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Geothermal Exploration of Mount Baker Hot Springs Through Ground-Based Magnetic and Gravity Surveys

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ABSTRACT

The Washington State Division of Geology and Earth Resources (WDGER), together with the USGS, Altarock Energy Inc., Colorado College, Temple University, Innovate Geothermal Ltd., University of British Columbia, and Western Washington University(WWU), conducted phase two of a geothermal play fairway exploration at three plays (Mount Baker, Mount St. Helens seismic zone, and Wind River valley) along the Washington Cascade Range. The Mount Baker (MB) play is an ideal location for further investigation as a potential geothermal resource due to the presence of thermal features, young volcanic centers, existing geothermal leases, accessibility, and its proximity to existing transmission lines at the Baker Lake Dam. The goal of phase II exploration at all three plays is to collect geologic and geophysical data to help constrain spatial changes in subsurface lithology and structures that may be associated with the geothermal systems. This paper discusses the geothermal potential of the southeast flank of Mount Baker, WA by interpreting newly collected ground-based gravity and magnetic data. The Mount Baker play was surveyed from July-September, 2016 by the USGS, WDGER, and WWU. Results of a detailed magnetic and gravity surveys of the region surrounding the Baker hot springs, the primary surface expression of the hydrothermal system, are presented here. Gravity data were collected at 495 stations in the study area amounting to an area of roughly 150 square km. Approximately 93 km of line magnetometer data were collected within the study area, over a dozen magnetic susceptibility measurements were taken at 50 locations and about 50 hand samples were collected for density measurements. Preliminary data and modeling suggest pronounced magnetic anomalies trending NE/SW, generally in line with previously mapped lineaments identified in LiDAR. We present a series of preliminary two-dimensional forward models of the gravity and magnetic data as well as a 3D inversion model of magnetic susceptibility and interpret these models in terms of the structural controls influencing the Baker hot springs and hydrothermal system.

INTRODUCTION

Phase II of a geothermal play fairway exploration was conducted along the Washington Cascade Range by the Washington State Division of Geology and Earth Resources (WDGER), together with the USGS, Altarock Energy Inc., Temple University, Colorado College (CC), Innovate Geothermal Ltd., University of British Columbia (UBC), and Western Washington University (WWU). Mount Baker is located within the Mount Baker-Snoqualmie National Forest in Washington state (Fig. 1.) During Phase II, the Mount Baker Play was surveyed to collect additional geologic and geophysical data to help constrain changes in subsurface lithology and structures associated with the geothermal system. No faults or other structures appear on any geologic map immediately surrounding Baker hot springs that could explain their presence (Norman et al 2014). Results of detailed magnetic and gravity surveys of the region conducted from July-September 2016 at the MB study area are presented here as well as a series of preliminary two-dimensional gravity and magnetic model profiles and a 3D magnetic inversion model.

GEOLOGIC AND GEOTHERMAL SETTING

Mount Baker is an active Quaternary stratovolcano located in northwest Washington on the western front of the north Cascades (Norman et al., 2014). The most recent eruption from Mt. Baker was a degassing event in 1880 which produced a lahar, and there has been unrest in the form of increased fumarolic activity as recently as 1975 (Crider et al., 2011). Fumarole activity manifests as steam and gas emitted from Sherman Crater and Dorr Fumaroles field located on the northeast flank of the volcano. These surface features, along with the Baker hot Springs, located on the lower eastern flank of the volcano, have led researchers to investigate the hydrothermal system at Mount Baker for geothermal potential. Norman et al., (2014) hypothesize that the hydrothermal system is convection-dominated with active magmatic-hydrothermal fluid systems and fault controlled circulation.

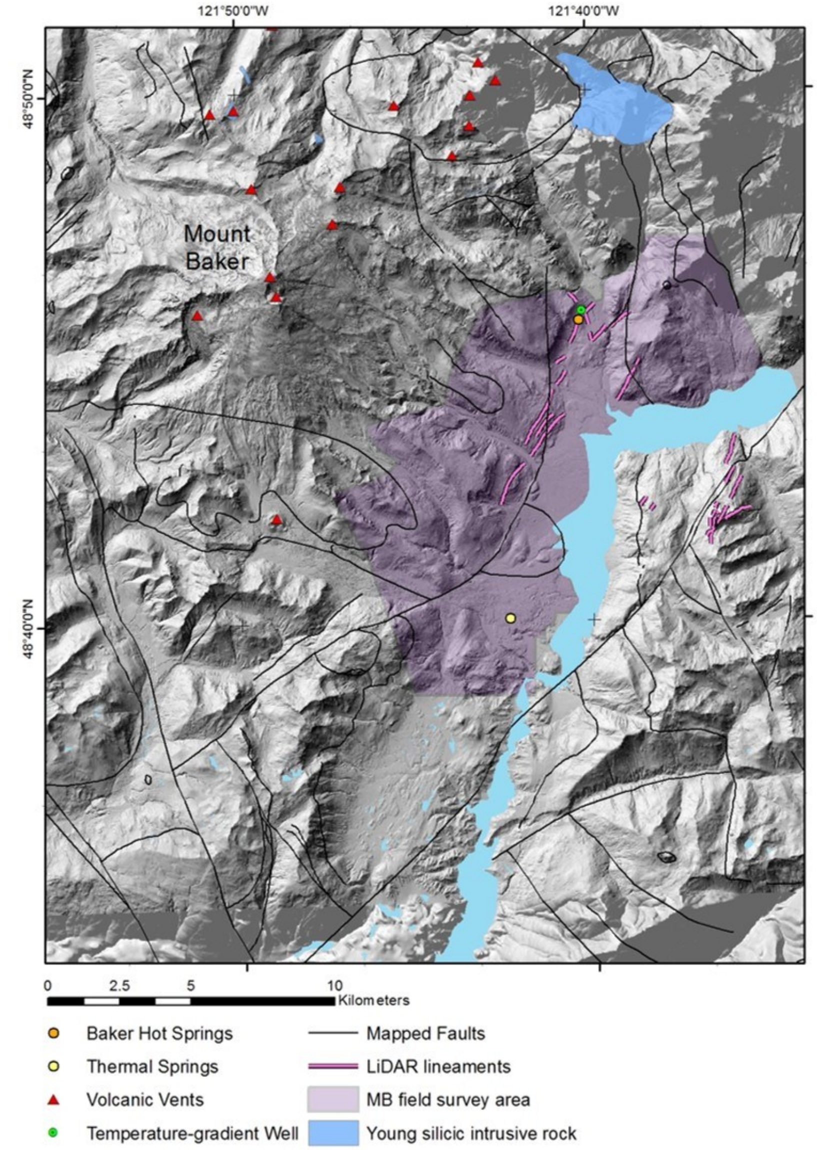

Figure 1. Location of Phase II field survey area in the Mount Baker-Snoqualmie National Forest in relation to Mount Baker as well as the location of features pertaining to geothermal exploration of the area.

Previous exploration at Mount Baker has included some detailed geologic mapping, spring sampling, geophysical surveys, soil mercury measurements and limited temperature-gradient drilling (Korosec, 1984). Chemical geothermometry of Baker hot springs suggests that the reservoir equilibrium temperature of the system may reach as high as 150° to 170°C (Korosec, 1984). A 140-m deep temperature-gradient well drilled near the Baker hot springs in 1983 had a bottom hole temperature of 48°C. A geothermal gradient calculated from the entire logged depth of the borehole was between 200° and 309 C/km, the highest temperature gradient in all of Washington State (Czajkowskie et al., 2014). However, this gradient may not represent a typical background value due to the wells proximity to the hot springs.

Baker hot springs are in an area overlain by a thick mantle of glacial till, alluvium and dense vegetation (Fig. 2). These unconsolidated glacial and fluvial deposits are underlain by the volcaniclastic facies of the Permian Chilliwack group. These rocks consist of pillow lavas and breccias in fine-grained marine sedimentary rocks (Tabor et al., 2003). Locally, the Chilliwack group volcaniclastic facies are thought to be underlain by the Cretaceous-Jurassic Nooksack Formation, presumably due to thrust faulting along poorly constrained fault traces (Tabor et al., 2003). In outcrops to the west of Baker hot springs, the Nooksack Formation, consisting predominantly of argillite and metasandstone, forms a contact with the Chilliwack group. Both units are typically highly, fractured; although no surface evidence of shallow hydrothermal alteration has been observed during reconnaissance field mapping (Czajkowskie et al., 2014). The contact between the Chilliwack group and Early Jurassic- Late Cretaceous Cultus formation composed of tuffaceous siltstone, sandstone, and argillites, is not well defined as exposures of both are rare in the valley floor where a thick mantle of glacial till and alluvium straddle the landscape. Both units are overlain along the Welker Peak Thrust fault to the East where they form a contact with the structurally higher Bell Pass Mélange, a Cretaceous- late Jurassic terrane containing the blue-schist of Baker Lake and composed of a wide variety of metamorphosed sedimentary and volcanic lithologies (Tabor et al., 2003). East of the Bell Pass Mélange lies the early

Cretaceous in age Easton Metamorphic Suite composed of the Shuksan greenschist and Darrington phyllite which experienced blueschist facies metamorphism and structurally comprise the Shuksan Nappe (Tabor et al., 2003).

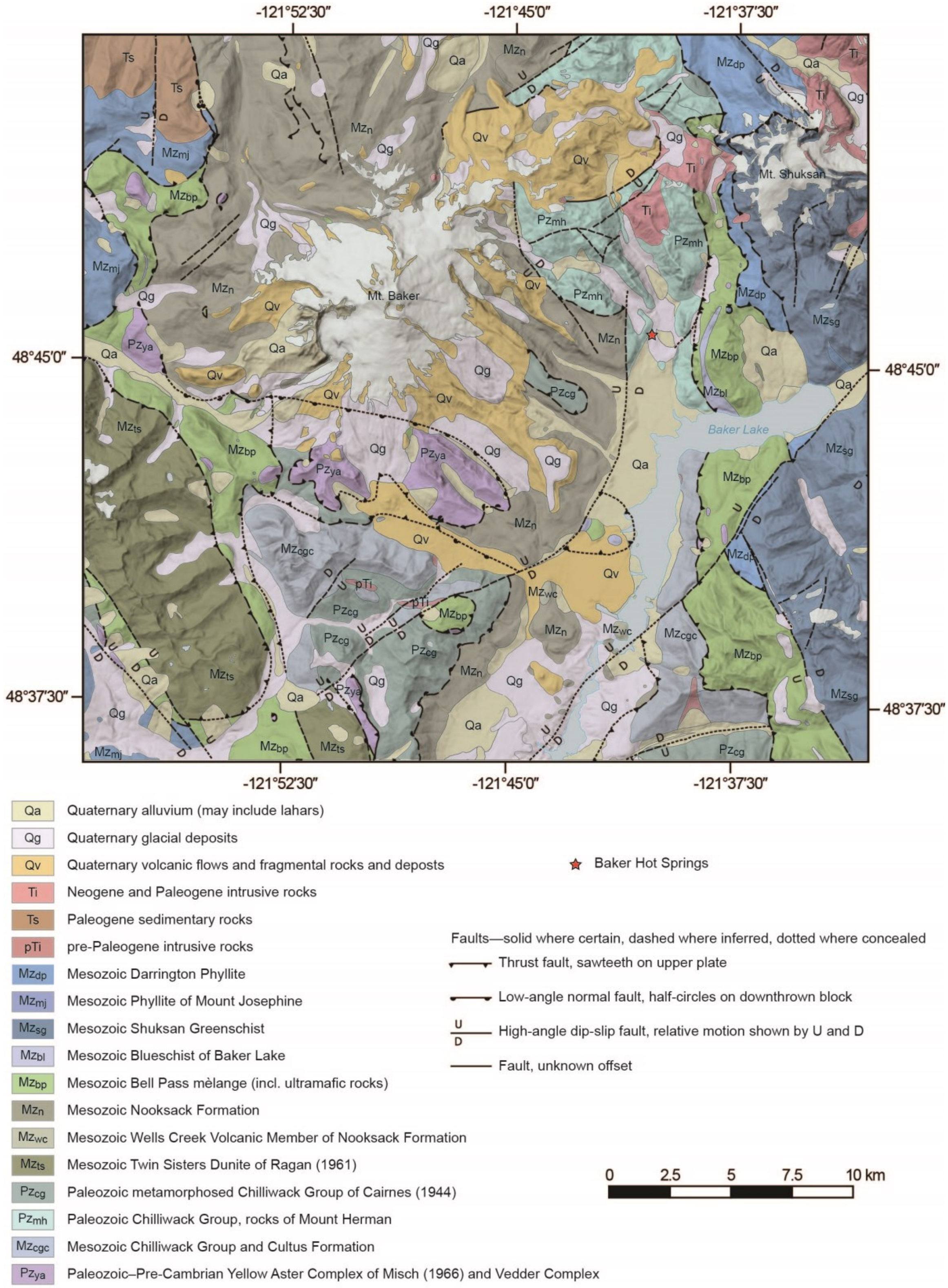

Figure 2. Geologic map of the region surrounding Baker Lake, in Mount Baker-Snoqualmie National Forest.

Faults mapped in the study area (Fig.1) were mapped at 1:100,000 scale and are considered to be last active in the Eocene (Tabor et al., 2003). The main challenge of geologic mapping (particularly when looking for fault indications) in the area is the lack of surface expression, a consequence of the rugged terrain, dense vegetation cover, sparse rocky outcrops and seasonal snow cover encountered in the Cascades. Another source of uncertainty is the small scale at which the area was mapped compared to the other plays (1: 100,000 scale at MB compared to 1: 24,000 scale at Wind River valley). The mapped locations and orientations (there are no measured fault dips near the hot springs) of previously mapped faults in the area were not sufficient for the level of detail needed for geothermal analysis. To this end, preliminary analysis of topography by the WDGER, using available LiDAR data, revealed numerous northeast-trending lineaments (Fig .1) near Baker hot springs, which may be the surface expression of unmapped faults. If these lineaments do represent faults traces, they may be associated with geothermal fluid circulation, and are therefore targets for geophysical data collection. Potential field surveys such as ground magnetic and gravity data, can detect contrasts in physical properties in the subsurface which offers a method to better interpret the structural controls that may be influencing a hydrothermal system.

DATA COLLECTION AND PROCESSING

-Magnetic Data

A total of ~93 line-km of magnetic data were collected at Mount Baker; 47 km of which were collected in mid July 2016 by the USGS Geophysical Unit of Menlo Park (GUMP) and 46 km were collected from Mid-August to late September 2016 by WWU students. Accessibility within the study area is largely dependent on the locations of forest service roads, trails, dense vegetation, steep slopes, and topographic barriers. Data collection on roads was prioritized, as roads offer the most efficient means to collect abundant data. The next priority was to conduct multiple traverses orientated perpendicular to LiDAR lineations. Using a Geometrics G-858 and G-859 cesium vapor magnetometers with integrated Global Positioning Systems (GPS). Magnetic intensity in nanoteslas (nT) and position were recorded simultaneously at 1-second intervals with the height of the magnetometer sensor set ~2 meters above the ground surface. A Geometrics G-856 proton procession base-station magnetometer was used to record and correct for diurnal variations of the Earth's magnetic field during the time of the surveys. Cultural features (culverts, signs, metal gates, bridges, and vehicles) encountered during the survey were noted and their erroneous signals removed during data processing. Raw magnetic data were filtered using MagMap2000 software to remove cultural noise, correct for diurnal variations recorded by the base station magnetometer and merge the recorded GPS and magnetic data.

-Gravity Data

A total of 495 gravity stations were collected in the study area from mid-July to mid-September 2016. Due to the terrain and vegetation, many cross-country lines were deemed unreasonable for gravity data collection, so data collection was largely restricted to Forest Service roads and trail systems. Gravity data were collected using a Scintrex CG-5 gravimeter and a La Coste & Romberg gravimeter, and GPS locations and elevations were obtained using a Trimble GeoXH GPS. All gravity stations were tied to a primary base station COPO located at the U.S Post Office in Concrete, Washington, at latitude 48° 32' 19.32762" (N), longitude 121° 44' 57.42098" (W), which had been tied to the absolute base station "Bellingham CA" at Western Washington University in Bellingham, WA.

Gravity data were reduced by using the following corrections: (a) Earth-tide correction, which accounts for the gravitational effects of the sun and moon; (b) instrument drift, which compensates for drift in the instrument's spring; (c) latitude correction, which accounts for the variation of the Earth's gravity with latitude: (d) free-air correction, which accounts for variation of gravity with respect to latitude; (e) Bouguer correction, which corrects for the attraction of material between the station and sea level;(f) curvature correction, which corrects the Bouguer correction for the effect of the Earth's curvature; (g) terrain correction, which removes the effect of topography to a radial distance of 167 km around the station; (h) isostatic correction, which removes long wavelength variations in the gravity field related to the compensation at depth of topographic loads at the Earth's surface.

Gravity and magnetic data were processed (gridded and filtered) using Oasis Montaj and modeled using the GM-YSY 2D modeling package. Newly collected gravity data was combined and gridded with existing gravity data found on PACES (Pan American Center for Earth and Environmental Studies) to construct a regional gravity map. Model bodies were assigned densities and susceptibilities based on values determined from rock lithology in the field or calculated from laboratory measurements of rock samples in the lab.

-3D Geophysical Inversion Modeling of Magnetic Data

Innovate Geothermal Ltd. performed 3D geophysical inversion modeling of the Baker hot springs Total Magnetic Intensity (TMI) data using SimPEG (simpeg.xyz; Cockett et al., 2015). To prepare for the geophysical modeling, the TMI data were gridded across an area of interest ~2.5 (E-W) x ~3.5 km (N-S) in size, centered approximately on the Baker hot springs. A geophysical model volume with these same dimensions was generated, extending from the land surface to a depth of 1,300 m below sea level. Public domain SRTM data were used to define the surface topography. The cell size in the model volume is 50 m in the X-Y direction and 100 m vertically. Numerous padding cells (a buffer), ~800 m thick on each side, were appended to the geophysical model volume to help minimize edge effects on the model output.

The geophysical modelling effort began with an equivalent source inversion of the TMI data to derive magnetic amplitude data. Then, the amplitude data were inverted to generate an effective susceptibility model. An Lp norm was also utilized to generate compact bodies. This geophysical modeling approach is described in detail in Fournier (2015) and is useful for minimizing the effect of magnetic remanence in the geophysical inversion process.

LITHOLOGIC PROPERTIES

Densities of collected samples were determined using the buoyancy method and electronic balance while the magnetic susceptibility values were measured from outcrops in the field using a Terraplus KT-10 susceptibility meter and from cores at the Menlo Park office of the USGS.

Each sample was weighed in air (Wa), saturated and submerged in water (Ww), and saturated in air (Was). The grain, saturated-bulk, and dry bulk densities were computed using the following formulas.

Grain density = 1,000 kg/m^3 x Wa/(Wa-Ww),

Saturated-bulk density = 1,000 kg/m^3 x Was/(Was-Ww), and

Dry-bulk density = 1,000 kg/m^3 x Wa/(Was-Ww).

RESULTS

Magnetic anomalies reflect variations in the strength of Earth's magnetic field and are used to infer lateral variations in the magnetization of rocks. Short wavelength, high amplitude signals are usually associated with moderately to strongly magnetic bodies such as volcanic rocks. The variation in wavelength, frequency, and the sharpness of magnetic intensity gradients reflects varying depth to magnetic bodies and contrast between lithologies with varying iron-rich minerals contents. The results of the newly acquired ground-magnetic surveys (Fig. 3) add increased resolution to regional Aeromagnetic surveys (Fig. 4) (USGS and NOAA, 2001). In the study area, several short wavelengths, high amplitude anomalies, identified by the ground based magnetic survey, are present within a 6 km^2 region encompassing Baker hot Springs (Fig. 5). The most prominent of these anomalies is a northeast-trending high intensity body with a parallel low intensity region immediately to the northwest, forming the largest gradient observed in the study area (Fig. 5a). This elongate feature is approximately 1.7 km in length and intersects the hot springs near its northern terminus. The highest gradient of this feature coincides with lineaments observed in the LiDAR. Other prominent features include a magnetic high southeast and northeast of the hot springs (Fig. 5 b, c) both of which are near other lineaments.

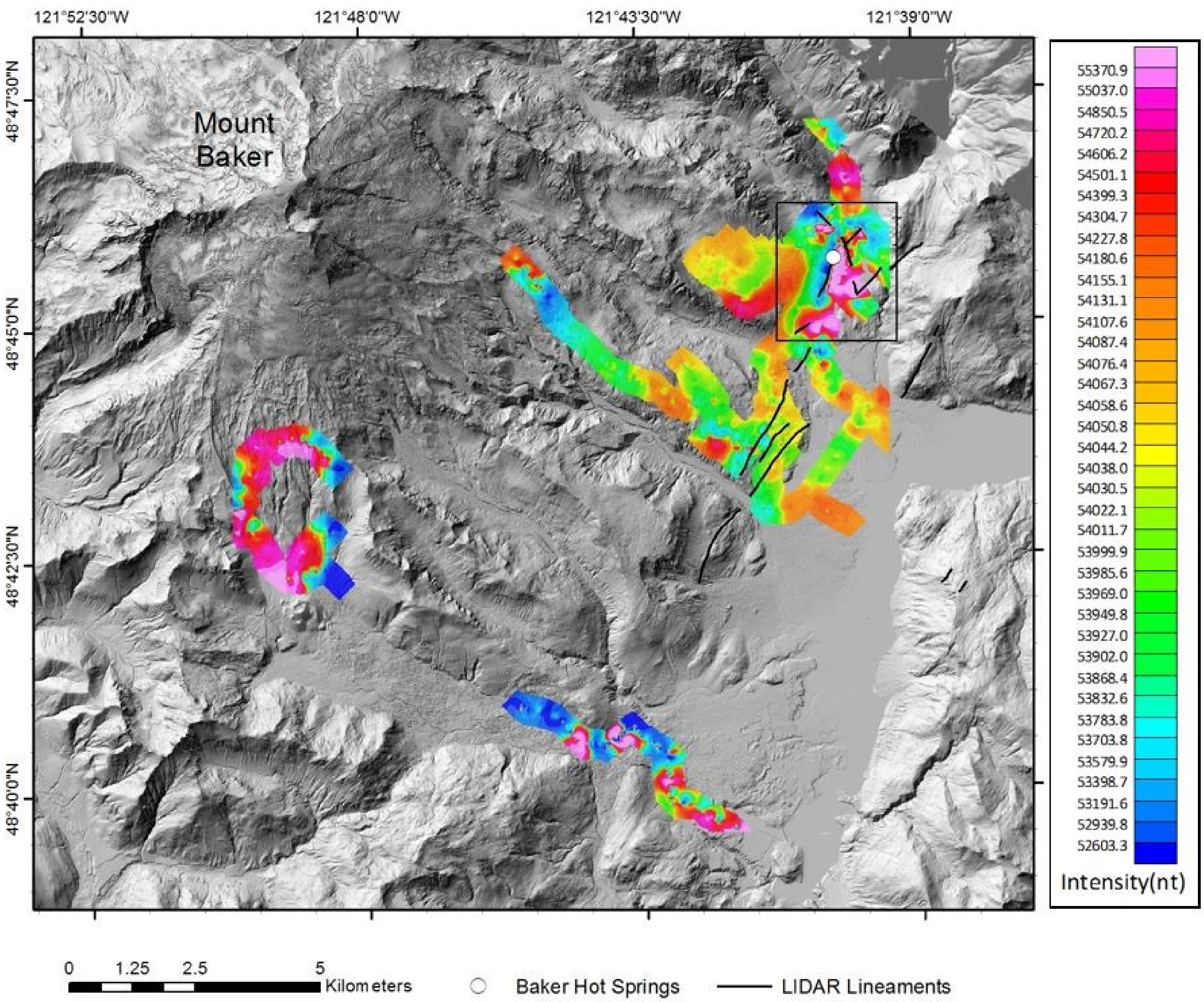

Figure 3. Map displaying Reduced to Pole (RTP) grid values in nT, produced from walked magnetic surveys (not shown here). Inset box corresponds to the area of Figure 5.

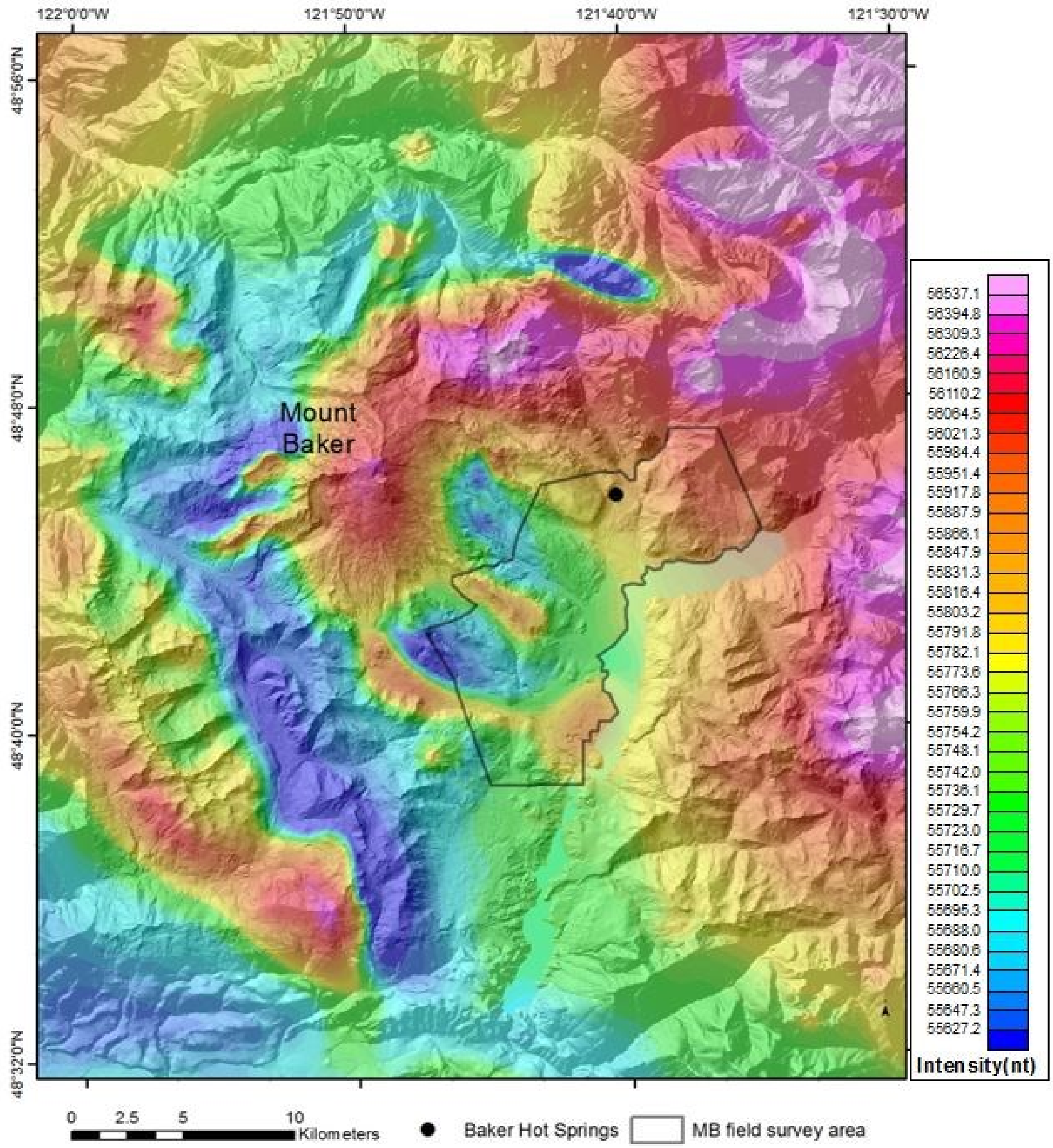

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Figure 4. Regional Aeromagnetic map of the Mount Baker Survey Area and surrounding region.

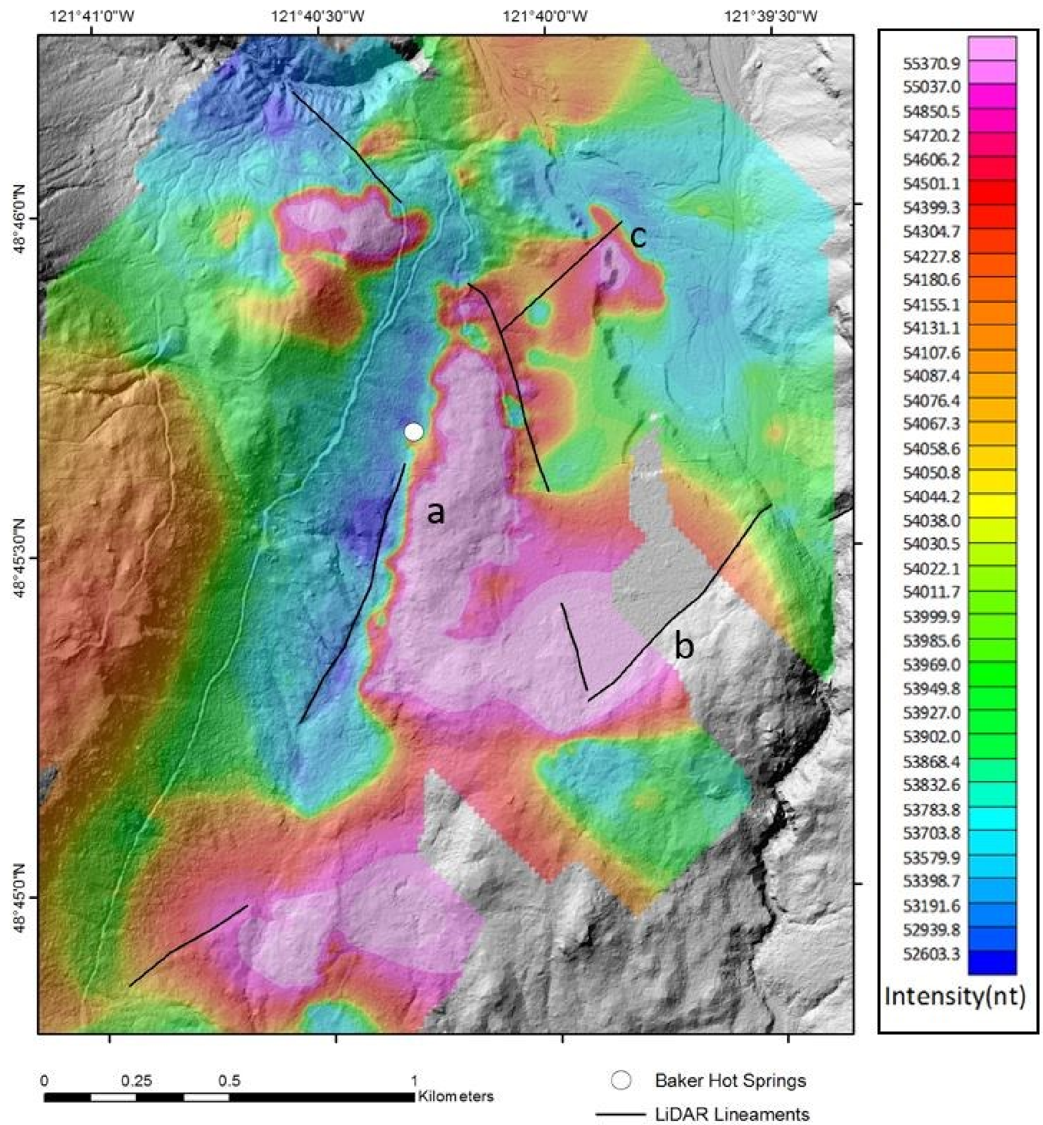

Figure 5. Detail of Figure 3., map centered around Baker hot springs displaying magnetic gradient anomalies, labeled a, b, and c, and their proximity to LiDAR lineaments (black lines). Grid values in nT.

Isostatic gravity anomalies (Fig. 6) reflect lateral variations in density of rocks in the subsurface commonly used to infer subsurface geology and structure (Santos and Rivas, 2009). A main feature of the isostatic gravity map is a prominent northeast trending gravity high that spans approximately 9.3 km along Baker Lake's western shore (Fig. 6.a). Another prominent northeast trending gravity high lies directly east of Baker Lake and is approximately 9 km in length (Figure 6.b). Other features include: a gravity low located over Kulshan Caldera (Fig. 6.c), a gravity low located over the young silicic intrusion shown in Figure 1 (Fig. 6.d), and a gravity low located in close proximity to the mapped Glacier Extensional Fault south of the summit of Mount Baker and in close proximity to low temperature thermal springs (Fig. 6 e.). The newly acquired gravity data was merged with the PACES data to put the newly acquired data in the context of regional gravity trends (Fig. 7).

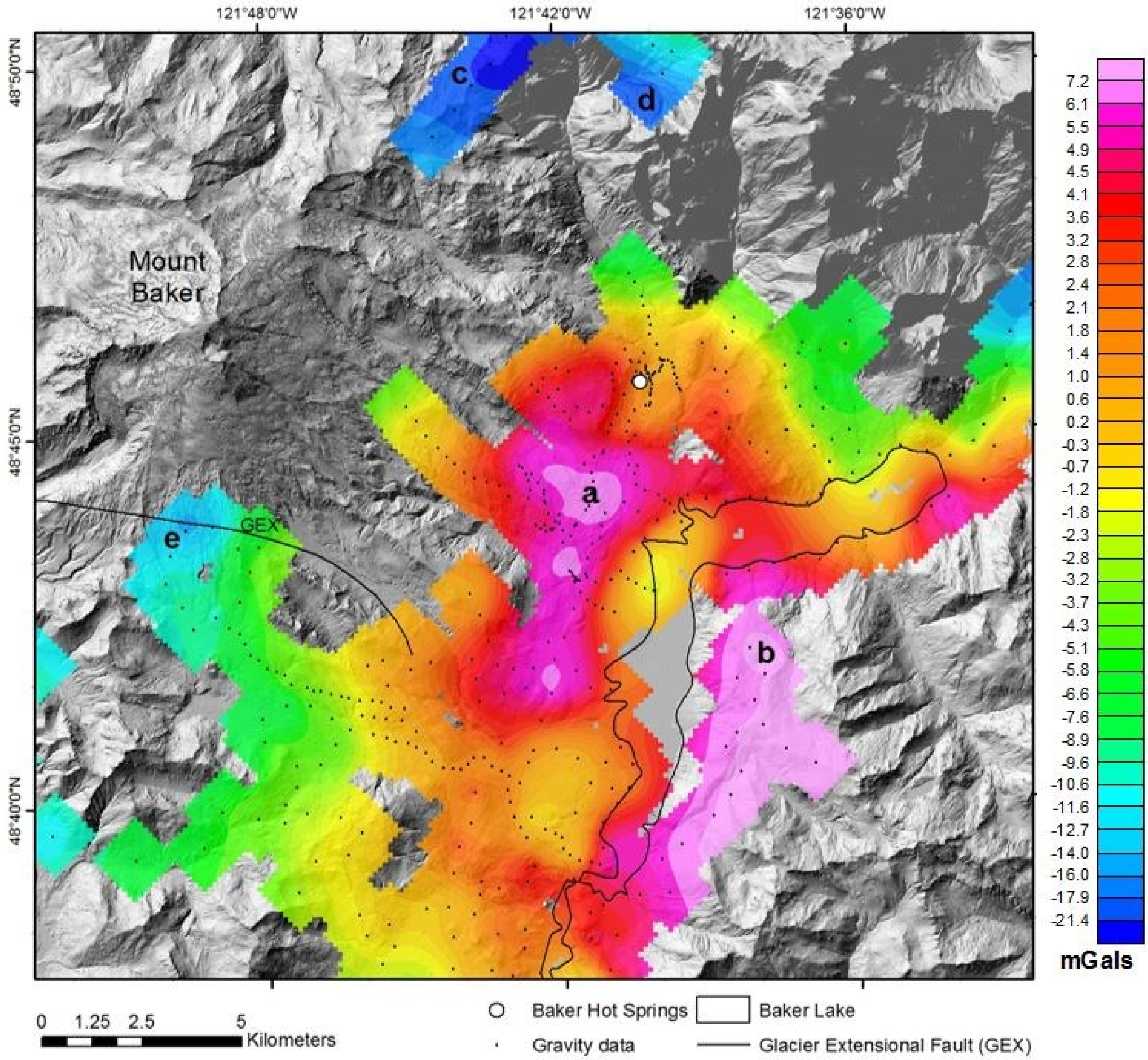

Figure 6. Isostatic gravity anomaly map produced from Phase II survey data. Key features labeled a-e.

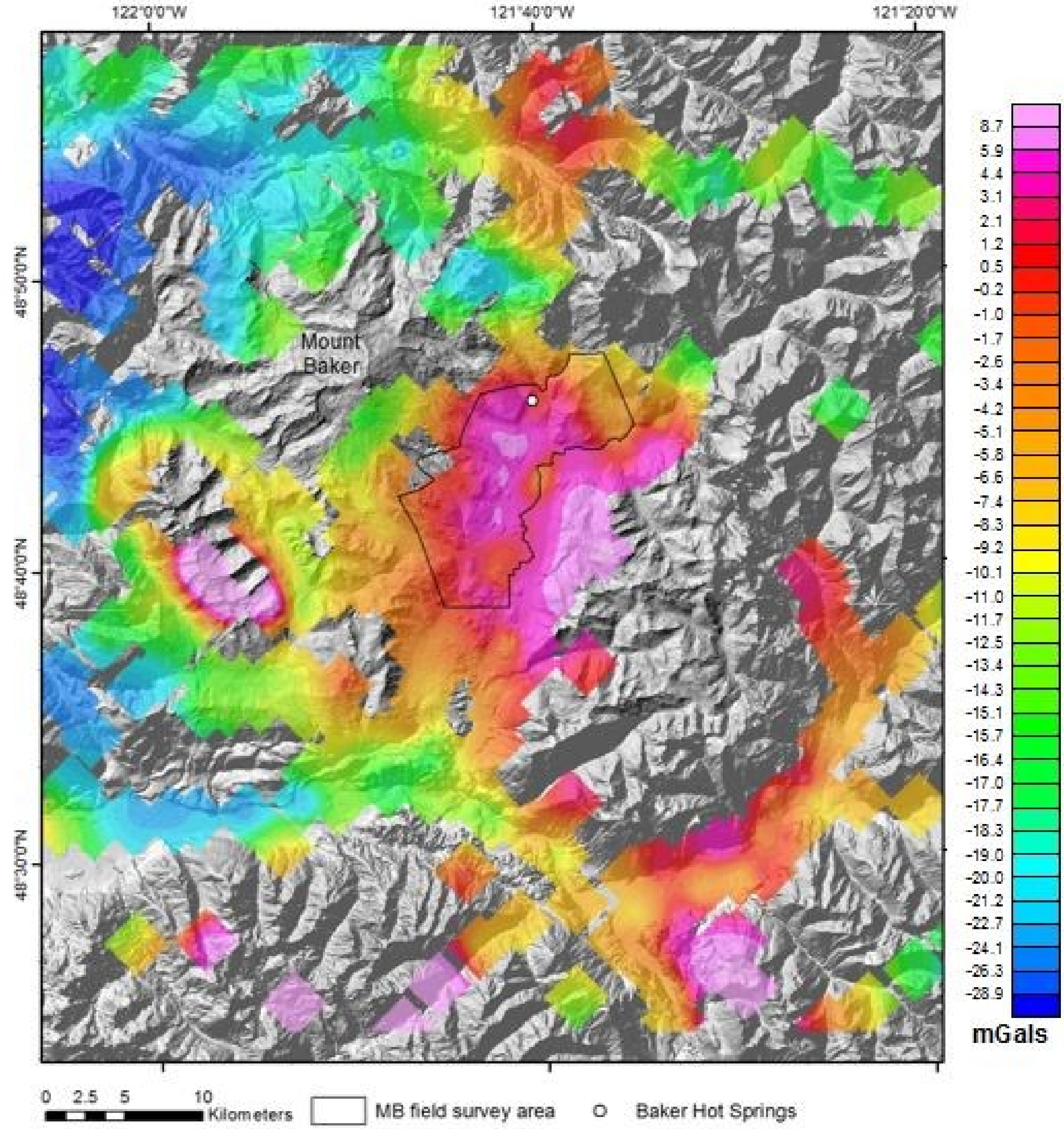

Figure 7. Regional isostatic gravity map produced from merging PACES data with newly acquired gravity data.

MODELING RESULTS AND DISCUSSION

We present 2D modeling results from two forward-modeled profiles as well as a 3D geophysical inversion model of magnetic data from the Baker hot spring area, which help constrain subsurface geology and identify possible structural controls influencing the hydrothermal system of the Mount Baker play.

The effective magnetic susceptibility inversion model generated is a semi-quantitative, 3D representation of magnetic susceptibility distribution in the subsurface beneath the Baker hot springs area (Fig. 8). The model result shows an elongate, vertically oriented region of high magnetization that strikes NNE. The northern end of this high magnetization region lies under the hot springs and extends ~1.7 km to the south of the Baker hot springs. The width of the body is ~200 m NW-SE. The top of the high magnetization region lies less than a few hundred meters below the surface and extends to about 1 km depth at its deepest point. A possible geologic interpretation of this magnetization model is that the region exhibiting high effective susceptibility represents a mafic intrusion that was intruded beneath and to the south of the hot springs. The margins of such a body could possibly provide sub-vertical, permeable pathways for the ascent of geothermal fluids that supply the hot springs.

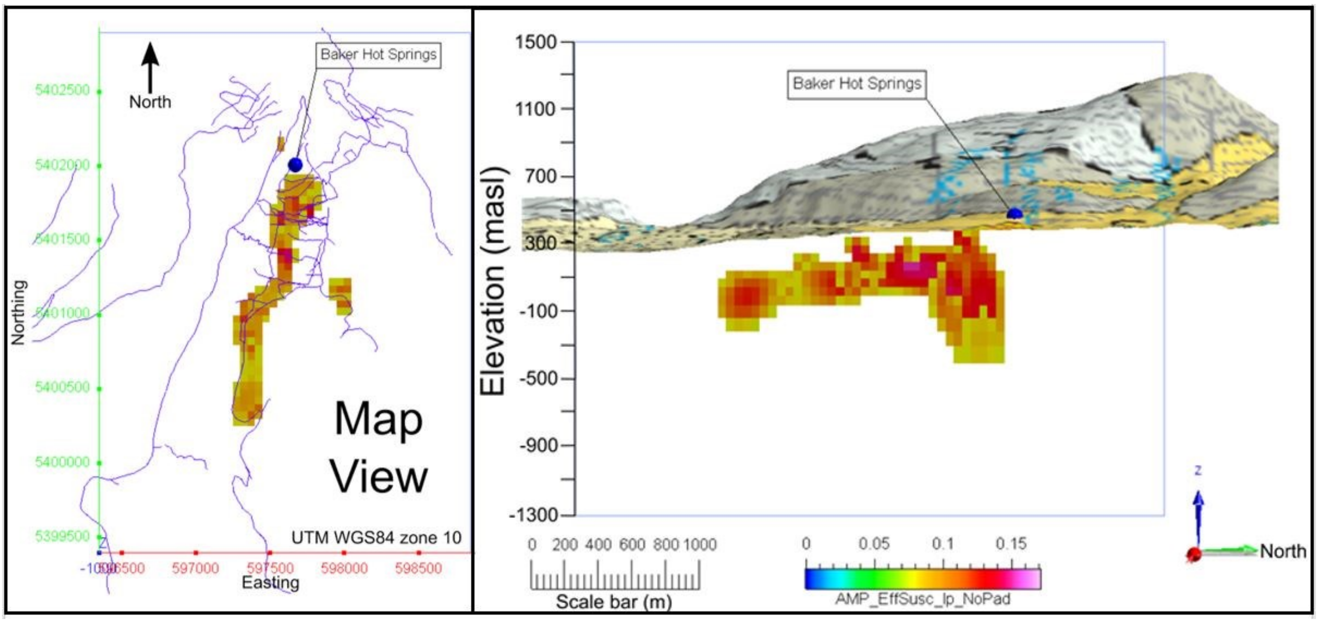

Figure 8. Map view of region of high magnetization(left) in 3D magnetic susceptibility model. Profile view, looking to the west, of the 3D magnetic susceptibility model generated in this study(right). 3D topography displayed with geologic map overlain. The location of Baker hot springs is shown for reference. The color bar on the bottom shows the "effective susceptibility" units of the 3D magnetization model. The effective "susceptibility units" are unit less. The red-orange-yellow body in the center of the image is the high effective susceptibility region. The outline of the geophysical model volume is shown by the blue box.

To validate the geologic interpretation, 2-D models were constructed using Oasis Montaj's GM-SYS software package along profile one (Fig. 9) trending WNW, perpendicular to the magnetic high (Fig. 5.a). The interpretation of an igneous intrusion was tested against different geometries and structures. The data were modeled separately as either a mafic igneous intrusion or a westward dipping fault (Fig. 10). Both models fit the data to some extent but the observed data representing the magnetic anomaly fits the geometry of a westward dipping fault remarkably well. Evidence for a fault is supported by the LiDAR data showing a lineament coincident with the modeled fault. It is also important to note that the magnetic properties of the mafic intrusion (Fig. 10) must be quite extreme in order to fit the data. Most producing geothermal systems have fracture dominated permeable pathways, which allow the thermal fluids to circulate from depth. Circulation of hydrothermal fluids most commonly occurs at fault terminations or intersections which can form active fracture networks due to the elevated and concentrated stress conditions (Curewitz and Karson 1997). If the modeled westward dipping fault exists and there is active displacement, depending on the geometry and stress condition present, the fault could produce a fracture network allowing fluid circulation and possibly explain the presence of the Baker hot springs. Permeable pathways could also result from the contrasts in physical properties between the modeled intrusive body and surrounding materials, allowing heated fluids to reach the hot springs, and depending on the size and age of the body it could also represent a potential heat source. These potential structures may play a key role in creating permeability and could explain the presence of the Baker hot springs. Paleomagnetic studies in the study area would provide critical control on magnetic remanence of the rock units to further constrain the geophysical models presented here.

Modeling results of Profile two (Fig. 9), which intersects the anomalous high gravity areas (anomalies a and b, Fig. 6) largely support geologic mapping of the area (Fig. 11). A significant deviation from the geologic map and model (Fig. 11) is an area at the western margin of the profile line where a single body labeled "unknown" was used to fit prominent magnetic and gravity anomalies. The geometry is inconsistent with mapped geology, and magnetic and density properties are not supported by collected physical property of any of the sampled units. An alternative explanation for the gravity and magnetic anomalies is that they are arising from two distinct sources in the subsurface. For example, a shallow buried volcanic unit could account for the magnetic anomaly and while the gravity, could be caused by a thick wedge of glacial strata.

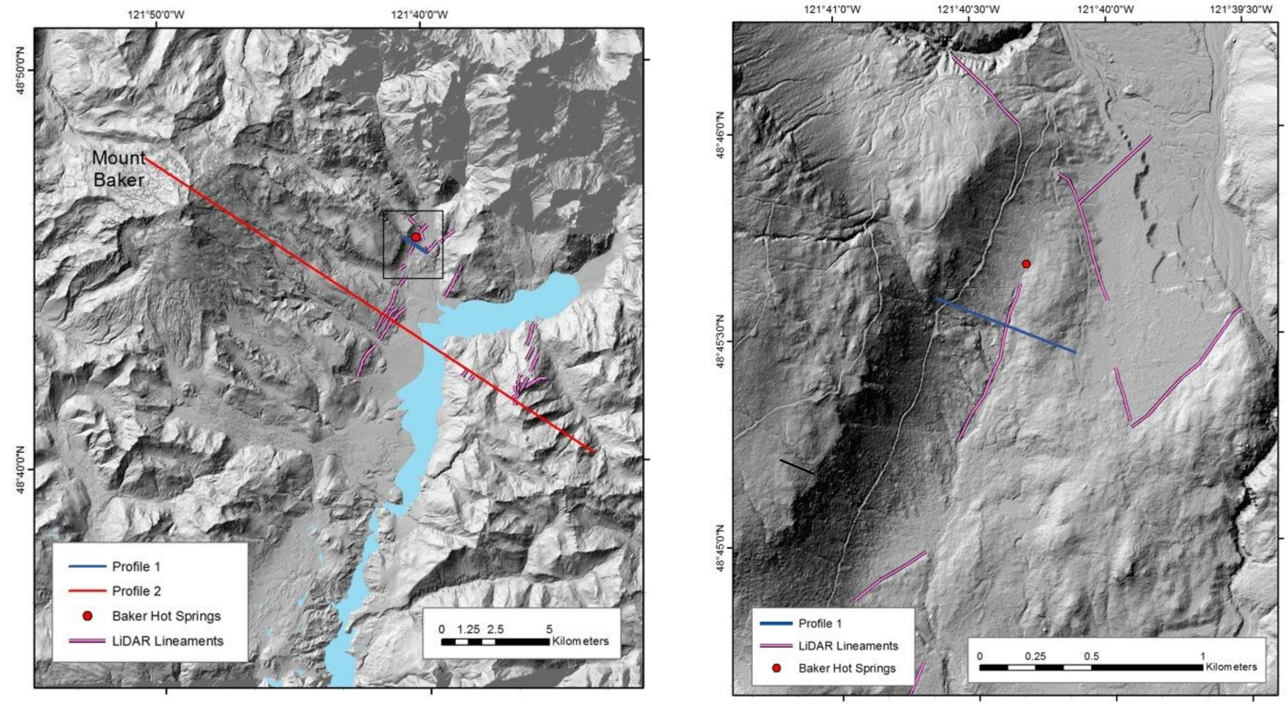

Figure 9. Location of modeled profiles one and two in the Mount Baker study area(left). Detail of Profile line one(right).

CONCLUSION

Geophysical surveys conducted in Phase II of the geothermal play-fairway study at Mount Baker have resulted in high resolution magnetic and gravity data sets which have helped identify structural features within the study area leading to a better understanding of the hydrothermal system. We developed 2D potential field forward models following two different conceptual interpretations to account for the magnetic anomaly around the Baker hot springs, the first model involving an intrusion yielded a reasonably good fit of the data. However, the modeled intrusion does not coincide with any mapped units in the area, and as a result the geometry and rock properties of this unit were unconstrained. Our alternative model involving simply a single westward dipping fault yielded a better fit of the data while being consistent with the geology. Evidence for a fault is supported by the LiDAR data showing a lineament coincident with the modeled fault. However, the model results from 3D inversion of magnetic susceptibility show an elongate, vertically oriented region of high magnetization which lies beneath the hot springs. The geometry of this tabular body is suggestive of an intrusion which would support the conceptual interpretation posed by the first 2D model. Rectifying these interpretations is the subject of future work and will be performed in conjunction with other geoscience datasets such as the magnetotelluric (MT) surveys conducted at Mount Baker during Phase II of the Play Fairway Exploration of Washington State.

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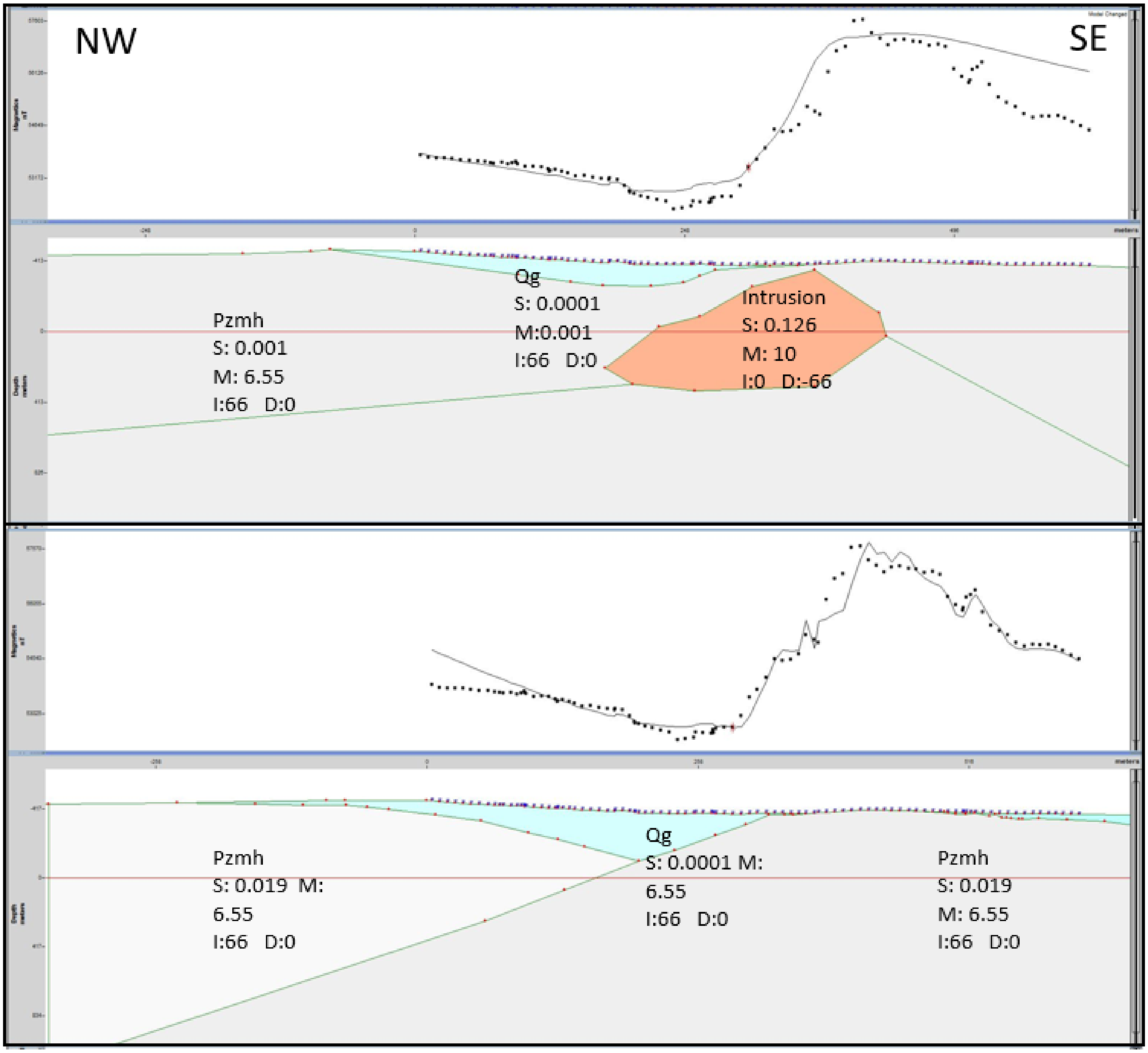

Figure 10. Cross-section view of Profile 1. (Fig. 9) Magnetic anomaly modeled over hot springs as an igneous intrusion(top) and a Westward dipping fault(bottom). The top window in each model shows the magnetic intensity in nanoteslas, the observed field as points and calculated field as the solid line, error is the difference between observed and calculated. Geologic labels and their respective rock properties are labeled in the bottom cross-section window view of each model. Lateral units are in meters and elevation is labeled in meters relative to sea level.

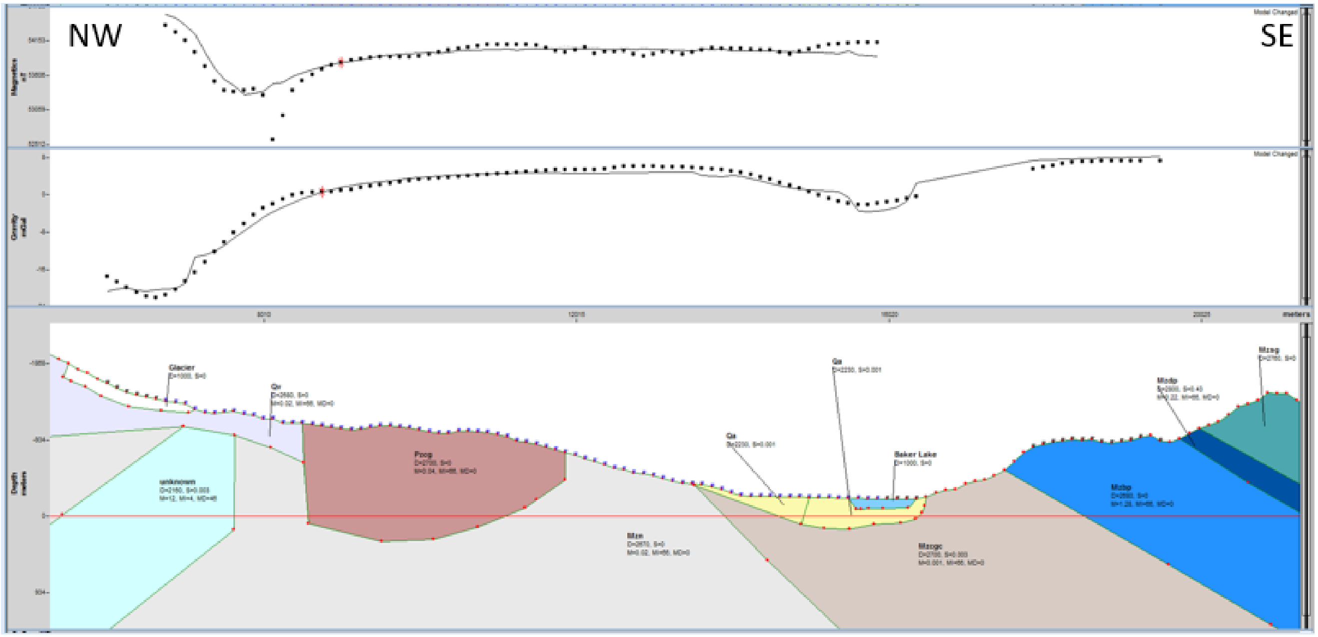

Figure 11. Cross-section view of Profile two (Fig. 9) The top window in each model shows the magnetic intensity in nanoteslas and isostatic gravity in milligals (mgals), the observed field as points and calculated field as the solid line, error is the difference between observed and calculated. Geologic labels and their respective rock properties are labeled in bottom cross-section window view of each model. Lateral units are in meters and elevation is labeled in meters relative to sea level.

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