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Geochemical and Isotopic Assessment of the Extensional M'deek Geothermal System, British Columbia, Canada

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ABSTRACT

The M'deek Geothermal System is a low-temperature (<180°C), fracture-controlled, geothermal system hosted in the transtensional Lakelse Graben 17 km south of Terrace, British Columbia. The system is expressed at the surface by the Lakelse Hot Springs, which are sodium-chloride-sulphate-type waters that reach temperatures up to 86°C. The temperature and chemistry of the Lakelse Hot Springs, and their proximal location to the Northern Cordilleran Volcanic Province, suggests that the system could be related to a magmatic heat source. To evaluate the temperature and source of the M'deek system, Kitselas Geothermal Inc. (KGI) conducted the most comprehensive investigation of the hot springs to date between 2021–2023. Water and gas samples were collected from the hot springs and regional water sources. These samples were analyzed for chemical composition and O, H, He and Ne isotopes. Physical properties including pH, temperature, and conductivity were also recorded. Na-K-Mg and silica geothermometers estimate a fluid temperature of 130–140°C for the M'deek system. This temperature is further supported by the hot springs' chemical and isotopic compositions that indicate that subsurface boiling does not occur. Additionally, $^{3}He/^{4}He$ concentrations up to 1.55 R/Ra in the hot spring waters confirm the presence of mantle volatiles; however, these concentrations are still low compared to many other magmatically heated systems. Instead, extensional structures such as the Kitsumkalum-Kitimat Fault and the active Amesbury Creek Fault may facilitate deep crustal circulation, and possibly the upwelling of mantle related fluids to the surface from the relatively shallow mantle material underlying the area.

1 INTRODUCTION

Decades of research have gone into the development of surficial investigation methods that can provide critical information about a geothermal resource without significant upfront investment (Powell and Cumming, 2010). Where surficial geothermal features such as springs or fumaroles are present, a whole suite of chemical and isotopic techniques can be used to characterize the geothermal resource before subsurface investigation takes place. Several of these methods have previously been used to investigate the M'deek Geothermal System.

The M'deek system is a fracture-controlled, graben-hosted geothermal system located 17 km south of Terrace, British Columbia within the north-south running Kitsumkalum-Kitimat Valley (KKV) (Alonso Torres et al., 2020). The valley is bounded by the Hazelton Mountains to the East and the Coast Mountains to the West, which reach heights of over 1,500 m above the valley floor. The main hydrogeological feature of the valley is Lakelse Lake, which drains via the Lakelse River into the Skeena River to the northwest. The M'deek system is expressed at the surface by the Lakelse Hot Springs at the southeast corner of Lakelse Lake (Figure 1a).

The hot springs have historically been divided into 5–7 groups (Odynsky, 1951; Nevin Sadlier-Brown Goodbrand Ltd. [NSBG], 1982; Grasby et al., 2000) (Figure 1b). The largest spring is a roughly 56°C round pool over 20 m in diameter found on the west side of Highway 37. The hottest spring is found on the east side of the highway at the foot of the bedrock cliffs that bound the eastern side of the valley. KGI has measured temperatures up to 86°C at this spring, although 87°C has been reported historically (Turner et al., 2007). Using the Silica and Na-K geothermometers, past studies have estimated that the M'deek system fluids reach temperatures of up to 115-160°C in the subsurface (NSBG, 1982; Alonso Torres et al., 2020).

The bedrock geology of the area consists of the metamorphosed Stikinia island arc terrane which has been heavily intruded by Carboniferous to Eocene age plutonic bodies. The bedrock beneath the Lakelse Hot Springs consists of an Eocene-aged granitic pluton. Faults forming a negative flower structure create the Lakelse graben within the KKV (Nelson, 2017). A transtensional deflection along the dextral-normal Kitsumkalum-Kitimat (KKM) Fault forms the eastern boundary of the graben while the normal Amesbury Creek Fault (ACF) and its splays form the southwest boundary (Nelson, 2009; Alonso Torres et al. 2020). Bedrock is overlain by up to 400 m of

unconsolidated sediments that line the KKV (NSBG, 1985). These sediments include an >100 m thick glacial marine clay unit, noted to contain high concentrations of SO_4 in pore fluids (Geertsema and Torrance, 2005).

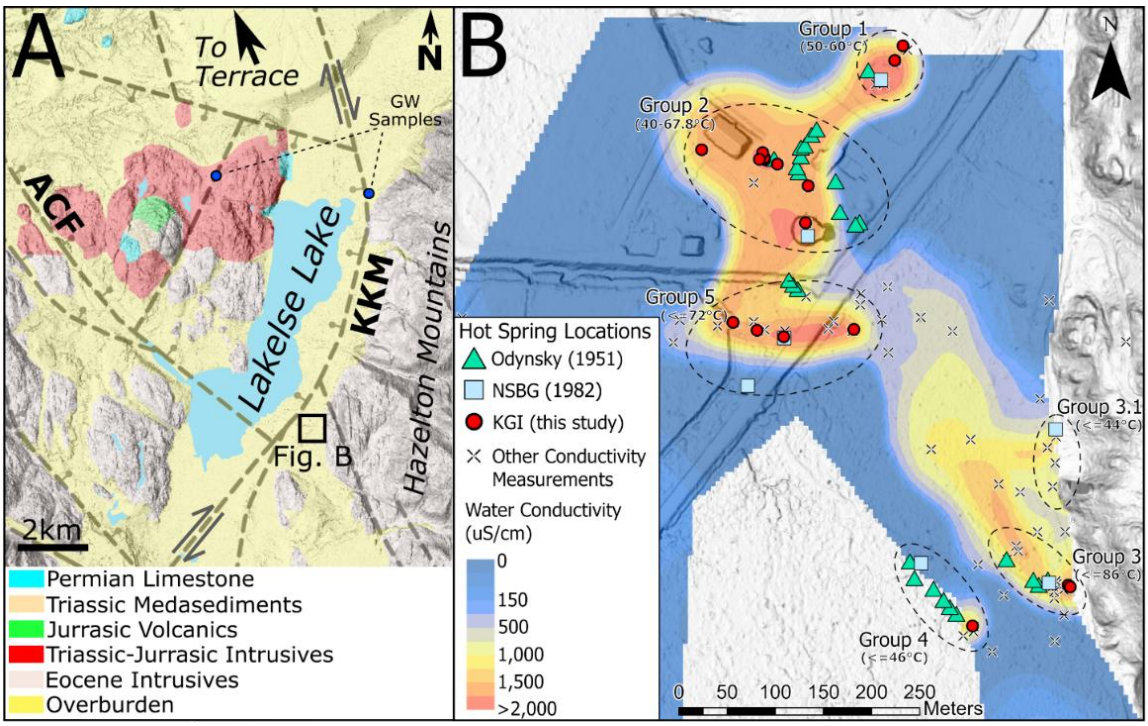


Figure 1. A) Map of the Lakelse area showing the regional features, local geology, and faults. Mapping data sourced from Cui et al. (2017) and Nelson (2017). B) The locations of the Lakelse Hot Springs as surveyed during current and past studies, divided into groups based on their locations. The conductivity of these springs and surrounding water bodies are contoured. LiDAR topography from Geertsema et al. (2018).

The M'deek system has often been assumed to be an extensional convective geothermal resource, but several factors suggest the M'deek system may be related to magmatic processes:

(1) Although no quaternary volcanics have been found near the M'deek Geothermal System, the system is <100 km south of the 300-year-old Tseax cone, the youngest volcanic centre of the Northern Cordilleran Volcanic Province (NCVP) (Turner et al., 2007). The NCVP is an area of Neogene-present day extensional volcanic activity, similar to the transtensional setting of the M'deek system (Edwards and Russel, 2000). Additionally, the Tseax cone is found along the KKM fault, which also underlies the location of the Lakelse Hot Springs, indicating this structure may be capable of transporting magmatic melts to higher crustal levels in the Lakelse area as well. Mid-late Eocene NW-SE oriented gabbroic dykes found in the area provide evidence that a structurally controlled cross-crustal conduit with a similar orientation to the KKM previously existed here (Heah, 1991).

(2) The Lakelse area has an estimated regional-scale heat flow of 75–90 mW/m^2 (Geoscience BC, 2016) and a conductive geothermal gradient of ~40°C/km (KGI unpublished data), which are anomalously elevated.

(3) Seismic modeling work conducted by Calkins et al. (2010) shows a prominent break and shallowing of the Moho beneath the Lakelse area, suggesting that upwelling hot asthenospheric material with potential for melt generation during extension may be present (Alonso Torres et al., 2020).

(4) The Lakelse Hot Springs have high SO_4 concentrations and plot in the volcanic fluids field of Giggenbach's (1991) ternary chloride-sulphate-bicarbonate (Tsch) diagram. These waters typically form when volcanic fluids boil in the subsurface and the H_2S rich vapour mixes with groundwater (Giggenbach, 1988). Although often acidic, interactions with surrounding rocks can raise the pH.

A definitive connection to a magmatic heat source would significantly impact the resource assessment of the M'deek system; however, radiogenic heat generation and the circulation of crustal fluids along regional faults could also be responsible for the system (Alonso Torres et al., 2020). This study reports on select findings of a comprehensive geochemical and isotopic sampling campaign conducted by KGI from 2021-2023 to address this possibility and better characterize the M'deek Geothermal System.

2 METHODOLOGY

A comprehensive hot spring and regional water sampling campaign was conducted in June 2021 with follow-up samples collected through to 2023. Groups of springs for sampling were identified from historic exploration campaigns and thermal drone surveys conducted by KGI (Zheng et al., 2019). Physical parameters were measured in the field using Hanna Instruments HI-98129 tester, and a Bluetooth thermometer if temperatures exceeded 60°C. Generally, only the most conductive and/or hottest spring from each group was sampled. Regional water samples were taken from regional water wells, Lakelse Lake, and precipitation. Samples were analyzed for cations, anions, silica, isotopes (O, H, He, Ne), and, if sufficient gas bubbling was present, non-condensable gases. Samples were filtered with a 0.45 µm filter as required and stored in HDPE bottles. Cation samples were preserved with 1.5 mL of diluted nitric acid. 20 mL of filtered water samples were added to 200 mL of distilled water for silica samples to prevent polymerization and precipitation upon cooling. Snow samples collected for isotopic analysis were tightly packed to minimize the amount of atmospheric contamination. Cation, anion, and silica samples were sent to ALS laboratories in Vancouver for analysis under their super trace analysis procedures using ICP-MS, ion chromatography, and colourimetric analysis, respectively. Water isotopes were analyzed by the Isotope Science Laboratory at the University of Calgary by Off-Axis Integrated-Cavity Output Spectroscopy (ICOS) using a Los Gatos Research DLT-100 instrument.

Non-condensable gases were collected in vacuum sealed glass ampules containing NaOH provided by Thermochem. An inverted funnel and tygon tubing were flushed and filled with hot spring water, connected to the ampule, and submerged above the bubble column. Once the collected gases had fully displaced the water in the system, the ampule's stopcock was opened and used to regulate the collection of gases until filled, ensuring water was not drawn up into the ampule. The collected gas samples were analyzed at the Thermochem laboratory in California using gas chromatography.

Dissolved He and Ne isotope water samples were collected according to the procedures recommended by the André E. Lalonde AMS Laboratory at the University of Ottawa (Clark and Lapp, personal communication, 2021). Water was pumped through a section of 3/8" copper tubing for 5 minutes. Flow out of the pipe was then restricted using a ball valve. Cold weld clamps or crimpers were used to seal the pipe, starting at the outlet. The samples were analyzed at the André E. Lalonde AMS Laboratory using a Thermo Fisher Scientific Helix SFT Noble Gas Mass Spectrometer.

3 RESULTS

A total of 5 different spring groups were sampled, with their locations shown along with previous studies in Figure 1b. Differences in spring location may reflect movement of the spring over time due to surface earthworks or surveying errors. Descriptions of these springs as observed by KGI from 2021-2023 are provided below:

> **Group 1:** A hot pool 20 m in diameter and 3–5 m deep, surrounded by a concrete viewing area. Temperatures of 53–56°C. Bubble columns continuously emit from the base of the pool.
>
> **Group 2:** A series of smaller springs variably mixed with surficial groundwater, several encased in buildings and concrete well boxes. Reaches temperatures of up to 67.8°C.
>
> **Group 3:** Springs that emerge along a utility service road at the base of a bedrock outcrop. Reached temperatures up to 83°C during this study. Has been dug into pools for bathing. A subgroup of small puddles found year-round along the utility road have been defined as Group 3.1. These puddles have conductivities of 500–1,400 µS/cm and temperatures usually just above air temperature.
>
> **Group 4:** Emerges directly along the bank of a stream and directly mixes with surficial waters. Historic reports suggest they emit along a NW-SE trend (Odynsky, 1951). Has temperatures of up to 46°C.
>
> **Group 5:** Found along an E-W trend on both sides of Highway 37. The hottest is a 72°C spring contained in well box. The southern springs from NSBG were covered by standing water and were not sampled.

3.1 Chemistry

All the new water samples from the Lakelse Hot Springs were determined to be near neutral Na-Cl-SO_4 type waters with SO_4 being the most abundant ion (up to 515 mg/L). Groups 1, 3, and 5 have the highest TDS content and are the least diluted with surficial waters. The conductivity of the hot springs varied from 1,180-1,910 µS/cm, while groundwater was <150 µS/cm and Lakelse Lake was around 50 µS/cm. Like the historic measurements, the hot spring samples collected as part of this study plot in the volcanic waters field of the Tsch diagram (Figure

2a). Pore fluids from the glaciomarine clays also plot within the volcanic waters field, despite not having a volcanic origin (Geertsema and Torrance, 2005). Shallow groundwaters plot in the HCO_3 corner and contain little Cl and SO_4 as these waters consist of meteoric water with little subsurface water-rock interaction. Samples from Lakelse Lake collected by KGI and Cleugh et al. (1978) contain higher amounts of Cl and SO_4 than groundwater.

Several ions in the hot spring samples are strongly correlated with each other including Cs, Na, K, Sr, B, Cl, F, and SO_4. Plotting these correlated ions against chloride, which is generally considered to be a conservative ion, reveals linear mixing-dilution trends with groundwater (Figure 2b). However, plotting chemistry data against temperature reveals that spring composition and temperature do not have a positive linear relation for all dissolved ions. This is best shown by plotting the May 2021 data in isolation to eliminate seasonal temperature effects (Figure 2c and d). Dissolved ions fall into 3 groups: 1) ions with a weak positive correlation with increasing temperature (Silica, Cs, K, Ba, Sr), 2) ions with a negative correlation with increasing temperature (Cl, Li, B, As), and 3) ions that do not change with temperature (Na, F, SO_4, Ca, Rb).

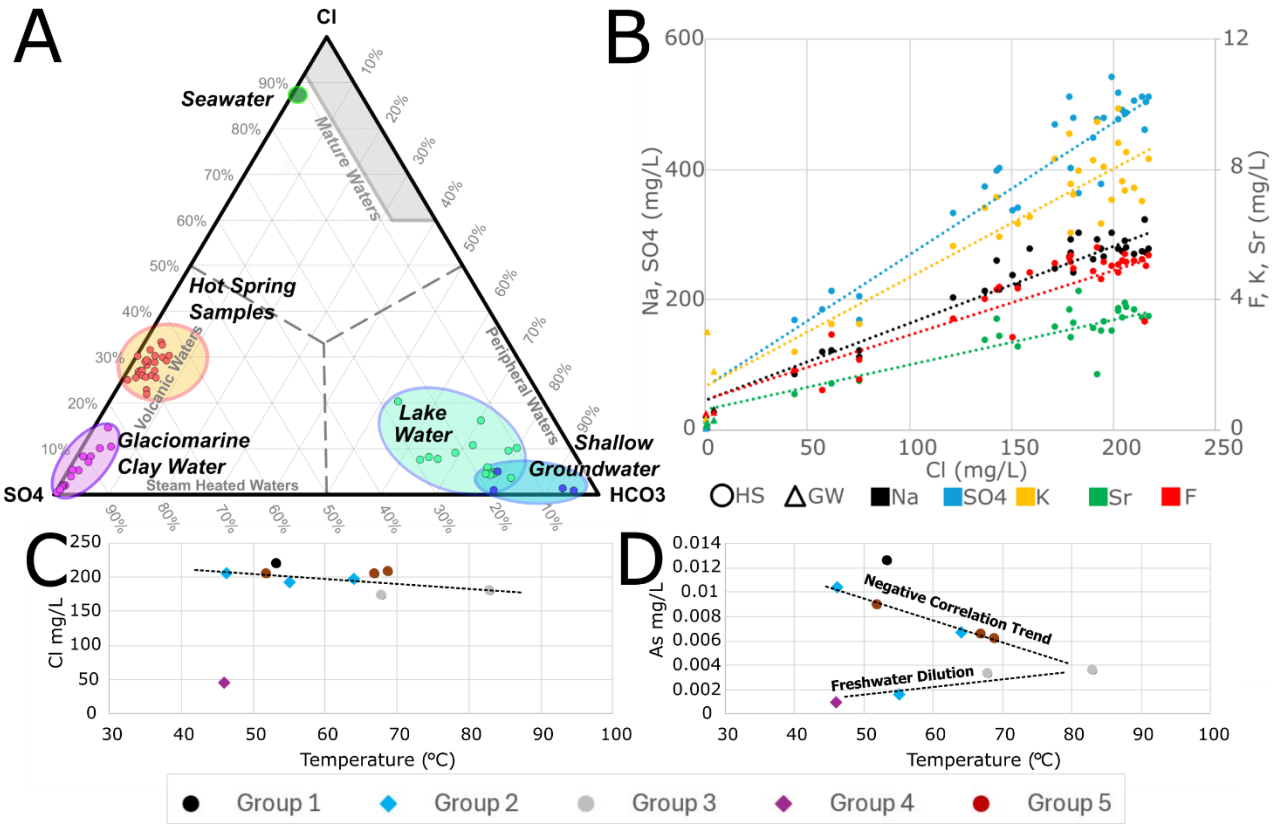


Figure 2. A) Tsch plot of the Lakelse Hot Springs (Souther and Halstead, 1973; Souther, 1976; NSBG Ltd. 1982; this study) and regional waters (Giggenbach, 1991; Cleugh et al., 1978; Geertsema and Torrance, 2005;). 2 anomalous hot spring samples from NSBG Ltd. (1982) are omitted. B) Major components of the hot spring and groundwater samples plotted against Cl. C) Hot spring Cl concentration plotted against temperature (negative correlation example). D) Hot spring As concentration plotted against temperature.

3.2 Gas Chemistry

Bubbling gases were only found in sufficient quantities for sampling at Groups 1, 2 and 3. Results of the gas analysis are presented in Table 1. The gases are dominantly N_2 but also contain >1% O_2 and Ar by volume and trace amounts of other gases. The presence of O_2 in the gas samples indicates that some degree of atmospheric contamination has taken place. Using the atmospheric composition from Lower (2024), the sampled gases were corrected for atmospheric contamination based on the amount of O_2 they contained (Table 1). The remaining gases are still mostly N_2. No detectable amounts of H_2S were found in the gas samples.

3.3 Water Isotopes

Water isotopes were analyzed for 10 hot spring samples, 2 groundwater samples, and 10 samples of meteoric water. Meteoric water samples were collected at elevations varying from 79 to 976 masl. All water isotopes are measured in δ-values in comparison to the Vienna Standard Mean Sea Ocean Water (VSMOW) in deviations of

parts per thousand (‰). Measurement error is 0.2‰ for $\delta^{18}O_{H2O}$ and 1.0‰ for δD_{H2O}. The hot springs have $\delta^{18}O_{H2O}$ values ranging from -15.7‰ to -17.2‰ and δD_{H2O} values ranging from -127‰ to -129‰, as plotted in Figure 3. Samples are compared to the Canadian Local Meteoric Water Line (LMWL) determined by Gibson et al. (2005). Both the rain and snow samples plot near the LMWL while the hot spring samples plot on and below the line.

Table 1. Composition of the non-condensable gases from 3 of the Lakelse Hot Springs, including concentrations corrected for atmospheric contamination, measured in % volume of dry gas.

Sample	CO_2 (%)	H_2S (%)	NH_3 (%)	Ar (%)	N_2 (%)	CH_4 (%)	H_2 (%)	O_2 (%)
G1	0.203	<0.0350	0.00229	0.904	97.3	0.0532	0.0540	1.53
$G1_{corrected}$	0.216	-	0.00247	0.901	98.8	0.0573	0.0582	0
G2	0.226	<0.0368	0.00277	1.40	97.9	0.0865	0.0561	0.282
$G2_{corrected}$	0.00281	-	0.00281	1.41	98.2	0.0877	0.0569	0
G3	0.507	<0.0372	0.00297	1.02	97.8	0.0882	0.0532	0.487
$G3_{corrected}$	0.519	-	0.00304	1.02	98.3	0.0903	0.0545	0

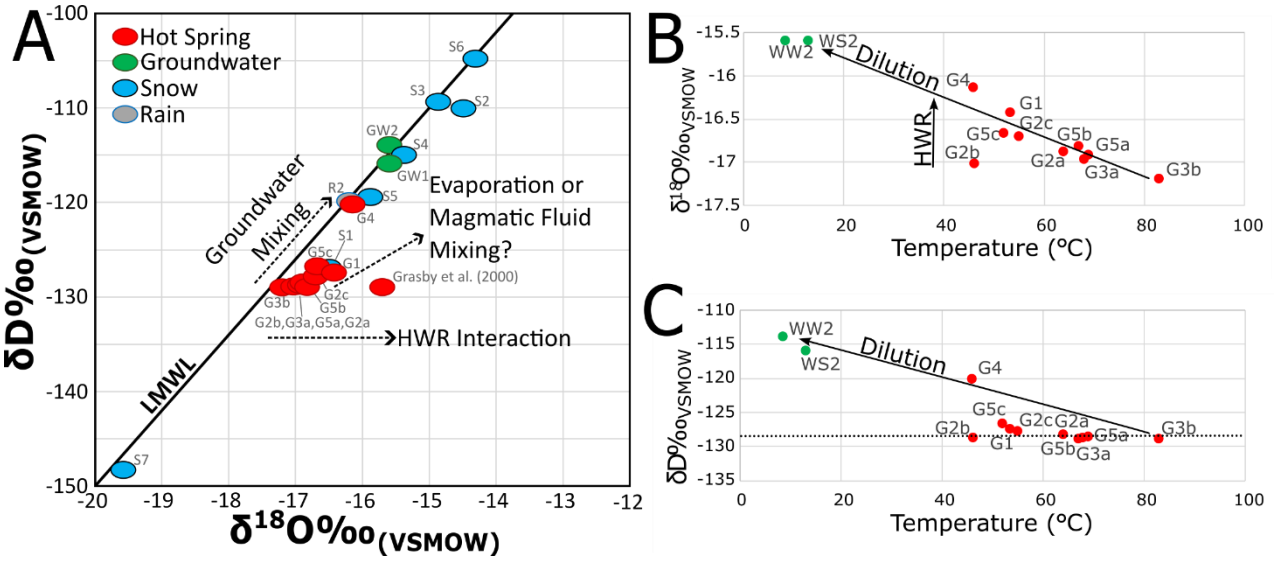


Figure 3. A) Stable water isotope plot of the Lakelse Hot Springs and regional water sources. Samples are scaled proportional to analytical error (±0.2‰ $\delta^{18}O$, ±1‰ δD). LMWL – Local Meteoric Water Line, HWR – Hot Water Rock. B) Plot of $\delta^{18}O$ vs. temperature. C) Plot of δD vs. temperature.

3.4 Noble Gas Isotopes

Noble gas isotope samples were collected from Groups 2 and 3. Analytical results are provided in Table 2. These samples show good sample purity, with a maximum error of 2.45%, and He concentrations in excess of that expected for air saturated waters. Sample G2 shows a negative excess air component, having less dissolved Ne than expected for water in equilibrium with the atmosphere. The isotopic concentrations of ^3He and ^4He were converted to R/Ra notation and corrected for atmospheric contamination using ^{20}Ne concentrations according to the methodology of Craig et al. (1978) (Table 2). The highest corrected R/Ra value is 1.55 in sample G2.

Table 2. Isotopic measurements of dissolved noble gases and R/Ra values for the Lakelse Hot Springs.

Sample	^4He (cc/cc)	^3He (cc/cc)	^{20}Ne (cc/cc)	R/Ra	$R/Ra_{corrected}$
G2	3.54E-06	7.59E-12	1.15E-07	1.55	1.55
G3a	1.63E-07	2.08E-13	3.95E-07	0.92	0.66
G3b	7.89E-06	1.42E-11	3.94E-07	1.30	1.31

4 Discussion

By analyzing the chemical and isotopic trends observed across the Lakelse Hot Springs, it is possible to infer several subsurface processes that take place in the M'deek system.

4.1 Chemistry and Temperature Variations

The strongly correlated ions identified in Section 3.1 with linear dilution-mixing trends with surficial groundwater samples (Figure 2b) are interpreted to be the major components of the geothermal endmember. These trends indicate that the Lakelse Hot Springs share a common geothermal source and all springs are variably diluted by shallow groundwater. This dilution is also expected to cool the hot spring fluids; however, plotting chemical composition of the springs vs. temperature illustrates that dilution with shallow groundwater is not the only control on spring temperature as some elemental concentrations such as Cl increase with decreasing temperature, opposite of what would be expected for dilution (Figure 2c). Plots of As vs. temperature also show two distinct compositional trends (Figure 2d). While the positively correlated As trend appears to result from dilution, as hot springs along this trend have been observed to mix directly with surface water, another process is needed to explain the negatively correlated trend. These other trends could be explained by longer subsurface travel times allowing for more conductive cooling and water-rock interaction. This process would allow for more interaction between hot spring fluids and clay alteration minerals, which may be reflected by the release of incompatible elements (increase of Cl, Li, and B in solution) in exchange for compatible elements (decrease of Cs and K) and conductive cooling (Reyes and Trompetter, 2012). In this scenario, the hotter springs reach the surface more quickly. This is compatible with the HWR interaction $\delta^{18}O_{H2O}$ trends shown in Figures 3a and b. Ultimately, differences in the amount of groundwater mixing and different subsurface velocities or pathways taken by the hot spring fluids as they travel to surface from a common upflow, may determine the composition and temperature of the Lakelse Hot Springs.

4.2 Geothermometry

The silica geothermometer and Na-K-Mg thermometer of Giggenbach (1988) were applied to the hot spring samples collected by KGI and past investigations to estimate maximum temperature reached by the M'deek system fluids. Since the silica geothermometer is affected by dilution (Fournier and Truesdell, 1974), a correction was applied by extrapolating the silica concentrations of hot springs samples to the concentration of an undiluted sample at the silica saturation line of Verma (2000) (Figure 4a). Only the May 2021 data is extrapolated to the silica saturation curve, to eliminate seasonal temperature variations. Quartz is assumed to be the phase that controls silica dissolution in the subsurface as the M'deek system is hosted in fractured granitic bedrock and the chalcedony and amorphous silica geothermometer estimates are at, or below, the temperatures of the hot springs. This results in an estimated undiluted silica concentration of 93 mg/kg and a maximum temperature of 131°C. This extrapolated trend intersects the y-axis at a silica concentration of 33 mg/kg, higher than expected for surficial water/shallow groundwater which should be closer to 0 mg/L.

Figure 4b plots the Lakelse Hot Spring samples on the ternary Na-K-Mg diagram of Giggenback (1988). The samples cluster within the 140–160°C temperature field of the partial equilibration zone, where diluted samples are expected to plot. A mixing trend with shallow groundwater can be inferred by extending this trend to the bottom right corner where groundwater samples plot. However, Powell and Cumming (2010) note that Na-K type geothermometers are not accurate for fluid temperatures below 150°C and the Na-K-Mg geothermometer was designed for higher temperature, magmatic systems with lower proportions of SO_4. As a result, a conservative estimate of the maximum fluid temperature is made by using the silica geothermometer and the low end of the Na-K-Mg geothermometer, resulting in an estimated temperature of 130–140°C.

4.3 Meteoric Fluid Source

The proximity of the Lakelse Hot Springs to the meteoric water line indicates that they are sourced from deeply circulated meteoric waters, like most other hot springs. Deviations below the LMWL can be explained by positive $\delta^{18}O_{H2O}$ shifts caused by hot water-rock (HWR) interaction. δD values of the hot spring waters are similar to those of rain and snow samples from elevations of 800-1,000 m elevation, suggesting that the M'deek system is recharged from precipitation at these elevations. This is consistent with the average heights of the Coast and Hazelton Mountains. A meteoric origin is also supported by the corrected composition of the gases emitting from the hot springs. As these gases are mostly N_2, it is possible these gases originated from the atmosphere but their original O_2 component was removed through redox reactions during transport in the reducing subsurface environment, with O_2 only being reintroduced near the surface. Trace gases including CO_2, NH_3, CH_4, and H_2 are found in much higher concentrations than atmospheric amounts and must be sourced from the subsurface.

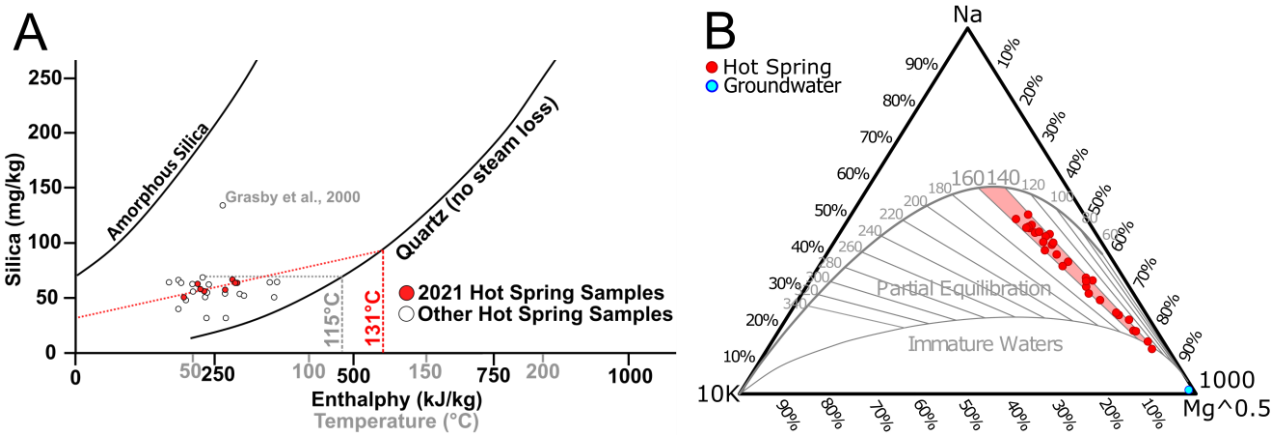


Figure 4. A) Silica-enthalpy diagram with saturation curves from Verma (2000). The temperature of liquid water at the corresponding enthalpy is plotted along the x-axis. Extrapolation of the June 2021 hot spring samples (red) estimates a maximum fluid temperature of 131°C. Samples from other studies are shown in white (Odynsky, 1951; NSBG, 1982; Grasby et al., 2000). B) Ternary Na-K-Mg geothermometry plot from Giggenbach (1988) including hot spring samples from this study and literature. Samples plot between the 140°C and 160°C isotherms and show a mixing trend with shallow groundwater.

4.4 Lack of Boiling

Subsurface boiling could also alter both the chemical and isotopic composition of hot spring fluids, but given the relatively low geothermometry estimate from the hot spring fluids (130-140°C), subsurface boiling is unlikely. If the springs consisted of condensed steam, the concentrations of Cl, which is preferentially incorporated into the liquid phase during boiling, would be much lower. Additionally, no samples have isotopic compositions above the LMWL, as would be expected for condensed steam. Alternatively, fluids consisting of residual brine from the boiling process, or sourced from magmatic fluids, would plot below the LMWL, as seen in the hot spring samples; however, these water isotope trends could be explained by HWR interaction (positive $\delta^{18}O_{H2O}$ shift, i.e., G2a, G2b, G3a, G5a, G5b), and dilution with freshwater (i.e., G4, G5c, and G2c) or surficial evaporation (i.e., G1) without invoking boiling or magmatic processes (Figure 3a). For HWR interaction to occur, fluids must have been in contact with rocks at the temperatures estimated from geothermometry for some time.

4.5 Source of SO_4

While SO_4 isotopic analysis was not conducted as part of this study, Grasby et al. (2000) reports a $\delta^{34}S_{SO4}$ value of 8.5‰ and a $\delta^{18}O_{SO4}$ value of 2.4‰ for the Group 1 spring. While the reported $\delta^{34}S_{SO4}$ value in the hot spring is compatible with both volcanic (-16 to 18‰) and sulphide mineral sources (typically -10 to 10‰; Thode, 1991), the $\delta^{18}O_{SO4}$ value is most consistent with a sulphide mineral source (-10 to 4‰). Magmatic fluids typically have $\delta^{18}O_{SO4}$ values of 10-13‰ (Marimon et al., 2007 and references within). Sea water has a higher $\delta^{34}S_{SO4}$ of ~21‰ (Rees et al., 1978), indicating that residual pore fluid from the glacial marine clay is not the main source of SO_4.

4.6 Possible Magmatic Connection

Although SO_4 does not appear to be magmatically sourced, He isotopes hint at a possible magmatic connection. While the majority of the excess He in these samples consists of crustal ^{4}He, some samples have corrected R/Ra values >1, which indicates that excess ^{3}He is present and a connection to a source of mantle-derived volatiles exists for the Lakelse Hot Springs. Sample G3a contains a low volume of dissolved He (only 3–4x that of air saturated water) and has a R/Ra value of <1, suggesting that it consists of a mixture of air saturated water and crustal ^{4}He. Both G3a and G3b were sampled from the same spring at different times and have very different He isotope compositions, likely due to varying amounts of contamination with surficial waters during sampling.

While the R/Ra values measured at the Lakelse Hot Springs indicate a connection to a source of mantle derived volatiles, they are too low to definitively indicate a connection to a nearby magmatic source. R/Ra values of 5.2–7.0 would provide more definitive evidence as these values are typical of subcontinental lithospheric mantle derived volcanic gases (Lee at al., 2019; Gautheron and Moreira, 2002). With regards to gas composition, gases sampled from the hot springs appear to mostly consist of O_2-depleted atmospheric gases, and non-atmospheric trace gases could reasonably be provided by microbial sources rather than a magmatic source (Schoell, 1988; Edwards et al., 2024; Etiope et al., 2024). Even if trace gases are magmatically sourced, their low abundance

suggests they would only represent a small fraction of the fluid input into the system. As discussed in Section 4.4 above, there is no need to invoke magmatic mixing in the interpretation of water isotopic trends either.

While magmatism could supply the ^{3}He needed to generate the R/Ra values observed at the Lakelse Hot Springs, there are other potential origins for the mantle volatiles. Large scale strike-slip faults are known to act as conduits for mantle related fluids to travel to the surface. Fluids from these systems have R/Ra values of <1 to 5.7, with higher R/Ra values proposed to correspond to deeper, more permeable conduits with shorter residence times and less crustal ^{4}He enrichment (Kennedy et al., 1997, Lee et al., 2019). These faults must either extend to the depth of the Moho to directly access mantle fluids/volatiles or tap into large sub-horizontal decollements which could act as reservoirs for mantle derived fluids (Kennedy et al., 1997). Both of these scenarios are plausible at the M'deek system. The KKM fault is a dextral-normal strike-slip fault that stretches over 100 km in length and the presence of the Tseax cone at its northern terminus indicates that it can serve as a conduit for mantle derived material. Alternatively, the KKM could tap into the Shames River mylonite zone, a low angle detachment surface that accommodated an estimated 25 km of normal movement from the Jurassic to the Paleocene (Heah, 1991), which could be acting as an intermediate reservoir for mantle derived ^{3}He gases.

5 Conceptual Model

Following this detailed analysis of the Lakelse Hot Springs, a more descriptive model of the M'deek Geothermal System can be constructed. The M'deek system is a fracture-controlled, liquid-dominated, convective geothermal system hosted in a transtensional graben structure. The M'deek system contains Na-Cl-SO_4-type waters that mix with shallow groundwater near the surface where they emerge as the Lakelse Hot Springs.

A combination of the silica and Na-K-Mg geothermometers allow for an estimation of fluid equilibration temperatures of 130–140°C for the M'deek system, classifying it as a low-temperature (<180°C) system (Sanyal, 2005). Assuming a geothermal gradient of 40°C and an average annual surface temperature of 6°C, a circulation depth of 3.1-3.4 km is proposed. Recharge fluids for the M'deek system consist of meteoric fluids that precipitate onto the surrounding mountains at an average elevation of ~800–1,000 masl. These supergene fluids entrain atmospheric gases and percolate downward along fractures to depth. Along this pathway, the fluids absorb heat from and react with surrounding granitic rocks and sulphide minerals, reducing the O_2 content of dissolved gases and introducing sulphate. The fluids must remain at the maximum estimated temperatures long enough for them to reach chemical equilibrium and undergo exchange of ^{16}O and ^{18}O at the low end of the HWR interaction temperature range, implying a long pathway or slow subsurface flow rates. Circulating waters mix with mantle derived hypogene fluids/volatiles at depth. These fluids/volatiles may originate directly from the mantle, from a magmatic intrusion, or from an intermediate reservoir of mantle fluids deep in the crust.

The geothermal fluids quickly travel upward after reaching permeable conduits associated with the KKM fault, likely at its intersection with the ACF (Alonso Torres et al., 2020). Fluids exit the fault and enter into the overburden that lines the KKV. These hot fluids then buoyantly travel upwards along the base of the impermeable glaciomarine clay until a pathway is found to the surface in the upper valley fill material, taking up little, if any, SO_4 from the glacial sediments in the valley. Variable flow pathways and subsurface residence times lead to differences in temperature and compositions of the spring fluids. As these fluids reach the surface, they mix with variable amounts of surficial waters depending on the vent location and seasonal precipitation trends.

6 Conclusion

Through a comprehensive geochemical investigation of the Lakelse Hot Springs, a better understanding of the M'deek Geothermal System was obtained. The system is expected to have a fluid equilibration temperature between 130–140°C and a calculated circulation depth of around 3.1-3.4 km. The Lakelse Hot Springs do not boil on their way towards the surface and do not incorporate condensed volcanic gases, despite their high SO_4 content. R/Ra ratios indicate that mantle derived volatiles are a component of the system, but clear magmatic signatures are not observed in isotope or gas chemistry data. While a connection to a magmatic intrusion is not ruled out, mantle volatiles could also be transported from depth by regional-scale permeable faults with a connection to the mantle or an intermediate reservoir of hypogene fluids. The evidence presented here favours a model by which the M'deek system is primarily heated through deep circulation and convection, rather than magmatism, but mantle derived-volatiles may also contribute heat to the system. Different amounts of water-rock interaction and conductive cooling have been proposed to explain the compositional and temperature variations observed across the Lakelse Hot Springs vents. While this model fits the collected data well, more work needs to be done to conclusively determine the cause of these variations. Collection of an undiluted sample of upwelling fluids from the subsurface could test many of the interpretations put forward in this study.

Based on the conceptual model of the M'deek system, future exploration efforts should focus on areas of fault intersections with the KKM fault, but a shallow hot aquifer may also exist within the sediments that line the valley.

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