control, access and possession (OCAP) over data generated in traditional territories (First Nations Information Governance Centre, undated).

Turning to geothermal resources, many Indigenous communities describe 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). First Nations across British Columbia have repeatedly identified water and decision-making about water as a priority (Union of British Columbia Indian Chiefs, 2010). However, the state regulatory structure for geothermal vests the "right, title, and interest in all geothermal resources" in the provincial government (Geothermal Resources Act 2008) without acknowledging Indigenous peoples or their authority in the lands where these resources exist. As a counterpoint to the regulatory capture of energy resources in the federal and provincial governments, many First Nations are using their Indigenous laws and procedures to establish policies and review proposed projects in their traditional territories (Curran, 2019). Further, Indigenous communities are beginning to evaluate large-scale natural resource projects through their processes rather than rely on state administrative processes like environmental

assessment. Adopting the lens of free, prior, and informed consent these communities are exercising their Indigenous environmental governance (Curran, 2019).

Geologic setting

Sloquet Hot Springs is located in the southern Coast Belt of the Canadian Cordillera (Brown et al., 2000) that consists mainly of granitic rocks ranging from Middle Jurassic to mid-Cretaceous (~170 to 90 ma) (Monger and Price; Monger & Brown, 2016) (Figure 2). Granitic bodies in the area intruded through stratified volcanic and sedimentary sequences that range in age from the Middle Triassic through Early Cretaceous (Monger and Price, 2000). Deformation in the region consists of shear zones that are spaced +/- 10 km apart and are associated with steeply dipping fault planes. More specifically, the region is characterized by north-northwest trending structures that reflect Cretaceous orogen-normal compression with southwest or northeast dips as well as Tertiary northeast-striking transcurrent faults that record right-lateral strike-slip and oblique-slip displacement (Grasby & Hutcheon, 2001; R. Hyndman, 2010; Journeay & Csontos, 1989; Journeay & Friedman, 1993; Lynch, 1990). These late Tertiary faults controlled emplacement of Miocene aged intrusive breccias and related volcanic complexes associated with the Pemberton Volcanic Belt and are further understood to control localized thermal spring systems (Journeay and Csontos, 1989). The largest of these Tertiary structures is the Glacier Lake Fault but they are typically marked by physiographic depressions and are rarely exposed (Lynch, 1990). Fault timing and kinematics suggest that these structures are a part of a regional system that formed in response to northeast-southwest shortening (Lynch, 1990). The timing and kinematics of both transcurrent and high-angle reverse faults suggest that these structures may be part of a regional system that formed along the continental margin in response to northeast-southwest shortening. These historic deformation events in the southern Canadian Cordillera, coupled with elevated heat flow and active tectonics, have created a geological environment that has significant potential for geothermal exploration and development.

Thermal springs across the southern Canadian Cordillera have been used as an indication of geothermal potential and it is understood that these springs are controlled by fault structures in the region (Grasby & Hutcheon, 2001; Journeay & Csontos, 1989; Journeay & Friedman, 1993; Lynch, 1990). Previous studies suggest that crustal heat flow in the southern Canadian Cordillera ranges between 40 to 130 mW/m^2 with local anomalies that exceed 200 mW/m^2 (Finley, 2019; Grasby & Hutcheon, 2001; Jessop, 2008; Lewis et al., 1992; Lewis et al., 2003). Previous studies in the region have 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. The Mount Meager example provides the incentive for more detailed local investigations of spring systems to understand the hydrogeological and geothermal conditions.

Sloquet Hot Springs is in the Coast Mountain physiographic region on the edge of two biogeoclimatic zones. The coastal western hemlock zone receives ~2.8 m of mean annual precipitation and has mean annual temperatures of 6.7 °C whereas the mountain hemlock zone receives ~3.1 m of mean annual precipitation and has mean annual temperatures of 2.8 °C (Moore et al., 2010). Biogeoclimatic zones and their associated climatic regime will be used as a 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 in steep terrain that rises to over 1500 masl. Dense vegetation and unconsolidated materials limit bedrock outcrops to forest service roads and along Sloquet Creek, where numerous cold, warm, and hot springs discharge from well-developed joint structures near the creek.

Exploration projects around the study site 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 reservoir temperature and fluid circulation depth estimates. Spring temperatures recorded through these studies show a temperature range from 60.8 to 71 °C (Grasby and Hutcheon, 2001; Hickson et al. 2016a) and suggest that thermal waters circulate from a depth of 2.3 km depth (Grasby and Hutcheon, 2001). Various geothermometry methods including Na-K-Ca and SiO_2 indicators were used to estimate reservoir temperature at depth of 110 - 135 °C (Grasby et al., 2000; Hickson et al. 2016b) while regional geothermal gradients and spring temperatures were used to predict circulation depths (Grasby and Hutcheon, 2001). Preliminary geothermal feasibility assessments were also completed and suggest that Sloquet Hot Springs has a moderate potential for harnessing thermal resources and could produce up to 10-20 MW of energy (Kerr Wood Liedal, 2015). These investigations of Sloquet provided informative data about the system at Sloquet but lacked information on in-situ conditions of the subsurface. We expanded the field investigations to better define hydrogeological and geothermal characteristics, herein called the hydrogeothermal system.

Methods

Community partnership

Community partnership involved building relationships, establishing protocols, conducting the research, reporting results, and ensuring ongoing relationships. Some Indigenous nations or communities have developed research applications, protocols, or agreements but this was the first time that the Xa'xtsa community had worked with natural science researchers which meant that we had to create our process for working together in good faith based on our previous experiences, discussions with other colleagues, reading literature, etc. Although Wong

et al. (2020) was not published when our research started, we find it relevant to review our methods as an example for other researchers and determine where we can improve practices for future projects, as we do below at the end of the Discussion and Conclusions.

Initial contact was made through mutual connections interested in Indigenous economic development with the first meeting in Tipella, BC in 2018 with the leadership of TTQ Economic Development Corporation. After this meeting, TTQ staff developed and signed a letter of intent supporting the scientific investigation of the hot spring using visual surveys, mapping, and drilling. The researchers and TTQ staff built relationships with the larger community through gatherings and feasts 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. 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 presented 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 a local investigation of the study site.

After these gatherings and feasts, we began to conduct the field geoscience described below and shared field experiences and initial results through a project website and blog (https://sloquethotspringstudy.weebly.com/). Before starting a new method, the researchers consulted with TTQ leadership to ensure the method was appropriate and as low impact as possible. After a year of mapping and monitoring the research partners agreed that it would be useful to drill a well to gather subsurface information. The research partners signed an agreement clarifying the ownership and use of the well for scientific monitoring only, and what do to if culturally sensitive items were found during drilling. Staff with the Province of British Columbia, who co-manage the site, were informed of the agreement and drilling. The research partners did not develop a comprehensive research agreement on data ownership and distribution but the parties had a verbal understanding that TTQ staff review and approval is required for all materials before publication.

Before reporting the results, TTQ staff reviewed the results for sensitive information. After approval, the researchers reported the results through an academic thesis (Van Acken 2021), a preliminary project report (van Acken and Gleeson, 2019) as well as to TTQ staff and the broader community in multiple ways, including the website and blog, a detailed project report for TTQ and a two-page project summary for the community in plain language. Instead of a community feast and gathering at the end of the project, because of COVID-19 restrictions, the researchers delivered gratitude bags with tea and salmon and the two-page project summary to community members. We plan to ensure ongoing relationships by developing an agreement to TTQ to maintain the well and download monitoring data and steward the data derived in this project.

Bedrock, structural, and spring mapping

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 springs. 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 precise location of transect lines and newly identified springs are not included in mapping as an agreement between the 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 so that low flow conditions in Sloquet Creek exposed more thermal springs.

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 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. 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 into the creek with one Solinst levelogger and Thermochron iButton at the base of the aluminum.

Well drilling, testing, and monitoring

The observation well (OBW1) was drilled in August 2019 using dual rotary methods to drill a 152 mm (6") diameter well (Well Tag Number: 118320). Drill chips were collected every 1.5 m to observe changes in lithology during drilling. OBW1 is cased from 0 to 40.5 meters, 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. The well was step tested at 0.17 m³/minute, 0.20 m³/minute, and 0.24 m³/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 m³/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. 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. 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.

Geoscience results

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 3). Updated mapping in Figure 4 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 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 4). 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 5). 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 clasts. The contact between the intrusive porphyry and clast supported conglomerate is depositional (Figure 5). 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 the 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. 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 clasts. The only observable structures present within the unit were anastomosing fractures that formed around clasts within the unit (Figure 3). 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 clasts that were surrounded by a silty clay matrix (Figure 3).

Structural 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 4 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 4a). Plotting structural data as poles (Figure 4c.) 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 2. 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 to present in the area and may be concealed by unconsolidated materials and the clast supported conglomerate.

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 6 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 6b 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 7 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.

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 8-10 present the 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. The drilling team encountered 38 meters of unconsolidated materials before encountering bedrock at ~39 meters below the ground surface. Water was encountered at ~32 meters below ground surface 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 sulfur 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 sulfur. 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 8).

Groundwater monitoring was initiated in the fall of 2019 and recorded nearly a full year of water level records (Figure 9). 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 9). 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 9 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 m3/minute, 0.20 m3/minute, and 0.24 m3/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 m3/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/day), transmissivity (5.6 to 7.2 m^2/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 too quickly re-equilibrate (Figures 9,10) 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.

Water temperature in OBW1 was collected on three different occasions to quantify temperature changes in the water column over time (Figure 10a). 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 10a.). An inflection point was consistently recorded at ~80 meters where the geothermal gradient is observed to decrease (Figure 10a.). 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 10b 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 8) 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 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.

Discussion and Conclusions

The discussion and conclusions begin with field geoscience followed by the community partnership as an example of reconciliation-based field geoscience. The scientific limitations of our methods and results are detailed in van Acken (2021).

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 4). 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 2 and 11) 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 the 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 11 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, the buried fault is probably 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 British Columbia 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 11) 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 11 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 ~4,500 ± 300 L/minute (based on summing the flux from springs in Figure 7 acknowledging that some of the spring flow estimates were semi-quantitative (Table 1). 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.

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 8 and 10). 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 9 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 m3/minute (as seen in Figure 8). 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 8 and 10). 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 10 to provide a bound on possible circulation depths.

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/day and do not make for optimal aquifer systems (Freeze and Cherry, 1979). The subsurface conditions at Sloquet have a bulk hydraulic conductivity of 3.7×10^{-2} to 4.7×10^{-2} m/day and transmissivity values of 5.6 to 7.2 m^2/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). Furthermore, calculating storativity without radius leads to gross overestimations as Theis and Cooper Jacob solutions do not account for pumpng well effects.

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 11 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.

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 11). 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 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 11 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 11). 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 the 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 11). The areal extent of recharge 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 Springsis the catchment (QGIS area analysis). The area based on fluxes is significantly larger than based on catchment suggesting 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 neighboring watersheds. Figure 11 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.

It is important to note that the conceptual models 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 expression of Indigenous knowledge and worldviews. Future work should focus on the redevelopment of conceptual models to increase practices of reconciliation as geoscientists work to produce knowledge that is of utility to the Xa'xtsa First Nation community.

The community partnership as an example of moving towards reconciliation-based geoscience

The community was interested in exploring the science of the hot springs to better understand the potential for the economic development of alternative soaking pools and/or the potential for a sustainable food system with heated greenhouses. The field geoscience we conducted helped them better understand the resources in their territory, which contributes to their efforts towards self-determination. This orientation of geoscience research can more fully meet the interests of the Indigenous communities on whose territory the research takes place, and support the self-determination goals of those First Nations. This type of research can be visualized in Figure 1 as in the middle of the five R's - resources and regulations, reconciliation, and resources and research – which are often considered to be separate.

Our methods combined traditional geoscience approaches with community-based research that centered reconciliation to develop new approaches within the field of geoscience. We evaluate this approach using the framework of the Wong et al's *10 Calls to Action for Natural Scientists* (2020; Table 1). Given the scope of this research, we found that Wong et al's *Calls to Action* 1-3, 5-7, and 10 were relevant to our work at Sloquet Hot Springs (as described in Table 2). Our team was able to implement each of these actions and we note room for improvement specifically related to calls 3 and 5. We 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, which would have allowed youth and community members to gain expertise in fieldwork, the implementation of monitoring equipment, and conducting scientific investigations. Although we are working to establish a long-term monitoring program, it would have been more productive to have established the initiative earlier in the research rather than at the end. Finally, a comprehensive research agreement would have been appropriate and a best practice.

Finally, building on Wong et al's *10 Calls to Action for Natural Scientists* and the OCAP Principles, geoscientists should support Indigenous geoscientists to lead a process to create a standard of practice for all field geoscience research. The standard would include expectations for how to approach, seek permission from and work with the Indigenous communities on whose traditional territory the activity is occurring, as well as template protocol agreements for ownership and use of the research, community involvement, and dissemination of the results. This standard could also help develop a robust and appropriate practice for integrating geoscience and Indigenous or traditional knowledge. Although beyond the scope of this manuscript, Wong et al's *10 Calls to Action for Natural Scientists* and our recommendation for a standard of practice require a reorientation of geoscience research to bring the discipline into the 21st century.

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Table 1: Wong et al's 10 Calls to Action for Natural Scientists

1. We call on natural scientists to understand the socio-political landscape around their research sites.
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
3. We call on natural scientists to enable knowledge sharing and knowledge co-production
4. We call on natural scientists studying animals to seek out advice from Elders for respectful ways of handling animals.
5. We call upon natural scientists to provide meaningful opportunities for Indigenous community members, particularly youth, to experience and participate in science.
6. To decolonize the landscape, we call on natural scientists to incorporate Indigenous place names as permitted.
7. We call upon natural scientists and their students to take a course on Indigenous history and rights.
8. We call on funding bodies to change approaches to funding.
9. We call on editors of all scientific journals to recognize that publication of research on Indigenous Knowledge and cultural resources require review and permission from the respective Indigenous communities.
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.

Table 2: Calls to action for natural scientists working towards reconciliation in Canada from Wong et al. (2020). Calls to action 4, 8 and 9 were not directly relevant to this 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.	Researchers worked closely with Xa'xtsa First Nation's TTQ Economic Development Corporation to understand the socio-political landscape in the village of Tipella and surrounding region. Research process involved both TTQ Economic Development Corporation as well as Recreation Sites and Trails BC as both organizations 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. Researchers 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, both generally and for the Sloquet Hot Springs. The letter of intent made clear that generating knowledge about the land was a goal shared with the community.
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 TTQ Economic Development Corporation staff 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 and sought Indigenous place names throughout the project. 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 researchers have all taken courses on Indigenous history and rights.
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.	We structured this manuscript outline an example of mainstreaming reconciliation in field geosciences. Researchers 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 prior 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 communicated to the community before they occurred (transparent) and inclusive of community member participation from start to finish with the Xa'xtsa First Nation partner approving the final graduate researcher's thesis for publication.
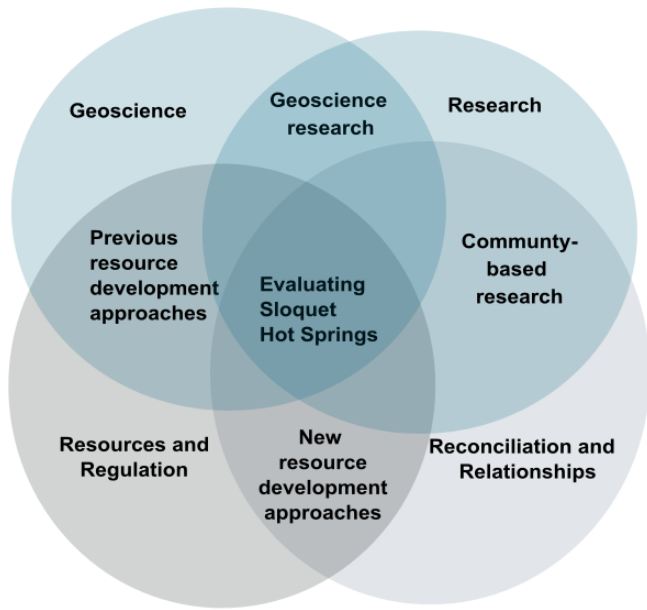
Figure 1: Situating our approach to research in a Venn diagram showing the overlap between the five R's from the multiple lenses of earth scientists and community members.
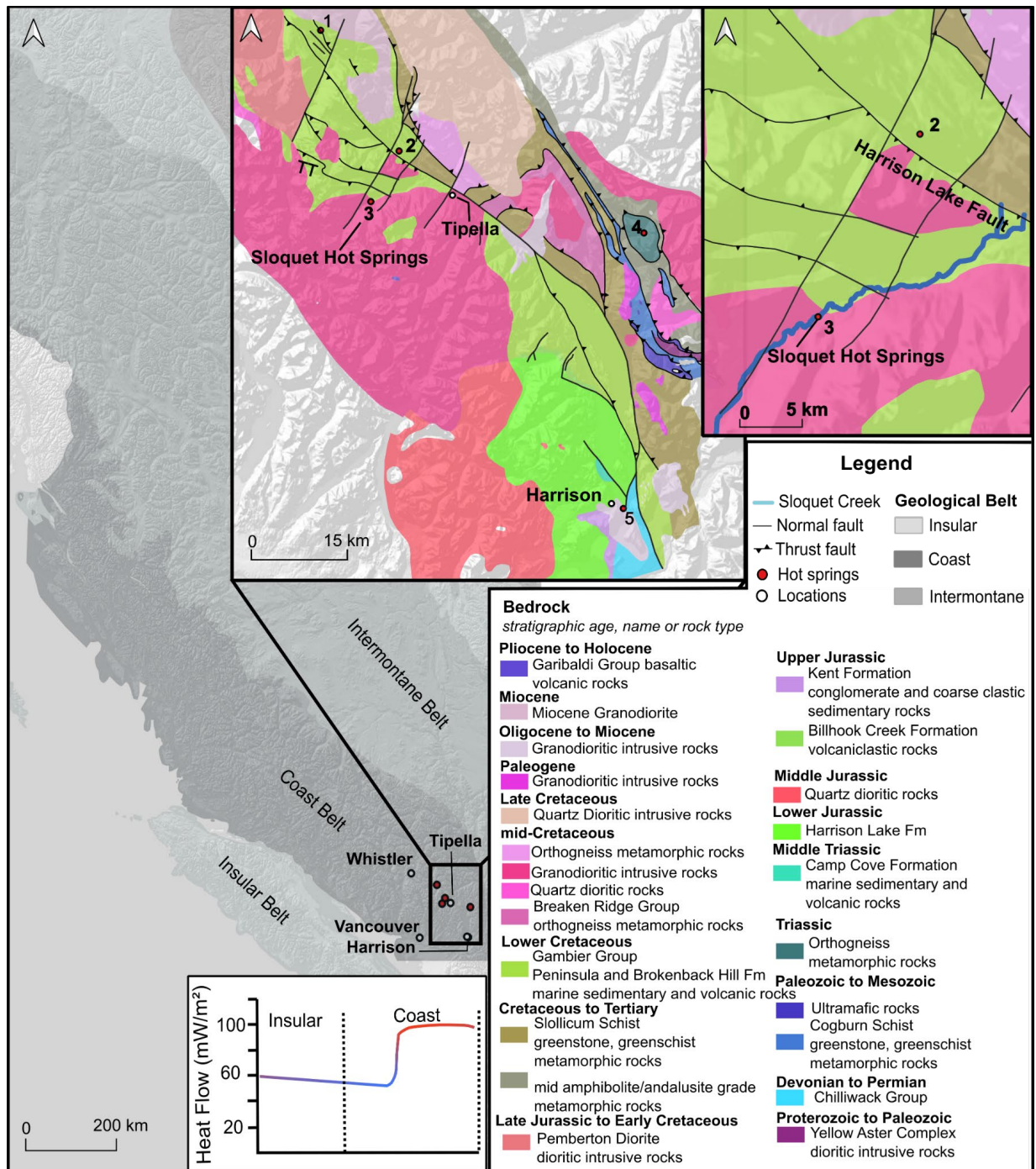
Figure 2. Regional geological and geothermal setting of Sloquet Hot Springs. (1) Skookumchuck Hot Springs; (2) August Jacob's Hot Springs ; (3) Sloquet Hot Springs; (4) Clear Creek Hot Springs; and (5) Harrison Hot Springs. Bedrock mapping from Journeay and Monger (1994) and heat flow as recreated from Grasby and Hutcheon (2001).

Figure 3. 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 clasts. (E) Undifferentiated Gambier Group appeared highly lustrous and metamorphosed.
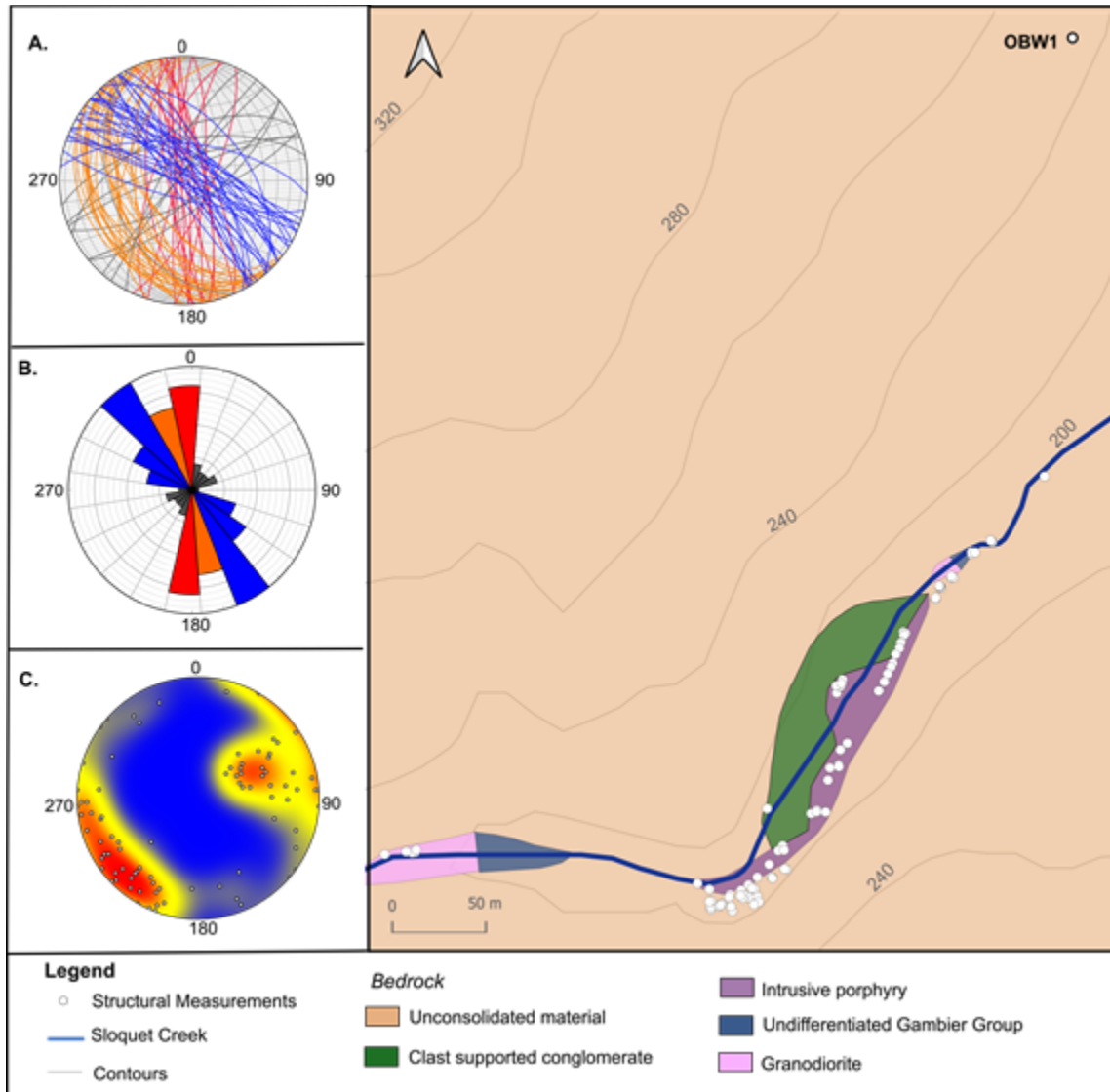
Figure 4: Bedrock and structural mapping surrounding Sloquet Hot Springs. Lithological units in the map were observed in the hundreds of meters surrounding the main recreation site and their extent was covered by dense vegetation and sediment load. (A) Spherical equal area projection of joint measurements. 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 5: 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 the unit was deposited. Photograph taken end of August 2019 and person in photo for scale.
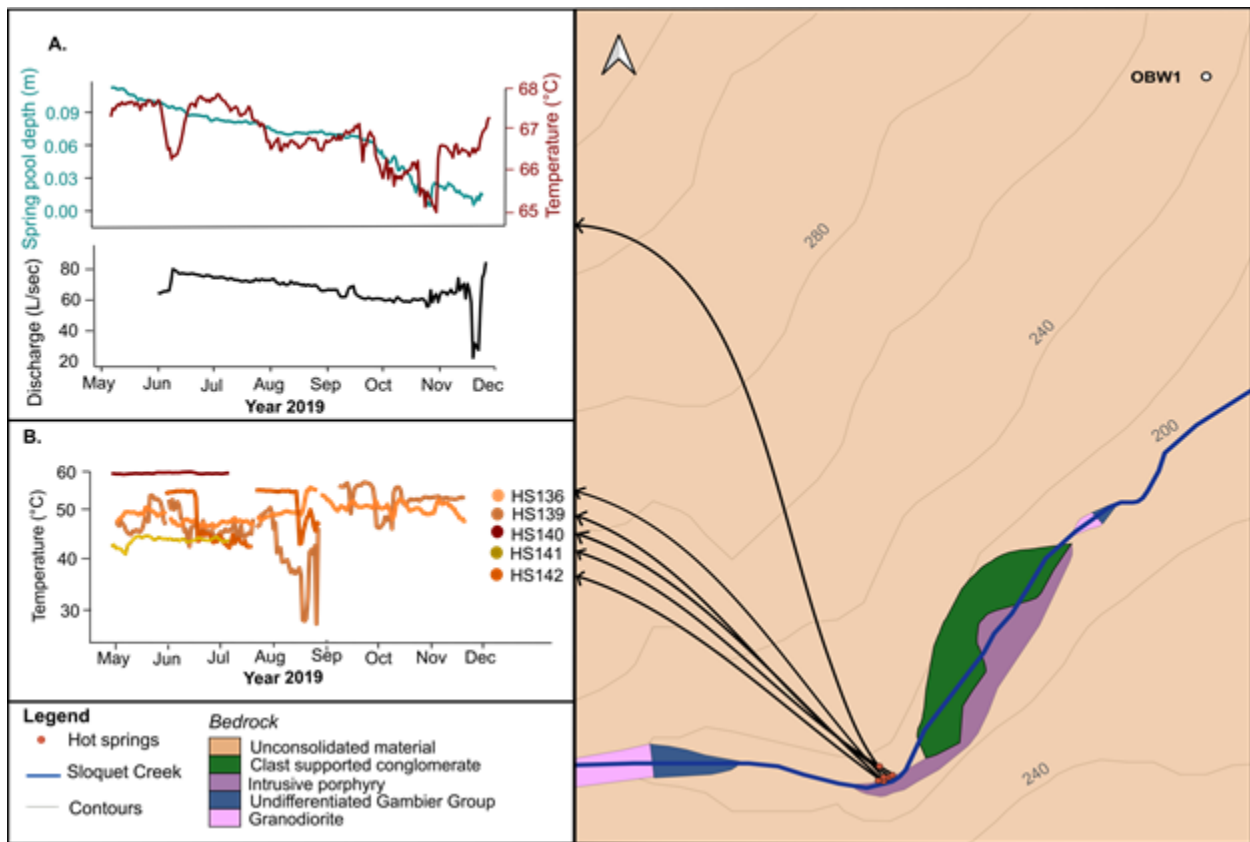

Figure 6: Temperature time series for thermal springs surrounding the recreational soaking area. (A) Spring pool depth (blue), temperature (red), and discharge (black) values for HS138. The main spring had a relatively stable temperature between 65 °C to 67 °C. Flow rates ranged between 30 – 80 L/s. (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).
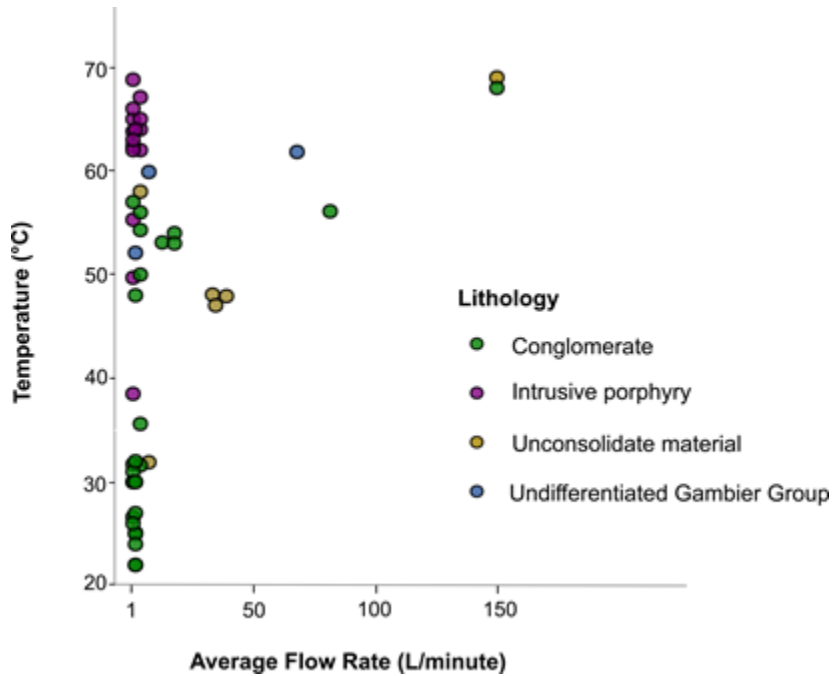

Figure 7: Spring temperature and flow rate observed along transect lines in the hundreds of meters surrounding Sloquet Hot Spring. Colours represent the lithological unit the spring was discharging from. Graph shows that the highest temperature springs were discharging from the intrusive porphyry while the clast supported conglomerate had variable flow and temperature values.
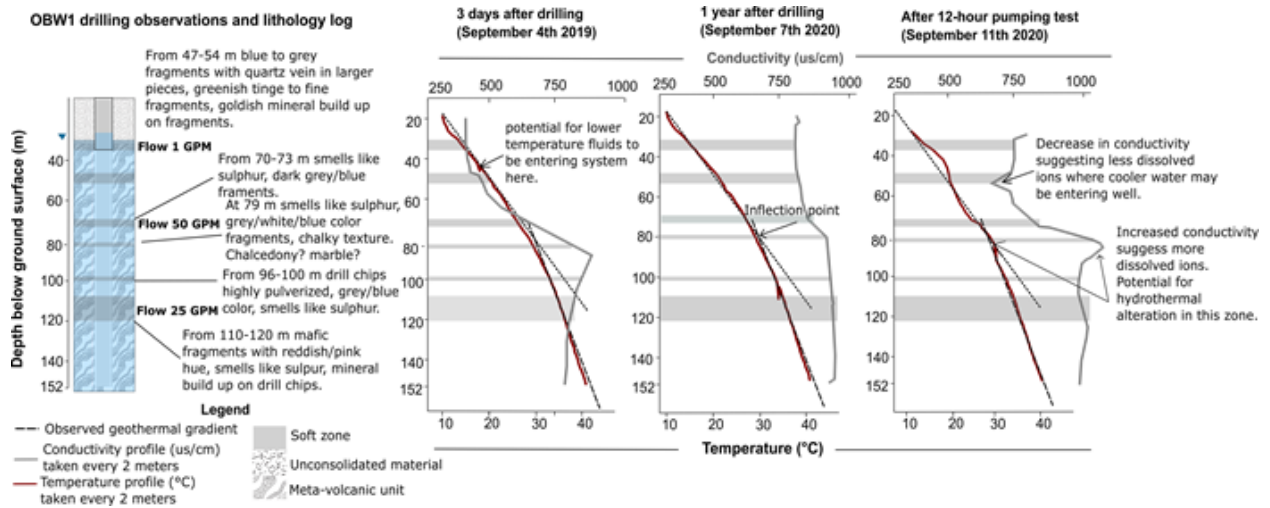
Figure 8: OBW1 drilling observations and lithology log compared with temperature-conductivity profiles from September 4th 2019, September 7th 2020, and September 11th 2020. Consistent inflection point ~80 m in all data profiles which appears to roughly align with a soft zone that has considerable flow in the subsurface. Potential for warmer, more conductive water to be entering the system at this site.
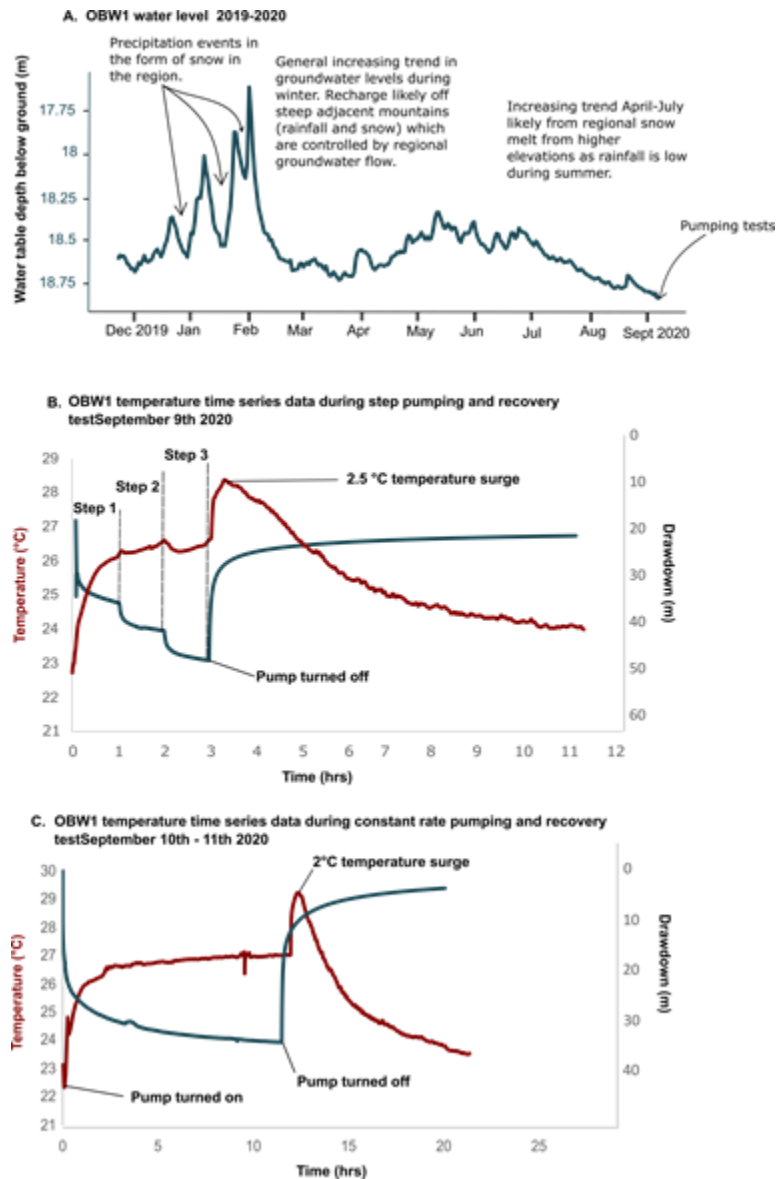
Figure 9: (A) Groundwater levels in OBW1 during 2019-2020. Groundwater levels fluctuate seasonally with minor variation in the water level depth (~1 meter). Water levels appear to be representative of regional groundwater flow rather than local flow conditions. (B) Temperature and drawdown time series data from OBW1 during step pumping test. (C) Temperature and drawdown time series data during constant rate pumping tests. During both pumping tests water temperature increased ~ 2 °C -3 °C suggesting a warmer inflow is located ~75m where the levelogger was recording data.
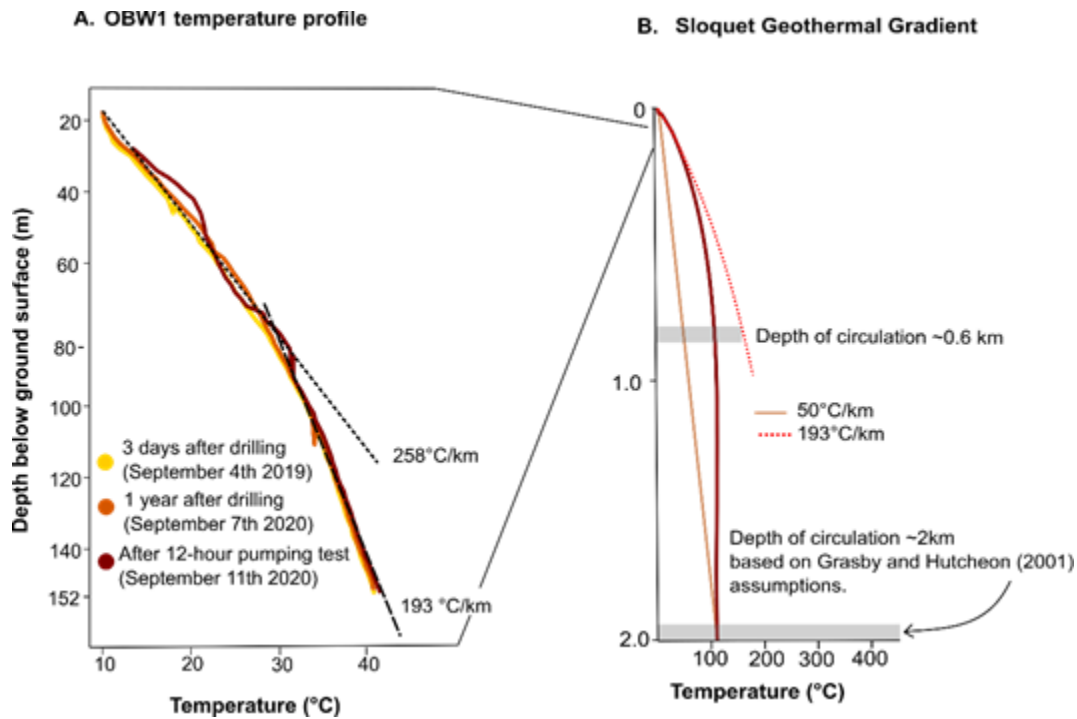
Figure 10: (A) OBW1 temperature profile as measured on September 4[th,] 2019 (yellow), September 7[th,] 2020 (orange), and September 11[th,] 2020 (red). The temperature in the water column ranges from 9 °C to 41 °C. The upper 80 meters of the well has an approximate geothermal gradient of 258 °C /km while the lower portion has a lower gradient of 193 °C /km. (B) Shows assumed the geothermal gradient from Grasby and Hutcheon (2001) as well the observed gradients in OBW1 and newly interpreted.
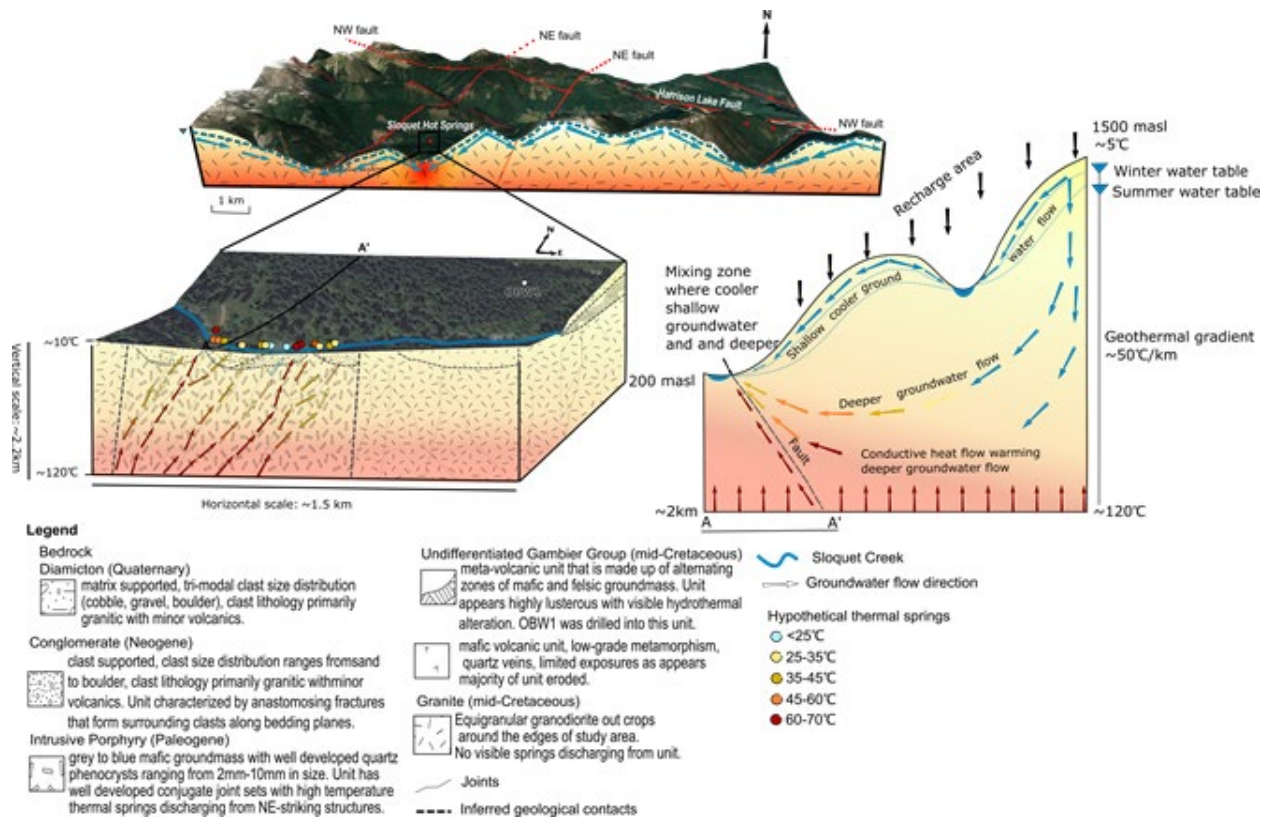
Figure 11: Regional and local conceptual model of the hydrogeothermal system at Sloquet Hot Springs. Regional model shows the location of Sloquet Hot Springs amidst large scale faults. The local conceptual model synthesizes field data hypothesizing the behavior of the system in the hundreds of meters 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.