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Geothermal Energy Potential of the Garibaldi Volcanic Belt, Canada

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ABSTRACT

Renewed interest in geothermal potential in Canada has motivated a research program focused on reducing exploration risk for geothermal energy associated with volcanic systems in the western Canadian Cordillera, the Garibaldi Volcanic Belt Geothermal Energy Project. This work aims to enhance techniques that can better predict the occurrence of hot and permeable aquifers in the sub-surface. Work includes new geophysical, geological, and geochemical exploration around the Mount Meager and Mount Cayley volcanoes. This report summarises the field program activities, the range of data collected and the integrated results being developed into new resource assessment models.

1. INTRODUCTION

Canada, like other nations, has set ambitious goals to transition from a hydrocarbon-based economy to one based on net zero CO_2 emissions by 2050. New options for renewable clean energy supplies are being actively explored. Canada has abundant hydropower as well as wind and solar potential, but each of those energy sources comes with challenges, from controversies over new large-dam construction to issues with intermittency of generation that require storage solutions to become a dominant supply to the grid. Research on geothermal energy potential in Canada has lagged behind these other resources; however, attempts are now being made to revisit the findings of the defunct Geothermal Energy Program which ran in Canada from 1975-85 (Grasby et al., 2012).

The Geothermal Energy Program operated for ten years in response to the energy crises of the 1970s. The program examined geothermal systems across the country and identified areas of high potential, including sedimentary basins as well as volcanic belts in Canada (Fig. 1). As part of this program, geothermal-exploration wells were drilled in the Garibaldi volcanic belt of southwestern BC, near active thermal springs on the southern flank of Mount Meager, as well as near other thermal springs on the southern flank of Mount Cayley (Fig. 2). Results defined high-temperature geothermal resources exceeding 250 °C (Jessop, 2008; Grasby et al., 2012; Witter, 2019) (Fig. 3). However, development was limited by the low permeability of rocks at depth. Subsequent industry drilling at Mount Meager defined higher permeability zones, but these have not been produced to date as the water tables were too far below the well pad, such that parasitic pumping costs were too high (Witter, 2019).

Revised interest in geothermal energy has led to a new research project to help reduce exploration risk for geothermal energy associated with volcanic systems, with support from Natural Resources Canada’s Emerging Renewable Power Program, and Geoscience BC, along with the Geological Survey of Canada, University of British Columbian, Simon Fraser University, University of Alberta, University of Calgary, and Carleton University. The main aim of this work was to develop new techniques and tools that can better predict the occurrence of hot and permeable aquifers in the sub-surface. To this end, a multidisciplinary geoscience field program was conducted at Mount Meager in the summer of 2019, with a reduced program in 2020 due to covid-19 restrictions (Grasby et al., 2020; 2021). A second phase of this work was initiated in 2021 to examine the geothermal potential of the Mount Cayley area, under ongoing covid-19 restrictions.

The field program focused on bedrock mapping and age dating of the volcanic eruption history, a gravity survey, establishing an array of magnetotelluric (MT) stations, passive seismic survey, a distributed acoustic sensing array (DAS), remote sensing, fracture studies, and ground temperature measurements. Field work was conducted through engagement with Squamish and Lil’wat First Nations whose traditional lands include the study areas. Access to the field area was by a network of logging roads, although the historic Mount Meager drill sites are cut off by washed out bridges. These drill sites and higher elevation locations along mountain ridges were accessed by helicopter. This report summarises results of these combined field activities to date.

2. GARIBALDI VOLCANIC BELT RESEARCH

The volcanic history of the Garibaldi Belt can provide insight into areas with higher temperatures related to shallow magma intrusions. Such knowledge can also aid in assessment of the volcanic hazards associated with any future development. Given this, work was conducted to refine the eruptive history of the Garibaldi Belt area, including producing new bedrock maps (Harris et al., 2022a). Novel combination of $^{40}Ar/^{39}Ar$ with paleomagnetic studies helped to refine total eruptive history of some events. The results also provided new insight into the history of the Cordilleran ice sheet over the past 500 ka, with newly dated glaciovolcanic deposits showing ice reached elevations of 1,650 and 2,000 m a.s.l. at ~450 ka and ~200 ka, respectively (Harris et al., 2022b). Whereas newly dated subaerial erupted lavas recorded an absence of ice at elevations below 1,700 m a.sl at ~500 ka and again at ~115 ka. This work was combined with structural geology studies to define the tectonic stresses and ages of fault rupture in relationship to eruption history.

In order to map subsurface geological structures below GVB centres, spatial gravity measurements were made at the Mount Meager and Mount Cayley volcanic complexes to determine density contrasts caused by subsurface mass change. A total of 142 stations were occupied around Mount Meager with an additional 142 stations measured around the Mount Cayley. To investigate both deep and large magmatic structures (depth >10 km) as well as shallower and more constrained features (such as resulting from hydrothermal activity), gravity measurements were collected in a dense grid (250 to 500 m spacing) near sites of interest such as known vents of previous eruptive activity and identified geothermal resources or hot springs. A network of broadly spaced stations was also occupied with increasing distance from volcanic centres and from areas where shallower activity was presumed. By removing temporal gravitational effects (e.g., instrumental drift, Earth tides) and unwanted gravitational influence produced by the sharp topography of the volcanoes, Bouguer anomaly maps were generated (e.g. Fig. 3). The gravity map for Mount Meager shows two negative anomalies below the southern and northern flanks of the massif, with the southern one centred on the location of the South Meager geothermal project, and the northern one consistent with the location of large pumice deposits from the most recent (2360 BP) eruption of Mount Meager. The map also shows a regional trend of decreasing gravity from south to north, which might be obfuscating other less clear anomalies around the massif. Future work will focus on removing these regional trends and performing inverse modelling of the resulting anomalies constrained by the geological and geophysical data collected during this field program (MT data, passive seismic, etc.). The Bouguer anomaly map of the Mount Cayley volcanic complex is still under development.

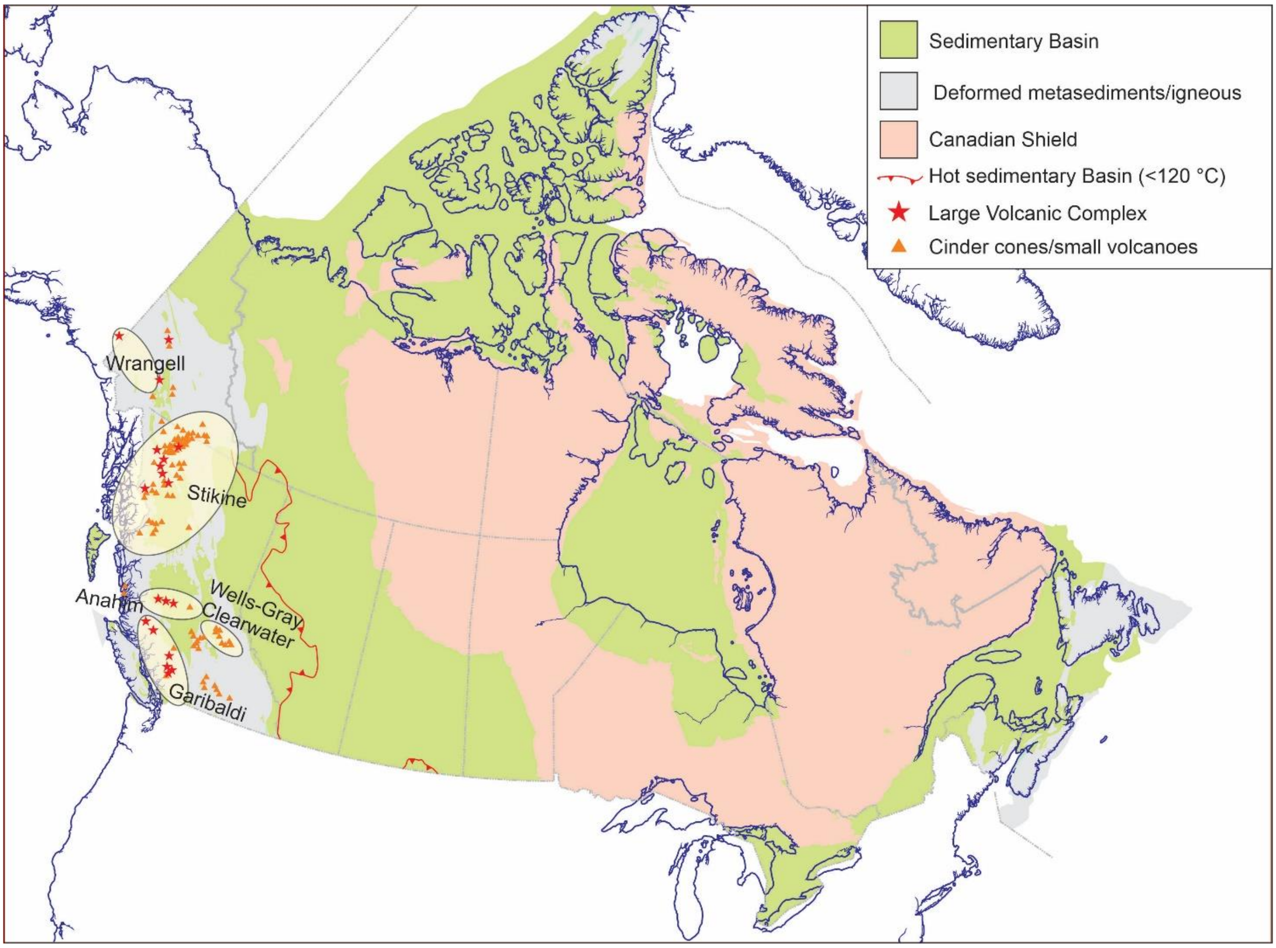


Figure 1: Map showing major geological regions of Canada along with regions of high temperature geothermal potential associated with hot sedimentary basins and volcanic belts in Canada.

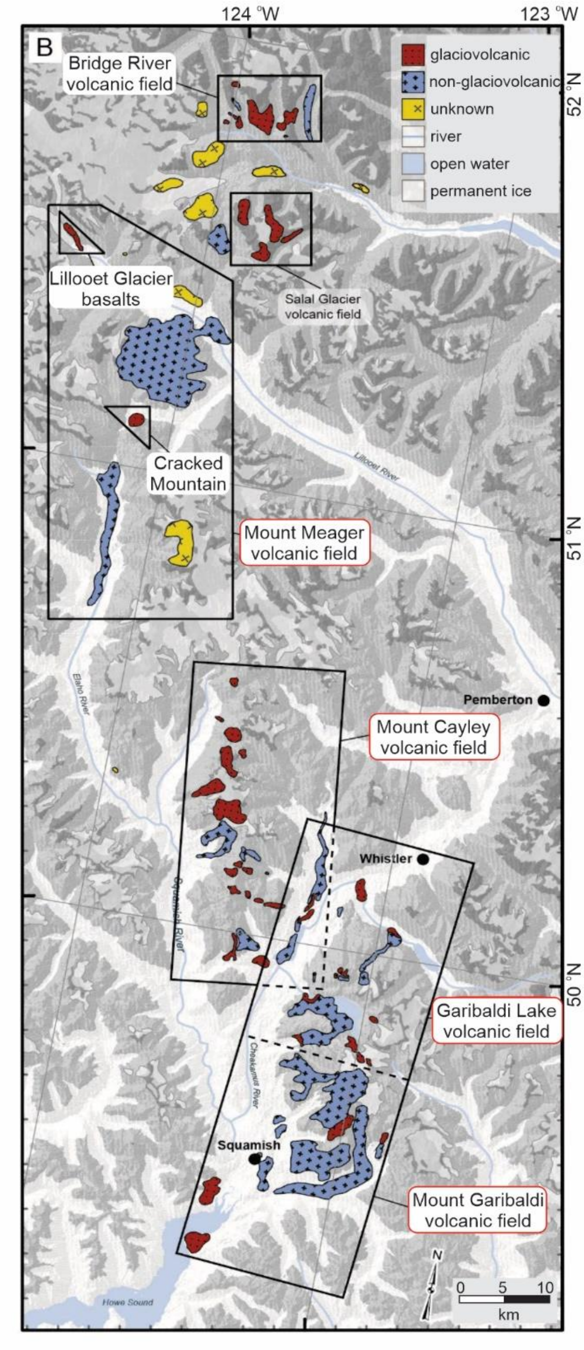


Figure 2: Map showing main volcanic centres of the Garibaldi Volcanic Belt (Modified after Wilson and Russell, 2018).

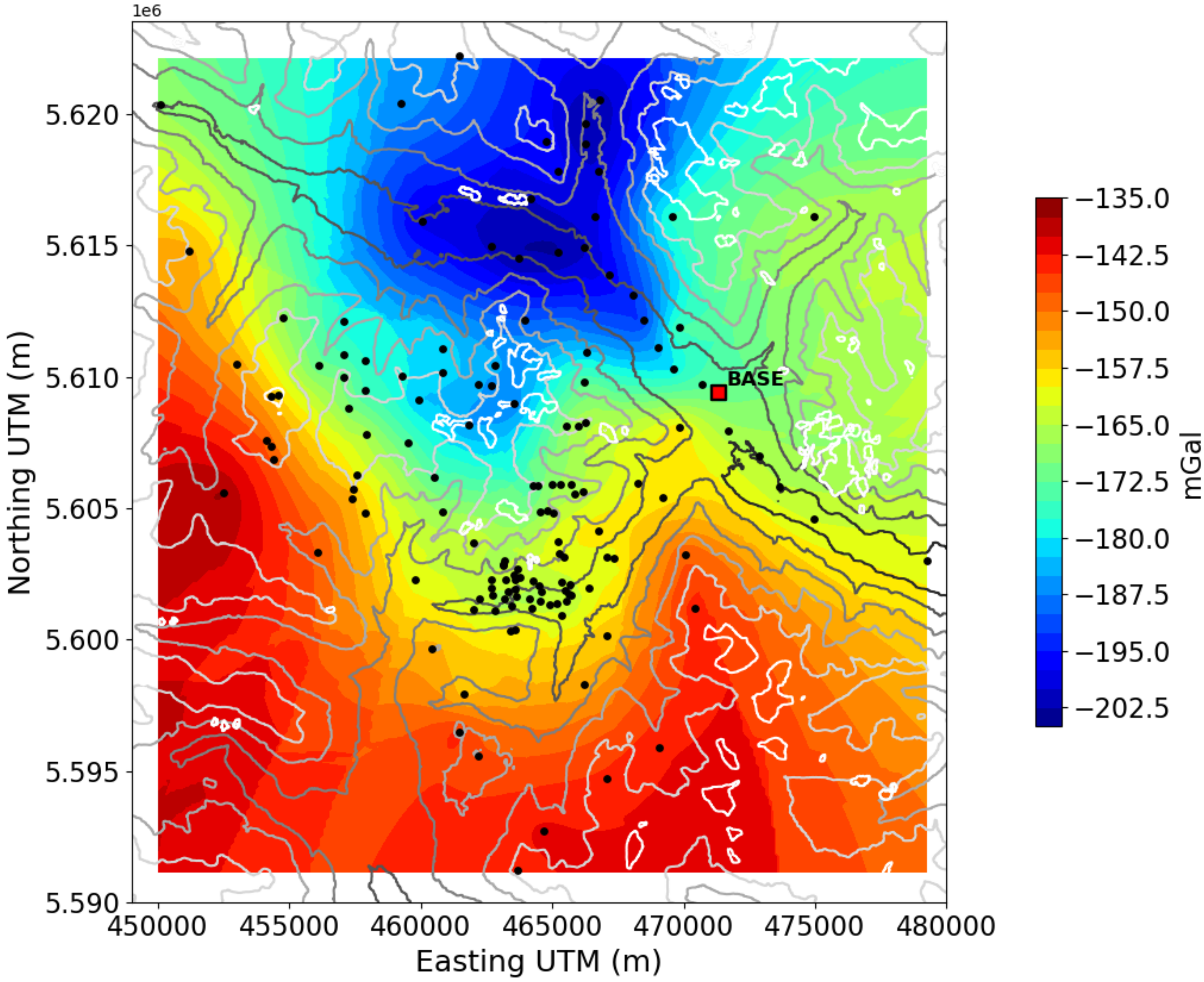


Figure 3: Bouguer gravity anomaly map of the Mount Meager volcanic complex and surrounding areas. Features of interest include a negative anomaly on the southern and northern flanks of Meager, located on the Southern Meager geothermal project area and on thick pyroclastic deposits from the last eruption at Meager, respectively.

Collection of magnetotelluric (MT) data greatly expanded coverage beyond that collected in the 1980s around Mount Meager (Jones and Dumas, 1993) and the Lithoprobe MT survey along the Sea-to-Sky Corridor, using modern and more field-portable instruments. The MT data collection was performed on two spatial scales. Deeper focused broadband MT surveys (BBMT) were designed to image pathways that carry fluids to the geothermal reservoir as well as to define the size and content of any magma bodies. In the region of the Mount Meager geothermal reservoir a dense grid of 84 audiomagnetotelluric (AMT) stations were also conducted to better image the geothermal reservoir itself. AMT sites are similar to BBMT sites, but the equipment measures at much higher frequencies (typically 10000 Hz -1 H) vs 400 Hz to 1000s for BBMT in order to study at shallow depths < 1 km. Both a traditional iterative algorithm and a deep learning (DL) based inversion were used for the BBMT data modelling. The iterative inversion was performed using non-linear conjugate gradients by ModEM (Kelbert et al., 2014), whereas the DL-based inversion algorithm was developed by Liu et al. (2022) to retrieve the subsurface resistivity distribution. The BBMT results show a large conductor at a depth of ~6 km, which is interpreted as possibly brines, or a partially melted magma body (along BB' in Fig. 4). Figure 5 shows a sliced vertical profile at latitude 50.65° N. Combining Figures 4 and 5 we can see a conductor which extends northeast and implies a heat source related to deep magma fluids. More detailed interpretations of this resistivity anomaly are still required. The presence though of a partial melt is consistent with deep long period earthquakes clustered approximately 45 km to the east–northeast of the Mount Meager Complex at depths between 4 and 45 km (Lu and Bostock, 2022). The AMT inversion is shown in Figures 6 and 7, which demonstrate the shape and location of near surface structures of the geothermal system in the region immediately south of Pylon Peak. The shallow high conductivity features are interpreted as the cap rock (C1 and C2, Figs. 6 and 7), below which the thermal fluid can trap (Hormozzade Ghalati et al, 2022). This zone was correlated with the smectite, illite, and rare kaolinite alteration minerals in geological well logs. Underlying the cap rock, higher resistivity features exist at the approximate depth of 1km below sea level and can be interpreted as the hot fluid reservoir. This zone illustrates possible conduits in relationship to the location of known hot spring manifestations at the surface. The AMT model shows that the conductive features are controlled by the Meager Creek Fault in the south and the No-Good Fault in the west. One conductor extends laterally beneath Meager Creek (C1) whereas another one shallows toward the southern portion of the No-Good fault (C2). The permeable damaged zone of these faults can provide pathways that transmit fluid, which is then trapped beneath the cap rock.

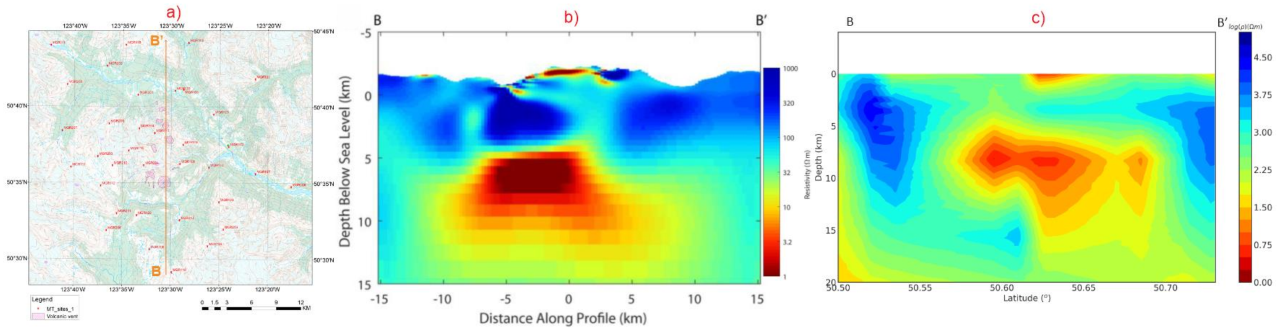


Figure 4. (a) Mount Meager study area and MT station distribution; (b) Vertical resistivity slice with ModEM; (c) Vertical profile with CNN inversion along BB'.

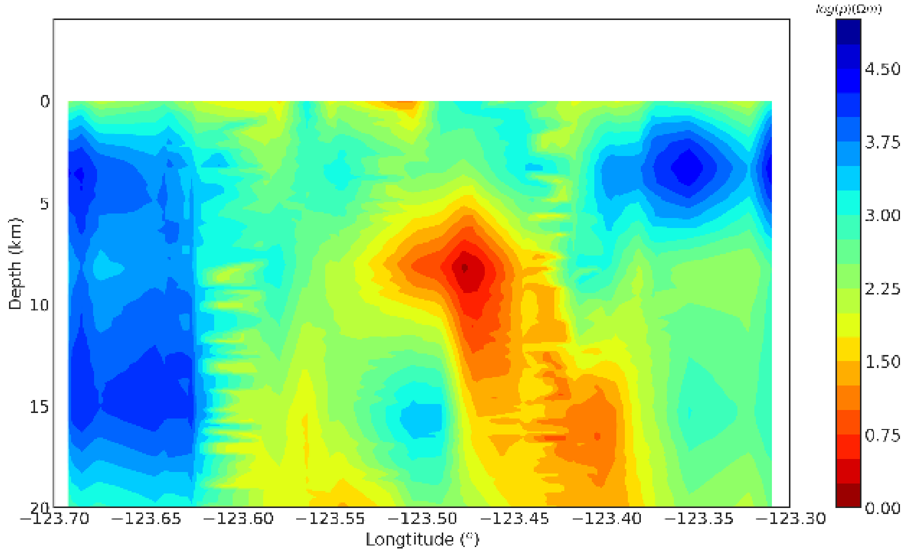


Figure 5. Vertical profile with CNN inversion at 50.65° N (profile line shown in Fig. 4a).

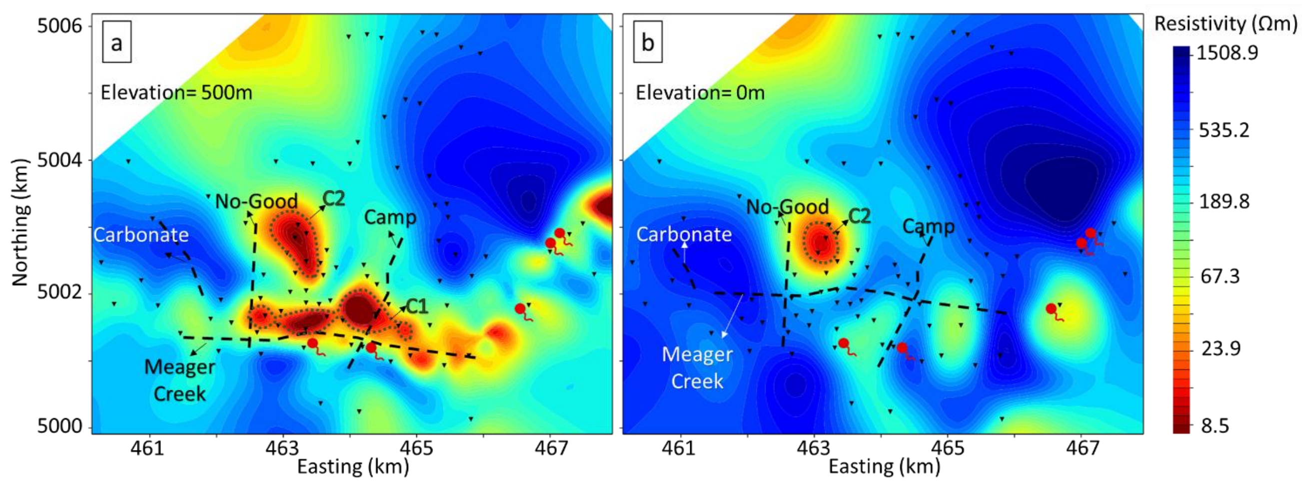


Figure 6. Horizontal plan view maps from the final AMT model at selected elevations of: (a) 500 m, (b) 0 m. Location of hot and warm springs, faults, and C1 and C2 are denoted in plots. Color bar is the same for both plots (coordinate system, UTM zone 10N).

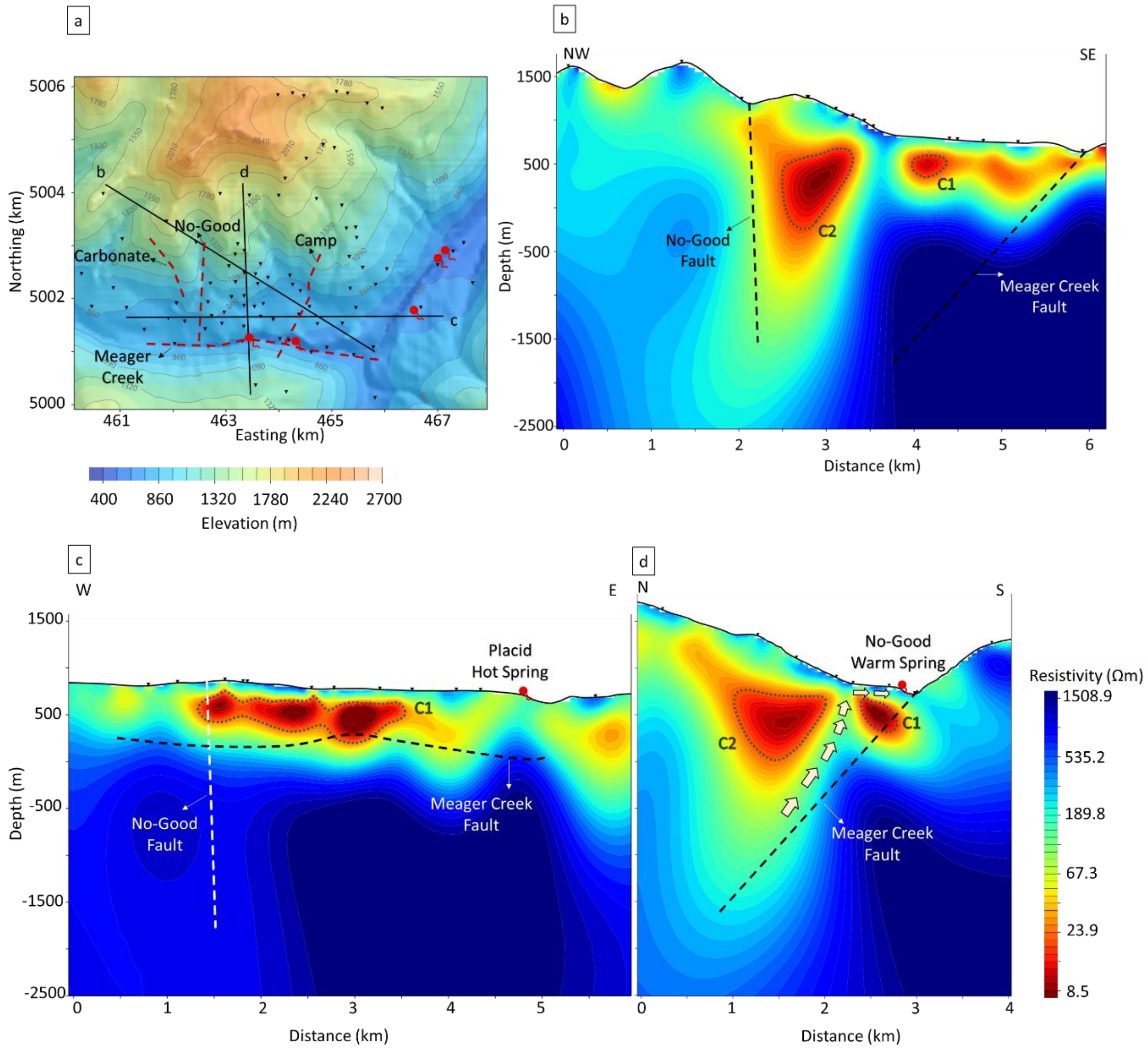


Figure 7. (a) Overview elevation map with lines representing the direction of profiles through which the 3-D model is sliced with labels denoting Figs. 7 b, c, and d. (b) Oblique sectional view through the final 3-D resistivity model in NW-SE direction. (c) East-west cross-sectional view; (d) North-south cross-sectional view through the final 3-D resistivity model. Plots show the relation to the Meager Creek fault, No-Good fault, thermal springs, and the caprock. (Coordinate system, UTM zone 10N).

Close to two thousand new fracture measurements collected show at least three types of fractures related to distinct geological processes. The first set are fracture groups related to regional tectonic deformation and are consistent in character and are common in basement rocks. Their strikes are often in good spatial alignment with volcanic eruption centers and veins, and earthquake events. The second set are fractures associated with volcanic doming and eruption activities that vary geographically. They are circular/radial segments and the strikes change spatially depending on their location relative to the eruption center. This is particularly true from the interpreted fault/fracture zones in Landsat images (Fig. 8). The third type are gravitational fractures parallel to slopes, as common in volcanic areas. This type of fracture causes instability in the mountain ridge and peak, and can lead to slides and rock avalanche, such as the 2010 Mount Meager avalanche (Roberti et a l., 2017).

A series of 22 data loggers were also placed in a grid to monitor ground temperatures over 330 days. This takes advantage of snow cover in higher latitudes that thermally insulates the ground from diurnal variations in solar radiation (Fig. 9). During the winter months then the temperature loggers record variations in ground heat flux that can be used to refine areas of preferential heat flow. These results were compared to studies of satellite thermal imagery, subsurface heat flow estimates, as well as extracted structure lineaments to investigate fracture/fault control on geothermal heat flow. The number of days of recorded flat temperature at around zero seems to be a good indicator of subsurface heat anomalies that are often bounded by fault and major fracture zone. Two types of geothermal heat flow anomalies are identified from the GST records, one related to shallow hot-warm springs and seep swarms, in the southeast and the south along the Meager Creek. The other is the area of identified geothermal reservoir.

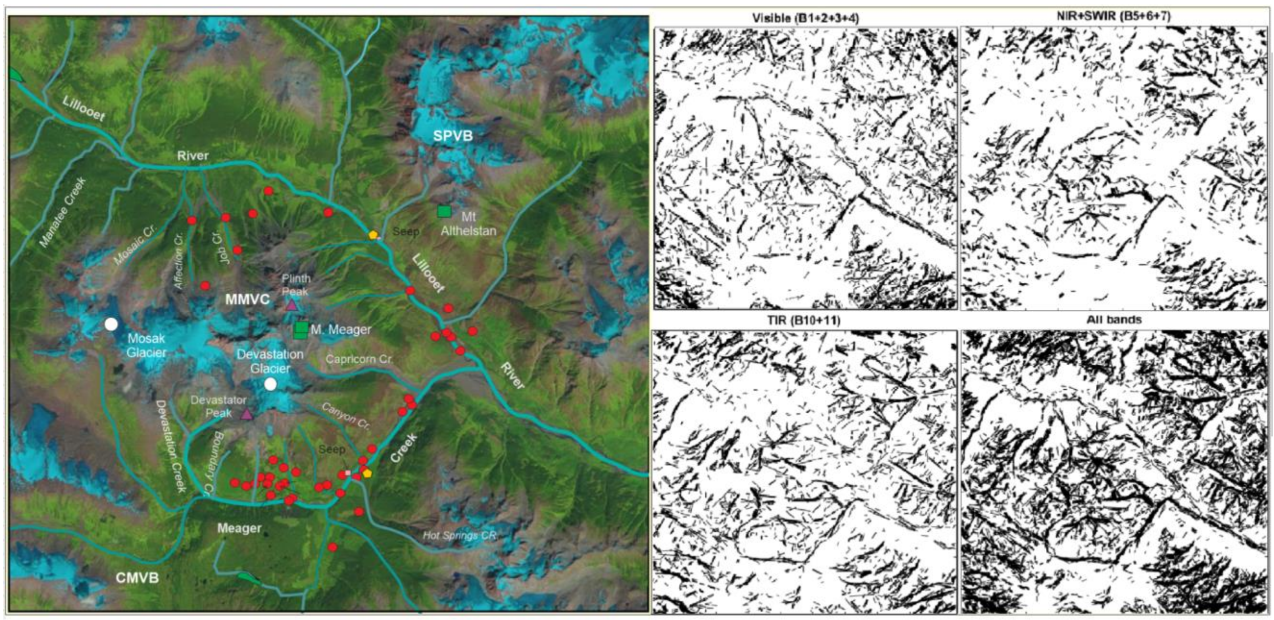


Figure 8. Left: A composite colour Landsat 8 image of the Mount Meager Volcanic Complex showing location of geothermal wells (red dots), hot springs (yellow pentagon), and major drainage system (blue lines). Right: Computer extracted linear features from multi-spectral images (2018-10-19). The linear features are combined as specific groups (visible, near infrared + short wave infrared (NIR+SWIR), thermal infrared (TIR) and all).

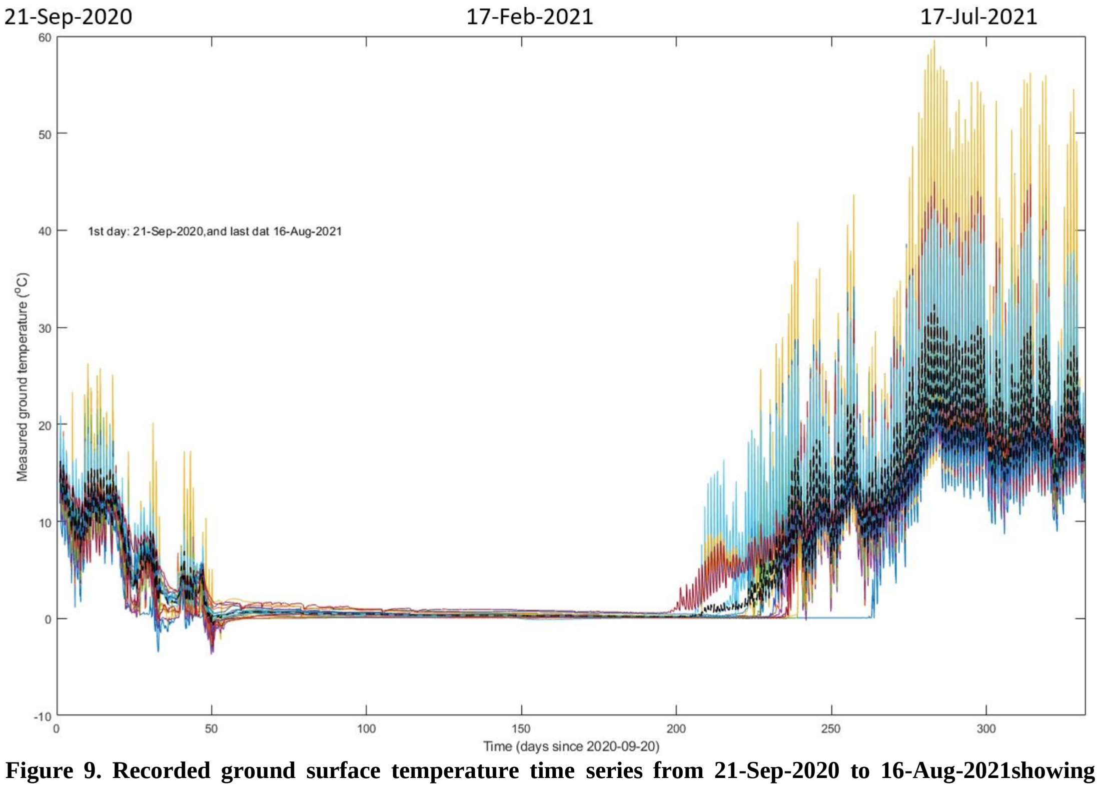
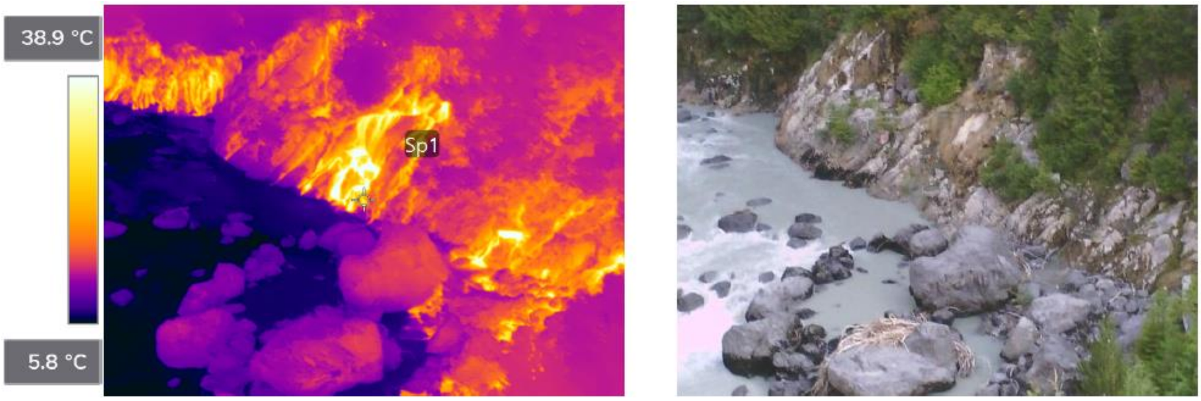
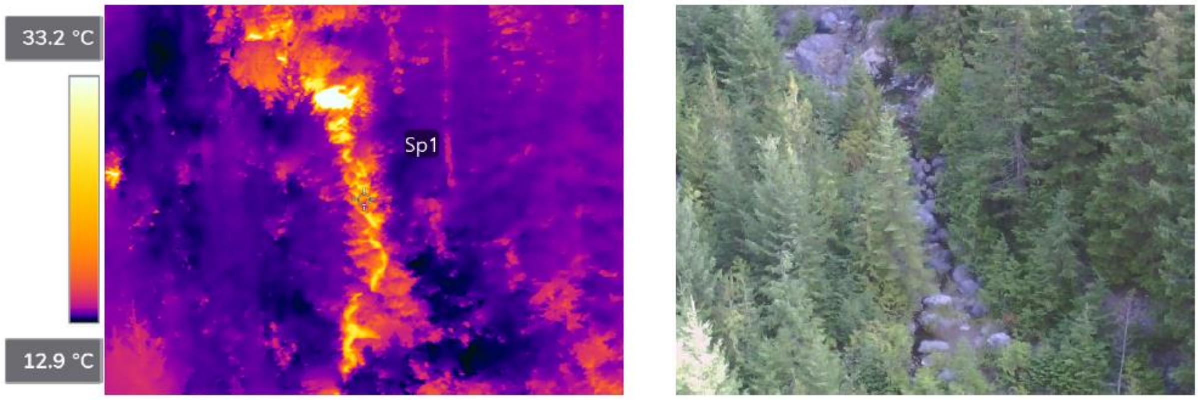


Figure 9. Recorded ground surface temperature time series from 21-Sep-2020 to 16-Aug-2021showing daily cycles and seasonal variations with a long flat temperature around zero in snow cover period.

A total of 1274 thermal images were taken with a thermal infrared camera during the 2021 summer fieldwork season. Various objects including distinct ground-surface, temperature logger station, and water bodies were considered to provide accurate ground temperature records for different purposes. A large portion of the images were taken from a helicopter about 500 m above ground level to help identify ground-temperature anomalies. As an example, Figure 10 shows three groups of thermal and visual images of riverbank area of the Lillooet River in the area northeast of Mount Meager. Hot springs are recorded seeping out of the rocks along the riverbank and flowing into the river (Fig. 10a). Hidden hot springs were easily identified from the thermal images (Fig. 10b). Figure 10c shows the flowing pathways of the hot springs merging into the Lillooet River.



A)



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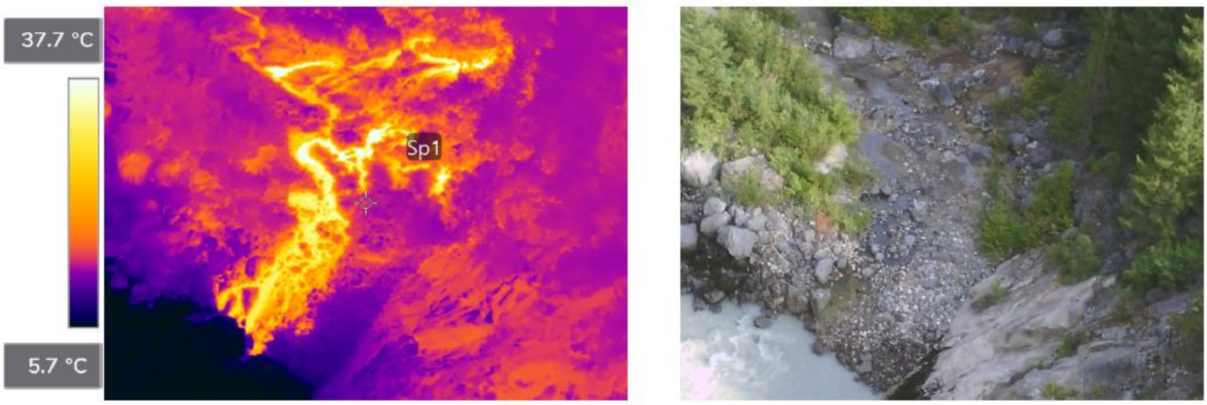

C)

Figure 10. Thermal (left) and true color (right) images of Pebble Creek Hot Springs along the riverbank areas of Lillooet River. A) hot springs seeping out of the rocks in the riverbank; b) the hidden hot spring stream in the rocks and trees; c) hot spring streams merging into the river. The images were taken using thermal infrared camera with iron palette from a helicopter about 500 m above ground level (Photos by W. Yuan).

CONCLUSIONS

Volcanic belts of western Canada hold significant promise for geothermal resources. To date the most explored volcanic system is the Mount Meager geothermal field, followed by the Mount Cayley area, both which fall within the Garibaldi Volcanic Belt. New research has focused on refining knowledge of the geothermal resources in these area. New geologic mapping has improved out understanding of the structural geologic setting as well as age of eruption history. Geophysical surveys have greatly enhanced our understanding of the subsurface and will help target the geothermal reservoirs that will be the focus of future drilling campaigns. Results of this work will support the successful development of geothermal resources in this region, supporting Canada's goal of reaching net zero emissions.

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