Geothermal Resource Potential of the Garibaldi Volcanic Belt, Southwestern British Columbia (Part of NTS 092J)

S.E. Grasby, Natural Resources Canada, Geological Survey of Canada–Calgary, Calgary, Alberta, steve.grasby@canada.ca

S.M. Ansari, Natural Resources Canada, Geological Survey of Canada–Central, Ottawa, Ontario

A. Calahorrano-Di Patre, Simon Fraser University, Burnaby, British Columbia

Z. Chen, Natural Resources Canada, Geological Survey of Canada–Calgary, Calgary, Alberta

J.A. Craven, Natural Resources Canada, Geological Survey of Canada–Central, Ottawa, Ontario

J. Dettmer, University of Calgary, Calgary, Alberta

H. Gilbert, University of Calgary, Calgary, Alberta

C. Hanneson, University of Alberta, Edmonton, Alberta

M. Harris, University of British Columbia, Vancouver, British Columbia

J. Liu, Natural Resources Canada, Geological Survey of Canada–Calgary, Calgary, Alberta

M. Muhammad, Simon Fraser University, Burnaby, British Columbia

K. Russell, University of British Columbia, Vancouver, British Columbia

R.O. Salvage, University of Calgary, Calgary, Alberta

G. Savard, University of Calgary, Calgary, Alberta

V. Tschirhart, Natural Resources Canada, Geological Survey of Canada–Central, Ottawa, Ontario

M.J. Unsworth, University of Alberta, Edmonton, Alberta

N. Vigouroux-Caillibot, Douglas College, New Westminster, British Columbia

G. Williams-Jones, Simon Fraser University, Burnaby, British Columbia

Grasby, S.E., Ansari, S.M., Calahorrano-Di Patre, A., Chen, Z., Craven, J.A., Dettmer, J., Gilbert, H., Hanneson, C., Harris, M., Liu, J., Muhammad, M., Russell, K., Salvage, R.O. Savard, G. Tschirhart, V., Unsworth, M.J., Vigouroux-Caillibot, N. and Williams-Jones, G. (2020): Geothermal resource potential of the Garibaldi volcanic belt, southwestern British Columbia (part of NTS 092J); *in* Geoscience BC Summary of Activities 2019: Energy and Water, Geoscience BC, Report 2020-02, p. 103–108.

Introduction

Growing policy demand to shift the Canadian economy to one supported by renewable energy resources has raised interest in geothermal energy potential. Compared to other renewables, geothermal energy has numerous advantages, namely in its low environmental footprint and ability to provide a stable baseload-power supply without the need for energy-storage solutions. Much greater exploration risk related to finding hot aquifers in the deep subsurface counters these advantages. The federal government's Geothermal Energy Program (1975–1985) provided essential insight into the thermal regime of Canada (Jessop, 2008; Grasby et al., 2011). This included highlighting some of the highest temperature systems related to hot sedimentary basins (found in the Northwest Territories, Yukon, British Columbia [BC], Alberta and Saskatchewan), as well as volcanic belts (Yukon and BC). One particular success of this program was geothermal-exploration wells drilled in the Garibaldi volcanic belt of southwestern BC, specifically on the southern flank of Mount Meager. This work defined high-temperature geothermal resources, exceeding 250°C (Jessop, 2008; Witter, 2019). Despite this success, the project was never economically viable because flow rates were too low to justify the power-transition cost over the distance required. Essentially, the technical success of the exploration program was limited by the ability to predict the occurrence of permeability at depth. To address this issue, a new research project was initiated to help reduce explora-

This publication is also available, free of charge, as colour digital files in Adobe Acrobat® PDF format from the Geoscience BC website: http://www.geosciencebc.com/updates/summary-of-activities/.

tion risk for geothermal energy associated with volcanic systems, with a focus on the Garibaldi volcanic belt. As part of the overall project goal, a multidisciplinary field program was conducted at Mount Meager in the summer of 2019, with a focus on developing novel tools to image zones of high permeability. This paper reports on the nature of the field program and data collected.

Garibaldi Project

The Garibaldi volcanic belt represents a chain of young (less than 11 000 years old) volcanoes in southwestern BC, in a region also known to have abundant thermal springs. In the 1980s, Natural Resources Canada (NRCan), along with BC Hydro, conducted initial exploration drilling at one of the volcanoes, Mount Meager. These results defined the highest temperature geothermal resources in Canada. While this will produce electricity, the fluid-production rate was not sufficient to justify the cost of the 60 km of new transmission lines required to reach the site (power generation is a function of both temperature of the fluid and the rate at which the fluid can be produced to surface). A key outcome of this research project was that, although a world-class thermal resource was found, the geological conditions required to exploit it were not economical. Despite the defined thermal resource, 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 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 reduce exploration risk through an integrated geological and geophysical field campaign. Project funding was provided through NRCan (Renewable and Electrical Energy Division and GSC), together with Geoscience BC. 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 extrapolate new knowledge gained from the Mount Meager field campaign to the overall Garibaldi volcanic belt, thereby developing 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 Meager Field Program

Given the difficulties of access, a helicopter-supported field program operated from July 2 to 24, supporting field teams from UBC, SFU, UofA, UofC, DC and GSC. Field plans began with consultation with First Nations and co-development of a modified field plan that limited impacts in areas of special concern. This included movement of planned survey points to new locations that still meet science goals but did not disturb the areas of special concern and, in other areas, focusing survey work on previously disturbed lands, which had the additional benefit of easier field access. The local knowledge provided through the consultation process was of significant benefit to field operations. Thirty-four project participants, including the pilot and a wildlife monitor from the Lil'wat First Nation, spent a total of 375 person days in the field. One field camp was established and the remainder of the field crew conducted daily set-outs by helicopter and worked from logging roads. The field program focused on establishing an array of seismometers (UofC), an array of MT stations focused on the shallow geothermal system (GSC) and the deeper volcanic plumbing (UofA), a gravity survey (SFU), bedrock mapping (UBC), fracture and rock-property studies (GSC), and thermal-spring geochemistry (DC and GSC; Figure 1).

Passive Seismic

Fifty-nine passive-seismic sites, each consisting of a Hawk field-station unit (INOVA Geophysical) connected to 10 Hz three-component geophones, were established (Figure 1). Each Hawk station is powered by a 288 watt-hour battery pack. Sampling Mount Meager in its entirety allows for characterizing crustal structures associated with the area of high geothermal heat and how those vary within the geothermal system. The observations from this array will be used to identify the distribution of low seismic-wave speeds, which can mark the distribution of fractures that serve as pathways for geothermal fluids, as well as magma chambers. Detecting and locating the local seismicity during this brief seismic deployment will provide constraints on the pattern of faults and fractures within Mount Meager that allow for fluid circulation through this geothermal system. The Hawk systems are also being tested for their ability to record more distant earthquakes and whether those signals can be used to measure structures within the Garibaldi volcanic belt.

In addition, a fibre-optic distributed-sensing network with 380 channels was installed on the East Ridge of Mount Meager. While this type of instrument installation is unprecedented, the data are expected to contribute improved resolution to the geophone array. Data will be analyzed in terms of seismicity in the area, tomographic studies for reservoir imaging and assessment of natural hazards.

Magnetotelluric

Collection of magnetotelluric (MT) data was aimed at greatly expanding coverage beyond that collected in the

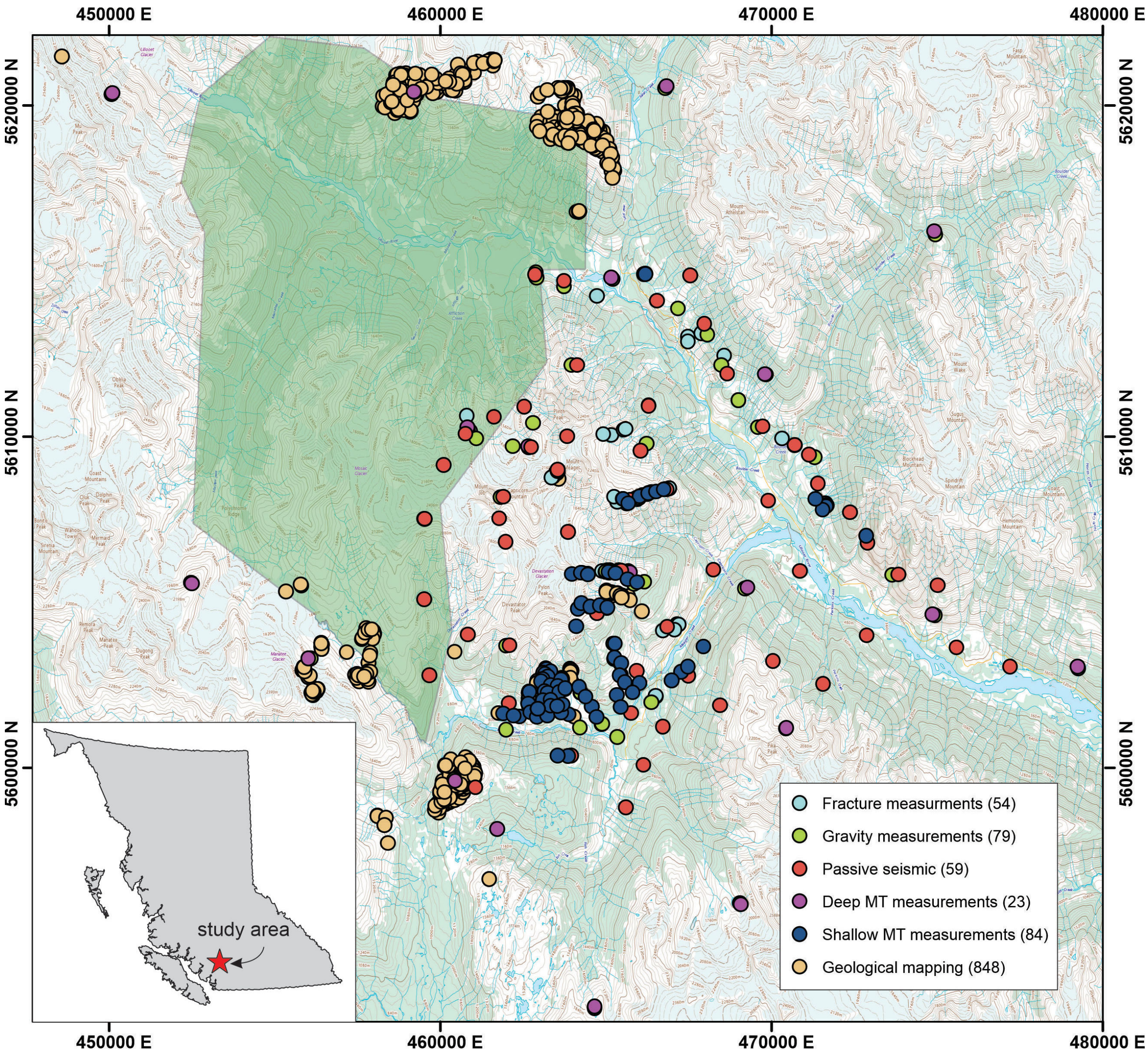

Figure 1. Mount Meager study area, showing field stations visited during the 2019 research program.

1980s (Jones and Dumas, 1993), using modern and more field-portable instruments. When combined with recently developed 3-D inversion techniques, a fully 3-D subsurface resistivity model will be developed. The MT data collection in 2019 at the Mount Meager Volcanic Complex was performed on two spatial scales. In the region of the geothermal reservoir on the south side of Pylon Peak, MT measurements were made in a dense grid of 84 stations by the GSC MT group to study the details of the geothermal reservoir (Figures 1, 2). The goal of the survey was to use the new MT data to determine permeability variations in the subsurface and link these to flow rates observed at the surface. Since the target was in the upper 1–2 km, this only requires high-frequency MT measurements in the band 1–10000 Hz, referred to as 'audio-magnetotelluric' (AMT) data. A related set of 23 MT measurements was taken by the UofA MT group to understand the deeper structure of the system, which requires longer recording time and consequently reduced the total number of measurement locations. The deeper focus MT survey was designed to image pathways that carry fluids to the geothermal reservoir and the fumaroles on Job Glacier. These deep MT measurements will also define the size and content of any magma bodies beneath the volcano. With the deeper exploration targets, lower frequencies were used in a broadband-magnetotelluric (BBMT) survey.

A key aspect of MT data analysis will be to elucidate the cause of zones of high and low resistivity found beneath Mount Meager. Resistivity contrasts in this type of environment can be caused by saline fluids, molten rock or minerals formed by hydrothermal alteration. External constraints are

Figure 2. Survey crew being set out by helicopter.

often needed to distinguish between these alternatives. It was once assumed that both geothermal reservoirs and magma bodies always had a low resistivity. However, careful laboratory experiments in recent years have shown that these assumptions are not always valid. The resistivity of magma depends on the composition, and a high silica content can often produce molten rock with a relatively high resistivity, thus making detection with electromagnetic methods challenging. Similarly, in high-temperature geothermal fields, the clay alteration minerals formed do not necessarily have a low resistivity, resulting in a reservoir that can be relatively resistive compared to the surrounding rock. Analysis of the new resistivity 3-D models from Mount Meager will be supported by other geological and geophysical datasets collected in the 2019 field campaign and from previous exploration activity.

Gravity

Spatial gravity measurements, in conjunction with other geophysical methods, are particularly useful in mapping the magmatic and hydrothermal subsurface features of volcanoes. During the summer of 2019, gravity measurements were taken at 79 stations around the Mount Meager Volcanic Complex (Figure 1), with the aim of mapping its internal structure. Gravity was measured with a Lacoste & Romberg spring gravity meter in order to develop a Bouguer anomaly map of the area. The network comprises both a dense distribution of sites near the volcanic edifice and more broadly spaced stations with increasing distance from the mountain. This distribution seeks to investigate the deep magmatic structures (depth >10 km) by comparing data from distal stations with data from the proximal dense network of stations. Smaller scale structures, such as the hydrothermal system of Mount Meager, will be mapped by analyzing gravity change between stations closer to the edifice. The measured Bouguer anomalies will be analyzed via an informed inverse-modelling approach, which combines information from geological and structural mapping, AMT, MT and seismic measurements. This will restrict the number of possible solutions for the inversion and ensure that the results best reflect plausible subsurface geological features.

Bedrock Mapping

Detailed bedrock mapping was conducted to enhance understanding of the nature of the spatial distribution of volcanic rocks that form the Mount Meager Volcanic Complex, with a particular focus on rock types with enhanced reservoir properties. Field mapping included recording rock-property observations at 848 field stations (Figure 1). These results will support the development of hydrogeological models for bulk-rock permeability to better characterize potential fluid flow at depth. High-density fracture zones appear to be associated with major fault and deformation belts. Identification and mapping of these zones using all available means (Landsat imagery and regional geophysical data, field observations, earthquake records) at a regional level will provide the basis for construction of geothermal-resource models. As well, regional mapping of faults and fracture systems will provide new predictive models of preferential orientation of fracture systems. Refined radiometric dating will also aid definition of the youngest (and hottest) flow units with the greatest heat-generation potential; this is critical information for outlining potential 'sweet spots' of geothermal resources.

Fracture Analyses

In order to develop an understanding of the nature of fracture systems and their potential influence on bulk-rock permeability, fieldwork was conducted to measure spatial distribution and variability in fracture orientation and fracture density (Figure 1). This was combined with remote-sensing image analyses and artificial intelligence to define trends, orientations and densities of lineaments through the study area. Identified lineaments were ground-truthed as part of the geological and geophysical mapping program to assess if they represent higher permeability fracture systems. Determination of the regional stress fields is more complex in areas of high topographic relief, as the free surface cannot be assumed to be flat. Methods being used for stress-field determination include well-borehole breakout analyses and bedding slip. Regional data will assist in refinement of the tensile portion of the regional-stress field, which would provide insight into preferred fluid-flow directions. The current stress system will be incorporated using geoscience information (magnitude, location and sense of motion) from historical records of earthquakes in the study area and surrounding vicinities, and constrained by deformation patterns and additional geoscience information from previously drilled boreholes.

Thermal-Spring Geochemistry

The occurrence of natural thermal anomalies in the form of thermal springs, and the chemistry of their water, are important geothermal-exploration tools. Temperature records from hot springs, coupled with water geochemistry, provide physical data that can be used to better understand heat energy in the deeper, hard-to-sample intervals and for critical physical properties of the hostrock. Thermodynamic modelling can also help in understanding fluid-flow paths and depths of steam separation, to better constrain the geothermal system. Calculations of aqueous geothermometers also require detailed fluid geochemistry to allow estimation of maximum temperatures of fluids at depth. Gas geochemistry, including that of noble gases, can also provide insight into the geothermal system. Therefore, new data will be collected through site visits to known thermal and mineral springs in the Mount Meager area, along with geochemical sampling and analyses, and thermodynamic modelling of heat flow in those thermal-spring systems.

Conclusions

The summer 2019 field program was a great success, with abundant new geophysical and geological data collected. These data are still being processed and will be incorporated into projects of three post-doctoral fellows, six Ph.D. projects, one M.Sc. thesis and one B.Sc. study. Final results will be integrated into a new 3-D model of the geothermal and volcanic plumbing of the Mount Meager complex. Results will provide novel new methods to help predict the occurrence of permeability at depth and greatly reduce the risk associated with drilling for geothermal reservoirs in volcanic systems of British Columbia.

Acknowledgments

The authors gratefully acknowledge the support of T. Jenkins and M. Bruce of Lil'wat First Nation in providing guidance in the field and logistical planning. Pilots M. Accurrso, D. Vincent and R. Slinger of No Limits Helicopters provided expert service. Innergex Renewable Energy Inc. provided significant support to the field program through access to their field bunkhouse. Field assistance was provided by K. Biegel, R. Bryant, J. Smale, H. Su, A. Williamson and A. Wilson. Funding for this project was provided by Geoscience BC and Natural Resources Canada. The University of Alberta group was supported by funding from the Natural Sciences and Engineering Council of Canada (NSERC) through a Canada First Research Excellence Fund (CFREF) award (Future Energy Systems) and a Discovery Grant to M. Unsworth. The University of Calgary group was supported by funding from the Canada Research Co-ordinating Committee through a New Frontiers in Research Fund award and a Discovery Grant to J. Dettmer. Financial assistance was provided to R. Salvage by the Microseismic Industry Consortium. E. Little provided a helpful review of this manuscript.

References

Grasby, S.E., Allen, D.M., Bell, S., Chen, Z., Ferguson, G., Jessop, A., Kelman, M., Ko, M., Majorowicz, J., Moore, M., Raymond, J. and Therrien, R. (2011): Geothermal energy resource potential of Canada; Geological Survey of Canada, Open File 6914, 322 p., <https://doi.org/10.4095/288745> [October 2019].

Jessop, A. (2008): Review of National Geothermal Energy Program, Phase 2 – geothermal potential of the Cordillera; Geological Survey of Canada, Open File 5906, 86 p., <https://doi.org/10.4095/225917> [October 2019].

Jones, A.G. and Dumas, I. (1993): Electromagnetic images of a volcanic zone; Physics of the Earth and Planetary Interiors, v. 81, no. 1–4, p. 289–314, <https://doi.org/10.1016/0031-9201(93)90137-X> [October 2019].

Witter, J. (2019): South Meager geothermal project – new perspectives from recently unearthed data; Geoscience BC, Report 2019-07, 5 p., URL <http://www.geosciencebc.com/i/pdf/Report-2019-07-Innovate-Geothermal.pdf> [November 2019].