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Using gravity and magnetics to delineate structural controls on geothermal fluids, northern Cache Valley, Idaho

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ABSTRACT

The Northern Cache Valley (NCV) of southeastern Idaho is a north-south trending Basin and Range graben that. During the 1970s and 80s, exploration of the geothermal system (involving geophysical, geochemical, and hydrological studies) culminated with the drilling of geothermal exploration wells by Sunedco Energy Development in 1979 and 1980. The test borehole temperatures were deemed too low (< 120o C) for power production using technology available at the time. In January of 2014, a water well drilled to 79 meters, encountered Na-Cl-HCO3 water with a measured bottom hole temperature of 104o C. Traditional magnesium corrected Na-K-Ca geothermometry of water from that well estimated the temperature of the thermal reservoir may be as high as 204° C. These results have revived interest in the area's geothermal potential that has motivated new studies utilizing updated geochemical and geophysical techniques. Present understanding of the NCV geothermal system suggests that fluid flow is associated with a fault(s) adjacent to Clifton Hill (aka Little Mountain) – a secondary horst complex rising from the floor of the Cache Valley graben. The existing data from the area are relatively sparse and are not suitable for pinpointing the location of faults responsible for directing thermal waters from depth to the shallow subsurface. We conducted high resolution potential field (gravity and magnetic) studies, collecting data along several profiles across the Clifton Hills, to map these structures. Geophysical modeling of these data, used in conjunction with existing hydrogeological and geochemical data, help to characterize the geometry of subsurface structures and to constrain the plumbing of the geothermal system.

Future work includes groundwater level and aquifer temperature mapping to explore the behavior of the shallow ground water aquifer in response to the discharge of thermal water through the system's faults. If funding allows, thermal imaging, utilizing an unmanned aerial vehicle (UAV), will be used to detect elevated ground surface temperatures thought to exist based on preferential melting of snow that has been reported to occur in this area.

1. INTRODUCTION

The NCV is a north-south trending horst-graben complex extending from the Idaho-Utah border north to Red Rock Pass between the Bannock and Portneuf mountain ranges. Located in the northeastern extent of the Basin and Range province, the NCV also contains indicators of subterranean heat such as thermal springs, wells and areas of accelerated snow melt. Historic geothermometry studies based upon analyses of local hot spring fluids suggested subsurface temperatures between 110 and 225°C (Mitchell, 1976; Avery, 1987). While the area's commercial geothermal potential was investigated by Sunedco in the late 1970's and early 80's, the area was deemed unsuited for power production and development plans were not pursued. Preliminary results of the new geothermometry tool [Reservoir Temperature Estimator, RTEst (Palmer et al., 2014; Mattson et al., 2015)] applied to water compositions of the hot springs and wells [previously measured and reported by Mitchell (1976) and Avery (1987)] indicate the presence of a potentially high temperature (ca. 170 ºC or ca. 338 ºF) system in the area (Neupane et al., 2015, 2016). Moreover, a shallow water well recently (January, 2014) drilled for the purpose of watering cattle, produced 104o C (217o F) water from a depth of 79 meters (260 ft). This well, called the Bosen well, is located on the western side of the valley at the toe of Clifton Hill (aka Little Mountain), 7 km (~4.4 miles) northwest of Preston, ID (Figure 1).

During commercial exploration of the area, two deep test wells were drilled to completion, attempting to intersect bounding faults on the east and west sides of Clifton Hill thought to be providing conduits for thermal fluids. In both cases the target faults were not encountered and the wells were deemed unsuccessful (McIntyre & Koenig, 1980). Current understanding of the structure of Clifton Hill indicates the bounding faults trend northwest and are steeply dipping (Wood et al., 2015). This interpretation is consistent with the conclusion of the Stocks 1-A evaluation that due to the steepness of the fault, the well did not penetrate deep enough to intersect any permeable zone that may surround it. Previous placement and orientation of the bounding faults in the subsurface is based on surface mapping and an early low resolution geophysical survey (Peterson & Oriel, 1970). The aim of our investigation is develop a better understanding of the orientations and locations of the Clifton Hill bounding faults that may provide permeable pathways for thermal fluids to reach the shallow subsurface. Later studies will explore the effect these faults have on the area's shallow aquifer and heat distribution. This paper details recent gravity and magnetic surveys which were undertaken in the summer and fall of 2015 in order to collect more data on the Clifton Hill system and to better characterize the local fault system as likely pathways by which thermal fluids may be reaching the shallow subsurface in the area.

2. GEOLOGIC SETTING

The origins of the basin and range horst-graben structures in the area dates back to early to middle Miocene, created from movement along planar to listric normal faults with moderate to steep dips (Carney & Janecke, 2004).The stratigraphy of the NCV consists of Pleistocene Lake Bonneville lacustrine sediments overlying a sequence of sedimentary rocks from the Tertiary Salt Lake Formation, which in turn overlies basement metamorphic rock of the Precambrian Pocatello Formation (Wood et al., 2015). The Oxford-Dayton fault acts as the controlling fault structure in the area, and is located at the base of the Bannock and Malad mountain ranges on the west side of the valley (Figure 1). Smaller secondary faults, of which the Clifton Hill bounding faults are included, are numerous throughout the graben (McIntyre and Koenig, 1978). Bounded on either side by high angle faults, Clifton Hill is composed of the Late Proterozoic Scout Mountain member and the Bannock Volcanic member of the Pocatello Formation and an associated diabase intrusion (Link & LeFebre, 1983; Link, 2015). It is currently thought that the high angle bounding faults surrounding Clifton Hill provide pathways for circulating thermal fluids to travel upwards into the shallow cold water aquifer. The thermal water mixes and moves with shallow ground water and is discharged to the numerous hot springs along the Bear River or are accessed by chance in shallow wells such as the Bosen Well. The primary Clifton Hill bounding faults are thought to be flanked by smaller secondary faults (Figure 1) which help to accommodate movement of the Clifton Hill horst block and increase permeability in the shallow subsurface (Wood et al., 2015).

3. DATA COLLECTION AND PROCESSING

Magnetics data were collected in mid-August, 2015 using a Geometrics G-859 Cesium vapor magnetometer with integrated GPS. In addition, a Geometrics G-862 RBS Cesium Base Station Magnetometer was used to record and correct for diurnal variations. Notes taken during the survey, detailing cultural features (fences, culverts, power lines, etc.) that may affect the measured signal, were used to guide preprocessing of the data. Lines were planned based on proximity to structures of interest and accessibility via roads and access to property. Ten survey lines were recorded, totaling over 30 km (Figure 2). Data reduction was carried out using Geometric's MagMap 2000 and Geosoft's Oasis Montaj software packages.

Gravity data from 300 stations were collected in September, 2015, using a LaCoste and Romberg gravimeter. Stations were positioned along lines where magnetic data were previously collected (Figure 3). Typical spacing of gravity stations was 50 meters when in close proximity to structures of interest, and further apart for the purpose of constraining the regional field. For this study, a new gravity base station was established at the Preston, ID Federal Post Office and tied to the Salt Lake City BM8 gravity base station (Winester, 1998), located in the President's Circle at the University of Utah. Gravity data were reduced using software developed by the United States Geological Survey.

Magnetic susceptibility values were measured on outcrops in the field using a Terraplus KT-10 susceptibility meter. Samples were collected at over 12 locations and processed in the laboratory for density.

Gravity and magnetic data were processed (e.g., gridded, filtered) with Oasis Montaj, and modeled using the GMSYS 2&¾ D modeling package. Model bodies were assigned densities and susceptibilities based on values determined in the field or calculated from laboratory measurements of rock samples. Where samples or outcrop measurements were not available, model properties were based on average values of equivalent units determined from a database of over 18,000 samples maintained by the USGS. Models were developed through a process involving both forward and inverse steps.

4. DISCUSSION

We present modeling results from 3 profiles that cross the Clifton Hill fault system (lines 3, 4 and 6; Figures 5, 6, 7. These profiles reveal a ~15mGal gravity high centered on the Clifton Hill ridgeline. This high cannot be accounted for solely by the Bannock and Scout Mountain members. A good match to the gravity data, however, is made when a third denser unit is introduced, that is represented in the models (Figures 4-6) as the diabase intrusive that outcrops in the southern and northern end of Clifton Hill. NNW-trending intrusions like this appear to be common in the NCV. Similar mafic dikes have been noted in the Bannock mountain range to the west. The Cub River Diabase (CRD) has been studied and mapped to the east and may be related to other intrusions in the southern portion of the valley (Carney and Janecke, 2005; Williard, 1972; Winter, 1985). Williard (1972) dates the CRD as late Pliocene, approximately 3.5 to 2.5 ma. Winter (1985) suggests that the CRD is related to other intrusive bodies throughout Cache Valley. Whether these intrusive bodies include the ones seen in the Bannock mountain range or Clifton Hill remains to be seen. Regardless, due to the preponderance of NNW-trending dikes in the region, we consider it a realistic scenario to envision a diabase dike to exist in the subsurface beneath Clifton hill.

The Precambrian basement rock and the diabase intrusion that form Clifton Hill also constitutes the footwall rock of the low angle normal fault system of the Oxford-Dayton fault (Figure 1) (Carney and Janecke, 2005). Carney and Janecke (2005) suggest that the significant portion of the movement on the Oxford-Dayton fault occurred after 4.4 ma. So it is possible that after the significant movement along the Oxford-Dayton fault complex (possibly 4 Ma) igneous intrusions formed dikes and sills between 3.5 and 2.5 ma. Subsequently, a portion of the Precambrian Pocatello Formation of the footwall, containing an igneous dike was uplifted to form Clifton Hill.

Of great interest to us are the angles of the faults that this portion of the Pocatello Formation was uplifted along. The Stocks 1-A exploration well drilled by Sunedco failed to penetrate the western bounding fault. McIntyre & Koenig (1978) postulate that the angle of the western bounding fault may be steeper than initially thought prior to drilling the Stocks 1 and 1A wells. Bert Winn #1 was placed southeast of Clifton Hill (Figure 1) to investigate a geoelectric anomaly; of which a cause was not identified nor was the eastern bounding fault encountered. The new geophysics data presented here supports the notion that the wells did not intercept Clifton Hill bounding faults. Models along lines 3 & 4 indicate that the western bounding fault is a steeply dipping normal fault. This would explain why the Stocks 1-A exploration well did not penetrate the western bounding fault, it didn't go deep enough. Modeling suggests that the eastern bounding fault is also steeply dipping (to the east).

The data confirm that the secondary faults surrounding Clifton Hill do exist, but additional data would be needed to better constrain their locations and orientations more accurately. Gaps in the current data coverage across these secondary faults has resulted in interpolations across the areas of interest which may not reflect reality. Current approximation of their positions was based on surface mapping by Dr. Ismail Kuscu of Blackrock Geosciences (personnel communication, 2015).

5. CONCLUSIONS

The NCV was the subject of commercial geothermal exploration activities during the 1970s and early 1980s, but due to underperforming geothermal test wells, the exploration was terminated. The exploration wells were designed to drill into permeable zones created by faults bounding Clifton Hill that are thought to carry thermal water from depth that discharges to hot springs in the area. Based on the failure of these wells to intersect permeability and measure a notable increase in temperature with depth, it was concluded that these permeable fault zones were likely missed by both wells and that the area was not adequately tested. A magnetic and gravity survey, presented here, was designed to constrain the location and attitude of the faults bounding Clifton Hill. Using forward and inverse modeling methods that employed material properties from the area, a reasonable match to the field gravity and magnetics was determined. The models indicate that the range front faults bounding Clifton Hill are steeply dipping, and indicate the presence of several secondary intrabasin faults. This explains why previously drilled exploration wells did not intersect a major permeable zone (i.e. fault plane). Our results indicate future exploratory drilling would need to be located close to the base of the hill, or drilled directionally towards the hill, in order to intersect the range front faults.

Future plans for the area include measuring water levels in wells to construct a potentiometric map and measure temperatures of the shallow aquifer to determine the direction of flow and temperature distribution in the shallow aquifer. These data may help identify where thermal waters from the Clifton Hill fault system are entering the shallow ground water system.

ACKNOWLEDGMENTS

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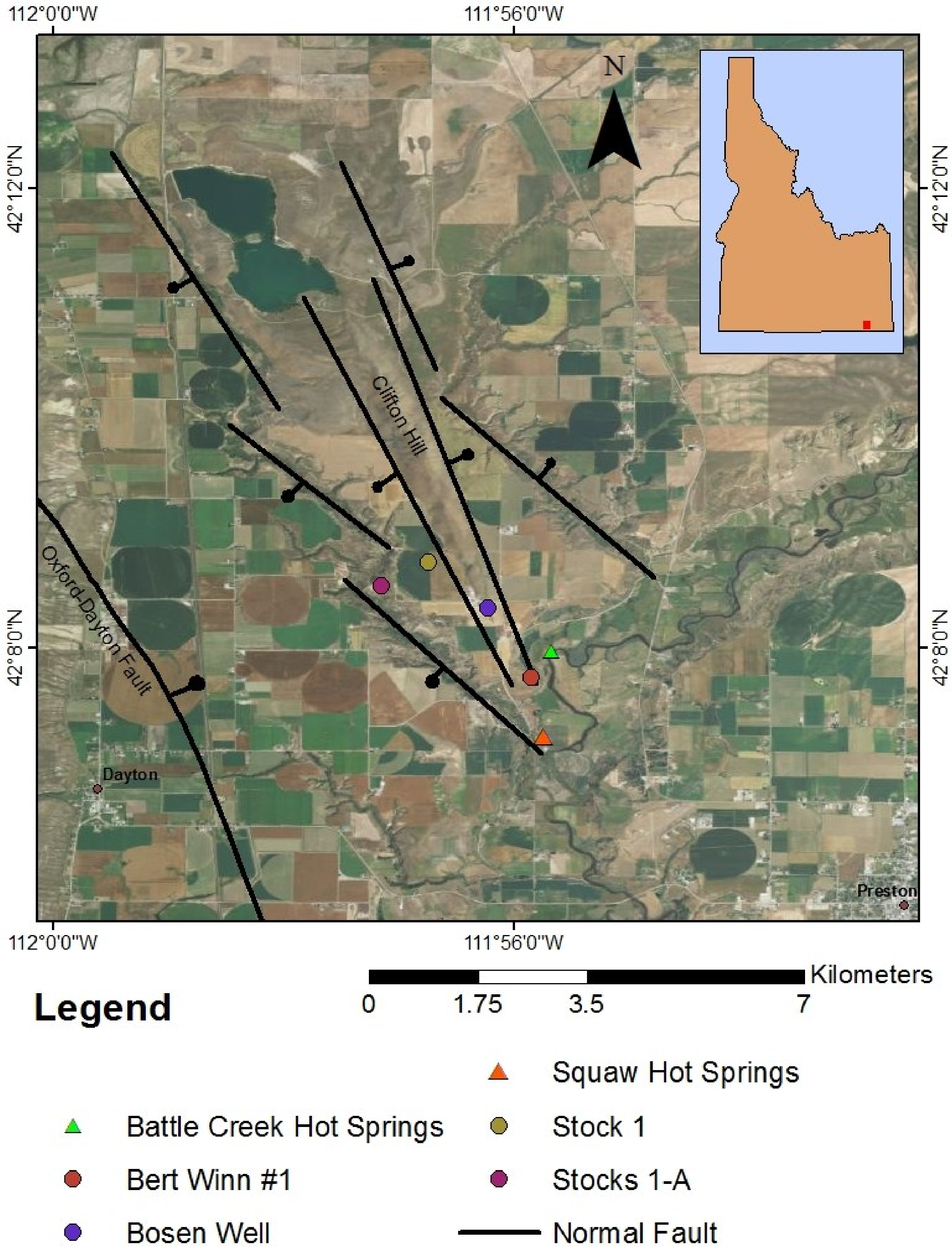


Figure 1. Location of study: Clifton Hill and surrounding land, located 6.5 kilometers (3 miles) to the northwest of Preston, ID. Any distortion of the aerial image is due to the projection used.

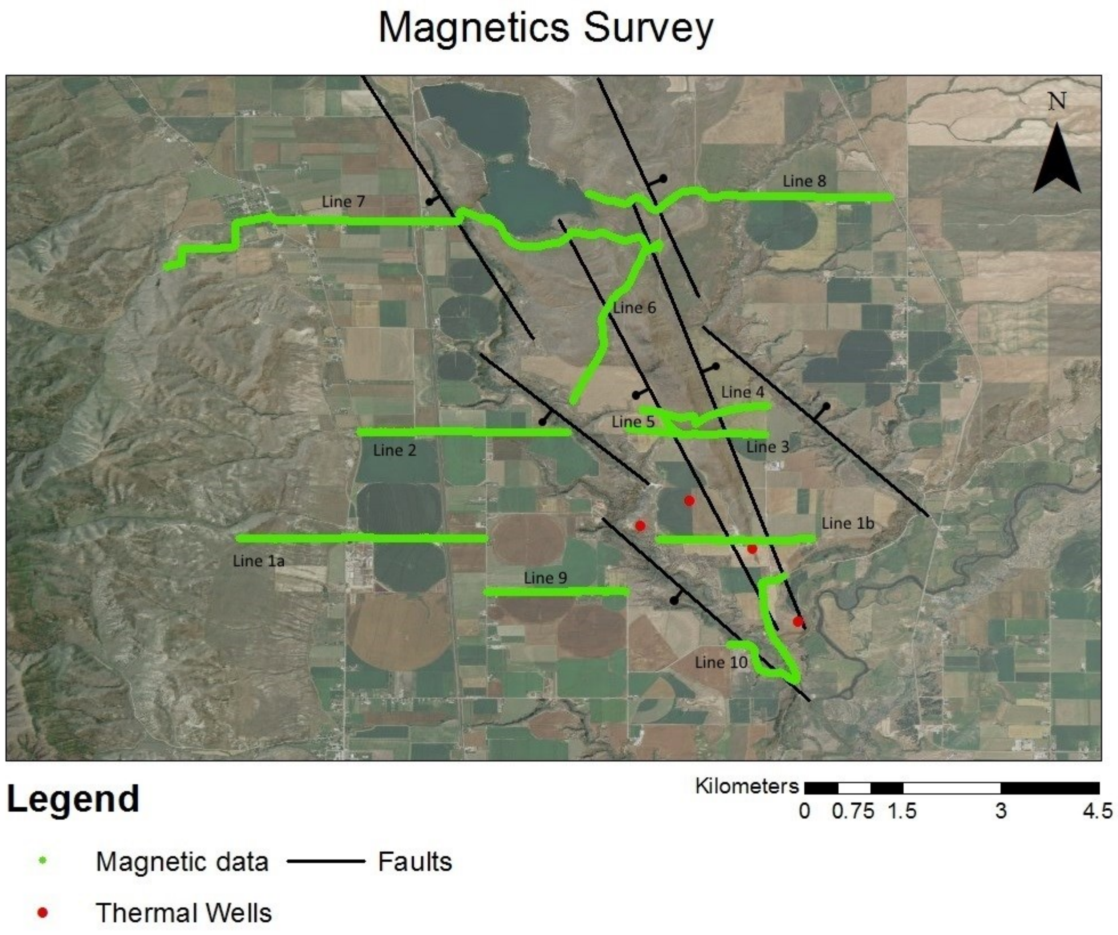


Figure 2. Map of the areal extent of the magnetics survey lines of the field work.

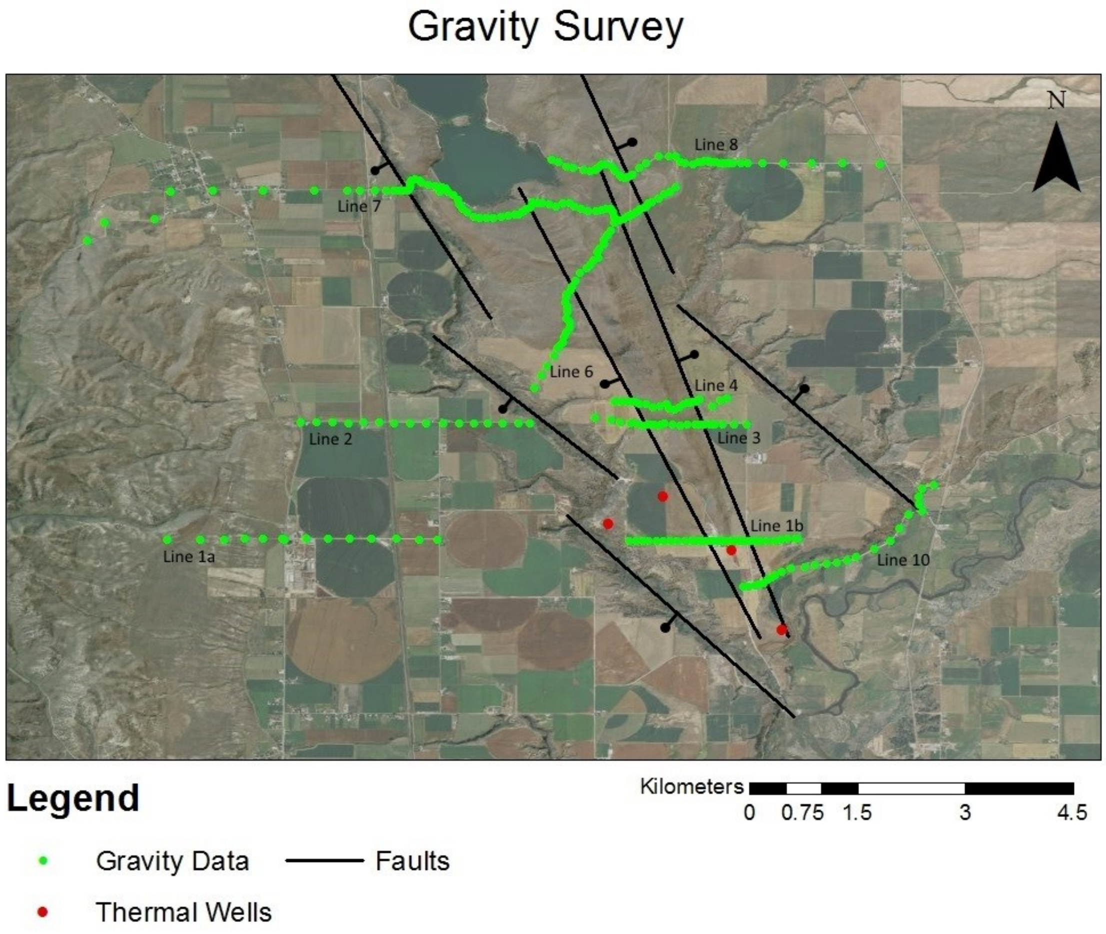


Figure 3. Aerial extent of the gravity lines of the field work. Note that for the gravity lines, there is no gravity data for line 5 because line 5 was very short and situated almost parallel to the western bounding fault, so gravity data along that line would not be very useful. There is no gravity data for line 9 due in part to time constraints of collecting gravity data and preferential selection of other lines due to likely usefulness in structural interpretation.

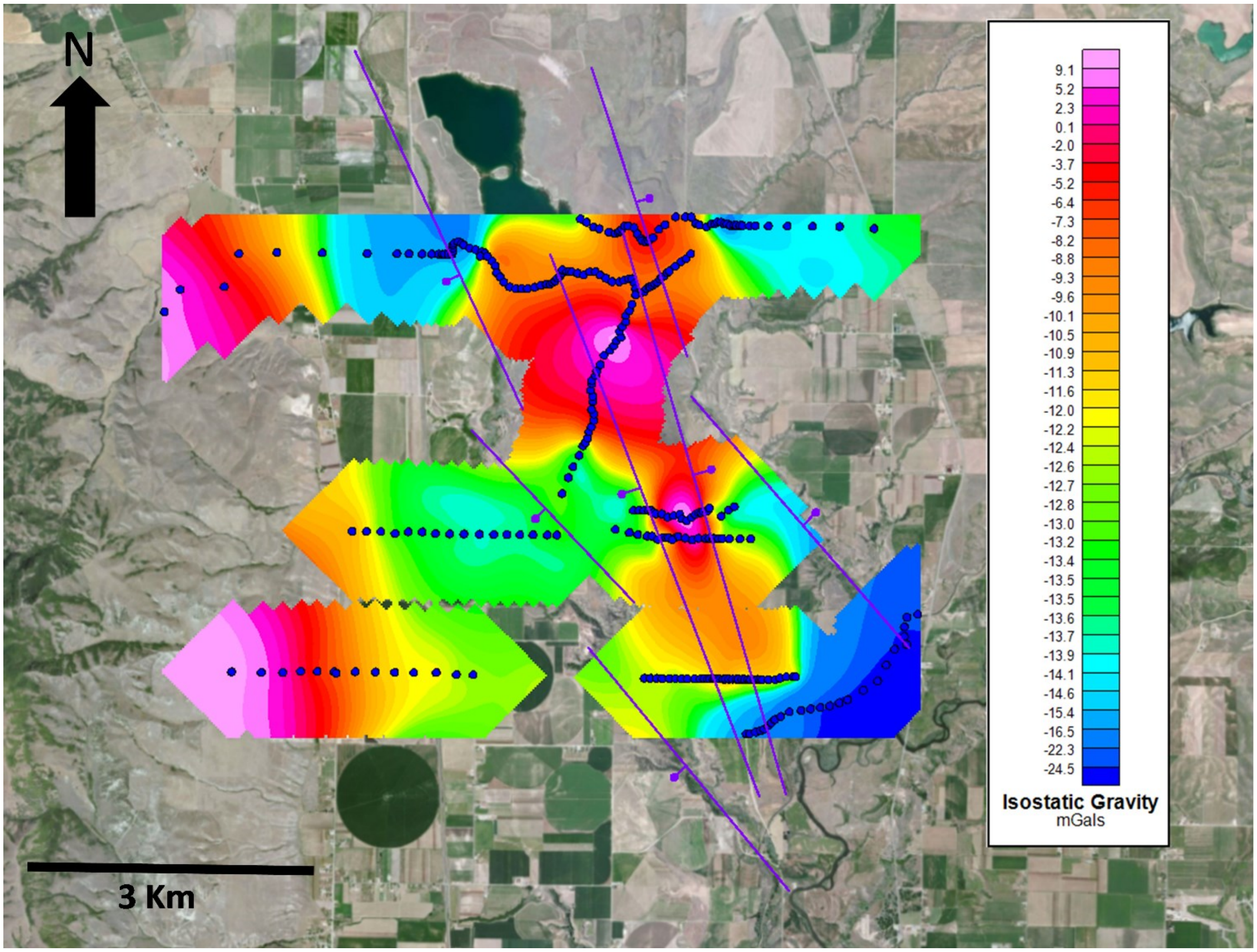


Figure 4. Isostatic gravity anomaly processed from gravity data across the study area. Purple solid lines indicates possible faults. Gravity anomaly units are in milligals.

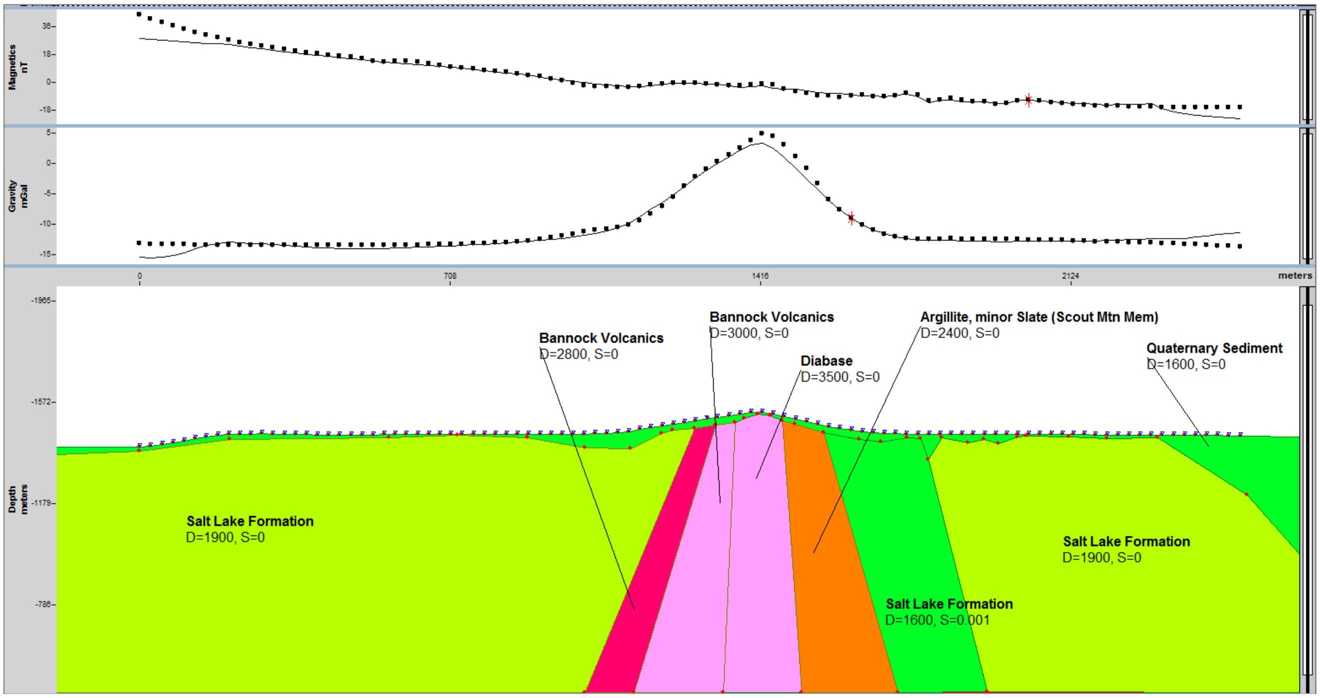


Figure 5. Structure of Clifton Hill along line 3 modeled with magnetics and gravity data. Colors are assigned by the modeling program Oasis Montaj based on density values used. D stands for the density value and S for the susceptibility value assigned to each block. Units of density are Kg/m3, susceptibility uses SI units. The points in the top two windows represent data measured in the field, the solid line represents modeled data calculated from the subsurface model in the bottom window.

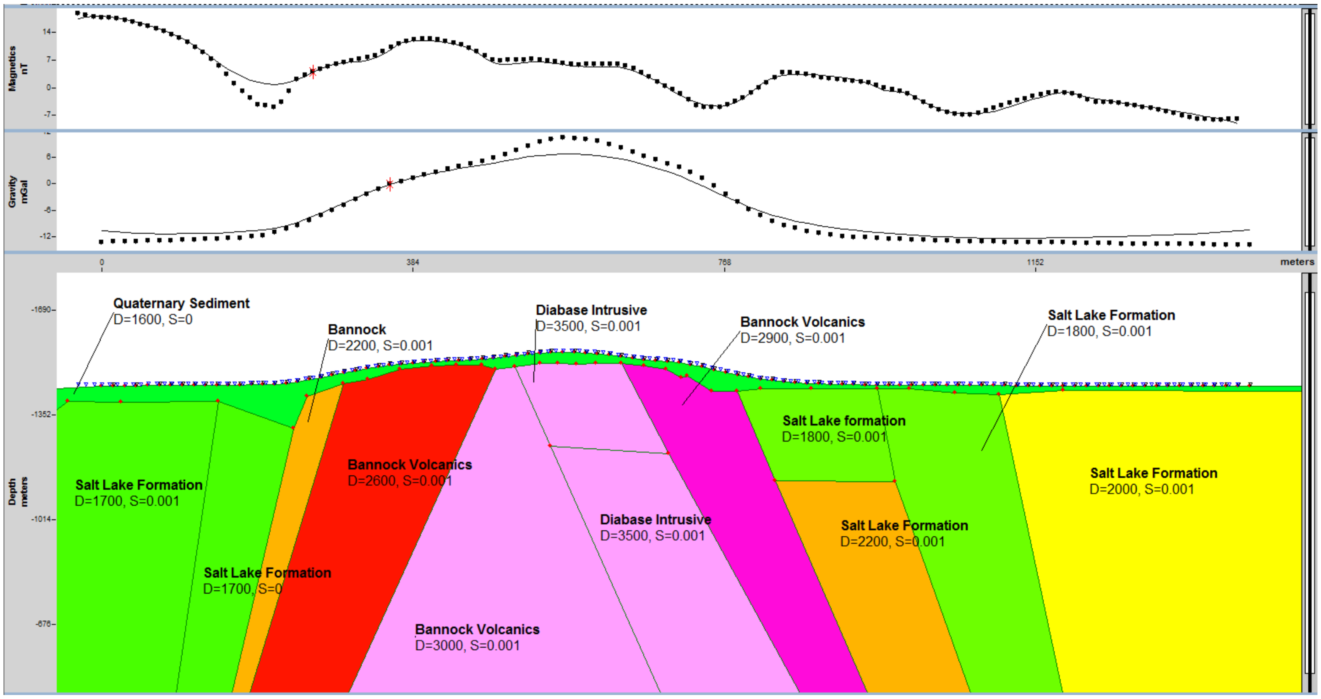


Figure 6. Structure of Clifton Hill along line 4 modeled with magnetics and gravity data. Colors are assigned by the modeling program Oasis Montaj based on density values used. D stands for the density value and S for the susceptibility value assigned to each block. Units of density are Kg/m3, susceptibility uses SI units. The points in the top two windows represent data measured in the field, the solid line represents modeled data calculated from the subsurface model in the bottom window.

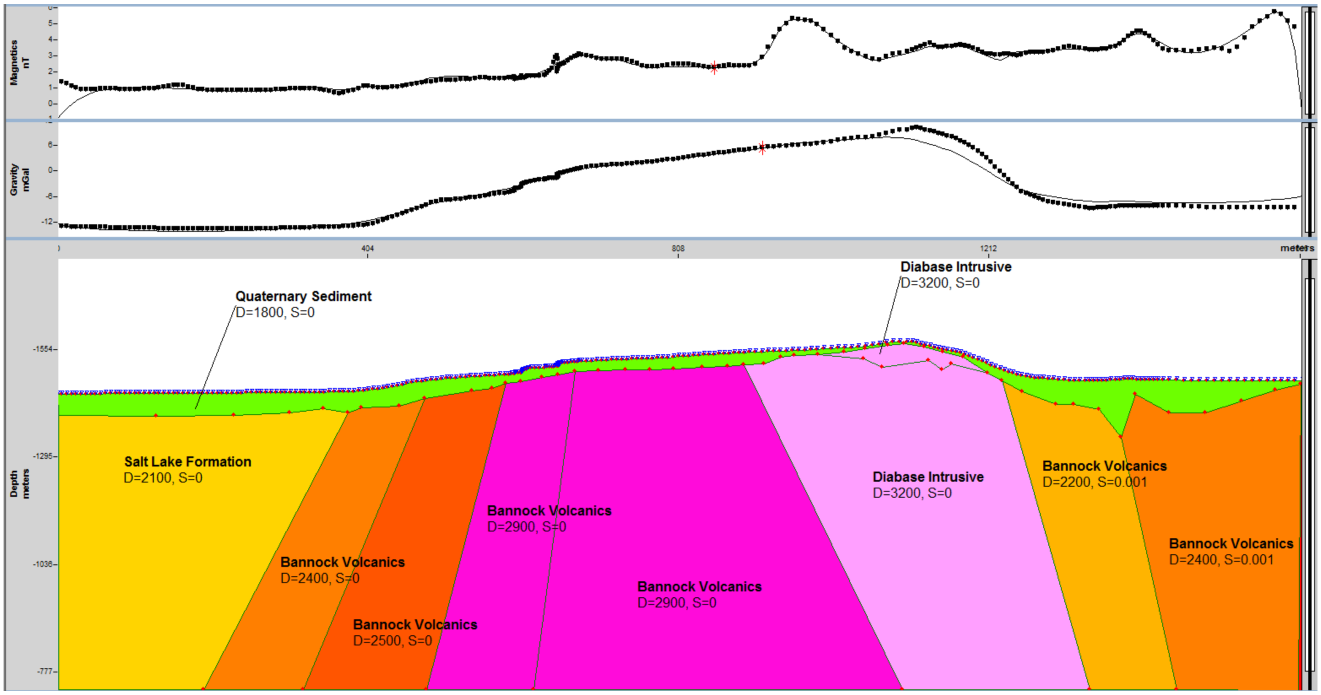
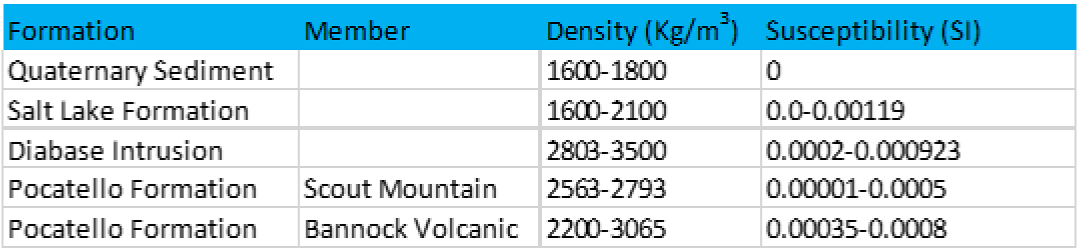


Figure 7. Structure of Clifton Hill along line 6 modeled with magnetics and gravity data. Colors are assigned by the modeling program Oasis Montaj based on density values used. D stands for the density value and S for the susceptibility value assigned to each block. Units of density are Kg/m3, susceptibility uses SI units. The points in the top two windows represent data measured in the field, the solid line represents modeled data calculated from the subsurface model in the bottom window.



Formation	Member	Density (Kg/m^3)	Susceptibility (SI)
Quaternary Sediment		1600-1800	0
Salt Lake Formation		1600-2100	0.0-0.00119
Diabase Intrusion		2803-3500	0.0002-0.000923
Pocatello Formation	Scout Mountain	2563-2793	0.00001-0.0005
Pocatello Formation	Bannock Volcanic	2200-3065	0.00035-0.0008

Figure 8. Ranges of values used for density and susceptibility while modeling Clifton Hill. These values are constrained by susceptibility measurements made in the field and laboratory and density measurements made on rock samples in the laboratory.