



## EXECUTIVE SUMMARY

### Geochemical Analysis and Geophysical Modeling For Hydrogeologic Assessment of the Steamboat Hills and Southern Truckee Meadows Area, Washoe County, Nevada

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Washoe County Department of Water Resources

July 31, 2001

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By John D. Skalbeck

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## ABSTRACT

Three studies constitute the hydrogeologic assessment of the Steamboat Hills area, Washoe County, Nevada. Geophysical modeling and geochemical analysis are used to assess the hydrogeologic connection between a fractured bedrock geothermal system used to produce electrical power and surrounding alluvial aquifer basins used for municipal drinking water supply. Understanding the hydrogeologic connection between these two water resources is important for long-term management of these resources.

Temporal variations in B and Cl concentrations, water levels, and temperature are used to assess the mixing of thermal and non-thermal waters in alluvial aquifers north of the Steamboat Hills. Previously undocumented temporal variations indicate that the degree of mixing is dependent upon the proximity to north-trending faults connecting the geothermal reservoir and the alluvial aquifer. Mixing trends at selected wells suggest temperature dependent boron adsorption to explain the trends in boron concentration of select wells.

Modeling of gravity and magnetic data constrained by geological and physical properties (density, magnetic susceptibility, remanent magnetic) data yields a detailed 3-D geologic model of the geothermal system and the alluvial basins. A new method is presented for modeling the geothermal reservoir based on altered physical properties of host rock that yields a reservoir volume estimate that is double the previously assumed volume. The configuration of the modeled geothermal reservoir suggests that a previously unrecognized thermal water up-flow zone may exist along the west flank of the Steamboat Hills. Model results delineate the elevation and thickness of geologic units that can be used in numerical modeling of groundwater flow and well field development.

Anomalously low ground magnetic data delineate a fault that conducts thermal water from the geothermal system to an alluvial aquifer. Vertical magnetic susceptibility from core measurements yields an average value for altered granodiorite used in forward modeling. Permeable fractures and a major fault zone noted in the core hole log correspond to low magnetic susceptibility values suggesting thermal alteration or mineral replacement along fractures.

## ACKNOWLEDGEMENTS

The author wishes to thank Dr. Robert Karlin for the use of the Mackay School of Mines (MSM) Paleomagnetic Laboratory, Dr. Robert Watters for the use of the MSM Geomechanics Laboratory, and Dr. Patrica Cashman and her research assistants for the refresher on paleomagnetic field and laboratory techniques. Dr. Robert Karlin, Dr. Lisa Shevenell, Dr. John Louie, Dr. Gary Oppliger, Dr. Jane Long, Dr. Steve Wheatcraft, and Michael Widmer provided critical review that is gratefully acknowledged.

## INTRODUCTION

This document is a condensed summary of the report titled *Geochemical Analysis and Geophysical Modeling for Hydrologic Assessment of the Steamboat Hills and Southern Truckee Meadows Area, Washoe County, Nevada* dated July 31, 2001. The purpose of this document is to provide a concise overview of the study by presenting the important elements of the full report. The reader should refer to the full report for details not included in this executive summary.

### Study Objectives

The overall objective of this study is to apply potential fields (aeromagnetic and gravity) modeling and magnetic methods to investigate the hydrogeology of the Steamboat Hills area, Nevada. Previous investigations (e.g., White et al., 1964 and White, 1968) identified ubiquitous faults throughout the study area and concluded in a general sense that some of these faults and their associated fracture network likely control the connection between the geothermal system and alluvial aquifers used as a drinking water resource. While faults are known to conduct thermal water from the geothermal system to the surrounding alluvial aquifer, identification and delineation of specific permeable faults has been elusive.

The main focus of this study was to investigate methods for identifying faults and fractures that conduct thermal water using the integration of geochemical, geologic, and physical properties (density and magnetic) data, potential fields modeling, and ground magnetic surveys. Geochemical analysis was used to demonstrate that specific faults conduct thermal water from the geothermal system to the alluvial aquifer. Modeling of gravity and magnetic data yielded a three dimensional model of the subsurface geology and structure that can be used as a tool in planning for both drinking water and geothermal exploration and as the framework for a numerical groundwater flow model. Finally, a strategy is proposed for geothermal resource exploration using aeromagnetic and ground magnetic surveys and core/borehole logging of magnetic properties.

### Organization

The full report includes 5 chapters. Chapter 1 presents an introduction of the study. Chapter 2 describes the analysis of temporal variations in boron and chloride concentrations, water levels, and temperature to evaluate the mixing of thermal and non-thermal waters. The data compiled for this manuscript are presented in Appendix A. In Chapter 3, potential fields (gravity and aeromagnetic profile) modeling is used to construct a 3-D geologic model of the Steamboat Hills geothermal system and the surrounding alluvial basins of the southern Truckee Meadows. The 3-D model can serve as a planning tool for municipal well field development and as a framework for a numerical model to estimate groundwater flow. Physical properties data for each block in the 2.75-D forward models and the data from the 3-D model are presented in Appendix B. Chapter 4 presents the results of using ground magnetic data to delineate a fault that conducts thermal water from the Steamboat Hills geothermal system into the Mount Rose Fan alluvial aquifer. Ground magnetic data from this chapter are presented in Appendix C. Chapter 5 presents the summary and conclusions of this study.

## **Water Resources Stakeholds**

The population growth of Reno has increased rapidly in the past 10 years and is expected to continue into the next decade. Much of this growing population is concentrated in the south Truckee Meadows where the responsibility for ensuring adequate water resources for new residential and business developments falls on the Washoe County Department of Water Resources (Washoe County, 1996). The additional production capacity to meet this growing demand for potable water comes primarily from groundwater in alluvial basins surrounding the Steamboat Hills.

Two geothermal electric power generation facilities (Far West Capital [FWC], operated by SB Geo, Inc.[SBG], and Caithness Power, Inc.[CPI]) are currently operating in the Steamboat Hills. The initiation of geothermal production around 1985 was coincident with Washoe County's development of the Mount Rose Fan well field. Hot-spring flow at Steamboat Springs began declining in 1986 and ceased completely in 1987. Recognizing that the long-term management of water resources in the Steamboat Hills area depends on a thorough understanding of the relationship between the alluvial aquifers and the geothermal reservoir, Washoe County and SBG. agreed in 1998 to share data for a cooperative study.

## **Hydrogeologic Setting**

The Steamboat Hills are a topographically prominent northeast-trending bedrock ridge that represents the southern extent of the fault-bounded Truckee Meadows basin, which contains the cities of Reno and Sparks approximately 15 km north of Steamboat Hills (Figure 1). The study area is bordered on the west by the Carson Range of the Sierra Nevada Mountains and on the east by the Virginia Range.

The core of these ranges consists of granodiorite beneath older metamorphic rocks, which are overlain by volcanic rocks. Alluvial fan and basin deposits (alluvium) range from clayey sand to boulder gravels. The alluvium and volcanic rocks are the primary source of water supply for Washoe County and private residences in the southern Truckee Meadows. Three prominent fault systems trending north-south, northeast-southwest, and northwest-southeast are found in the study area. A series of five rhyolite domes occur along the northeast-southwest fault trend. The Steamboat Hills geothermal field occurs predominantly along northwest-southeast trending faults within the granodiorite and metamorphic rocks. Thin surface deposits of silica sinter are associated with the geothermal discharge area near the Steamboat Springs Fault System along the east flank of Steamboat Hills.

Groundwater originates primarily from recharge in the Carson Range and flows eastward toward Steamboat Creek. Depths to groundwater range from around 80 m (262 ft) near the center of the alluvial fan to land surface at Steamboat Springs. Similarities in water chemistry and water level fluctuations suggest that the geothermal reservoir and alluvial aquifer are hydrologically connected. Mixing trends between thermal and non-thermal waters within the alluvial aquifer indicate that north-trending faults provide the hydraulic connections between the drinking water and geothermal water resources.

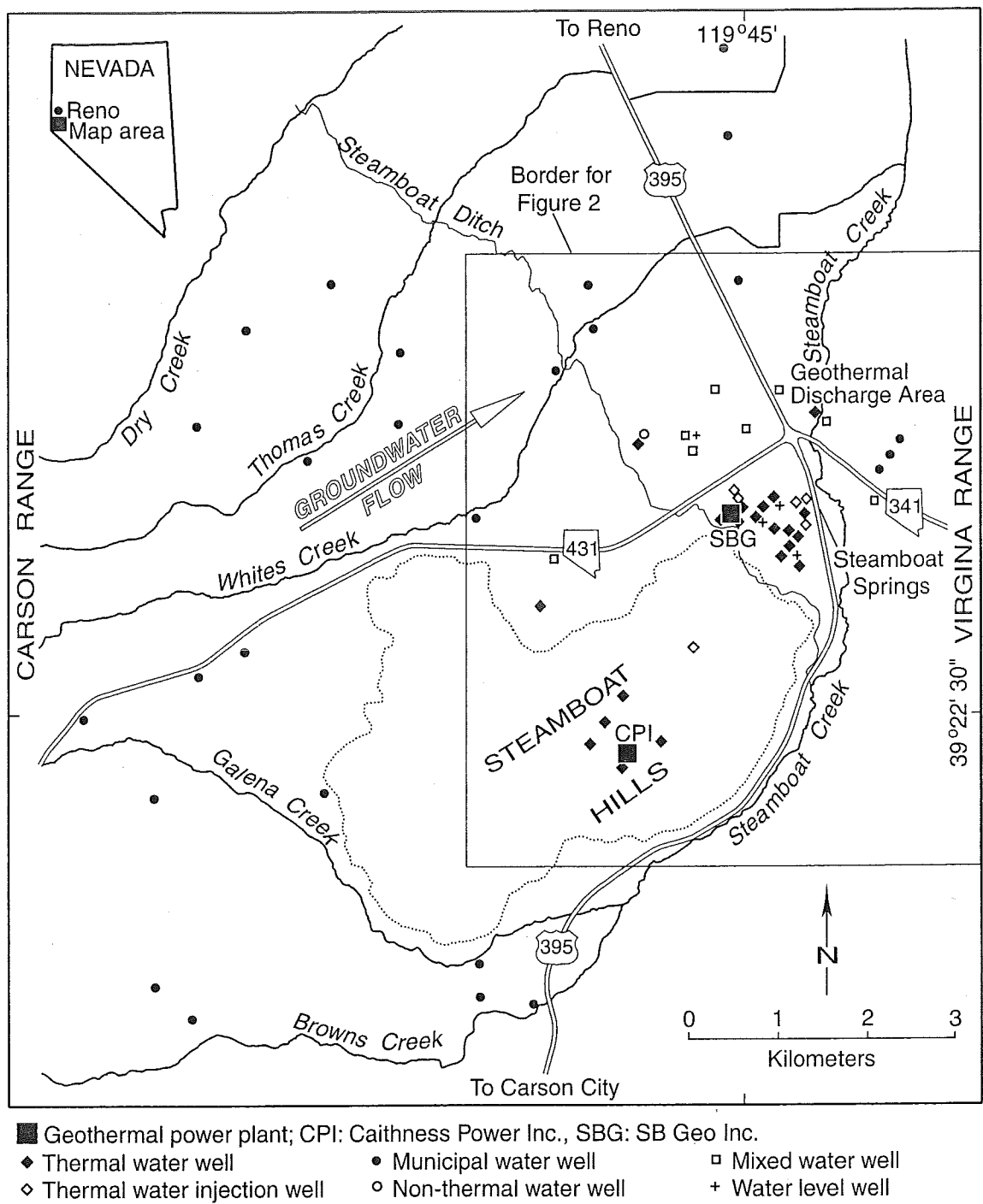


Figure 1. Location map of the Steamboat Hills area, Nevada.

## CHEMISTRY OF THERMAL AND NON-THERMAL GROUNDWATERS

### Introduction

The development of both thermal and non-thermal water resources has affected wells in the combined discharge area east of Steamboat Hills near Steamboat Creek (Figure 1). The purpose of this study is to identify causes of water quality degradation or improvement at public and domestic water supply wells in this discharge area, and to document changes in the contribution of thermal waters to this area, along with possible causes. The temporal relationship of production activities and water quality trends for both of these water resources is evaluated to determine the importance of faults to fluid flow. These results are published in the journal *Geothermics* (Skalbeck et al, 2001).

### Methods

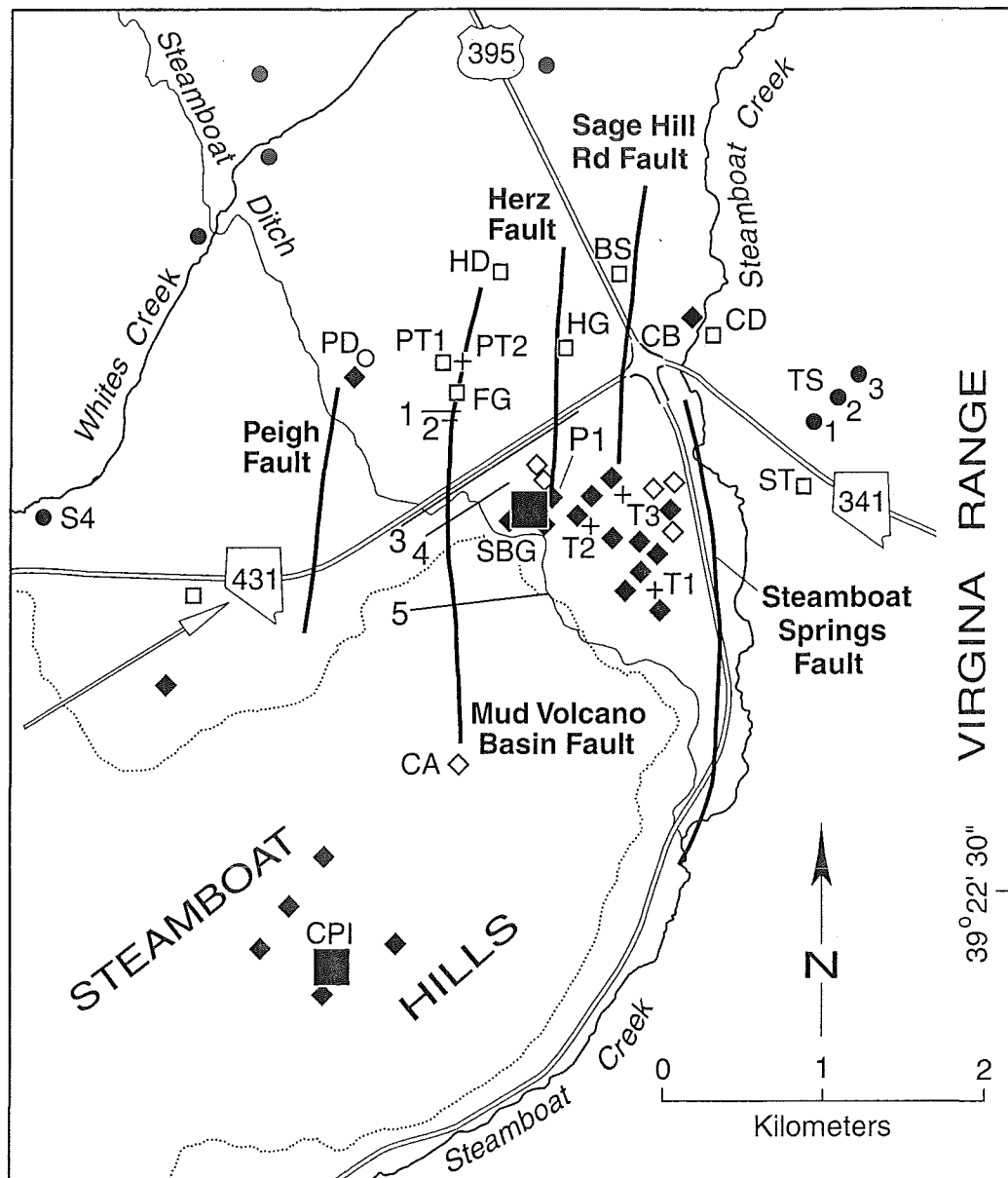
Data compiled by Washoe County from SBG and CPI reports and data from Nehring (1980), Ingraham and Taylor (1991), and Mariner and Janik (1995) were used for this study. Wells selected to represent non-thermal, thermal, and mixed waters (Figure 2) were evaluated by assessing the temporal variations in boron and chloride concentrations, water levels, temperature, and calculated the percent of thermal water in alluvial wells located in the discharge area of the geothermal system. Available well log data and mapped faults were used to assess groundwater flow paths and the possible hydrologic connections between the fractured bedrock geothermal system and the alluvial aquifer.

### Results

The boron versus chloride data are plotted on Figure 3. These data represent cold waters (springs, creeks, snowmelt, non-thermal wells), non-thermal domestic and municipal wells, domestic wells with mixed non-thermal and thermal water and geothermal production wells. The majority of data fall along the same linear trend suggesting simple mixing of thermal and non-thermal waters and indicate a common source fluid for the thermal waters produced at both power plants. These data suggest a single geothermal system for Steamboat Hills as postulated by Sorey and Colvard (1992) and Mariner and Janik (1995).

The Flame well shows a steady trend from predominantly non-thermal water in 1985 to mixed type water chemistry through the last sampling date in June 1990. The Pine Tree Ranch #1 (PTR-1) well shows a similar trend; however, the maximum concentrations are approximately 20 percent of the maximum concentrations in the Flame well. The boron versus chloride temporal variation along the local mixing trend suggests a direct connection with the geothermal reservoir, with steadily increasing inputs of thermal water to the Flame well from 1985 to 1990. The Flame well is located along the northern portion of the north-trending Mud Volcano Basin Fault (MVBF) while the PTR-1 well is located approximately 30 m (98 ft) west of the fault (Figure 2). The Flame well illustrates that migration of thermal water occurs along a permeable fault. The CPI Cox I-1 geothermal injection well, situated near the southern extent of the MVBF, was





- |  |   |  |
|--|---|--|
| ■ Geothermal power plant<br>CPI:Caithness Power Inc.<br>SB:SB Geo Inc. | ○ Non-thermal water well<br>PD:Peigh Domestic   | + Water level well<br>PT2:Pine Tree Ranch #2                   |
| ◆ Thermal water well<br>P1:SB Geo; SBG-PW1<br>CB:Curti Barn Geothermal | ◻ Mixed water well<br>BS:Brown School<br>ST:Steinhardt  | T1:SB Geo; SBG-TH1<br>T2:SB Geo; SBG-TH2<br>T3:SB Geo; SBG-TH3 |
| ◇ Thermal water injection well<br>CA:Caithness; Coxl-1                 | CD:Curti Domestic<br>HD:Herz Domestic<br>HG:Herz Geothermal<br>FG:Flame Geothermal<br>PT1: Pine Tree Ranch #1 |  |
| ● Municipal water well<br>S4:STMGID #4<br>TS:TranSierra wells 1,2,3    |   | 1 — Ground Magnetic<br>Transect                                |

Figure 2. Study area location map. Thermal, non-thermal, mixed water, and water level wells and hydrologically significant faults referenced in this study are labeled. Location of ground magnetic transects across Mud Volcano Basin Fault are shown.

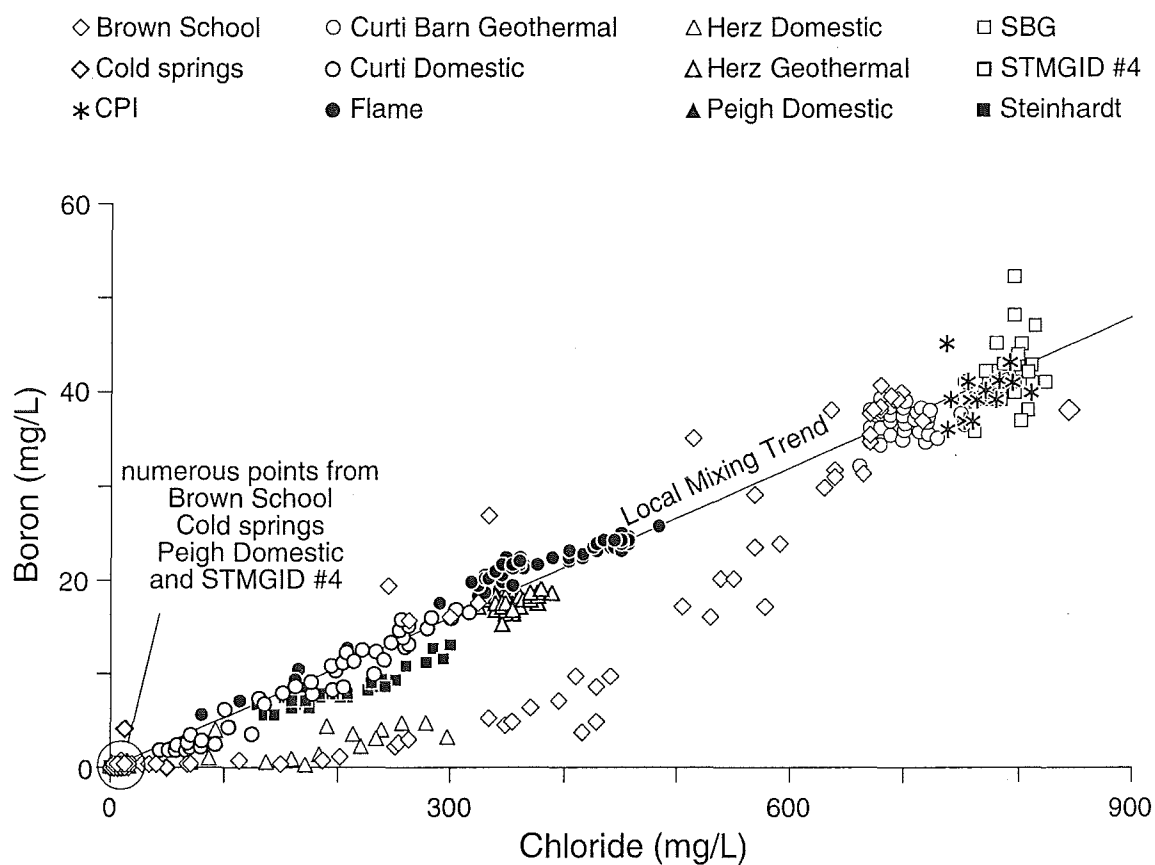


Figure 3. Boron versus Cl for various water types in the Steamboat Hills area, Nevada. Local mixing trend is from the origin to maximum B/Cl concentration represented by the CPI/SBG geothermal production data. This local mixing trend is included on subsequent B versus Cl plots. Data for Cold Springs, Peigh Domestic, and STMGID #4 plot near the origin but are hidden under other symbols.

likely installed to utilize the permeable nature of this fault. The decrease of boron and chloride concentrations with distance from this fault suggests that most of the geothermal fluid flows along the permeable fault rather than through the matrix of the geothermal reservoir. Mixing of thermal and non-thermal water is greatest in close proximity to a permeable fault and thermal water characteristics decrease with distance from the fault.

Chloride vs boron concentrations in the Herz Domestic and Brown School wells illustrate three distinct mixing trends. The first trend shows significant increases in chloride with only slight increase in boron through 1991 for the Herz Domestic well and through 1989 for the Brown School well. The second trend shows boron and chloride variations trending toward the thermal type water signature through 1992 (Herz Domestic well) and through 1996 (Brown School well). The 1996 chloride and boron concentrations in the Brown School well are nearly identical to the thermal type water found in CPI wells. The third trend is defined by decreasing boron and chloride concentrations through the last sampling date of 1994 (Herz Domestic well) and 1998 (Brown School well). The Brown School well is located approximately 50 m (164 ft) west of the north-trending Sage Hill Road Fault, whereas the Herz Domestic well is situated between the north-trending Herz Fault and Mud Volcano Basin Fault approximately 250 m (820 ft) from each fault (Figure 2). The greater changes in boron and chloride concentrations at the Brown School well compared to those at the Herz Domestic well could be a result of its closer proximity to a north-trending fault. The mixing trends observed in these two wells may result from boron adsorption on clays in the alluvial aquifer as fluids flow away from the faults into the porous media of the alluvial aquifer. The boron and chloride concentrations observed in other wells plot along the local mixing trend line; however, the first mixing trend observed at the Herz Domestic and Brown School wells clearly shows that boron is retarded relative to chloride. This trend suggests that clays in the alluvial aquifer may adsorb boron.

## **GEOLOGIC MODEL OF STEAMBOAT HILLS AND ADJOINING AREAS**

### **Introduction**

Potential fields modeling provides non-unique solutions since numerous different model geometries and assigned physical properties can produce fields that closely match the observed anomalies. For example, decreasing the model's density contrast between alluvium and bedrock, and increasing the depth to bedrock could both produce a computed field similar to the previous configuration. However, geologic insight and additional geological and geophysical data can more realistically constrain models. Forward modeling of gravity and aeromagnetic data with input of physical property data, surface geology, and subsurface geology from well logs greatly constrains possible interpretations of the subsurface structure in the Steamboat Hills area.

### **Methods**

The modeling of gravity and aeromagnetic data on ten N45W and one N20E oriented profiles (Figure 4) was done using the commercially-available modeling program (GM-Sys<sup>TM</sup> by Northwest Geophysical Associates). This modeling yields an

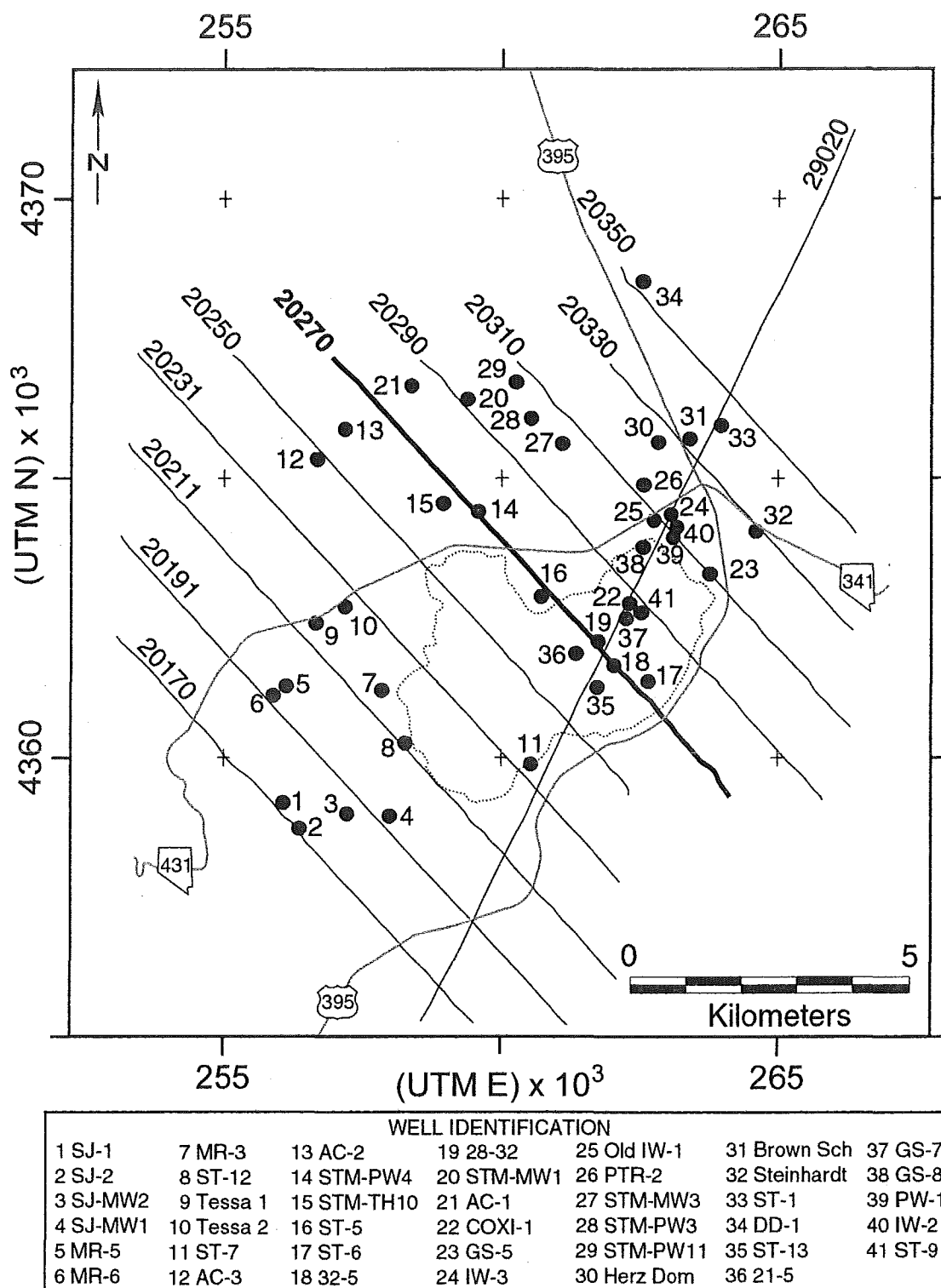


Figure 4. Map showing locations of model profiles and of wells used for vertical control of geologic blocks in models. Bold profile (20270) indicates profile discussed in text (Figure 5). Other profiles are discussed in full report.

interpretation of the geologic cross-section. The mapped surface geology provides horizontal control of geologic blocks and was strictly honored for all profiles. Well log data from domestic, Washoe County, and geothermal wells provided vertical control of geologic blocks; however, strict adherence to this vertical data proved somewhat subjective because of the projected distance of wells to model profiles. Data from wells located near a profile were weighted more heavily than from wells located further from a profile. A large number of iterative adjustments to geologic block configuration, density, and magnetic properties were made to minimize the error between observed and calculated gravity and aeromagnetic anomalies. Care was taken to maintain reasonable consistency of density and magnetic properties between profiles.

## Results

Results of the 11 profiles modeled in this study are discussed in the full report. Profile 20270 (Figure 5) is described here to highlight key features within the study area. The upper portion of the figure shows the aeromagnetic profile data while the center section shows the gravity profile data. The lower section illustrates the geologic model where the horizontal distances are relative to the northwest end of the profile and elevations are relative to mean sea level.

Profile 20270 crosses the Washoe County well field in the Mount Rose Fan alluvial basin, the production area of the CPI geothermal field located at the crest of the Steamboat Hills, and the southern extent of Steamboat Valley. Excellent vertical geologic control data are provided from 6 wells. Alluvium and the underlying volcanic rocks show maximum thickness of 190 m (623 ft) and 370 m (1214 ft), respectively, near distance 2350 m (7710 ft). Shallow volcanic rock creates two sub-basins in the alluvial fan near well STM-TH10 where alluvium thickness is 30 m (98 ft) and volcanic rock thickness is 135 m (443 ft). In well ST-5, 113 m (371 ft) of alluvium overlies granodiorite suggesting faulting and erosion eliminated volcanic rock in this area. Altered granodiorite is projected to a depth of 2750 m (9022 ft) in the CPI geothermal field near wells 28-32 and 32-5. Volcanic rock underlies the entire valley with maximum model thickness of 350 m (1148 ft).

Thickness of alluvium, volcanic rocks, and combined metamorphic rocks were obtained from the model profiles to yield a 3-D model of the subsurface geologic structure. Only the alluvium thickness results are discussed in this executive summary. The alluvium thickness map derived from the forward models (Figure 6) indicates that the alluvial deposits surrounding Steamboat Hills originate predominately from the Carson Range. The Galena Fan appears as a southeast-trending basin west of the Steamboat Hills with maximum alluvium thickness of 210 m (689 ft) near Nevada Hwy 431. The Mount Rose Fan consists of two sub-basins over 200 m (656 ft) thick within an east-trending trough that is generally parallel to slope of the alluvial fan and the groundwater flow direction. The maximum alluvium thickness (315 m, 1033 ft) is found in the western sub-basin, near the base of the Carson Range. The saddle of thinner alluvium (165 m, 541 ft) that divides the Mount Rose Fan occurs along the Serendipity Fault. An eastern sub-basin reaches maximum alluvium thickness of 270 m (886 ft) near US Hwy 395. A small circular sub-basin adjacent to Nevada Hwy 431 north of the

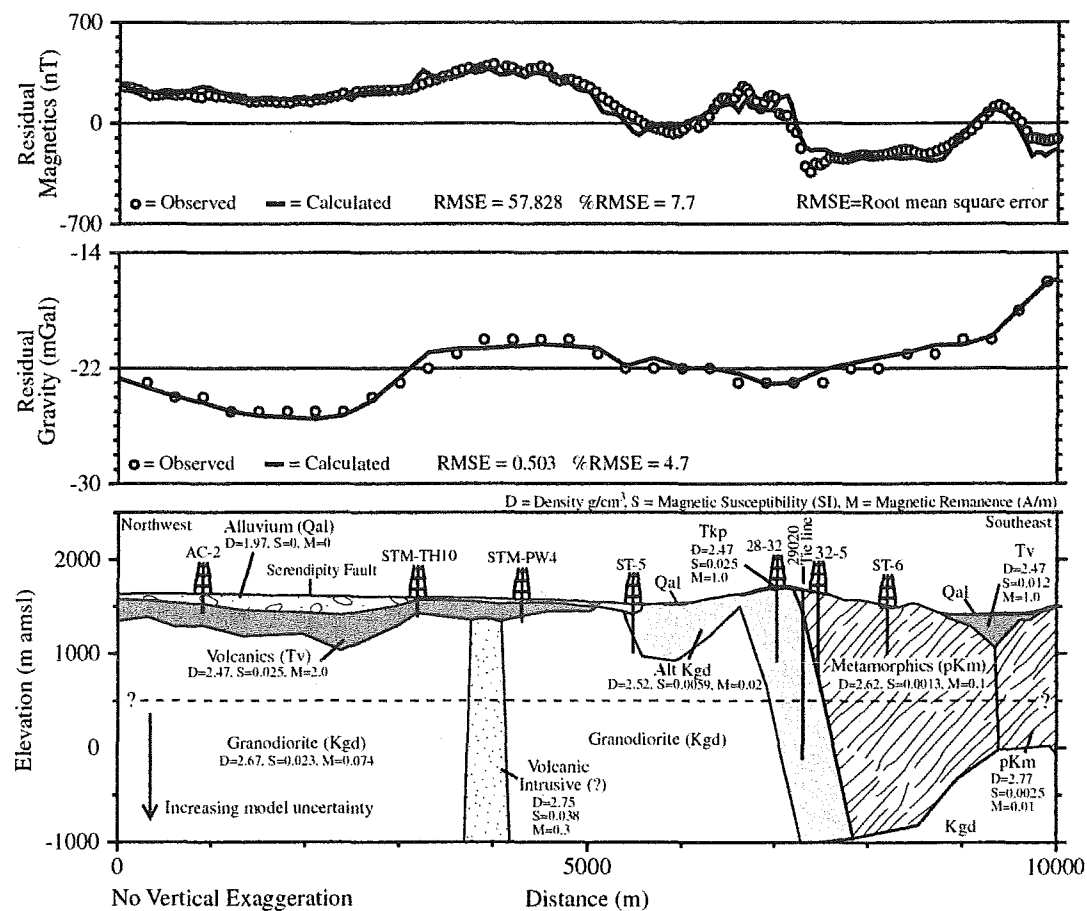


Figure 5. Profile 20270 cross-section as computed by modeling of gravity and aeromagnetic data.

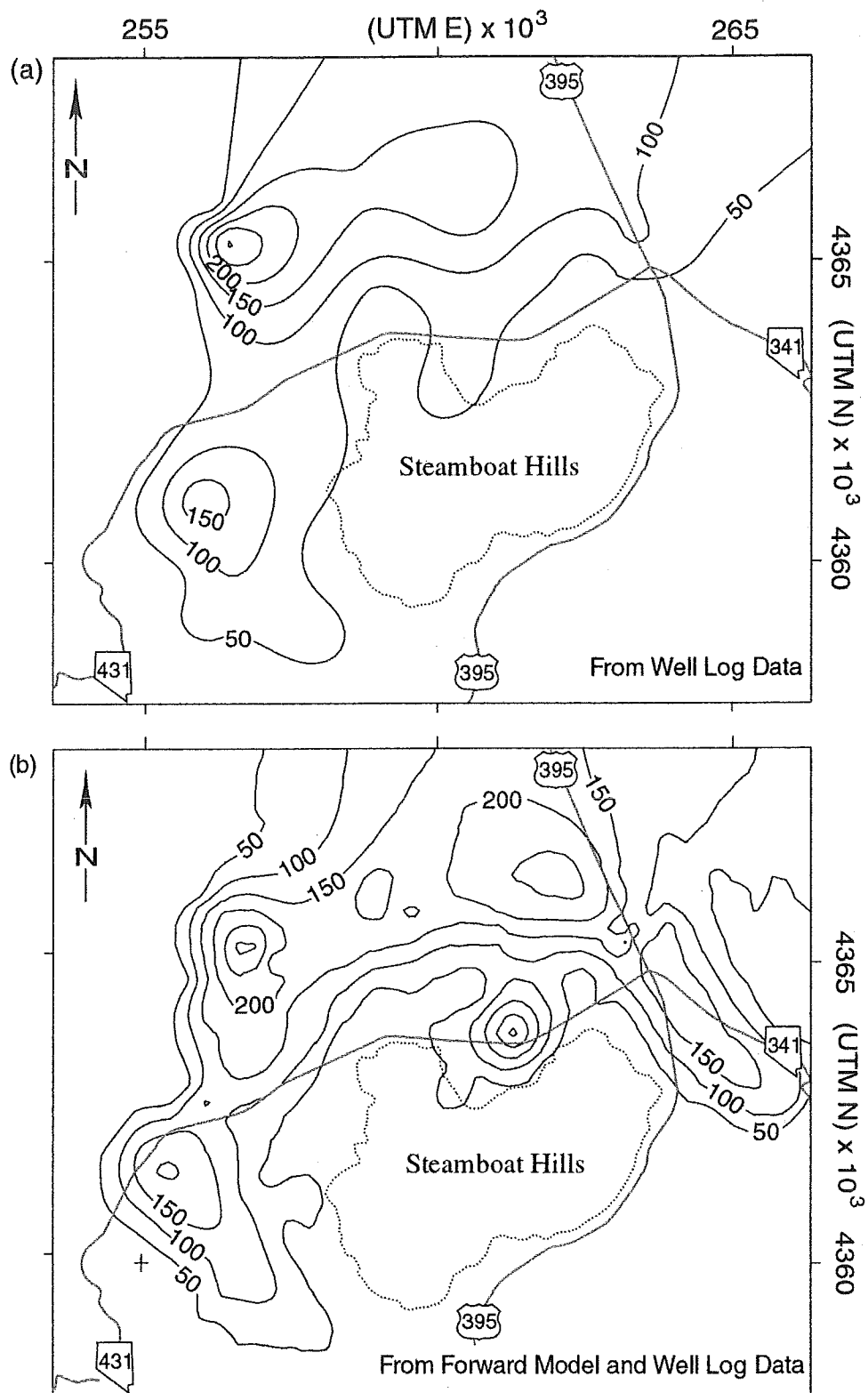


Figure 6. Alluvial thickness in basins surrounding the Steamboat Hills. (a) Derived from well log data alone. (b) derived from models of gravity and areomagnetic data and well log data. Contour interval is 50 m.

Steamboat Hills reaches maximum alluvium thickness of 270 m (886 ft). A northwest-trending basin with maximum alluvium thickness of 195 m (640 ft) occurs along Nevada Hwy 341 east of the Steamboat Hills. Steamboat and Pleasant Valleys have maximum alluvium thickness of 90 m (295 ft) and 55 m (180 ft), respectively.

We compare alluvium thickness derived from the modeling of gravity and aeromagnetic data and well log data with alluvium thickness obtained from only well log data (Figure 6). Although the general configuration of the alluvial basins is similar, the additional data derived from the gravity and aeromagnetic data increases the definition of these basins. The three sub-basins located north and northeast of the Steamboat Hills are not defined with only well log data. Also the maximum depths in both the Mount Rose and Galena Fans are greater for the map derived from the potential fields and well log data. The volume of the alluvial basins defined by only the well log data is 7 km<sup>3</sup> compared with a volume of 11.5 km<sup>3</sup> defined by potential fields modeling and well log data, which represents a 64% increase. The more detailed alluvial basin configuration and increased basin volume estimate based on the alluvium thickness results obtained from this study indicates that potential fields modeling adds valuable information for water resource investigations in the Steamboat Hills and southern Truckee Meadows area.

Figure 7 shows that Tertiary volcanic rocks are thickest (2130 m, 6988 ft) in the northeast and thinnest (10 m, 33 ft) beneath Steamboat Valley. Volcanic rock is absent only in a small area on either side of Steamboat Creek between Pleasant and Steamboat Valleys where metamorphic rock crops out and in small areas in the Steamboat Hills and northeast of Steamboat Valley where granodiorite crops out. Volcanic rock thickness is 1140 m (3740 ft) in the Carson Range near Thomas Creek. A broad southeast-trending zone of volcanic rock gradually thins to 440 m (1443 ft) near the fault swarm along Callahan Ranch Road and increases to 840 m (2755 ft) at Maguire Peak. A narrow northwest-trending zone of thin volcanic rock (50 m, 164 ft) lies beneath the Galena Fan basin. Along the western extent of the Mount Rose Fan basin, two narrow northwest-trending zones with minimum volcanic rock thickness of 90 m (295 ft) are separated along the Serendipity Fault where volcanic rock thickness is 180 m. At the southern end of this basin, another narrow northwest-trending zone has a minimum volcanic rock thickness of 140 m (459 ft) near well STM-PW3. The northwest-trending area between these thin zones has a maximum volcanic rock thickness of 940 m (3084 ft).

## **GEOLOGIC FAULTS AND INFLUENCE OF GEOTHERMAL FLUIDS**

### **Introduction**

The hydrogeologic setting at the Steamboat Hills geothermal area is an excellent field site for testing methods based on principles of rock magnetism to identify hydrologically significant faults and fractures. Thermal and chemical alteration of magnetic properties in rocks results in distinct magnetic low anomalies for rocks adjacent to faults and fractures that conduct thermal water. These magnetic low anomalies are used to: (1) outline the geothermal resource area; (2) identify faults that conducts thermal water from the geothermal system to the alluvial aquifer; and (3) delineate productive fractures in core rock from a slim hole drilled within the geothermal reservoir.



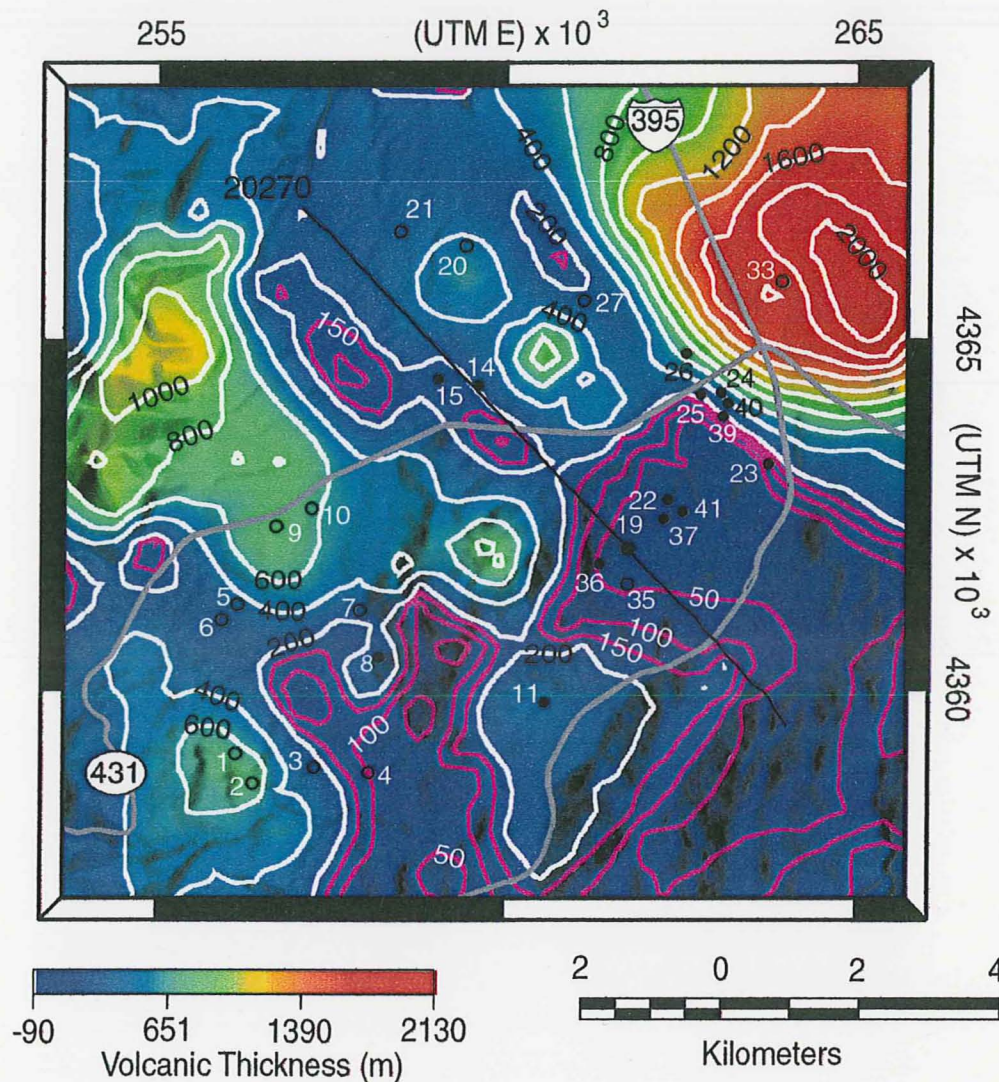


Figure 7. Thickness of Tertiary volcanic rocks from 3-D model as derived from 2.75-D forward models of gravity and aeromagnetic data. Contour interval is 50 m (pink) and 200 m (white). Solid circles indicate wells that constrain volcanic thickness, open circles indicate wells that constrain only the top of volcanic unit. Well numbers correspond to Table 3.

The Mud Volcano Basin Fault is thought to act as a significant hydrogeologic connection between the geothermal system and the alluvial aquifer. Because of this, we decided to characterize the magnetic signature surrounding this fault. Our objective was to identify the trace of the fault hidden beneath the alluvial deposits north of the geothermal area. Delineation by magnetic methods of faults that conduct thermal water could be important for geothermal exploration, site characterization, well field development, and further delineation of sources of poor water quality.

## **Methods**

Total field magnetic intensity ground data were collected using a magnetometer along 5 east-west transects, ranging in length from 100 to 1200 m (328 to 3937 ft), across the MVBF (see Figure 2). The 3-point moving average data of total field magnetic intensity along the five transects of the ground magnetic survey are shown in Figure 8.

## **Results**

All five transects show a pronounced magnetic low anomaly (200 to 400 nT) corresponding to the MVBF. The magnetic low is interpreted as representing highly altered magnetic minerals in rocks adjacent to the MVBF resulting from thermal water conducted along the fault. The surface trace of the MVBF is verified along Transect 4 by steam vents located within 3 m (10 ft) of the minimum total field magnetic intensity measurement. A measurement was not obtained directly over the steam vent due to an obvious safety issue, so a lower minimum total field magnetic intensity may actually correspond to the fault. The degree of resolution for locating the surface trace of the MVBF suggested by the magnetic low anomaly for Transect 4 represents much greater resolution than topographic or digital elevation model maps, aeromagnetic maps, or geomorphic indicators (e.g., topographic depressions). The MVBF trace in the other four transects is inferred from the magnetic low. Transects 1 (northern most) through 4 show the magnetic low anomaly over very narrow distances. The width of the anomalies decreases with increasing distance from the geothermal area suggesting that the thermal alteration along the MVBF is focused more narrowing beneath the alluvial deposits to the north. Unlike the other four transects, Transect 5 (closest to the geothermal production area) shows a gradual increase in total magnetic intensity east of the low associated with the MVBF and appears to be associated with pervasive alteration observed at ground surface in the Mud Volcano Basin.

## **SUMMARY AND CONCLUSIONS**

### **Summary**

#### *Geochemistry (Chapter 2)*

Temporal variations in boron and chloride concentrations, water levels, and temperature in alluvial aquifer wells are used to evaluate the mixing of thermal and non-thermal waters. Data were compiled from a groundwater monitoring program begun in 1985 at two geothermal facilities in the Steamboat Hills area, Nevada and from three studies related to the geothermal system. Important findings are as follows:

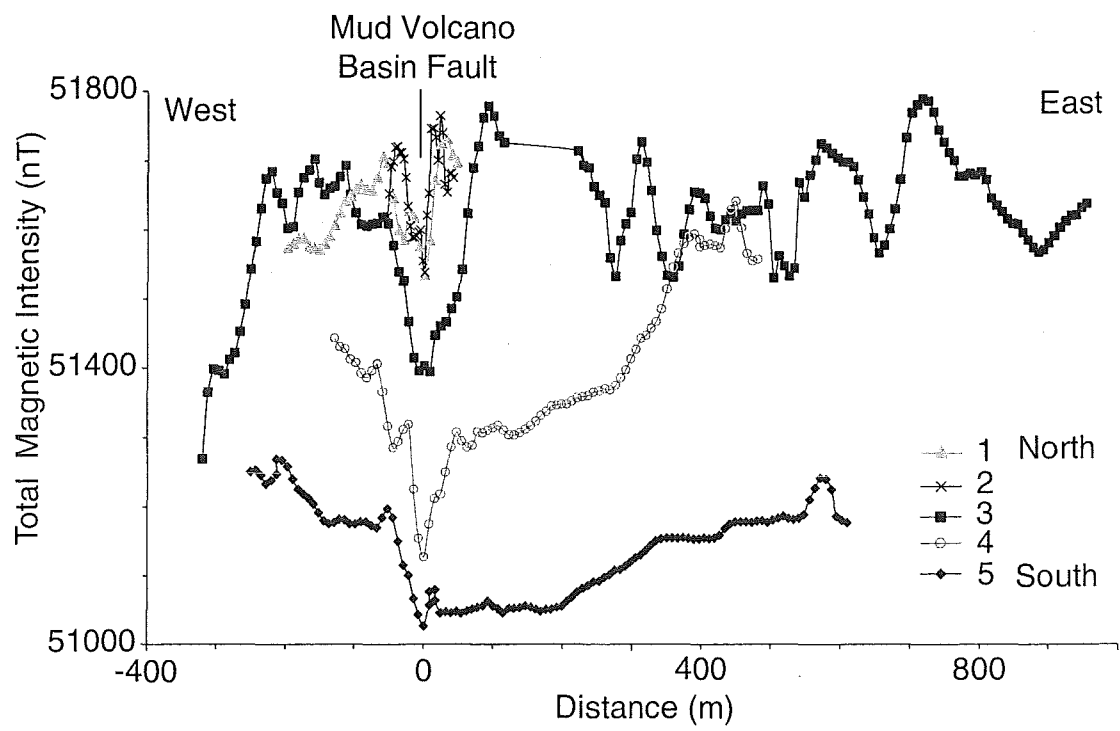


Figure 8. Total magnetic intensity along transects across Mud Volcano Basin Fault (MVBF). The distance to the magnetic low associated with the MVBF was set at zero in each transect to illustrate the consistent anomaly. Transect locations shown in Figure 2.

- Results suggest a common origin for thermal and non-thermal waters. B and chloride concentrations from all types of water (creeks, cold springs, non-thermal groundwater, mixed, and thermal waters) plot along a linear local trend. This trend suggests a common origin of the geothermal waters and simple mixing of non-thermal groundwater and thermal waters.

- Results indicate thermal water flows along north-trending faults. The characteristics of thermal and non-thermal water mixing indicate that a number of north-trending faults conduct thermal water into the alluvial aquifer. The results show increasing thermal water along the local trend line in the Flame and Pine Tree Ranch #1 wells that is dependent on proximity to the north-trending MVBF. The Flame well, located on the MVBF, shows maximum boron and chloride concentrations similar to the characteristic mixed type waters observed in the Herz Geothermal well. The Pine Tree Ranch #1 well, located 30 m (98 ft) west of the MVBF, shows maximum boron and chloride concentrations that are roughly 20% of the Flame well concentrations.

- Temporal changes document initiation of thermal and non-thermal water mixing. Potential mechanisms for the initiation of changes in the proportions of thermal and non-thermal waters include: reduced non-thermal water component due to increased groundwater extraction from alluvial aquifers for municipal water supply; reduced non-thermal water component from decreased recharge due to reduced irrigation and below normal precipitation; and increased thermal water component due to injection of thermal waters in geothermal reservoir areas with greater connectivity to the alluvial aquifers than the extraction areas.

#### *Modeling Gravity and Aeromagnetic Data (Chapter 3 and Appendix B)*

Modeling of gravity and aeromagnetic data along 11 profiles is constrained by mapped geology, well log data, and measured physical properties (density, magnetic susceptibility, and remanent magnetization). These model results are used to construct a 3-D geologic model of the Steamboat Hills geothermal system and the surrounding alluvial basins of the southern Truckee Meadows. The 3-D model yields detailed depths, elevations, and thicknesses of Quaternary alluvium, Tertiary volcanic rock, pre-Cretaceous metamorphic rock, and Cretaceous granodiorite. Altered granodiorite and metamorphic rocks are modeled to represent the geothermal reservoir with altered volcanic rock as the cap rock. Important findings are as follows:

- A better definition of alluvial basin configuration is observed in the 3-D model. The alluvium thickness map derived from potential fields model and well log data shows a volume that is 64% greater than determined from well data only. This new estimate will be useful for assessing current well field utilization and planning future well field development of Washoe County drinking water supply. The alluvium elevations along with elevations for volcanic rock and granodiorite will be useful for constructing a groundwater flow model for the basins in the southern Truckee Meadows.

- A revised estimate for the thickness of Tertiary volcanic rocks is obtained. The 3-D model suggests that volcanic rock thickness may be up to 600 m (1968 ft) beneath the western portions of the Mount Rose Fan and Galena Fan rather than the 390 m (1279 ft) thickness indicated previously by well log data. These rocks represent an increasingly important source of municipal water supply for Washoe County.

#### *Magnetic Methods (Chapter 4)*

The aeromagnetic low anomaly observed for the Steamboat Hills geothermal resource area from a draped helicopter survey results from thermochemical alteration of the magnetic minerals in the reservoir and cap rocks. This type of magnetic signature can be an indicator of geothermal resource potential at other uncharacterized or blind sites. Ground-based magnetic measurements across the MVBF show a strong magnetic low anomaly (amplitude of 200 to 400 nT) associated with demagnetization from thermal alteration of the bedrock adjacent to the fault. The magnetic anomalies delineate the trace of the MVBF beneath the alluvial fan deposits north of the geothermal area. The best-fit 2.75-D forward model of one Transect 4 shows the fault as a narrow (5 to 10 m) zone of altered volcanic rock. This suggests that thermal water is conducted along a focused preferential flow path into the alluvial aquifer. Magnetic susceptibility data from rock core yields a mean value for altered granodiorite used in forward models. Low magnetic susceptibility values are used to infer zones of altered magnetic mineralogy indicating fractures that conduct or have conducted thermal water. Permeable fractures noted on the core log match the inferred alteration zones; however, the magnetic susceptibility values suggest a higher fracture frequency. Negative magnetic susceptibility values are attributed to calcite- and/or quartz-filled fractures.

#### **Conclusions**

The 3-D geometry of the Steamboat Hills and southern Truckee Meadows area derived from modeling of gravity and aeromagnetic data is important for developing a numerical model for groundwater flow and planning exploration drilling for drinking water and geothermal wells. The basin configuration and maximum alluvium thickness in the Mount Rose Fan from our study agree quite well with the depth to bedrock results from Abbott and Louie (2000) derived from gravity; however, since we have vertical geologic control from numerous well logs we can confidently model 50 m (164 ft) alluvium thickness contours that yields definition of the Galena Fan, Steamboat Valley, and Pleasant Valley basins. The combined thickness of altered granodiorite and metamorphic rock results show a northwest-trending elongated zone coinciding with a north-trending fault that may represent a thermal water up-flow zone for the geothermal system. A north-trending zone of thick altered granodiorite and metamorphic rock extending from the Caithness Power, Inc. to the Far West Capital production zones that coincides with the Mud Volcano Basin Fault suggests that the two production zones are in hydraulic communication. Recognition of subtle aeromagnetic low anomalies over faults (e.g., Herz and Sage Hill Road Faults) known to transmit thermal water, based on boron vs chloride and temperature data, allows us to model these faults as vertical zones of altered volcanic rock. The 3-D model results support the proposed hydraulic connection between the geothermal reservoir and the Mount Rose Fan along north-

trending faults (e.g., Mud Volcano Basin Fault, Herz Fault, Sage Hill Road Fault). The results of this study can also be used to evaluate fully 3-D forward modeling methods.

The use of magnetic methods is important for geothermal resource exploration and characterization. Ground magnetic data is effective for high-resolution delineation of faults that conduct thermal water and are concealed by alluvial deposits. Identification of these hydrologically significant faults is critical for exploratory drilling site selection and for siting production and injection wells. A vertical magnetic susceptibility profile generated from rock core measurements yields important property information for forward modeling of aeromagnetic data and shows promise for delineating permeable fractures.

Temporal variation in boron and chloride concentrations in the Flame well indicates increased thermal water in the alluvial aquifer during the monitoring period from 1985 to 1990 that may be related to geothermal injection. The boron and chloride variation along the local mixing trend and the location of the Flame well along the trace of the Mud Volcano Basin Fault (MVBF) suggest that this fault represents one connection between the geothermal system and the alluvial aquifer. The Pine Tree Ranch #1 well, located 30 m (98 ft) west of the Flame well, also displays an increasing component of thermal water along the local mixing trend but with concentrations of only 20% relative to the Flame well. This illustrates that migration of geothermal water occurs within a narrow zone along the permeable fault. The lower boron and chloride concentrations suggest that thermal water is conducted along the MVBF in a narrow preferential flow path. Ground magnetic transects show pronounced magnetic low anomalies associated with the MVBF. Steam vents confirming the location of the fault were observed at the location of the magnetic low. The magnetic low anomalies allow delineation of the fault trace where obscured beneath alluvial deposits. Forward modeling results of the ground magnetic data for Transect 4 indicates that the best fit is obtained using a 5 to 10 m (16 to 33 ft) wide alteration zone to represent the MVBF. The model results support water chemistry data that suggest the MVBF is a narrow permeable zone for preferential flow.

### **Future Investigations**

The alluvium thickness map derived from potential fields modeling and well log data indicates the western portion of the Mount Rose Fan and the northwest portion of the Galena Fan contain the thickest alluvial fill. Additionally, the modeled thicknesses of volcanic rocks are significant in these portions of the basins. These results suggest that future water supply development by Washoe County should focus on these areas.

For the potential field models, altered granodiorite and metamorphic rocks were modeled to represent the geothermal reservoir. A thick zone of these altered rocks that coincides with a north-trending fault along the west flank of the Steamboat Hills suggests an up-flow zone of thermal water may be responsible for this feature. Drilling exploration slim holes in this area should be conducted to test this hypothesized up-flow zone. Better understanding the geothermal system and perhaps additional geothermal production could be realized if an up-flow zone were found in this area.

The results of boron versus chloride time series data indicate preferential flow of thermal water along north-trending faults (e.g. Mud Volcano Basin, Herz, Sage Hill



Road). These results suggest that important information could be gained by conducting tracer tests. Tracer studies would be useful for confirming the flow path of thermal water from the geothermal system to the alluvial aquifer and for estimating hydraulic conductivity of and flow velocities along these faults. A tracer test at the CPI Cox-I1 injection well with monitoring at the Pine Tree Ranch #1 and #2 wells would allow characterization of the MVBF. Characterization of the Herz Fault could be accomplished with a tracer test at the FWC IW-2 or IW-3 injection wells with monitoring at Herz Geothermal, Herz Domestic, and NDOT (replacement for Brown School well). The tracer compounds 1,5-naphthalene disulfonate, fluorescein, and rhodamine WT have been found to act conservatively and remain stable in the FWC production area at Steamboat Hills (Rose et al., 1999; Rose and Adams, 1994). Using a batch of these compounds would allow for evaluation of their effectiveness as conservative tracers in the higher temperature CPI field and in the alluvial aquifers. Additionally, a tracer test performed at the CPI CoxI-1 with monitoring wells in the FWC production field may help resolve the whether a single geothermal system or two separate systems exist at Steamboat Hills.

Analysis of interference tests by Petty (1992) indicates that the CPI production zone receives pressure support from injection at the Cox I-1 well; however, Sorey and Colvard (1992) suggest that data from these tests are difficult to interpret and provide no conclusive evidence of pressure support. The conceptual model developed from this study indicates the Cox I-1 injection well is located at the southern end of the Mud Volcano Basin Fault and geochemistry data indicate that this fault conducts thermal fluid toward the north into the alluvial aquifer. Although the 3-D model of subsurface geologic structure developed here does not directly resolve the pressure support debate, it does provide a more detailed geologic framework for future analysis and system modeling. This new geologic model will be useful for reanalysis of production and injection well locations.

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