The geothermal potential of Nazko Cone, British Columbia

by

Megan Dewit

Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science Honours in the Earth Sciences

Faculty of Science

© Megan Dewit 2014

SIMON FRASER UNIVERSITY

Fall 2014

All rights reserved. However, in accordance with the Copyright Act of Canada, this work may be reproduced, without authorization, under the conditions for "Fair Dealing." Therefore, limited reproduction of this work for the purposes of private study, research, criticism, review and news reporting is likely to be in accordance with the law, particularly if cited appropriately.
Approval

Name: Megan Dewit
Degree: Bachelor of Science Honours
Title: The geothermal potential of Nazko Cone, British Columbia

Examining Committee: Chair: Glyn Williams-Jones
                        Associate Professor

Glyn Williams-Jones
Senior Supervisor
Associate Professor

Firstname Surname
Senior Supervisor
Assistant/Associate/Professor

Firstname Surname
Supervisor
Assistant/Associate/Professor

Firstname Surname
Supervisor
Assistant/Associate/Professor

Firstname Surname
Supervisor
Assistant/Associate/Professor

Firstname Surname
Internal Examiner
Assistant/Associate/Professor
School/Department or Faculty

Firstname Surname
External Examiner
Assistant/Associate/Professor
Department
University

Date Defended/Approved: Month ##, ####
Partial Copyright Licence

The author, whose copyright is declared on the title page of this work, has granted to Simon Fraser University the non-exclusive, royalty-free right to include a digital copy of this thesis, project or extended essay[s] and associated supplemental files ("Work") (title[s] below) in Summit, the Institutional Research Repository at SFU. SFU may also make copies of the Work for purposes of a scholarly or research nature; for users of the SFU Library; or in response to a request from another library, or educational institution, on SFU's own behalf or for one of its users. Distribution may be in any form.

The author has further agreed that SFU may keep more than one copy of the Work for purposes of back-up and security; and that SFU may, without changing the content, translate, if technically possible, the Work to any medium or format for the purpose of preserving the Work and facilitating the exercise of SFU's rights under this licence.

It is understood that copying, publication, or public performance of the Work for commercial purposes shall not be allowed without the author's written permission.

While granting the above uses to SFU, the author retains copyright ownership and moral rights in the Work, and may deal with the copyright in the Work in any way consistent with the terms of this licence, including the right to change the Work for subsequent purposes, including editing and publishing the Work in whole or in part, and licensing the content to other parties as the author may desire.

The author represents and warrants that he/she has the right to grant the rights contained in this licence and that the Work does not, to the best of the author's knowledge, infringe upon anyone's copyright. The author has obtained written copyright permission, where required, for the use of any third-party copyrighted material contained in the Work. The author represents and warrants that the Work is his/her own original work and that he/she has not previously assigned or relinquished the rights conferred in this licence.

Simon Fraser University Library
Burnaby, British Columbia, Canada

revised Fall 2013
Abstract

Nazko Cone, located in the Nechako basin near Quesnel, British Columbia, is the youngest volcanic member of the Anahim volcanic belt, an eastward-younging field of small volcanic centers related to a hot spot. While the last eruptive activity in the area dates to 7200 BP, an earthquake swarm in 2007 was in all likelihood the result of magma injection into the lower crust. Initial exploration into a possible deeply-circulating/volcanic geothermal system associated with the volcano has revealed geothermal manifestations such as travertine mounds, both fossil and actively forming, and vigorous CO₂ degassing (up to 14% concentration in the diluted, diffuse gas) from various vents in two bogs near Nazko Cone. Chemical analyses of the gases collected in pre-evacuated Giggenbach-style bottles indicate that CO₂ is the dominant species with minor amounts of CH₄ and He (< 1 wt %) (Alterra Power, pers. comm.). Isotopic analyses of the $^{13}$C$_{CO₂}$ suggest the gas is mainly of magmatic origin, although additional analyses need to be carried out to fully characterize the emissions. In this regard, a shallow ground temperature survey was performed in the bogs. A Bouguer gravity survey was carried out to map the subsurface structures in the area to determine the relationship, if present, between subsurface structures/geology and the surface manifestations. The geophysical and geochemical data collected were modelled in 3D (inverse/forward) to determine the extent and potential of any geothermal system in the Nazko Cone area.

Keywords: gravity; CO₂; geothermal; Nazko; volcano
For my parents, who supported me every step of the way, and who took me on the fateful trip to Stromboli which inspired my love for volcanoes.
Acknowledgements

I would like to thank my friends and family for keeping me sane when I was going crazy from the stress of writing my first thesis. My last semester was especially difficult, and they helped me get through it more than they know.

Thank you to my professor, Glyn, who read all the versions of my thesis, gave valuable comments, and put up with rookie me in the field.

Thanks Patricia for being a great field assistant (even though you were a grad student and I was an undergrad!). Having a friend like you in the field and in the lab made everything so much fun!

I’d also like to thank Craig, my other field assistant, for all his guidance in creating my first gravity survey and efficiently carrying out field work. Going through all the processing and reworking of my data was time-consuming and frustrating, to say the least, and Craig’s patience, help, and input was invaluable.

Thank you to Jeff, my labmate, whose goofyness always cheered me up when the work was bogging me down, and whose expertise was definitely needed and wholly appreciated.

Thank you Nathalie, for going through all of my long and tedious versions of my thesis, and giving me great feedback to make it a final product I can be proud of.
# Table of Contents

Approval ................................................................................................................................. ii
Partial Copyright Licence ...................................................................................................... iii
Abstract ................................................................................................................................. iv
Dedication ............................................................................................................................... v
Acknowledgements ................................................................................................................ vi
Table of Contents .................................................................................................................. vii
List of Figures ......................................................................................................................... viii
List of Acronyms .................................................................................................................... ix

## Chapter 1. Introduction ................................................................................................. 1
1.1. Regional Geology ........................................................................................................... 2
1.2. Anahim Volcanic Belt ................................................................................................. 4
1.3. Nazko Cone Geology ................................................................................................. 6

## Chapter 2. Methodology ................................................................................................. 9
2.1. CO₂ ............................................................................................................................... 9
2.2. Gravity .......................................................................................................................... 12
  2.2.1. Correcting the Data .............................................................................................. 14
  2.2.2. Regional Gravity Field ......................................................................................... 16
  2.2.3. GROWTH Modelling ....................................................................................... 19

## Chapter 3. Results .......................................................................................................... 21
3.1. CO₂ ............................................................................................................................. 21
3.2. Gravity ........................................................................................................................ 26

## Chapter 4. Discussion ..................................................................................................... 34

## Chapter 5. Conclusions .................................................................................................. 39

References ............................................................................................................................ 41

Appendix A. Nettleton’s Method ......................................................................................... 43
Appendix B. Regional Gravity Field ................................................................................... 47
Appendix C. Stable Carbon Isotope Values ....................................................................... 61
Appendix D. Gravity Model Depth Slices .......................................................................... 62
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tectonic regime of western North America.</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Terrane map of British Columbia.</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Map of location of Nazko Cone.</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>Geological map of Nazko Cone.</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>Carbon dioxide measurement apparatus for dry sediment.</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>Carbon dioxide measurement apparatus for water-saturated sediment.</td>
<td>11</td>
</tr>
<tr>
<td>7</td>
<td>Thermocouple used to obtain temperature measurements.</td>
<td>11</td>
</tr>
<tr>
<td>8</td>
<td>Map showing gravity stations.</td>
<td>13</td>
</tr>
<tr>
<td>9</td>
<td>Relationship between distance averaged in each filter and RMS values.</td>
<td>18</td>
</tr>
<tr>
<td>10</td>
<td>Schematic diagram of Cache Creek and Stikinia terranes.</td>
<td>19</td>
</tr>
<tr>
<td>11</td>
<td>Map of stabilized (equilibrium) concentrations of CO$_2$.</td>
<td>22</td>
</tr>
<tr>
<td>12</td>
<td>Map of maximum CO$_2$ concentrations reached.</td>
<td>23</td>
</tr>
<tr>
<td>13</td>
<td>Map of gas samples taken for stable carbon isotope analysis.</td>
<td>24</td>
</tr>
<tr>
<td>14</td>
<td>Map of temperature (°C) profiles obtained in the North bog.</td>
<td>25</td>
</tr>
<tr>
<td>15</td>
<td>Residual gravity anomaly map of Nazko field area.</td>
<td>27</td>
</tr>
<tr>
<td>16</td>
<td>Depth slice at 210 m above base station height.</td>
<td>28</td>
</tr>
<tr>
<td>17</td>
<td>Depth slice at 50 m above base station height.</td>
<td>29</td>
</tr>
<tr>
<td>18</td>
<td>Depth slice at 130 m below base station height.</td>
<td>30</td>
</tr>
<tr>
<td>19</td>
<td>Depth slice at 330 m below base station height.</td>
<td>31</td>
</tr>
<tr>
<td>20</td>
<td>Depth slice at 560 m below base station height.</td>
<td>32</td>
</tr>
<tr>
<td>21</td>
<td>Regional geological map of Nazko Cone and the surrounding area.</td>
<td>36</td>
</tr>
<tr>
<td>22</td>
<td>Map of CO$_2$ and gravity anomalies with relation to Nazko Cone.</td>
<td>38</td>
</tr>
</tbody>
</table>
List of Acronyms

SFU        Simon Fraser University
AVB        Anahim Volcanic Belt
BBD        Bella Bella dyke swarm
KIP        King Island Pluton
RMS        Root mean square
m.a.s.l.    meters above sea level
Chapter 1.

Introduction

Nazko Cone is a small polygenetic cinder cone in central British Columbia, Canada. It is the easternmost center in the Anahim Volcanic Belt (AVB), an east-west trending, eastward-younging chain of volcanic centers theorized to have formed by a mantle hot spot (Bevier et al., 1979). The AVB is host to several forms of volcanic edifices, ranging from intrusive complexes (exposed dyke swarms and plutons) at its Western reaches, to extrusive volcanic features to the East, such as composite shield volcanoes and cinder cones (Bevier et al., 1979). The volcanic centers of the AVB generally overlie Miocene flood basalts of the Chilcotin Group, which in turn overlie the Devonian to Middle Triassic Stikinia volcanic arc terrane (Johnston & Borel, 2007; Souther et al., 1987).

Nazko was formed by three eruptions: two subaerial and one subglacial, generating several types of deposits which built up to form the modern edifice, which rises approximately 200 m above the surrounding topography (Souther et al., 1987). The region has shown significant seismicity in the past, evidenced by a swarm of 800 microquakes at a depth of 25-30 km in 2007, which occurred 20 km southwest of Nazko Cone (Cassidy et al., 2011).

Preliminary field studies by Alterra Power Corp. around Nazko Cone detected cold CO₂ gas seeps and carbonate deposits in two bogs to the northwest of the cone. The occurrence of active degassing near the cone, as well as recent seismicity, indicated the possibility of some sort of activity in the area, so we decided to investigate further. Geothermal resources require the presence of a heat source and circulating fluids, so we aimed to determine the geothermal potential of Nazko Cone, through an investigation of the carbon dioxide gas content in the soil around the cone and bubbling
up in the two bogs, as well as through the mapping of the subsurface plumbing system of the volcano by means of a Bouguer gravity survey (Grasby et al., 2012). The chemistry of the gases being emitted in the vicinity of the cone is useful in determining the presence or absence of geothermal fluids in the area, and knowledge of the plumbing system of the volcano allows us to determine if there are viable heat sources for these fluids.

1.1. Regional Geology

![Figure 1. Tectonic regime of western North America: PP=Pacific Plate; JdFP=Juan de Fuca Plate; NAP=North American Plate; large dots are volcanic centers of the AVB, Pemberton Volcanic Belt (squares), Garibaldi Volcanic Belt (triangles), Alert Bay Volcanic Belt (stars); ages of the volcanic centers (in Ma) are shown by numbers. Solid black lines indicate transform faults, double solid lines are ridges, solid line with triangles indicates subduction zone; shaded area delineates area of Chilcotin Group basalts, arrows show relative plate movements (Bevier et al., 1979).](image)

There are three major plates involved in the tectonics of western North America: the Juan de Fuca, North American, and Pacific plates (Figure 1) (Bevier et al., 1979).
The relative movements between these plates creates a dextral transform margin between the North American and Pacific plates (in British Columbia, this is the Queen Charlotte fault), a divergent margin between the Pacific and Juan de Fuca plates, called the Juan de Fuca Ridge system, and a convergent subduction margin between the Juan de Fuca and North American plates (Bevier et al., 1979).

Figure 2. Terrane map of British Columbia, with Nazko field area indicated by blue-dashed box (Nelson & Colpron, 2007).

The western margin of the North American plate, including most of the province of British Columbia, was formed from the accretion of exotic terranes caused by subduction (Figure 2) (Johnston & Borel, 2007). This subduction created the Canadian Cordilleran orogen, which is made up of five geomorphological belts; from west to east these are the Insular, Coast, Intermontane, Omineca, and Foreland belts (Talinga & Calvert, 2014). From west to east, the central-British Columbian Intermontane belt is composed of the Stikinia arc terrane (light green in Fig. 2; ST), the Cache Creek accretionary complex (shown in red in Fig. 2; CC), and the Quesnel arc terrane (light green in Fig. 2; QN) (Nelson & Colpron, 2007; Talinga & Calvert, 2014). Central British Columbia consists largely of the Stikinia terrane, which is characterized by basal
sedimentary sequences of Devonian and Upper Permian to Middle Triassic age, which were subsequently superposed by arc magmatic sequences and reefs in the Upper Triassic (Johnston & Borel, 2007). The Stikinia arc is overthrusted by the Cache Creek accretionary rocks, which consist of melange belts (oceanic strata and limestones with Permian Tethyan fusulinid faunas), mafic-ultramafic volcanic-plutonic complexes, and large stratigraphic sequences of reef carbonates (Johnston & Borel, 2007; Nelson & Colpron, 2007; Talinga & Calvert, 2014).

Three main groups of young volcanic rock types occur in British Columbia: continental arc-related calc-alkaline rocks of the Garibaldi and Pemberton volcanic belts, back-arc basalts of the Chilcotin Group plateau lavas, and alkaline to peralkaline rocks which occur in the Anahim Volcanic Belt (Bevier, 1989). Subduction of the Juan de Fuca plate created North-South trending continental volcanic arcs in southern British Columbia, the Garibaldi and Pemberton volcanic belts (Bevier et al., 1979). The Chilcotin Group basalts are thought to be the result of backarc volcanism from this subduction, erupted from numerous vents along a northwest trend in the Early Miocene to Early Pleistocene (Souther et al., 1987). These basalts cover an area of approximately 25,000 km² in south-central British Columbia, extending from the Okanagan Highland in the southeast, to the Quanchas Range and Poplar Buttes in the northwest (Mathews, 1989). The majority of the volcanic centers of the Anahim Volcanic Belt overlie the Chilcotin Group basalts, and are discordant to the continental arc trend of the Garibaldi and Pemberton volcanic belts (Bevier et al., 1979).

1.2. Anahim Volcanic Belt

The Anahim Volcanic Belt (AVB) is an approximately East-West trending belt of upper Miocene to Quaternary plutonic and volcanic rocks, which extends across central British Columbia from the west coast, near Bella Bella, to the Interior Plateau, near Quesnel (Figure 1) (Bevier et al., 1979; Cassidy et al., 2011; Souther et al., 1987). The AVB extends for approximately 600 km at about 52° latitude (Bevier et al., 1979). The westernmost volcanic feature in the belt is the Bella Bella dyke swarm (BBD), dated at 14.5-12.5 Ma, moving east to the subvolcanic King Island Pluton (KIP), aged at 13-10.3 Ma (Souther, 1986). The central portion of the belt is characterized by three large
composite shield volcanoes: Rainbow Range (8.7-6.7 Ma), Ilgachuz Range (6.1-4.1 Ma) and Itcha Range (3.5-1.1 Ma), with minor basaltic cones and flows (Bevier, 1989; Souther et al., 1987; Souther, 1986). The BBD and KIP are alkaline to peralkaline in composition and are petrographically similar to the volcanic complexes in the central portion of the AVB, and so are thought to represent the root of a peralkaline magma system in which the BBD are magma conduits connecting the magma chamber, thought to be the KIP, to the volcanic center at the surface, inferred to be the Ilgachuz Range (Souther, 1986). These formerly subvolcanic features are presently exposed at the surface due to uplift (of about 0.5-4 km) and subsequent erosion in the Coast Mountains over the past ten millions years (Bevier, 1989). The easternmost and youngest volcanic center in the AVB is a polygenetic cinder cone, Nazko Cone, dated at 340-7.2 kya (Souther, 1986).

There are three main hypotheses for the origin of the AVB: continental rifting, melting of the slab edge or mantle magmas rising in a slab window from the subduction of the Juan de Fuca plate beneath North America, or the AVB is the surface trace of a mantle hot spot (Cassidy et al., 2011). The onset of volcanism at each center in the AVB decreases in age eastwards along the belt, which can be explained by the generally accepted theory that the North American plate is moving westwards over a hot spot (Bevier et al., 1979). Using the dates of the centers and the distances between, it was determined by Bevier et al. (1979) that the rate of eastward migration of volcanic activity is 2.0-3.3 cm/year, which is consistent with both the movements of the hotspots beneath Yellowstone (Wyoming, U.S.A.) and Raton (New Mexico, U.S.A.), calculated to be 2.7 cm/year, as well as the calculated rate of movement of the North American plate (2.5 cm/year) (Bevier et al., 1979). Seismic body-wave tomography profiles show a low velocity anomaly centered beneath Nazko Cone and extending to a depth of ~400 km, which occurs beneath the entire AVB, and is flanked on all sides by high velocity anomalies (Mercier et al., 2009). This also supports the hot spot theory, in that it possibly indicates a source for the magmas of the AVB (Cassidy et al., 2011).
1.3. Nazko Cone Geology

![Map of Cariboo region of British Columbia, showing location of Nazko Cone (red marker) in relation to Quesnel and Prince George (Google Maps, 2014).](image)

Nazko Cone lies about 130 km southwest of Prince George, British Columbia, and about 75 km east of Quesnel (Figure 3). It is a polygenetic cinder cone; its edifice was generated from multiple, or in this case three, eruptions (Souther et al., 1987). The first eruption at Nazko produced olivine-phyric basalt lava flows, which have a whole-rock K-Ar date of 0.34 ± 0.03 Ma (magenta-coloured unit in Figure 4) (Souther et al., 1987). These flows show no evidence of subaqueous quenching, so are inferred to have been erupted subaerially during an interglacial interval in the Pleistocene (Souther et al., 1987). A unit of quenched blocky basalt and tuff breccia with local pillow formations were erupted in a second episode of activity at Nazko, forming a conical mound on the west side of the cone (yellow unit in Figure 4) (Souther et al., 1987). Given the evidence suggesting the material was erupted subaqueously, this second
eruption presumably occurred during the Fraser Glaciation (25-10 kya) when the cinder cone was submerged in glacial meltwaters underneath 1500-2000 m of ice (Souther et al., 1987). The third and last known eruption of Nazko cone issued basaltic tephra and pyroclastic material (bombs and agglutinated spatter) from three adjacent vents, which built up to form the cone present today (blue, green, and orange units in Figure 4, respectively) (Souther et al., 1987). The vents were breached on their western rims by two olivine-phyric basalt lava flows, which were deflected around the subglacially erupted mound of material as they flowed down the west flank of Nazko (Souther et al., 1987). Peat layers directly above and below the tephra layer in a bog which lies 2.5 km north-northwest of the cone were radiocarbon dated, and give an age for this eruption of about 7.2 kya (Souther et al., 1987). As only a single layer of tephra was identified in this bog, it is unlikely there were other Holocene eruptions at Nazko (Souther et al., 1987). The edifice rises approximately 120 m above the local topography, and was built up by a total volume of material estimated to be less than ~0.1 km$^3$ (Souther et al., 1987).

The composition of Nazko lavas is classified as basanite, due to a calculated 10-15% normative nepheline, whereas other basalts in the Anahim Volcanic Belt contain less than 5% normative nepheline, and so are classified as alkali olivine basalts and hawaiites (Souther et al., 1987). This compositional variation reveals an apparent eastward trend of increasingly silica undersaturated alkaline lavas in the AVB, which possibly indicates a deeper or less depleted mantle source for more easterly volcanics (Souther et al., 1987). There is a decrease in alkalinity with time within the lavas of the different eruptions at Nazko itself, which probably indicates small-scale mantle heterogeneity, also exemplified by the variable chemistry of local Chilcotin Group lavas (Souther et al., 1987).

Though Nazko has not erupted since 7.2 kya, a significant seismic swarm including eight earthquakes of magnitude 2.3-2.9 occurred within 20 km southwest of the cone on the 9-10 October, 2007 (Cassidy et al., 2011). During the following three weeks, more than 1000 microquakes of magnitude 1-2 occurred within a 5 km radius of the initial epicenters (Cassidy et al., 2011). Examination of the S-P wave times suggests the foci were at approximately 25-35 km depth, with the Moho inferred to be at 30 km
depth (Cassidy et al., 2011). This led to the interpretation that the earthquakes represent the injection of magma into the lower crust beneath the Nazko region (Cassidy et al., 2011).

Figure 4. Geological map of Nazko Cone; modified from Souther et al., 1987.
Chapter 2.

Methodology

To examine the geothermal potential of Nazko Cone, we measured the carbon dioxide gas content within the soils around the cone and bubbling up in two bogs to the northwest of the cone. In addition, we conducted a Bouguer gravity survey to image the subsurface plumbing system of the volcano. We collected these data over two field seasons in August 2013 and August 2014.

2.1. CO₂

We completed the carbon dioxide survey using a hand-held Vaisala GM-70 CO₂ system with a measurement range of 0-20%. The apparatus included the Vaisala pump, connected through tubing to either a funnel (which sat ~5 cm into water, at sites within the bogs) or a hollow metal probe with holes at the end (which was inserted ~30 cm into the soil), with a particle/water filter and pipette bulb (the location into which the syringe was inserted to obtain samples of the gas) along the tubing line (Figure 5, Figure 6). We recorded both when the CO₂ values plateaued (when they stabilized) and the maximum concentration reached. When pumping the soil and bog gases through the CO₂ detection system, if a concentration of 1% was reached, we collected a sample of the gas in an evacuated tube, and subsequently sent it to the University of Calgary to obtain stable carbon isotope analyses. To gain insight into a possible temperature anomaly associated with the degassing bogs, we carried out several profiles across the north bog with a 12 cm-long thermocouple which was inserted fully into the ground (Figure 7).
Figure 5. Carbon dioxide measurement apparatus for dry sediment; metal probe is inserted into ground (middle of photo behind case), and connected via tubing to the pump and meter (in yellow case in foreground). Along the line is a particle filter.
Figure 6. Carbon dioxide measurement apparatus for water-saturated sediment (within the bogs); a funnel (middle right) is inserted ~5cm into the water, and is connected via tubing to the pump and meter (left, foreground). Along the line are a particle filter (white) and pipette bulb (red).

Figure 7. Thermocouple used to obtain temperature measurements in the North bog.
2.2. Gravity

We carried out the gravity survey centered on Nazko Cone, covering an area of approximately 12 km by 14 km (Figure 8). The spacing of the stations varied between 100-500 meters, with closer spacing near and over the cone, and wider spacing further out to capture any regional signatures. We utilized a G127 LaCoste-Romberg gravity meter, which was precisely located using a Leica GPS-500 differential GPS system. We collected the gravity data around Nazko at one-second intervals, then processed the station gravity values using MATLAB code called gTOOLS, which calculates the instrument drift, performs Earth tide corrections, averages repeat values, and references all stations to the base station (Battaglia et al., 2012).
Figure 8. Map showing the stations at which gravity values were obtained, and the base station to which all heights and corrections were referenced.
2.2.1. Correcting the Data

Observed gravity values obtained in the field must be corrected for several natural variations in the Earth's gravity field, as these are sources of error in the computation of the local gravity in the study area.

One such correction is applied to compensate for the variable pull on the Earth by other planetary bodies, such as the Sun and the Moon. This gives rise to Earth tides, similar to those observed in the oceans as a response to the pull of the gravity of the Moon (Reynolds, 1997). As with ocean tides, Earth tides occur on a regular cycle, and so can be easily computed; in this case, I removed the effect of the Earth tides on the Nazko gravity data using the MATLAB code gTOOLS (Battaglia et al., 2012), which also removes the error induced in the data by instrumental drift. Due to the mechanism within the gravity meter being a spring and a mass, it is subject to elastic creep, which causes the gravity values to slowly increase or decrease over the course of a day (Reynolds, 1997). To compensate for this drift, it is possible to calculate the change in gravity over the day by carrying out repeated measurements at the same location every few hours (Reynolds, 1997). In the case of Nazko, it was not possible to return to the base station multiple times throughout the day, as the driving times would have made the number of stations collected every day much smaller. Instead, we measured the value of the gravity at the base station at the beginning and end of every field day, and repeated measurements at various other stations when time permitted.

The Earth is approximated as a sphere, but in reality, it has a larger radius at its equator than it does at its poles. Thus, as you move north or south from the equator, the distance between the surface of the Earth and its center decreases (Reynolds, 1997). According to Newton’s law of gravity, if the distance to the center of mass decreases, the gravitational effect of that body increases. Gravity therefore increases with latitude, and so must be corrected for this difference when trying to observe the local gravitational field (Reynolds, 1997). I used the base station, GRB (Figure 8), as a datum for the latitudinal gravity corrections, meaning all stations further north than GRB, because it is in the Northern Hemisphere, will have their latitude corrections subtracted from the observed gravity, and all stations more south than GRB will have their latitude corrections added.
The elevations for all the stations of course, are different. The difference between the height of the station and the reference height (the height of station GRB) will cause a difference in the gravity field measured, because any station above the datum height will have a greater distance from the center of the Earth and therefore a lower gravity value, and vice versa. This variation in the gravity field measured is compensated for by the Free Air correction, which offsets the change in gravity from the altered distance to Earth’s center of mass (Reynolds, 1997). If the station in question is higher in elevation than the height datum, the Free Air correction will be added to the observed gravity value, and if it is lower than the datum, the Free Air correction is subtracted. The Free Air correction does not account for any extra or less rock mass between the station and the center of the Earth, so this is where the Bouguer correction is applied. The Bouguer correction compensates for an infinite slab of a specified rock density ($\rho$) and thickness $h$, where $h$ is equal to the difference in height between the elevation datum and the station height (Reynolds, 1997). Extra rock mass between the station and the datum would increase the pull of gravity, thereby increasing the observed gravity values, and less rock mass above the station up to the datum would decrease the pull upwards on the gravity and thereby also increase the observed gravity; the Bouguer correction therefore is always subtracted (Reynolds, 1997).

The variation in topography between stations causes perturbations in the observed gravity values. This is because if the station is on top of a topographic high next to a valley, the lack of rock mass within the valley will pull less on the mass in the gravity meter, and will decrease the observed gravity at that station. In a similar fashion, if the station is within a valley next to a topographic high, the increased rock mass above the station will pull up on the mass in the gravity meter, thereby also decreasing the observed gravity. For this reason, the terrain correction, whereby changes in the surrounding terrain are compensated for, is always added to the observed gravity (Reynolds, 1997).

At most of the stations, we used the Hammer method, as described in Nowell (1999), to estimate the inner terrain corrections up to a distance of 50-200 m, depending on how much the local topography changed (the greater the variation, the greater the distance to which we estimated the terrain corrections) (Nowell, 1999). For the
remaining stations, I used a code called Grav_Terr_Corr (Supri Soengkono, 2014, pers. comm.) to convert 8 meter Canadian Digital Elevation Data (CDED) to values for inner Hammer circles. To evaluate the outer terrain corrections, I used the same program to convert the 8 m CDED into Hammer circle values for distances up to 22 km from each station.

After I applied the drift, Earth tides, and latitude corrections to the Nazko gravity data, I used Nettleton’s method to obtain an estimate of the density of the regional rocks (Reynolds, 1997). This involves calculating the Bouguer anomaly (the resulting gravity from the application of the Earth tides, instrumental drift, latitude, Free Air, Bouguer, and terrain corrections) for a range of densities (1600-2900 kg/m³) and determining, by graphical means, which density results in an anomaly which least resembles the topography. When computing the Bouguer anomaly, it is necessary to also apply the free air and terrain corrections, so I calculated these using the range of densities as well. I created three profiles in a roughly northwest-southeast trend, showing the Bouguer anomaly for the various densities against the topography for the same station profiles (see Appendix A). The rock densities which least followed the topography were between 2300-2400 kg/m³ in every profile, so I used an average density of 2350 kg/m³ to calculate the final Bouguer anomaly.

2.2.2. Regional Gravity Field

The final correction to be applied before modelling was the subtraction of the regional gravity field. In order to find the regional Bouguer gravity anomaly, I created a 100 m grid in Surfer of the Bouguer gravity anomaly values from only the stations outside of the dense network over and around Nazko cone. I carried out two different methods of calculation on this regional Bouguer gravity anomaly to obtain the optimal regional field: polynomial regression and low-pass filters (see Appendix B). To quantitatively describe the level of fit of the regional model to the actual data, I used Surfer to calculate the residual gravity values once the surface had been subtracted from the regional Bouguer anomaly, and subsequently found the root mean square (RMS) of the residuals. The lower the RMS value, the smaller the residuals are, which means the calculated surface fits the actual data more accurately, and vice versa. When this value
is too low, however, the surface fits the data too well, and shows high-frequency variations in gravity, which is not ideal when trying to determine an overall trend in the regional gravity. The ideal root mean square, therefore, is usually chosen to be an average value between the highest and lowest values.

In polynomial regression, I tested several orders of polynomials to find the best-fit surface to describe the regional gravity trend. The quadratic surface, or second-order polynomial, fit the data best, and showed the lowest RMS value of the set of polynomial regression surfaces. The lower order polynomials gave higher values for the RMS, and therefore did not fit the data as well, but displayed a more generalized regional field (showing less variation than in higher-order polynomial surfaces).

I also investigated several Gaussian-weighted low-pass filters, and varied the number of neighbouring cells used in the calculation over a range of 11 x 11 cells at a cell width of 100 m (equivalent to ~1 x 1 km), to 33 x 33 cells at a cell width of 300 m (equivalent to ~10 x 10 km). Low-pass filters remove high-frequency variations in the field, and average each cell based on the values in the neighbouring cells, meaning the more cells used to average, the less variation there will be in the values of the cells. In the same way as with the polynomial regression surfaces, I computed the residuals and the root mean square values of these residuals. To observe any trends in the RMS values, I plotted them against the distance to which the averaging was done in each of the successive filters. As expected, the more cells involved in the averaging of the gravity values, the greater the RMS value, as the filtered data fits the observed data less and less (Figure 9). As the radius to which the values were being averaged increased to being closer to the size of the field area, the resulting regional trend did not change significantly between models. Therefore, the filter where the distance to which cell values were averaged was closest to the dimensions of the field area was the optimal regional gravity trend from the low-pass filters; in this case the optimal filter was the 10 x 10 km filter.
A very simplified geometry of the Canadian Cordilleran orogen can be represented by multiple thrust sheets of accreted terranes, with thrust faults striking roughly north-south (Figure 10). In the Nazko region, the Stikinia volcanic arc terrane, consisting of intermediate composition arc volcanics overlying sedimentary sequences, is overthrust by the accretionary complex of the Cache Creek terrane, which includes former oceanic crust (mafic to ultramafic volcanic and plutonic rocks), as well as carbonate sequences (Johnston & Borel, 2007; Talinga & Calvert, 2014). The more mafic nature of the Cache Creek rocks suggests a higher density overall for the Cache Creek terrane than the Stikinia terrane. In terms of the regional gravity field this means that further east, the denser Cache Creek rocks will increase in thickness, thereby increasing the gravity. Assuming the dip of the thrust fault separating the two terranes is constant, this increase in gravity will occur in a linear fashion, giving rise to gravity values which gradually rise to the east.

Though on such large scales this simple geometry may hold true in general terms, the actual geometries of the thrust slices are not perfectly even and smooth. The surfaces of the faults and thicknesses of the terranes in fact are quite irregular, and will therefore result in a locally variable gravity field superimposed on the large-scale linear field. At the scale of the gravity survey we completed, we might expect to see a regional gravity gradient such as this, with slight variations to the overall increasing gravity to the east. This is why I have selected the 10 km Low-Pass Filtered gravity to represent my
regional gravity trend, as it incorporates a roughly linear increasing trend from northwest to southeast with slight perturbations to this pattern.

![Figure 10. Schematic diagram of the relationship between Cache Creek and Stikinia terranes.](image)

I utilized GROWTH version 2.0 software (Camacho et al., 2011) to invert the gravity residuals (the gravity values which remain after subtracting the regional field) into a three-dimensional model of the subsurface.

### 2.2.3. GROWTH Modelling

When creating an inverse model with GROWTH, there are several different parameters which can be adjusted. When modelling the Nazko data, I varied a total of three parameters: the density contrast (difference in density compared to the average regional density), balance factor (balance between the model's fit with the data and the smoothness of the model), and random search coefficient (the precision of the model); others, such as the homogeneity factor, were kept constant. The option to increase density with increasing depth was unused in my model iterations, because the depths I modelled were not deep enough to result in any significant change in density. I had already accounted for the regional terrain density and regional gravity trend using Nettleton's Method and a low-pass Gaussian filter, respectively, so these options were also unused in my GROWTH model calculations.

In my first iterations, I varied the density contrast between models to obtain maximum and minimum values for the Nazko data by experimenting when the model failed, i.e., when it was unable to calculate. The optimal density contrast for my data
should occur somewhere between these two values, in this case 150-700 kg/m$^3$, so I used the average value of ±400 kg/m$^3$ in subsequent models.

The homogeneity factor describes the density transition between anomalies in the model, where a minimum value of zero exhibits sharp boundaries between anomalous bodies, and a maximum value of one makes boundaries more diffuse and dilute (Camacho et al., 2011). More realistic models of gravity have an average homogeneity factor, as most anomalies will not be completely distinct from each other, but also will probably not be fully merged either. I kept the homogeneity factor at 0.2 for all of my models because I wanted the modelled density anomalies to have somewhat sharp boundaries, as it makes discrete structures easier to identify.

The following factor I adjusted was the balance factor ($\lambda$), which describes the balance between model fitness and model smoothness; high $\lambda$ values give small and smooth (diffuse) anomalies, and low $\lambda$ values give a good fit to the data and exhibit many structures (Camacho et al., 2002). It is ideal for this value to be near the middle of its range, because the data is noisy, so too well of a fit with the data will not show real anomalies. In most of my model iterations, I kept the balance factor at the preset value of 30. When I ran the model with an auto-adjustment for the balance factor, the resulting optimal value according to GROWTH was 35.6, so the preset value of 30 is most likely a good fit for the Nazko gravity data.

After obtaining the optimal density contrast, homogeneity, and balance factor, the final adjustable parameter was the random search coefficient ($r$). In a model with $m$ cells, an $r$ value greater than one tests values for $m/r$ cells in the model, so the model is less precise but calculates quickly; an $r$ value of one gives the most precise solution because values are tested for all $m$ cells in the model (Camacho et al., 2011). The $r$ value was set at 5 for the first model iterations, to find the best fit values for the other parameters, but was set at 1 to find the final model solution.

I took the cell values for the final solution calculated with GROWTH, and created several “slices” corresponding to certain depths within the model using Surfer.
Chapter 3.

Results

3.1. CO₂

The values of equilibrium CO₂ gas concentrations at each station have been plotted (Figure 11), and show that most of the samples contained insignificant concentrations (less than 1%). The maximum concentrations measured at each of the stations also show that the majority of samples exhibit unremarkable values (less than 1%), however there are several exceptions, the majority of which are located within two bogs to the northwest of Nazko Cone (Figure 12). The soil gas maximum concentrations of CO₂ at locations away from the bogs ranged between 0 and 1.25%, whereas the maximum CO₂ concentrations of samples of gases bubbling up through bog waters range between 0.369 and 14%. Upon examination of the distribution of the maximum concentrations reached at each sample location (Figure 12), the only trend apparent is that the concentrated CO₂ seeps are localized within these bogs, and do not occur in any other recognizable pattern. The higher values of CO₂ in the bog gas are quite significant when compared to the global average atmospheric concentration of CO₂, which is currently about 0.03%.
Figure 11. Map showing stabilized (equilibrium) concentrations of CO$_2$ at each site.
Figure 12. Map of Nazko region showing maximum CO$_2$ concentrations reached at each site.

Gas samples were extracted from soil and bog gases in several locations, mostly within or near the two bogs to the northwest of the cone due to the occurrence of higher concentrations of CO$_2$ at these locations (Figure 13). Stable carbon isotope analyses obtained from these samples show a definite pattern of highly negative $\delta^{13}$C $\%$ values
(ranging between approximately -20 ‰ to -24 ‰) occurring in locations outside of the bogs, and less negative δ¹³C ‰ values (ranging between approximately -6 ‰ to -7 ‰) within the bogs (see Appendix C). These δ¹³C values correspond to concentrations of carbon dioxide gas of ~0.9-1.8 % and ~2.4-9.3 %, respectively.

Figure 13. Map showing locations of gas samples taken for stable carbon isotope analysis.

Temperature profiles completed in the north bog show no significant variation in the values, which range from 11.1°C to 16.8°C (Figure 14). The average temperature
observed was 14.2°C, with 76% of the temperatures collected ranging between 13.5°C-15.8°C. At sites near the edges of the bogs (in dry sediment), ground temperatures were generally higher than those within the bogs (in water-saturated sediment).

Figure 14. Map showing the temperatures (°C) obtained in the North bog.
3.2. Gravity

Subtraction of the calculated regional gravity field from the Nazko data Bouguer anomaly resulted in a residual gravity anomaly map (Figure 15). Five areas of higher-than-average density values can be distinguished, located to the southeast, south, southwest, and just east of Nazko Cone, as well as a much larger anomaly to the north. Significantly lower than average density values solely occur to the northwest of the cone.

The final inverse model calculated with GROWTH shows several density anomalies in the field area. To the north of Nazko Cone is a large positive gravity anomaly which, in all depth slices, appears to be two positive anomaly peaks which are connected to each other by less dense (but still denser than average) material. A large negative anomaly lies to the northwest of Nazko, exhibiting as small, disjointed, and discrete anomalies near the surface, but becomes connected and has a sinuous character with depth. Two more positive anomalies occur to the southwest and southeast of Nazko Cone, but these masses of greater density are smaller than the positive anomaly to the north of the cone, and do not extend to as great a depth. A small positive anomaly extends from the cone itself to just east of Nazko cone, and has a linear geometry trending approximately east-northeast.
Figure 15. Residual gravity anomaly map of Nazko field area. Dots are stations, with higher density of stations indicating location of Nazko Cone. Values are in mGal.
In the depth slice 210 m above the base station height (approximately 1200 meters above sea level) (Figure 16), many small, discrete density anomalies are visible. A notable positive anomaly (~300 kg/m$^3$ density contrast) occurs just to the east of Nazko Cone, and is slightly crescent-shaped. Other significant positive anomalies occur to the southeast and northeast of the cone, with maximum magnitudes of ~350 kg/m$^3$ density contrast.

Figure 16. Depth slice at 210 m above base station height. Contoured values are density contrast in kg/m$^3$. 
At 50 m above the base station height (~1050 m.a.s.l.) (Figure 17), two small negative anomalies develop near Fishpot Lake, with magnitudes of ~-350 kg/m$^3$, along with a crescent-shaped negative anomaly of ~-400 kg/m$^3$ which occurs to the west of the cone. The positive anomalies to the southeast and northeast of Nazko Cone grow in size and magnitude (~400 kg/m$^3$), and several new significant positive anomalies occur to the north, southwest, and south of the cone (250-350 kg/m$^3$). The crescent-shaped positive body to the east of Nazko Cone increases in magnitude (~350 kg/m$^3$) and occurs slightly north of its location in the previous depth surface, trending about south-southwest.

Figure 17. Depth slice at 50 m above base station height. Contoured values are density contrast in kg/m$^3$. 
At a height of about 870 m.a.s.l. (~130 m below base station height) (Figure 18), a semi-continuous, sinuous negative positive anomaly (up to -450 kg/m$^3$) extends from just west of Nazko Cone to Fishpot Lake. This negative anomaly correlates with the disconnected negative anomalies observed in the 1050 m.a.s.l. depth slice, suggesting the smaller, shallower anomalous bodies are interconnected at depth. The positive anomalies to the north and northeast of the cone become less distinct bodies, almost merging into a single large positive gravity anomaly (up to 400 kg/m$^3$ density contrast). The positive bodies to the southwest, south, and southeast of Nazko do not appear to grow significantly in size between depth slices, but slightly increase in magnitude (~300-350 kg/m$^3$). The positive anomaly to the east of Nazko Cone obtains a more linear shape and moves further north, increasing in magnitude to ~400 kg/m$^3$.

**Figure 18.** Depth slice at 130 m below base station height. Contoured values are density contrast in kg/m$^3$. 
At a depth of approximately 330 m below base station height (~670 m.a.s.l.) (Figure 19), the anomalous body to the south of Nazko Cone disappears, while other positive anomalies to the north, northeast, southwest and southeast increase in size and magnitude (~400 kg/m$^3$). The sinuous negative density body near Fishpot Lake decreased in length, but gained in width and magnitude (~450 kg/m$^3$) between depth slices, occurring further from Nazko Cone with depth. The linear positive body to the east of Nazko begins to decrease in size and magnitude, exhibiting a maximum density contrast of ~300 kg/m$^3$, and again occurs further north than in the previous depth slice.

Figure 19. Depth slice at 330 m below base station height. Contoured values are density contrast in kg/m$^3$. 
In a depth slice of ~560 m below base station height (~440 m.a.s.l.) (Figure 20), the positive anomalies to the southwest and southeast of Nazko Cone decrease in size and magnitude (~300 kg/m$^3$). The interconnected positive bodies to the north and northeast of Nazko decrease in size but retain similar magnitudes, and the negative anomaly to the northwest of the cone decreases in length, obtaining a wider, more irregular shape. The linear positive anomalous body near Nazko Cone disappears at this depth, which gives a total range in elevation for the anomaly between 1200-500 m.a.s.l. (700 m depth range).

**Figure 20.** Depth slice at 560 m below base station height. Contoured values are density contrast in kg/m$^3$. 
The remaining depth slices show decreasing trends in size and magnitude for all remaining anomalous bodies (see Appendix D). The negative anomaly near Fishpot Lake persists to the greatest depth (>1.4 km below base station height), and the smaller positive anomalies near Nazko extend to depths no greater than approximately 1000 m below base station height (approximately sea level).
Chapter 4.

Discussion

Degassing of significant concentrations of carbon dioxide is occurring in two bogs to the northwest of Nazko Cone. Concentrations above 1.8 % are not observed outside of the bogs, indicating the emissions are localized, and the conduits for the rising gases are likely discrete structures. The maximum concentration recorded was 14 %, which is very significant considering the atmospheric CO$_2$ content is only about 0.03 %, and that gas seeps are usually very diluted and diffuse. The stable carbon isotope values of gas samples taken outside of the bogs are in the light δ$^{13}$C ‰ range (-20 to -24 ‰), consistent with carbon from a biologic origin (approx. -30 to -10 ‰ for sediments and plant organics; Sano & Marty, 1995; Cheng, 1996). Isotope values of samples taken from within the bogs, however, show heavy δ$^{13}$C (-6 to -7 ‰), which likely indicates a magmatic character for the carbon-13 in the carbon dioxide gas (-6.5 ‰ for MORB/Mantle; Sano & Marty, 1995). A magmatic character, however, does not necessarily indicate the gas originated from a magma chamber, but rather that the gas is not generated in shallow regions and most likely came from depth.

There was no substantial thermal anomaly associated with the CO$_2$ gases; rather the bog temperatures were lower than atmospheric temperature. The lack of significant thermal variance likely indicates there is no vigorous shallow hydrothermal system in the area, and that if there is a geothermal system at depth, the heated fluids do not reach the surface. The cooler gas temperatures, however, could be due to the reaction between CO$_2$ and water being endothermic; thus when the gas came into contact with the water in the bogs, any thermal anomaly associated with the CO$_2$ may have been used up in the reaction. The temperature profiles we completed in the north bog, however, were done with a temperature probe which was not long enough to reach
beyond the very upper layer of soil/mud, which is possibly not deep enough to observe temperatures beyond diurnal variations.

The solution calculated with GROWTH is non-unique, due to the way the program ‘grows’ the model with cells. The station array to the North and South of Nazko Cone is also limited, which may result in non-real anomalies due to sparse data, however through multiple iterations, similar patterns and magnitudes of anomalies were present in all models over a broad range of density contrasts; thus we are quite confident the modelled anomalies are real.

The various density anomalies observed in the gravity model can most likely be explained by the regional geology of the Nazko area. Most of the region is covered by Quaternary alluvium and glacial deposits, which is comparatively of low density when measured against local occurrences of various volcanic rocks (Figure 21). The high positive anomaly to the north of Nazko Cone coincides spatially with the occurrence of Paleogene Endako Group volcanics, which consist of andesite, basalt, and minor dacite (Massey et al., 2005), accounting for the higher density than the calculated regional average. Apparently connected to this anomaly is another high positive anomaly to the northeast of the cone, occurring in a location consistent with Fishpot Mountain, a local topographic high composed of Paleogene Ootsa Lake Group volcanics (mainly rhyolite, dacite, and trachyte flows) (Massey et al., 2005). The positive anomaly to the southeast of Nazko lies in an area of Quaternary volcanics (Massey et al., 2005), which could possibly be another cinder cone in the region. More Ootsa Lake Group volcanics occur west-southwest of Nazko Cone (Massey et al., 2005), which might explain the presence of a positive gravity anomaly.

The large negative anomaly to the northwest of the cone is overlain by the Quaternary sediment cover (Massey et al., 2005). No corrections were made for the effect of higher amounts of water in certain areas (wetlands, bogs, Fishpot Lake), which may account for minor errors in the observed gravity near water-saturated areas. The depth to which this large negative anomaly near Fishpot Lake persists (>1.4 km), however, is too large to be solely explained by an excess of water in this region as opposed to surrounding areas, and therefore might be explained as a negative anomaly.
compared to the average due to a possible presence of a glacial paleo-valley. The anomaly does not extend beyond the bounds of the Quaternary cover, but instead its occurrence stops abruptly at boundaries coincident with the occurrence of Triassic to Jurassic Takla Group volcanic rocks (Massey et al., 2005).

Figure 21. Regional geological map of Nazko Cone and the surrounding area; modified from Massey et al. (2005).

Nazko Cone and its immediate surroundings consist of Quaternary volcanics (Massey et al., 2005), presumably generated by the various eruptions at Nazko. This
material is denser than the surrounding glacial deposits, hence a positive gravity anomaly near the surface at Nazko Cone. This anomaly, however, extends to approximately 700 m depth, and so cannot be fully explained by the Nazko deposits. The northern migration and apparent lack of change in size and shape of the linear body with depth suggest the anomaly could be semi-planar in three dimensions. The continuous, but slow northern migration with depth of the dense body suggests a high dip angle (~60-80°) to the north.

Near the surface, the west end of the linear positive anomaly is coincident with the location of the vents of Nazko’s last known eruption 7.2 kya, from which two lava flows were emitted. The planar geometry of this mass of higher density material may suggest the presence of a solidified complex of dykes, possibly even feeder dykes to the Nazko eruptions, based on the anomaly location. The strike of the positive anomaly near Nazko Cone is approximately consistent with a dyke observed in outcrop at the southern base of the cone, which strikes at about 062° and is sub-vertical (Figure 22).

The coincidence of the modelled anomalies with regional geological features most likely corroborates my choice of a regional gravity field. If the regional field was not properly removed, the density anomalies in the resulting GROWTH model would likely have not fit so well with the regional geology, with either an excess number of or missing anomalies. The low density anomaly near Fishpot Lake, however, occurs in terrain covered by Quaternary non-volcanic deposits, which occurs over the entire field area (excluding the various volcanic features). If all the area between the volcanic features in the region is covered by the same material, it is curious, then, why only this small area exhibits a lower-than-average density. This may be explained by the presence of a paleo-valley infilled by sediments of lower density than the Quaternary cover, which was then subsequently overlain by the Quaternary cover. Otherwise, the low anomaly may be an indication that the calculated regional field was close to the actual field, but was not quite the same and so resulted in a stray anomaly.

The Nazko Cone region exhibits significant degassing of carbon dioxide in two bogs to the northwest of the cone, a south-southwest trending linear positive gravity anomaly which extends to ~700 m depth just east of the cone, and has shown significant
seismicity to the southwest of the cone in the past. While the structures observed around Nazko Cone may not necessarily be directly connected to each other, they may represent structures connected to a deeper volcanic plumbing system. The active degassing of CO$_2$ from depth suggests there are structures allowing for fluid movement in the area, and a possible solidified dyke complex may act as a heat source for circulating fluids; these observations could be a positive sign in the way of geothermal potential at Nazko Cone.

Figure 22. Map of Nazko Cone and immediate area showing geographical relationship between observed CO$_2$ and gravity anomalies. Dashed green line shows approximate trend of the dyke observed in outcrop.
Chapter 5.

Conclusions

Nazko Cone is a small cinder cone in central British Columbia which was generated by multiple eruptions in the past several hundred thousand years. The occurrence of cold CO₂ gas seeps and a significant swarm of microquakes near the cone prompted further research into the area, thus we investigated the shallow volcanic/hydrothermal plumbing system of the Nazko region through CO₂ gas concentration and Bouguer gravity surveys.

The distribution of significant CO₂ concentrations exhibited localized degassing in two bogs to the northwest of Nazko Cone, and stable carbon isotope values of gases obtained from the bogs indicated a possible magmatic signature. Temperature profiles in the northern bog did not exhibit significant variation. Thus, the emissions of carbon dioxide likely indicate the presence of discrete structures allowing for degassing from depth, however the lack of thermal anomaly associated with the gas likely rules out the presence of a vigorous shallow hydrothermal system.

Inverse modelling of the gravity data revealed several density anomalies in the Nazko region, mostly associated with various regional geological features. A linear positive gravity anomaly occurred just to the east of Nazko Cone from the surface to ~700 m depth, and is possibly a complex of dykes. The trend of the anomaly is approximately south-southwest, which roughly lines up with a dyke observed in outcrop at the southern base of Nazko Cone.

The structures observed around Nazko are not necessarily interconnected, but may represent structures connected to a deeper volcanic system. Further investigation and more rigorous calculations of the regional gravity field, possibly incorporating aerial gravity data, are needed in order to better constrain the subsurface anomalies.
Investigations completed thus far are still preliminary, and more detailed work (such as an in-depth hydrogeological study of the region), is required to find any possible hydrothermal systems at depth, if they exist. For now, it is not possible to conclude without question that Nazko Cone and the surrounding region have geothermal potential. However, the existence of these localized systems of structures and gas movement, which demonstrate the possibility of recent/present activity at Nazko, is a positive sign.
References


Appendix A.

Nettleton’s Method

Figure A1. Map of Nazko field area showing locations of Nettleton's Method profiles. A=Baezaeko Road profile, B=bogs to Nazko Cone profile, C=4000 Road profile.
Figure A2. Profile along Baezaeko Road showing calculated Bouguer gravity anomalies for various densities (in kg/m³) against topography.
Figure A3. Profile from the bogs to Nazko Cone showing calculated Bouguer anomalies for various densities (in kg/m$^3$) against topography.
Figure A4. Profile along 4000 Road showing calculated Bouguer gravity anomalies for various densities (in kg/m$^3$) against topography.
Figure B1. Bouguer anomaly calculated using only regional stations, shown as dots. Values are in mGal.
Figure B2. Regional gravity field calculated using a planar polynomial surface. Values are in mGal.
Figure B3. Regional gravity field calculated using a bilinear saddle polynomial surface. Values are in mGal.
Figure B4. Regional gravity field calculated using a quadratic polynomial surface. Values are in mGal.
Figure B5. Regional gravity field calculated using a low-pass Gaussian-weighted filter averaging 11 x 11 cells over a 100 m grid (1.1 km averaging). Values are in mGal.
Figure B6. Regional gravity field calculated using a low-pass Gaussian-weighted filter averaging 21 x 21 cells over a 100 m grid (2.1 km averaging). Values are in mGal.
Figure B7. Regional gravity field calculated using a low-pass Gaussian-weighted filter averaging 31 x 31 cells over a 100 m grid (3.1 km averaging). Values are in mGal.
Figure B8. Regional gravity field calculated using a low-pass Gaussian-weighted filter averaging 41 x 41 cells over a 100 m grid (4.1 km averaging). Values are in mGal.
Figure B9. Regional gravity field calculated using a low-pass Gaussian-weighted filter averaging 25 x 25 cells over a 200 m grid (5.0 km averaging). Values are in mGal.
Figure B10. Regional gravity field calculated using a low-pass Gaussian-weighted filter averaging 31 x 31 cells over a 200 m grid (6.2 km averaging). Values are in mGal.
Figure B11. Regional gravity field calculated using a low-pass Gaussian-weighted filter averaging 35 x 35 cells over a 200 m grid (7.0 km averaging). Values are in mGal.
Figure B12. Regional gravity field calculated using a low-pass Gaussian-weighted filter averaging 41 x 41 cells over a 200 m grid (8.2 km averaging). Values are in mGal.
Figure B13. Regional gravity field calculated using a low-pass Gaussian-weighted filter averaging 31 x 31 cells over a 300 m grid (9.3 km averaging). Values are in mGal.
Figure B14. Regional gravity field calculated using a low-pass Gaussian-weighted filter averaging 33 x 33 cells over a 300 m grid (9.9 km averaging). Values are in mGal.
Appendix C

Stable Carbon Isotope Values

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\delta^{13}$C ‰</th>
<th>CO₂ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAS14-1</td>
<td>-20.585</td>
<td>1.700</td>
</tr>
<tr>
<td>GAS14-2</td>
<td>-20.792</td>
<td>1.700</td>
</tr>
<tr>
<td>GAS31-1</td>
<td>-21.368</td>
<td>0.920</td>
</tr>
<tr>
<td>GAS31-2</td>
<td>-21.921</td>
<td>0.920</td>
</tr>
<tr>
<td>NBOG1-1</td>
<td>-6.800</td>
<td>5.120</td>
</tr>
<tr>
<td>NBOG1-2</td>
<td>-6.677</td>
<td>5.120</td>
</tr>
<tr>
<td>NBOG5-1</td>
<td>-6.279</td>
<td>9.300</td>
</tr>
<tr>
<td>NBOG5-2</td>
<td>-6.356</td>
<td>9.300</td>
</tr>
<tr>
<td>SBOG1-1</td>
<td>-6.901</td>
<td>5.700</td>
</tr>
<tr>
<td>SBOG1-2</td>
<td>-6.324</td>
<td>5.700</td>
</tr>
<tr>
<td>SBOG2-1</td>
<td>-6.166</td>
<td>2.400</td>
</tr>
<tr>
<td>SBOG2-2</td>
<td>-6.786</td>
<td>2.400</td>
</tr>
<tr>
<td>SCR32-1</td>
<td>-22.650</td>
<td>0.920</td>
</tr>
<tr>
<td>SCR32-2</td>
<td>-22.889</td>
<td>0.920</td>
</tr>
<tr>
<td>XMP18-1</td>
<td>-24.377</td>
<td>1.800</td>
</tr>
<tr>
<td>XMP18-2</td>
<td>-24.386</td>
<td>1.800</td>
</tr>
</tbody>
</table>

Table C1. Stable carbon isotope values with corresponding concentrations of carbon dioxide in each sample. Two samples of the gas were taken at each location, indicated by -1 and -2.
Appendix D.

Gravity Model Depth Slices

Figure D1. Depth slice at 810 m below base station height. Contoured values are density contrast in kg/m$^3$. 
Figure D2. Depth slice at 1090 m below base station height. Contoured values are density contrast in kg/m³.
Figure D3. Depth slice at 1390 m below base station height. Contoured values are density contrast in kg/m³.