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Geochemical analysis of thermal fluids from southern Mount Meager, British Columbia, Canada

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ABSTRACT

Thermal fluids from springs and wells in the southern Mount Meager geothermal field were analyzed to understand the fluid origin, assess controls on chemistry from effects of mixing and water-rock interaction, and determine the reservoir temperature and composition. Chloride and boron concentrations range from 100 to 3300 ppm and 0.3 to 28 ppm, respectively. These very high conservative element concentrations cannot alone be explained by rock dissolution and are instead likely supplied by a single magmatic source. Calculated reservoir compositions suggest that select deep wells have experienced significant CO_2 degassing from reservoir to the surface, and high SO_4 content present from surface samples is traced down to the reservoir. These data corroborate the hypothesis that a magmatic component exists and contributes to B, Cl, CO_2 and SO_4 fluid composition, although CO_2 and SO_4 may have alternate sources. Select geothermometers calculated reservoir temperatures of up to 283 °C for central deep wells. Like many high-temperature geothermal systems, the compositions of thermal fluids appear to be controlled by the equilibrium between the fluid and observed secondary minerals. Hot springs and wells on the eastern and northern sides of the reservoir are of low temperature and likely define the boundaries of peripheral waters. Wells to the southeast contain anomalously high Cl and SO_4, suggesting a possible magmatic input of these components which may be controlled by the east-west running Meager Creek Fault Zone. There is a significant source of hot, Cl- and CO_2-rich thermal waters supplying deep wells MC-1, MC-2, MC-6 and MC-8, and possibly MC-3. These NaCl waters likely define the high temperature, central location of the geothermal reservoir.

1. INTRODUCTION

Geochemical composition of thermal fluids may be used to understand fluid origin, mixing between two or more fluid sources, and degree of water-rock interaction, and to estimate reservoir temperature and composition. As such, geothermal geochemistry is one of the key tools applied in geothermal exploration (Arnórsson & D'Amore, 2000). Conservative elements such as boron and chloride have been used to trace water sources and degree of mixing of two or more water types, and to assess water-rock interaction (Arnórsson & Andrésdóttir, 1995). In meteoric source water, their concentrations are usually low and, upon water-rock interaction and mixing with, for example, seawater, the elemental concentrations and relative ratios change. These changes can, in turn, be used to quantify the various sources of the two elements.

Studies of alteration mineralogy and fluid composition in geothermal systems show that equilibrium is closely approached between the geothermal fluids and secondary minerals formed in the systems except for mobile elements such as chloride and boron (e.g., Giggenbach 1981, 1988; Arnórsson et al., 1983a; Pang & Reed 1998; Stefánsson & Arnórsson, 2000). Such mineral-fluid equilibria provide the basis for application of calculating reservoir temperatures using solute and gas geothermometry. Solute geothermometers include quartz (Arnórsson et al., 1983a; Fournier, 1977; Fournier & Potter; 1982), chalcedony (Arnórsson et al., 1983b; Fournier, 1977), and cations such as Na-K (Arnórsson et al., 1983b; Fournier, 1979a; Giggenbach, 1988; Tonani, 1980; Truesdel, 1976), K-Mg (Giggenbach, 1988), Na-K-Ca (Fournier & Truesdel, 1973), Na-K-Ca Mg (Fournier & Potter, 1979) and Na-Li (Fouillac & Micard, 1981).

Numerous studies have been carried out for thermal fluids and alteration minerals in the Mount Meager geothermal field as part of earlier exploration programs, including chemical analyses of the hot springs and/or well fluids (Hammerstrom & Brown, 1977; Adams et al., 1985; Ghomshei et al., 1986; Adams & Moore, 1987; Ghomshei & Clark, 1993; Grasby et al., 2000), chemical analyses of reservoir rocks and drill core to reconstruct the hydrothermal events in the system (Moore et al., 1983; 1985; Adams & Moore, 1987), and stable and radioactive isotope data studies (Clark et al., 1982; Ghomshei & Clark, 1993; Phillips, 1994; Clark & Phillips, 2000). Despite the number of publications on thermal fluid geochemistry in the area, there is still uncertainty about the temperature and characteristics of the geothermal reservoir. This study aims to use existing data to classify the origin of the geothermal waters, to understand the controls on water chemistry and the effects of mixing and water-rock interaction, and to calculate the reservoir temperatures and compositions of the southern Mount Meager geothermal reservoir. Reservoir fluid temperatures and compositions were estimated using geothermometry and geochemical modeling, respectively. In addition, conservative elemental relations were used to assess the source and mixing of fluids. Together, these results help to construct an overall model of the geothermal system to support future geothermal development at Mount Meager.

Research has continued since the writing of this paper. In the summer of 2019, field work was conducted at Mount Meager as part of the Garibaldi Geothermal Volcanic Assessment Project, funded by Natural Resources Canada and Geoscience BC. The goals were to continue resource mapping and to reduce exploration risk; this was done by assessing controls on rock permeability, utilizing remote sensing, magnetolleluric and gravity surveys, passive seismic, and field mapping (Grasby et al., 2019).

2. GEOLOGICAL SETTING

The Pleistocene to Recent Mount Meager Volcanic Complex (MMVC) lays 150km north of Vancouver, British Columbia, Canada and is transected by two volcanic and plutonic belts (Read, 1977; Lewis & Souther, 1978). The MMVC is dominantly calc-alkaline and is made up of assemblages composed of andesite and dacite flows, basaltic lava flows and pyroclastic deposits, dacite domes and flows, and pyroclastic units, all which lie unconformably on a basement of plutonic (granitic to quartz diorite) and metamorphic rocks (Stasiuk & Russell, 1989; Read, 1977) These units are shown on the geological map in Figure 1. The assemblages are products of around 2.2 My of intermittent volcanic activity (Read, 1977; 1990). The initial eruption was explosive and gas-rich, which fractured the basement; it has been postulated that this caused the basement to seal itself, creating a geothermal reservoir (Lewis & Souther, 1978).

Large volumes of fluid loss during shallow well drilling indicate high permeability in the basement rock; as such, geothermal waters are thought to originate from the quartz diorite basement and occupy permeable fractures and faults (NSBG, 1980). However, permeability in the upper portions of the reservoir is low, limiting fluid flow above the basement rock (Moore et al., 1985). Petrographic, mineralogical, and trace element studies by Adams and Moore (1987) have established that upward movement of geothermal fluids in the reservoir is focused by fault and fracture zones, steeply dipping dikes, and hydrothermal breccias related to recent volcanic activity. Many wells have been drilled in the southern reservoir since the 1970s. This research focused on several wells and springs which have the fluid chemical and temperature data required for analysis; this includes deep wells MC-1, MC-2, MC-3, MC-3, MC-5, MC-6, MC7, and MC-8, diamond wells M1, M2, M7and M12, and several hot, cold, and warm springs. The locations are shown on Figure 1.

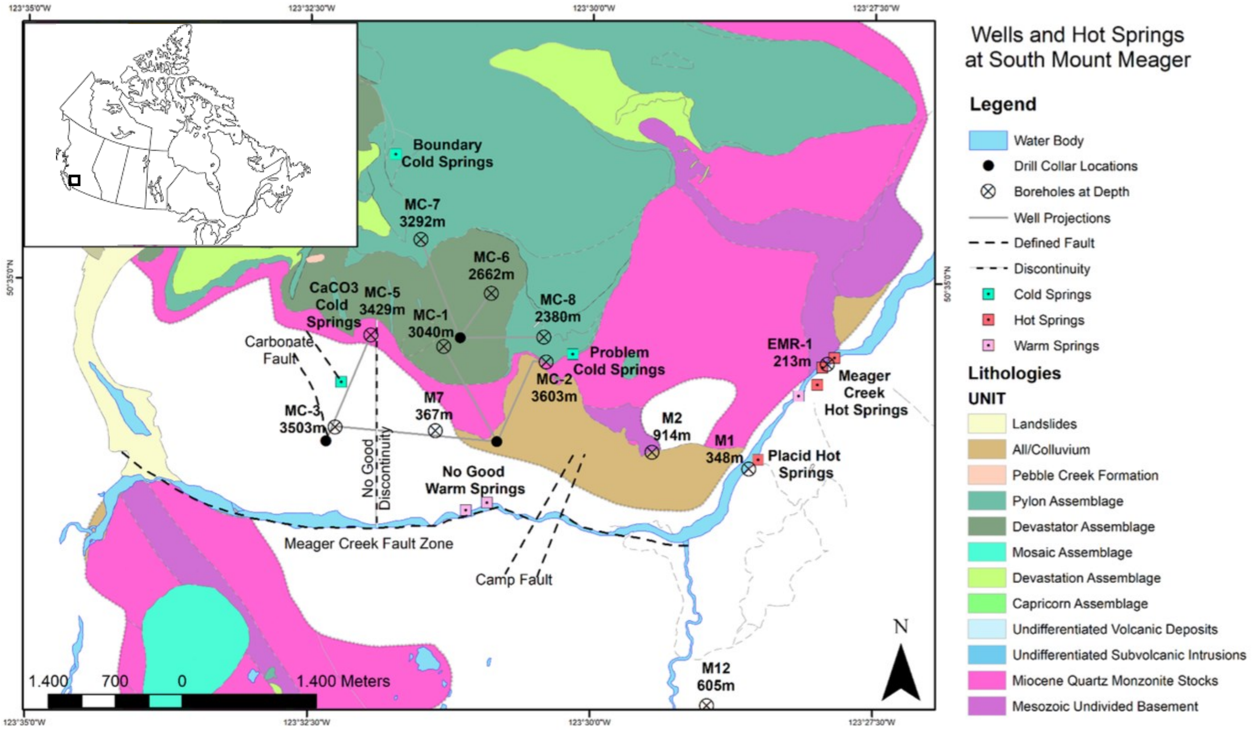

Figure 1: Geological map showing the volcanic assemblages of the southern region of the MMVC. Hot, warm, and cold springs along with several wells are mapped (adapted from Proenza, 2012; GeothermEx, 2005).

3. DATA HANDLING

3.1 Estimation of fluid origin and mixing using conservative element behavior

The sources of B and Cl in geothermal waters are considered to be the source water including seawater and meteoric water, rock leaching, and magma degassing. These elements originate from sea spray and precipitation, directly from seawater that filters through the groundwater systems. The boron and chloride composition of seawater is well established and meteoric water (precipitation) closely follows the B/Cl seawater ratio (Arnórsson & Andrésdóttir, 1995). Upon water-rock interaction (water dissolving the rock), the water becomes more enriched in B relative to Cl and the reaction will continue until the Cl/B ratio reaches that of the rock. These elements are therefore able to trace water source(s) and assess the effects of progressive water-rock interaction and mixing ratios between different water sources. B and Cl data on chemical composition of local precipitation and rocks at Mount Meager are not available; instead, the most common rock unit, quartz diorite, was taken as a proxy for the host rock of the thermal fluids, as well as average basalt for comparison. Average composition of precipitation in Canada was used.

3.2 Reservoir fluid composition and temperature

The WATCH speciation program of Arnórsson et al. (1982), version 2.4 (Bjarnason, 2010), was used to calculate the component concentrations in the reservoir fluid for the present study. For these calculations, the chemical compositions of samples from non-thermal and sub-boiling wells were taken to represent the compositions of the waters in the producing reservoir. On the other hand, water samples collected from the two-phase wells (vapour and liquid) and boiling hot springs are not representative of the parent reservoir water, since boiling and degassing have modified the chemical composition from the reservoir to surface. The WATCH program uses data on water and steam samples collected at the surface to calculate the reservoir fluid composition. In the case of unavailable steam data, steam loss and gas (CO_2 and H_2S) partitioning can be estimated assuming the reservoir and sample collection temperatures to be known. For these calculations, boiling was taken to be adiabatic (isolated thermodynamic system) and no steam was assumed to be present in the reservoir beyond the zone of depressurization boiling.

At temperatures around 150-250 °C, the solubility of quartz controls the concentration of dissolved silica, and equilibrium between water and quartz is closely approached at around 180°C (Fournier & Rowe, 1977). At lower temperatures, chalcedony appears to control dissolved silica concentration, while equilibrium is closely approached between water and chalcedony at about 100 °C (Fournier, 1977). Therefore, the quartz geothermometer and chalcedony geothermometer were taken as reservoir temperature if the quartz geothermometer yielded temperatures above 180 °C and between 100 to 180 °C, respectively. This changeover temperature has been found to be valid for most active geothermal systems associated with geologically young volcanic rocks (Stefánsson & Arnórsson, 2000). For samples with measured temperature of less than 100°C, the measured temperature was used as reservoir temperature. In addition to the silica geothermometry, other cation geothermometers based on Na, K, Ca, and Mg were used to estimate the reservoir temperatures.

3.3 Aqueous speciation and mineral saturation

Past studies have suggested that the composition of geothermal waters is controlled by equilibrium between minerals and solution for major components of the system except mobile elements like chloride (Ellis, 1970; Michard, 1991; Arnórsson & Andrésdóttir, 1995). For example, equilibrium is closely approached between water and microcline and low-albite for temperatures above 200 °C (Browne, 1978; Stefánsson & Arnórsson, 2000). It has been suggested that this equilibrium, based on the reaction low-albite + K^+ = microcline + Na^+, controls the Na^+/K^+ activity ratio in high temperature waters (Giggenbach, 1981; Arnórsson et al., 1983a). The select cations are based on alteration minerals observed in the system, including epidote (as clinozoesite), calcite, chlorite (as clinochlorite), K-feldspar, and quartz together with wollastonite, garnet (grossular) and prehnite that have not been unambiguously reported within the geothermal system. As Fe and Al concentrations were rarely reported in the dataset of the fluid samples, mineral buffer reactions were constructed to study mineral-fluid equilibria together with some single mineral- solute reactions. The following chemical reactions were considered:

$$\text{A. wo} + 2H^+ + H_2O = Ca^{2+} + H_4SiO_4$$

$$\text{B. } 0.6\text{gro} + 2H^+ = 0.4\text{czo} + 0.6\text{qtz} + 0.8H_2O + Ca^{2+}$$

$$\text{C. } 1.5\text{pre} + 2H^+ = \text{czo} + 1.5\text{qtz} + 4H_2O + Ca^{2+}$$

$$\text{D. K-feld} + Na^+ = \text{alb} + K^+$$

$$\text{E. } 0.8\text{mus} + 0.2\text{chl} + 5.4\text{qtz} + 2K^+ = 2.8\text{K-feld} + 1.6H_2O + Mg^{2+}$$

$$\text{F. cc} = Ca^{2+} + CO_3^{2-}$$

where wo = wollastonite, gro = grossular, czo = clinozoesite, qtz = quartz, pre = prehnite, K-feld = K-feldspar, alb = albite, mus = muscovite, chl = clinochlore and cc = calcite.

PHREEQC (Parkhurst and Appelo, 2013) was used to calculate each cation activity, which in turn were used to calculate (⍰⍰⍰Q) for each reaction. Finally, the solubility (⍰⍰⍰⍰) was calculated for each respective reaction to assess how closely each mineral approached equilibrium.

4. RESULTS AND DISCUSSION

4.1 Fluid origin and mixing

The relationships between B and Cl concentration, and the Cl/B molal ratio with chloride concentration are shown in Figure 2: The relationship between (A) B and Cl and (B) Cl/B molal ratio and Cl for the thermal waters. Precipitation content is plotted along with average compositions of andesite and basalt. Progressive rock leaching (ξ) from 0.01 to 1 is also graphed. Chloride and B concentrations ranged from 100 to 3300 ppm and 0.3 to 28 ppm, respectively. Hot spring waters contained the lowest Cl and B content (100-675 ppm and 1-3.3 ppm), followed by deep well waters MC-3 and MC-6, MC-1 and MC-2, MC-8 (250-3030 ppm and 1.6-20.7 ppm), and finally shallow wells with the highest concentrations (2640-3300 ppm, 22-28.2 ppm). The latter were possibly anomalously high due to sampling error. Non-thermal springs do not include B data but contain the lowest Cl content (0.3-1.2 ppm).

In all cases, a positive linear relationship between Cl and B concentration was observed, and most samples had similar Cl/B molal ratios, mostly grouping from 30-55. The Cl and B concentrations of the waters were far too high, and Cl/B ratios far too low, to consider seawater or meteoric water (precipitation) as the dominant source of Cl and B. In contrast, the Cl and B systematics suggest the water to be of meteoric origin with Cl and B concentrations similar to what can be expected in the region, followed by leaching of Cl and B from the primary rocks and minerals. Given the geological complexity of the area, it is unlikely that all the reservoir fluids have encountered the same host rock composition and mineralogy in all cases, and the waters reflected more closely the Cl/B ratio of basalts rather than andesite. The reason for this is unclear. Also, the Cl and B content reflects high rock to water ratio (ξ) corresponding to >1 kg of rock dissolved per liter of water. Such high values may suggest an additional source of Cl and B than only dissolution of primary rocks, for example direct magmatic degassing (e.g., White, 1970; Bégué et al., 2015). Given the linear Cl and B systematics, a magmatic gas source of similar origin would be more likely rather than multiple magmatic sources. Characterizing and quantifying the magmatic component using only these relations is difficult if not impossible due to similar chemical signals as upon rock leaching (Bégué et al., 2015). However, the generally elevated Cl and B concentrations of Mount Meager thermal waters may be indicative of magma degassing associated with slab subduction (Symonds, 1992; Sanchez, 1993; Arnórsson, 2000; Bégué et al., 2015. Guðmundsson, 2015; McCaig et al., 2018; Wang & Xiao, 2018).

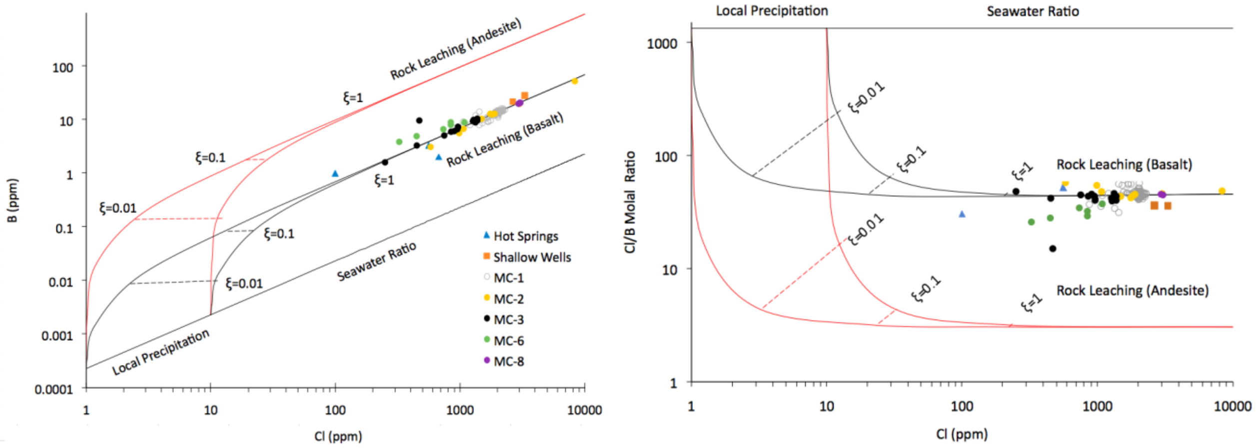

Figure 2: The relationship between (A) B and Cl and (B) Cl/B molal ratio and Cl for the thermal waters. Precipitation content is plotted along with average compositions of andesite and basalt. Progressive rock leaching (ξ) from 0.01 to 1 is also graphed.

4.2 Reservoir temperature and fluid composition

Geothermometry results are plotted in **Error! Reference source not found.**. For all temperatures, the chalcedony geothermometer yielded results that closely followed those of quartz, calculating slightly lower temperatures. The K-Ca geothermometer calculated the lowest temperatures, followed by K-Mg, Na-K, and finally Na-K-Ca geothermometer yielding the highest temperatures. The Na-K and K-Ca geothermometry data are likely scattered at T_{quartz} <100-150 °C because ratio chemical geothermometers are limited by equilibrium which may not be attained in low temperature and non-thermal waters. Fluid mixing may also contribute to the observed trends.

After selecting the appropriate geothermometer for each sample, the reservoir temperatures ranged from 4.5 to 9.0 °C, 29.5 to 56.0 °C, 10.1 to 68.5 °C, and 101.6 to 282.8 °C for cold springs, hot springs, shallow wells, and deep wells, respectively.

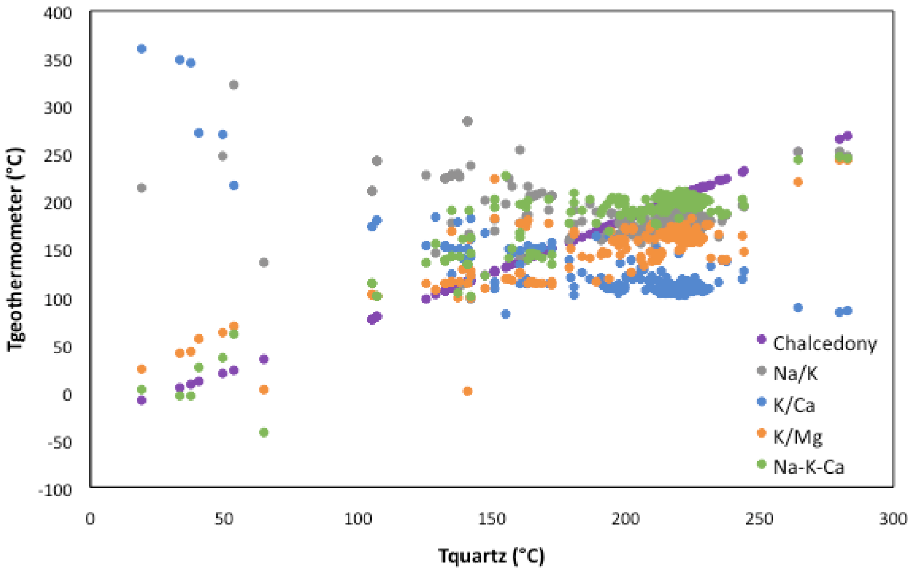

Figure 3: Comparison of different geothermometers.

The concentration ranges of these samples are given in Table 1. To assess the how boiling affects water composition from the reservoir to surface, fluid composition was compared between the boiling hot springs (degassing) model and the sampled compositions. Samples from MC-6 and MC-1 have experienced moderate to significant CO_2 degassing between 100-190 °C. Some waters from MC-1 and MC-2 were sampled with high SO_4 content, which, along with CO_2 content, did not change significantly when degassing was considered. This indicates that the surface waters represent reservoir waters in terms of CO_2 and SO_4, suggesting that a source such as magma may contribute to the high gas content in these waters. Non-boiled waters from M1-74D and M12-80D were even higher in SO_4 content.

Table 1: Range of concentrations for reservoir compositions of samples that degassed.

	MC-1	MC-2	MC-3	MC-6	MC-8
B	6.3 – 13.2	2.7 – 49.6	1.4 – 8.5	3.6 – 8.1	14.7 – 15.8
SiO_2	86.7 – 342.6	124.1 – 367.9	211.3 – 361.4	97.9 – 192.3	408.0 – 462.1
Na	615.8 – 1238.8	347.9 – 5010.4	255.3 – 982.8	724.4 – 1201.6	1267.0 – 1316.8
K	47.8 – 107.1	24.4 – 429.5	23.8 – 68.7	40.9 – 91.4	200.3 – 212.4
Mg	0.2 – 96.7	0.5 – 13.6	0.7 – 2.5	0.2 – 5.7	0.02 – 0.2
Ca	2.8 – 408.6	29.1 – 725.3	10.3– 96.4	48.8 – 62.6	33.8 – 47.7
F	0.1 – 2.6	0.7 – 6.9	0.6 – 2.1	–	1.7
Cl	823.0 – 1898.7	504.5 – 7921.2	220.1 – 1206.4	302.2 – 686.9	2164.0 – 2306.2
CO_2	282.7 – 43692.5	243.2 – 11277.4	170.8 – 3240.7	5110.0 – 23789.7	3582.4 – 6279.0
SO_4	71.4 – 946.8	117.4 – 1336.1	283.0 – 473.8	356.0 – 421.3	65.9 – 71.0

4.3 Fluid-mineral interaction

The reaction quotients (⍰) based on the aqueous speciation calculations are compared with solubility curves (⍰⍰⍰⍰) for the reactions as a function of reservoir temperature in Figure 4. These data suggest that activities of H_2SO_4 and Ca^{2+}, Ca^{2+}, and Mg^{2+} and K^+ are likely controlled by equilibrium between the solution and secondary minerals observed in the geothermal systems. The slight discrepancies observed in Figure 4 may be attributed to several factors in calculation. Regardless, the cation activities overall indicate that equilibrium is observed between secondary minerals and solution at high temperatures, and that there is likely mixing of colder waters with the thermal fluids. The observed trends are in accordance with other geothermal waters globally, especially the close approach between calcite and solution (i.e. Giggenbach, 1981; Arnórsson et al., 1983a, Stefánsson & Arnórsson, 2000; Arnórsson, 1978; Arnórsson, 1989).

5. DISTRIBUTION OF GEOTHERMAL ACTIVITY

The distribution of key parameter Cl, SO_4, CO_2, and temperature may indicate hydrogeological and geochemical controls on the system. The mean values of each parameter were used to create the distribution maps in Figure 5. Highest temperatures are found at deep well MC-8 and extend to MC-1 and MC-2. There is also a temperature anomaly at MC-3. Cl distribution is high around the temperature peak at MC-8, MC-1, and MC-2. Cl also increases around shallow well M1, and further increases towards the south at

M12. This southerly-trending anomaly is correlated with the elevated SO_4 concentration of the waters. There is also a slight SO_4 content elevation around MC-6.

The overall data suggest a significant source of hot, Cl- and CO_2-rich thermal waters around deep wells MC-1, MC-2, MC-6, and MC-8, and possibly MC-3, although more data is required to confirm the latter. The Carbonate Fault or the No Good Discontinuity to the east of MC-3 may be controlling cold water supply to the $CaCO_3$ Cold Spring and to M7. The east-west running Meager Creek Fault Zone may structurally control the Cl- and SO_4-rich waters presenting at M1 and M12 to the south, with the source of Cl and SO_4 possibly related to rock composition or deep magma degassing. The latter is, however, not correlated with elevated CO_2 concentration as would be expected.

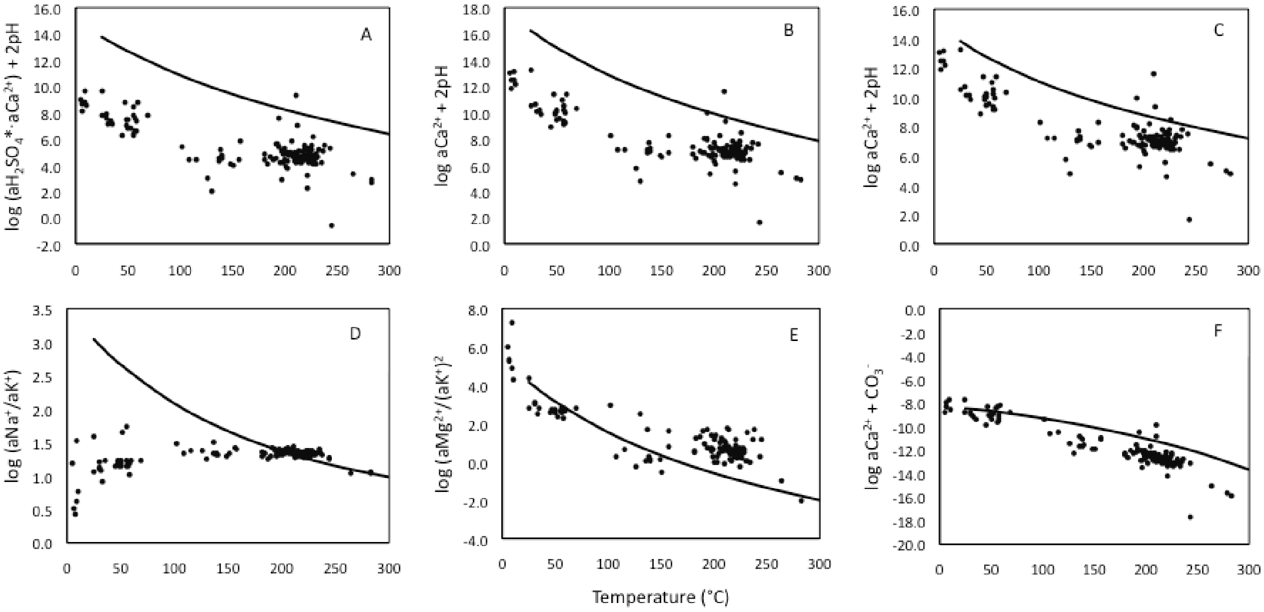

Figure 4: Activities of major cations as a function of temperature. The solid line shows *logK* for each reaction.

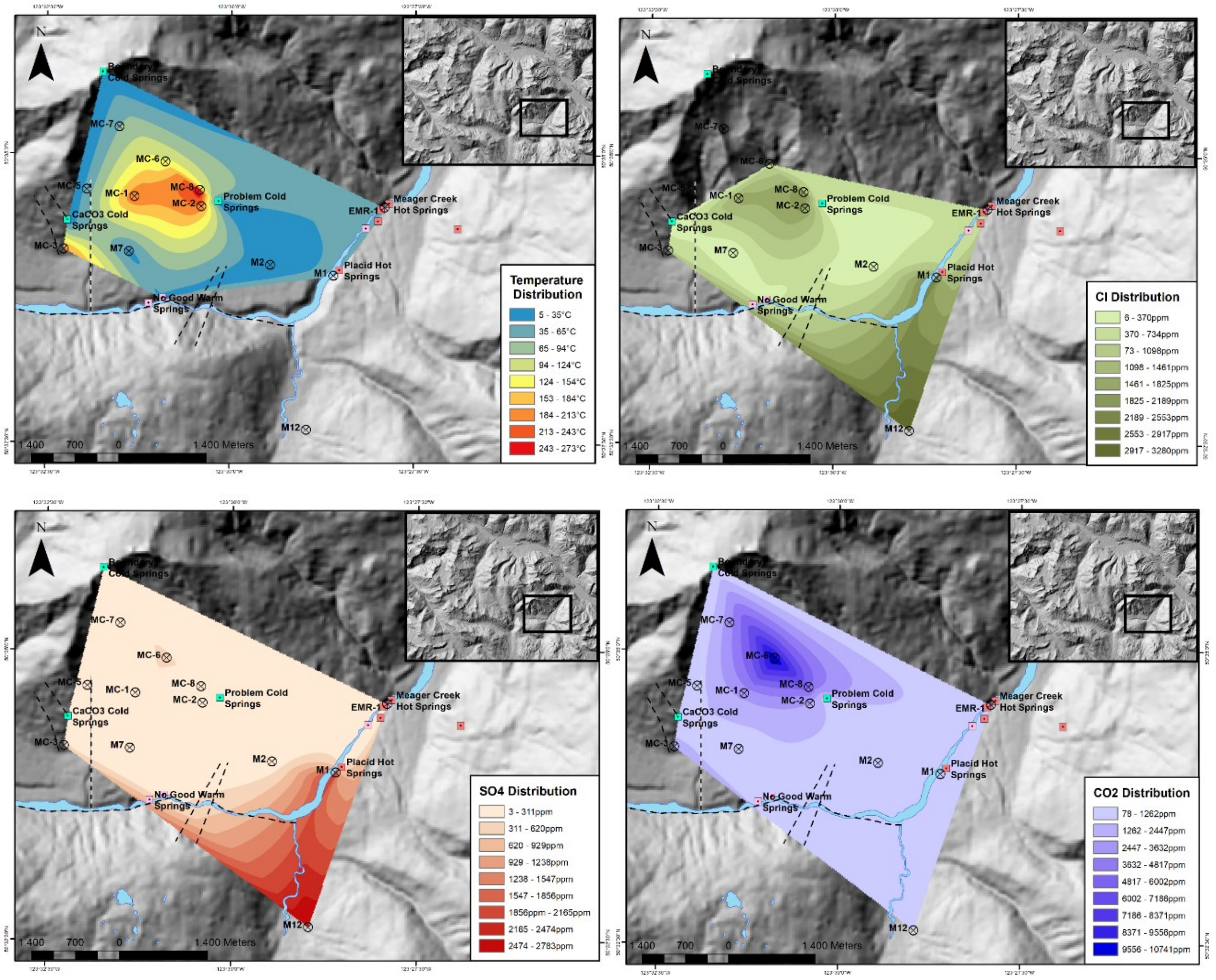

Figure 5: Distribution of reservoir Cl, SO_4, CO_2, and temperature.

6. CONCLUSION

For this study, geochemistry of thermal fluids from the southern reservoir at Mount Meager was analyzed to delineate fluid origin, reservoir temperature and composition, degree of mixing and boiling, and saturation state of the waters.

Conservative element analysis used chloride and boron content of the waters to understand degree of water-rock interaction and mixing and to identify the sources for the fluids. High Cl and B concentrations of 100 to 3300 ppm and 0.3 to 28 ppm, respectively, as well as high Cl/B molal ratios of 25 to 55, indicated that a single magmatic source is likely contributing to fluid composition.

Several geothermometers were compared, providing reservoir temperatures ranging from 4.5 to 9.0 °C, 29.5 to 56.0 °C, 10.1 to 68.5 °C, and 101.6 to 282.8 °C for cold springs, hot springs, shallow wells, and deep wells, respectively. Calculated reservoir fluid compositions indicate that wells MC-1 and MC-6 experienced significant CO_2 degassing during fluid ascent, while high SO_4 content of wells to the south of the Meager Creek Fault Zone can be traced down to the reservoir. Saturation states of the waters indicated that the Mount Meager south reservoir is of a typical geothermal system where the thermal waters are controlled by equilibrium between the solution and observed secondary minerals at high temperatures. The results also suggested a component of colder water mixing with the thermal waters.

Hot springs and wells on the eastern and northern sides of the reservoir, which are of low temperature and low CO_2, likely define the boundaries of peripheral waters. Wells to the southeast contained anomalously high Cl and SO_4, suggesting a magmatic input of these components that may be controlled by the east-west running Meager Creek Fault Zone. There is a significant source hot, Cl- and CO_2-rich thermal waters supplying deep wells MC-1, MC-2, MC-6 and MC-8, and possibly MC-3. These NaCl waters likely define the high temperature, central location of the geothermal reservoir. Overall, the deep wells seem to have drilled into the high-temperature geothermal reservoir at Mount Meager.

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