Garibaldi Geothermal Volcanic Belt Assessment Project, Southwestern British Columbia (Part of NTS 092J), Phase 2: 2022 Field Report

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Introduction

Renewable energy demand is increasing greatly to meet Canada's goal of reaching net-zero emissions by 2050. This has led to renewed interest in geothermal energy as a source of both green heat and power. A particular focus has been placed on high-temperature resources of the Garibaldi volcanic belt (Figure 1), first defined by research wells drilled in the early 1980s near Mount Meager and Mount Cayley, two volcanic systems within the larger Garibaldi belt (Jessop, 2008; Grasby et al., 2011). A new research project, funded by Natural Resources Canada's Emerging Renewable Power Program and Geoscience BC, was initiated, with the first phase focused on the Mount Meager area in the summers of 2019 and 2020 (Grasby et al., 2021). A second phase moved the focus to the Mount Cayley area, an area with limited previous exploration. This paper reports on the nature of the 2022 field program and data collected in the final year of phase 2 of the Garibaldi Geothermal Volcanic Belt Assessment Project.

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Garibaldi Volcanic Belt

The Garibaldi volcanic belt represents a chain of young (less than 11 000 years old) volcanoes in southwestern British Columbia (BC), in a region also known to have abundant thermal springs. Natural Resources Canada (NRCan), along with BC Hydro, conducted initial exploration drilling in the 1980s at the Mount Meager volcano that defined high-temperature geothermal resources, exceeding 250°C (Jessop, 2008; Witter, 2019). Results of this work defined a world-class thermal resource, although the permeability was insufficient to allow economic development. A lack of geoscience information regarding the regional controls on permeability posed a significant drilling risk for subsequent industry exploration in the region (Witter, 2019).

A project to reduce exploration risk was initiated in 2019 by the Geological Survey of Canada (GSC) of NRCan, in partnership with The University of British Columbia (UBC), Simon Fraser University (SFU), Douglas College (DC), University of Calgary (UofC) and University of Alberta (UofA), to develop a multidisciplinary approach to reducing exploration risk through an integrated geological and geophysical field campaign. The project incorporates a range of geoscience tools, including remote sensing, bedrock mapping, fracture measurements, geochemistry, and magnetotelluric (MT), gravity and passive-seismic surveys. The ultimate project goal is to develop new predictive tools for finding permeable aquifers at depth. Results will also aid development of new geothermal-resource models, creating greater certainty in national geothermal-resource assessments and supporting development of effective regulatory environments.

Mount Cayley Field Program

Field teams from UBC, SFU, UofA and the GSC participated in the 2022 field program. Fieldwork was focused on logging roads along the flanks of Mount Cayley, as well as areas around the massif accessible by helicopter. Field planning began with engagement with Squamish First Nation and co-development of a modified field plan that limited impacts in areas of special concern. The local knowledge provided through the engagement process was of significant benefit to field operations. As well, Environmental Monitors from the Squamish First Nation were engaged to ensure that helicopter work to reach higher levels of Mount Cayley did not cause any wildlife disturbance. The field program focused on

1) establishing an array of MT stations to image the volcanic plumbing (UofA);
2) establishing audio-magnetotelluric (AMT) stations to study the shallow structure that included the hydrothermal systems (GSC);
3) a gravity survey that will provide insight into potential magma chambers (SFU);
4) bedrock mapping and paleomagnetic studies to provide information on the rock types that form the geothermal reservoir, and eruption history (UBC);
5) ground-temperature survey, and fracture, rock-property and thermal-anomaly studies (GSC) that will provide information on permeable networks, heat conduction and heat production; and
6) structural geology studies (SFU) to elucidate the regional stress fields and associated fault and fracture systems.

Work Conducted During the 2022 Field Program

Broadband Magnetotelluric

Previous MT studies in the Garibaldi belt have shown the presence of a low-resistivity layer in the crust in the depth range 5–10 km. These have included previous MT studies around Mount Meager and Mount Cayley in which the low-resistivity

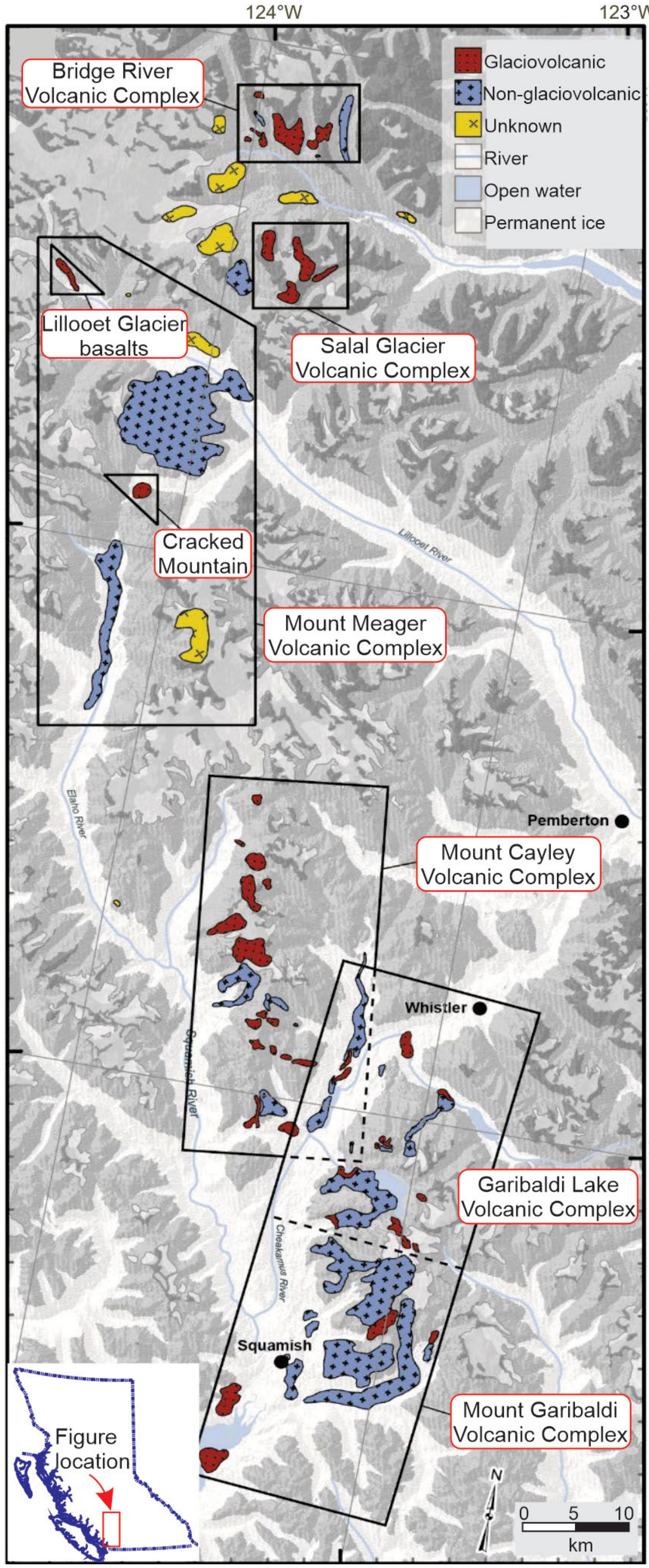

Figure 1. Volcanic complexes of the Garibaldi belt, showing the location of Mount Meager, the focus of phase 1, and the Mount Cayley area, the focus of phase 2 (after Wilson and Russell, 2018).

layer was interpreted as being due to a region of aqueous fluids or partial melt. Understanding the spatial extent and composition of this layer is important in both geothermal research and investigations of volcano hazards.

Magnetotelluric data collection by this project since 2019 has greatly improved knowledge of this low resistivity layer. The station distribution after the 2021 field season is shown in Figure 2a. In the winter of 2022, the UofA undertook 3-D inversions of the MT data that were used to produce 3-D resistivity models of the crust within the Garibaldi belt. This type of subsurface imaging is analogous to procedures used in medical imaging to look inside the human body. These 3-D resistivity models gave new insights into the geometry of the low-resistivity layer beneath Mount Cayley and Mount Meager. However, the 3-D inversions also showed that the nonuniform MT station coverage limits the ability to effectively map the low-resistivity layer and, by implication, the distribution of geothermal fluids. The MT data collection in 2022 (Figure 2b) was planned to address the following shortcomings in the existing MT dataset (Figure 2a):

1) Existing coverage is limited around Mount Cayley. Additional MT stations are needed to better understand the spatial distribution of subsurface aqueous fluids and partial melt beneath surface geothermal manifestations.
2) Existing coverage is sparse in areas between the major volcanic centres in the Garibaldi belt. Additional MT stations are needed to understand if partial melt is localized beneath the most recently active volcanic centres or more uniformly distributed along the entire Garibaldi belt.

In the summer of 2022, the UofA continued the regional magnetotelluric (MT) exploration to address these points. This research used Phoenix MTU-5C instruments, owned by the university, to collect broadband MT data that could image electrical resistivity from the surface to a depth of 20–30 km. Measurements of electrical resistivity are sensitive to the presence of aqueous fluids and partial melt, and provide important information about the supply of fluids and heat to shallow geothermal reservoirs.

In 2022, broadband MT data were collected at 15 locations in the Mount Cayley area, with each recording lasting 1–2 days.

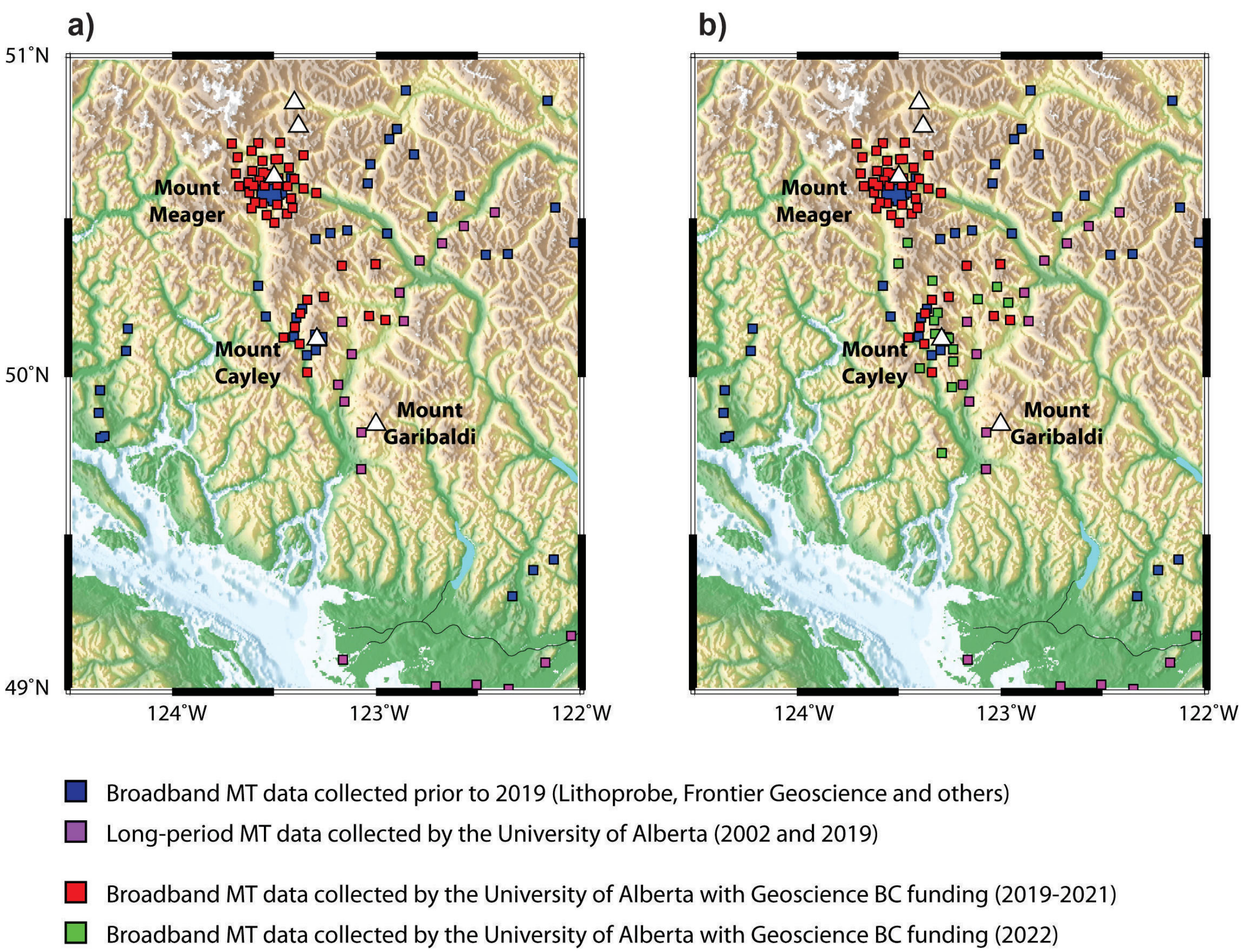

Figure 2. Distribution of magnetotelluric stations in the Garibaldi belt, showing **a)** MT data coverage after the 2021 field season, and **b)** the grid with the addition of the new MT data collected in the 2022 field season.

The MT data collection began on Saturday, August 20 and concluded on Monday, August 29. Strong geomagnetic signals and careful installation of sensors resulted in high-quality MT data. The station locations are listed in Table 1. The time-series data were recorded with sample rates of 150 Hz and 24 000 Hz, and the total volume of data from the 15 stations was 60.7 GB.

The new MT data are currently being processed to obtain the best possible estimates of impedances and vertical–magnetic-field transfer functions. The processed MT data will be used to update the 3-D inversions later in 2022.

Table 1. Location of broadband MT stations in the Mount Cayley area in August 2022.

Station name	Data folder name	Latitude (°)	Longitude (°)	Access
CAY200	10352_2022-08-20-202459	50.246	-123.112	Road
CAY201	10379_2022-08-21-000133	50.235	-122.963	Road
CAY202	10351_2022-08-21-194753	50.285	-123.018	Road
CAY203	10379_2022-08-22-201854	50.423	-123.457	Helicopter
CAY204	10351_2022-08-23-181219	50.088	-123.233	Helicopter
CAY205	10430_2022-08-23-205628	50.203	-123.309	Helicopter
CAY206	10351_2022-08-24-180540	50.304	-123.335	Helicopter
CAY207	10379_2022-08-24-212027	50.358	-123.502	Helicopter
CAY208	10430_2022-08-25-184417	50.137	-123.322	Helicopter
CAY209	10351_2022-08-25-222546	50.123	-123.254	Helicopter
CAY210	10430_2022-08-26-172126	50.028	-123.397	Helicopter
CAY211	10379_2022-08-26-212410	50.049	-123.233	Helicopter
CAY212	10430_2022-08-27-231634	49.968	-123.239	Helicopter
CAY213	10379_2022-08-28-181550	49.759	-123.289	Helicopter
CAY214	10351_2022-08-28-210413	50.179	-123.327	Helicopter

Audio-Magnetotelluric

Magnetotelluric (MT) is a passive geophysical technique that measures Earth's electric and magnetic fields, from which one can calculate a subsurface resistivity model. Resistivity is sensitive to lithology, porosity and permeability of the rock; composition and temperature of associated fluids; and host-rock metallic content (including sulphides and graphite). As a result, MT data are useful in geothermal studies because they can generate images of the relationships between fluid pathways and hydrothermal alteration. Previous regional broadband MT surveys (Jones and Dumas, 1993) identified potential alteration zones below Mount Cayley; however, the nature and geometry of the systems was poorly resolved due to the limited aperture, bandwidth and inversion resources at the time (e.g., only 2-D modelling was available). As well, the region is incredibly difficult to access, with limited helicopter-landing sites and steep topography making acquisition of ground geophysical datasets tenuous and costly. Imaging parts of the geothermal system that are in the upper 1–2 km only requires high-frequency MT measurements in the band 10 000–1 Hz, referred to as audio-magnetotelluric (AMT) measurements, or airborne techniques that can also image the near-surface resistivity. Rather than doing extensive ground geophysical surveys, this study will acquire airborne passive electromagnetic (EM) data augmented with ground AMT data to provide the extensive coverage and systematic sampling for this inaccessible terrain.

Data from 10 AMT stations were collected at Mount Cayley during August 2022 and a request for procurement of a passive EM survey is currently in development. This study will integrate the two geophysical methods (AMT and passive EM) to test the ability of joint AMT-EM inversions to image and detect geothermal-system parameters at shallow depths (hundreds of metres), and ultimately test whether the fluid conduits imaged in the models can be related to the locations of known warm and hot springs. If the technique is indeed sensitive to hostrock lithology, alteration and porosity, there is also potential to infer rock shear strength and detect zones of weakness that are more susceptible to mechanical failure, which would contribute to reducing the risk of landslides when developing geothermal resources. Analysis of the new resistivity 3-D models from Mount Cayley will be supported by other geological and geophysical datasets collected in the 2022 field campaign and during previous exploration.

Gravity Survey

During the summer 2022 field season, the Simon Fraser University (SFU) team continued with the gravity exploration of the Mount Cayley Volcanic Complex. In the 2021 field season, 75 gravity sites had been surveyed around Mount Cayley and surrounding peaks (e.g., Mount Callaghan, Mount Brew, Brandywine Mountain) through several days of surveys conducted by helicopter, truck and foot. In a similar way, three gravity surveys were conducted during the summer of 2022 around the Mount Cayley Volcanic Complex to increase the density of gravity measurement sites on the already-established grid. Two of these surveys were conducted with an SFU truck (July 4–8 and August 15–17, 2022) and one employed a helicopter (September 2–3, 2022).

The main focus of these three surveys was to a) infill the gravity grid on the western flank of the Mount Cayley Volcanic Complex, particularly alongside the Squamish River Forest Service Road (SRFSR) and perpendicular logging roads; b) partially cover the area inside the Callaghan Conservancy, east of Mount Callaghan; and c) resolve any other lingering voids between measured sites (e.g., on the east flank of Mount Brew). Infilling the western flank of Mount Cayley had proven difficult in the past because the SRFSR tends to flood when the river level increases above 4 m, so surveys need to be carefully planned and, even then, an excursion might not be possible. The Callaghan Conservancy area posed other accessibility challenges, as the team had no permission to land a helicopter in this area of very few roads. Therefore, all the measurements in this large area would have to be done on foot, making it difficult to cover.

Despite these challenges, all three surveys were successfully completed during the summer field season, with 67 additional gravity sites being measured using two LaCoste & Romberg relative gravity meters around the Mount Cayley Volcanic Complex. All measurements were related to a survey reference station in Squamish (SFU 1), which was measured at the beginning and end of the survey loop, and secondary reference sites for instrumental drift control were chosen based on the locations of sites measured that day. Since SFU 1 had been previously tied to the absolute gravity grid established by the GSC, the absolute values for all survey points around Mt Cayley can be calculated based on the relative gravity measurements. The position of each gravity site was measured using a Juniper Geode GNSS receiver. The total number of gravity sites for the Mount Cayley Volcanic Complex grid is now 142 (Figure 3); data from these sites will be used to produce a Bouguer anomaly map of the volcanic complex.

Bedrock Mapping and Paleomagnetic Sampling

The UBC team conducted work in three distinct areas (Figure 4) to constrain the recent eruption history of the area: the Elaho basalts and Free Will peak in the Mount Meager volcanic field, and the Ember Ridge domes in the Mount Cayley volcanic field.

Elaho Basalt Mapping and Paleomagnetic Sampling

The team from UBC completed two days of vehicle-supported mapping and paleomagnetic sampling of the southern portion of the Elaho basalts, and two days of helicopter-supported mapping and sampling in the northern portion of the Elaho and Meager valleys. They collected seven paleomagnetic samples from minimum and maximum stratigraphic locations at the Elaho waterfall (local name) and at the Clendinning Creek–Elaho River confluence. Corresponding hand samples were collected for geochemistry and Ar/Ar dating. Analysis of these samples will determine the duration of this eruption; coupled with new and previous Ar/Ar dates, these analyses will clarify the timing of the Elaho eruption in relation to the Mount Meager volcanic field. Elucidation of the most recent eruptions will assist in understanding the activity of potential magma chambers in the subsurface. New mapping has increased the aerial extent of volcanics ~4 km east of the Elaho waterfall. Paleovalley reconstruction, coupled with thickness measurements, will provide an approximate erupted volume. Geochemical analysis will clarify stratigraphic units and possibly provide information on magma-chamber depth and dynamics.

Free Will Mapping and Paleomagnetic Sampling

The UBC team also completed three days of mapping and paleomagnetic sampling on Free Will peak, as well as helicopter-supported photogrammetry. Initial results indicate that Free Will peak is a pre- to syn-Fraser–age subglacial eruption of interbedded lapilli to ash tuff, and hyaloclastite and autobrecciated pillow basalt. Superficially, the Free Will volcanic edifice resembles the nearby Crack Mountain volcanic edifice. It is highly glaciated and has crystalline glacial erratics both atop the volcanic edifice and included as accidental clasts within the ash and lapilli tuff, indicating that the eruption may have preserved evidence of the ice-melting process during the initial stages of the subglacial eruption. Analysis of high-resolution photogrammetry of the steep, inaccessible edifice slopes will provide insight into volcaniclastic and crosscutting dike structures, as well as total erupted volume. Argon/argon radiometric, geochemical and paleomagnetic analysis will clarify the timing and duration of the eruption.

Mount Cayley Volcanic Field Paleomagnetic Sampling

The UBC team further completed two days of paleomagnetic sampling of the glaciovolcanic edifices of the Mount Cayley volcanic field. Some locations were resampled to improve the accuracy of 2021 paleomagnetic datasets. New

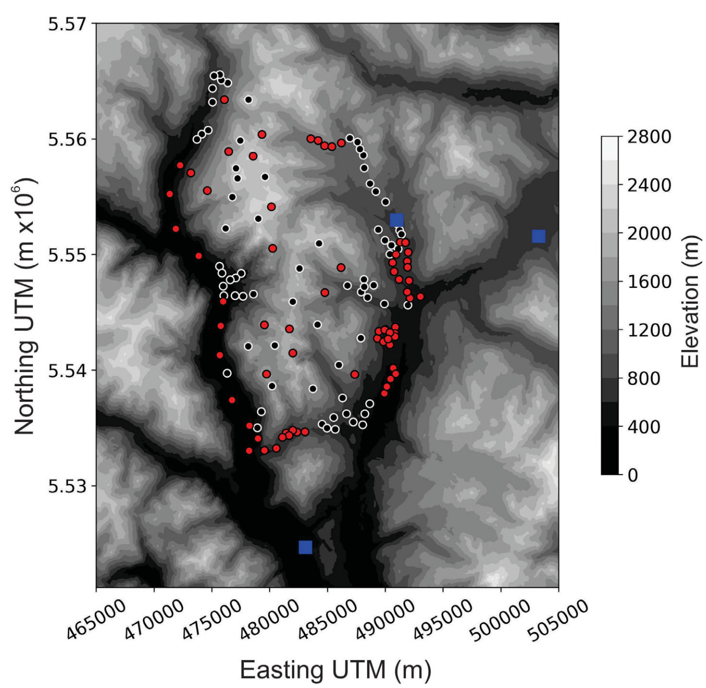

Figure 3. Shaded-relief map of the Mount Cayley area, showing locations of gravity survey stations. Red dots are new stations measured in 2022, black dots are stations collected in 2021, and blue squares are base stations.

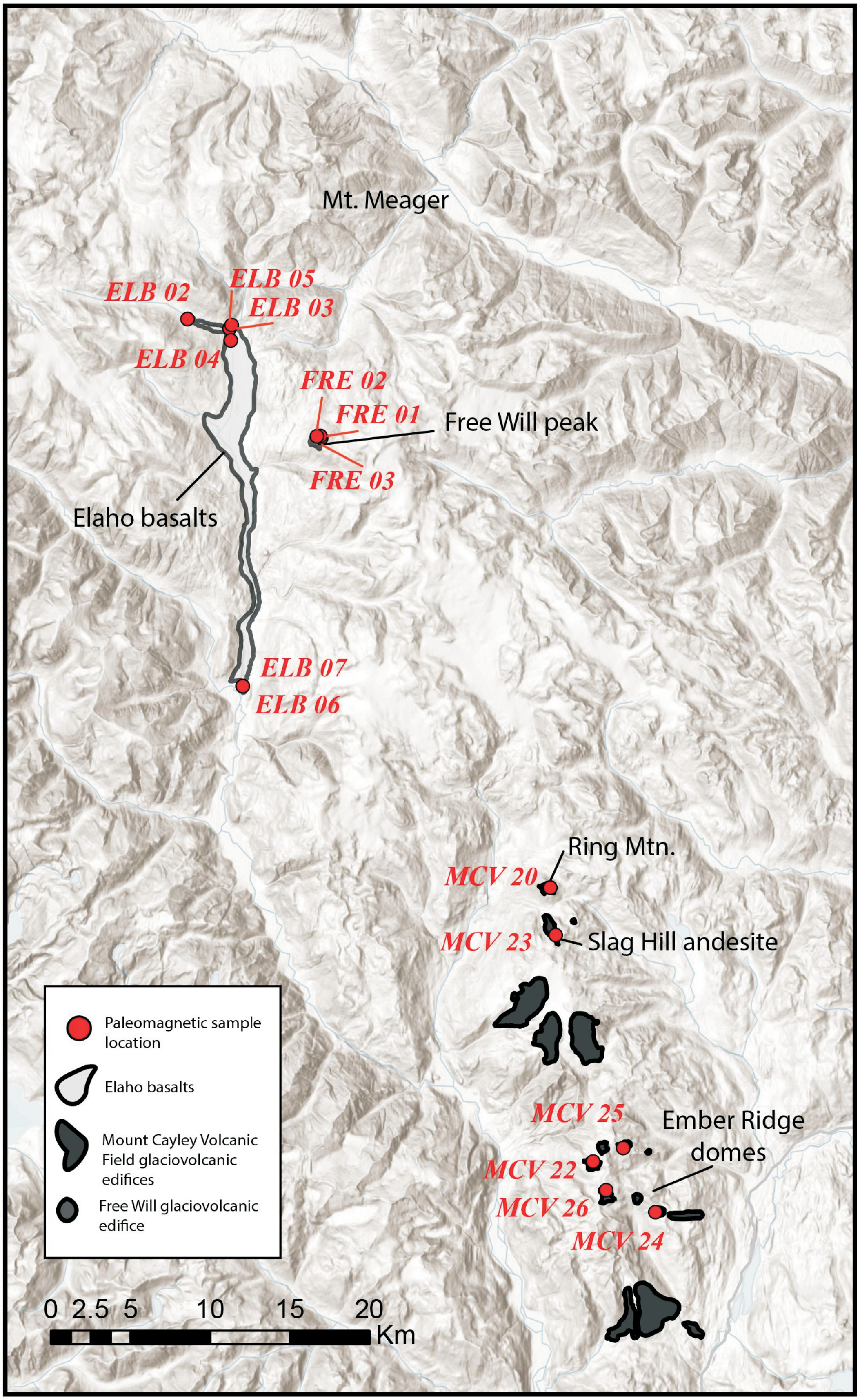

Figure 4. Location of 2022 paleomagnetic-sampling programs targeting the Elaho basalts and Free Will volcano in the Mount Meager volcanic field and the Ember Ridge domes in the Mount Cayley volcanic field.

locations, including multiple individual Ember Ridge glaciovolcanic edifices, were also sampled. Coupled with Ar/Ar data, this suite of paleomagnetic samples will form a local paleosecular variation curve for the Mount Cayley, Mount Garibaldi and Mount Meager volcanic fields.

Temperature Survey

Twenty-six temperature loggers were used in 13 sites at Mount Cayley by the GSC to record variations in ground-surface temperature. Ground temperatures were measured using miniature temperature-data loggers (HOBO® Water Temp Pro v2). The temperature-data logger has a resolution of 0.2°C and temperature range of –40 to 70°C in air and up to 50°C in water. At each site, two HOBO temperature loggers were buried in soil and set to record the environmental temperature every 30 minutes. One was deployed on the surface to account for the solar radiance and the other was buried at a depth of 30–50 cm, depending on the ground condition. Figure 5 shows the temperature recorded for the last winter and spring seasons at the Mount Cayley ground-temperature monitoring sites. At each site, thermal and the associated visual photos were taken to evaluate the environmental factors, such as shadiness and vegetation covering.

A total of 155 thermal images were taken at the key field sites. These include 48 images from 13 logger sites in the Squamish Valley, 15 images from the Shovelnose warm spring, 12 images and 1 video from the Pebble Creek hot spring and 3 images from the No Good warm spring. Comparative analysis of these data is ongoing.

Fracture Measurements

Fracture measurements were taken at seven outcrop stations on the ridges around Mount Cayley. In total, 87 fractures were measured for strike, dip direction and dip angle (Figure 6). These data will be analyzed further for study of the stress regime and drilling design.

Structural Geology

Previous exploration of the Mount Meager area defined faulting as being related to 1) tectonic stress during the onset of mountain building (e.g., Owl Creek fault), 2) volcanism, and 3) mass creep and gravitational failure (Fairbank et al., 1980, 1981). In the summer of 2022, a new type of tectonic-stress–related fault was identified that is synchronous with and/or postdates the latest volcanic activity at Mount Meager. This work is ongoing and will include analyzing paleomagnetic samples and conducting radiometric dating. This work helps to date the latest tectonic fault activity and potentially define the trigger mechanism for the latest volcanic eruption 2400 years ago on Mount Meager.

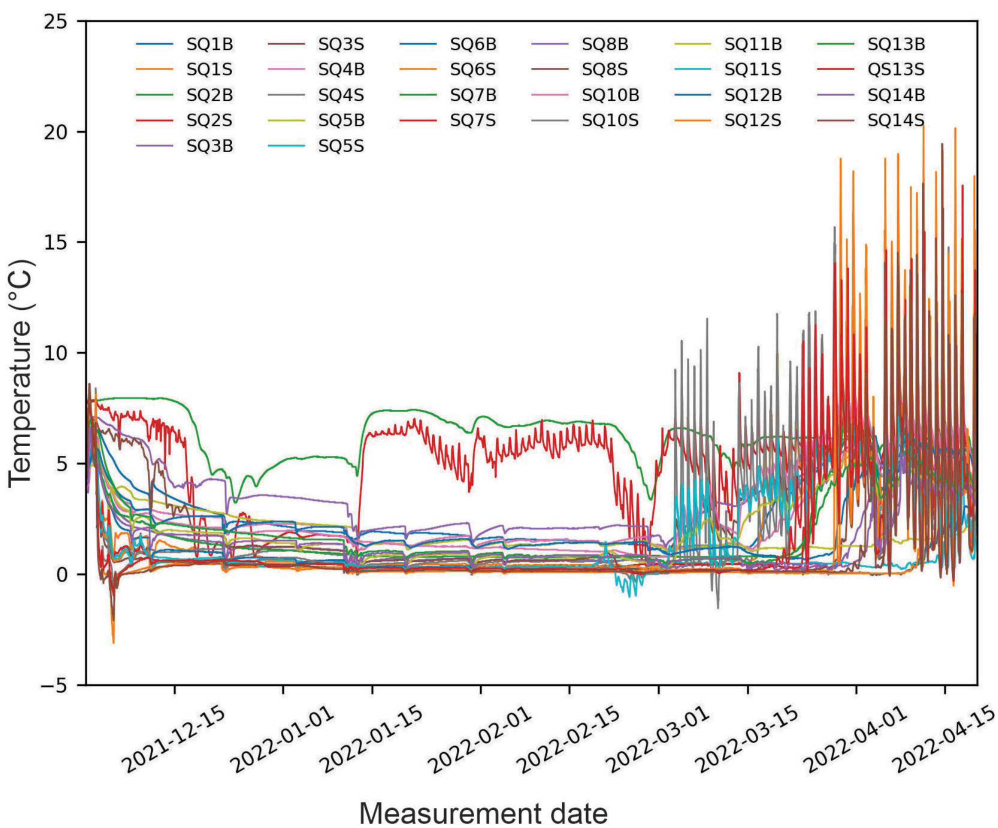

Figure 5. Temperatures recorded at 13 ground-temperature monitoring sites at Mount Cayley.

Figure 6. Collection of fracture measurements from outcrops along the ridges of Mount Cayley.

In addition, it will help improve understanding of the tectonic history of the Mount Cayley area.

Summary

Summer 2022 was a successful field season, with large volumes of new data collected as part of geophysical and geological surveys in the Mount Cayley area. Data collected are currently being processed and interpreted. All raw data will be released in 2023 and interpreted results will be presented in a series of reports, peer-reviewed scientific papers and presentations by various members of the project. The Garibaldi Geothermal Volcanic Belt Assessment Project will also wrap up in 2023.

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