GEOPHYSICS, VOL. 70, NO. 3 (MAY-JUNE 2005); P. B1–B9, 8 FIGS., 2 TABLES.
10.1190/1.1925739

Case History

Gravity and aeromagnetic modeling of alluvial basins in the southern Truckee Meadows adjacent to the Steamboat Hills geothermal area, Washoe County, Nevada

John D. Skalbeck[1], Robert E. Karlin[2], Lisa Shevenell[3], and Michael C. Widmer[4]

ABSTRACT

The concurrent development of the Steamboat Hills geothermal area for power production and the adjacent alluvial aquifers for drinking water in Washoe County, Nevada, necessitates a good understanding of the hydrogeologic connection between these water resources. The problem is that adequate characterization of the subsurface geologic structure is not possible with existing geologic data. This need prompted us to construct a detailed 3D representation of the subsurface geologic structure based on 2.75D forward modeling of 11 gravity and aeromagnetic profiles constrained by geologic data and physical (density, magnetic susceptibility, remanent magnetic) properties. Potential-fields modeling results provided greater definition of the alluvial basins, and when combined with well-log data, yield an overall basin volume surrounding Steamboat Hills that is 64% greater than the volume derived from well-log data alone. A representation of the geothermal reservoir, consisting of altered granodiorite and metamorphic rocks, illustrates that the flow of thermal water is fault controlled. The model also suggests that thermal water may upflow along an unexplored fault flanking western Steamboat Hills. North-trending faults that conduct thermal water from the geothermal system to the alluvial aquifer appear to be zones of altered volcanics that produce subtle aeromagnetic anomalies.

INTRODUCTION

Most hydrogeologists rely on limited borehole logs (lithologic and geophysical) and surface geologic mapping for development of municipal well fields and the construction of numerical models for flow and transport simulations. This often requires correlating geologic units across large distances and assuming basement structure from sparse data. Some groundwater and water-resource studies have used geophysical (gravity, magnetic, seismic) data to estimate basement structure (e.g., Blakely et al., 1998; Berger et al., 1996; Ayers, 1989; Haeni, 1986). However, limited data for model constraint may require simplification of the conceptual models. These assumptions and simplifications add uncertainty to the simulation results and accuracy of the model. We have incorporated potential-fields (gravity and aeromagnetics) modeling to obtain well-constrained results for estimating the structure of multiple geologic units within a complex hydrogeologic setting that includes both potable and geothermal water resources. Although potential-fields modeling does not directly detect thermal water migrating into the fresh-water aquifer, the modeling results yield detailed geologic structure that is consistent with this hydrologic connection. This article presents details relating to characterization of the alluvial basins in the southern Truckee Meadows south of Reno and important findings related to the adjacent geothermal system at Steamboat Hills. Detailed characterization of the geothermal system is presented in Skalbeck et al. (2002a).

The study area is located along the western margin of the extensional basin and range province in the western

Manuscript received by the Editor August 21, 2003; revised manuscript received September 27, 2004; published online May 23, 2005.
[1]University of Wisconsin–Parkside, Department of Geosciences, 900 Wood Road, Kenosha, Wisconsin 53141. E-mail: skalbeck@uwp.edu.
[2]University of Nevada, Reno, Graduate Program of Hydrologic Science, MS 172, Reno, Nevada 89557-0138. E-mail: karlin@mines.unr.edu.
[3]Nevada Bureau of Mines and Geology, University of Nevada, Reno, MS 178, Reno, Nevada 89557-0088. E-mail: lisaas@unr.edu.
[4]Washoe County Department of Water Resources, 4930 Energy Way, Reno, Nevada 89520-0027. E-mail: mwidmer@mail.co.washoe.nv.us.

United States. Steamboat Hills is 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 geology of the area has been described by White et al. (1964), Thompson and White (1964), Tabor and Ellen (1975), Bonham and Rogers (1983), and Bonham and Bell (1993), among others. A simplified geologic map is presented in Figure 1. The core of these ranges consists of Cretaceous granodiorite (Kgd) beneath older metasedimentary and metavolcanic rocks (pKm), which are overlain in turn by Tertiary volcanic flows, breccias, and tuffs (Tv). A veneer of Quaternary alluvial fan and basin-fill deposits (Qal) range from clayey sand to boulder gravels. Thin layers of hydrothermal deposits (sinter) at the surface surrounding Steamboat Hills are included with Qal for the modeling in this study. Qal deposits and Tv rocks are the primary source of water supply for Washoe County and private residences in the southern Truckee Meadows. At least three prominent fault systems trending north–south (most abundant), northeast–southwest, and northwest–southeast (White et al., 1964) are found in the study area. A series of five Pleistocene rhyolite domes (Qsh) occur along the northeast–southwest fault trend. The Steamboat Hills geothermal field occurs predominantly along this same northwest–southeast-trending fault system within the Kgd and pKm rocks.

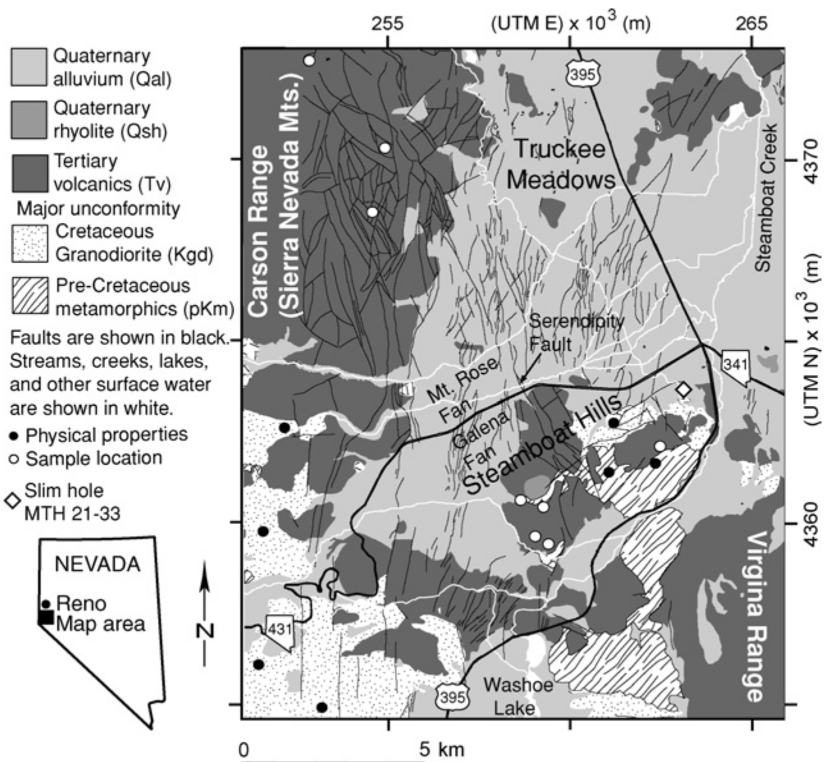

Figure 1. Generalized geologic map modified after Bonham and Rogers (1983), Bonham and Bell (1993), and Tabor and Ellen (1975). Map shows geologic contacts used for horizontal control of geologic blocks in forward models and sample locations for physical properties measurements. Black dots and white circles represent outcrop locations, a white diamond represents the location of slim hole MTH 21-33.

Groundwater originates primarily from snowmelt infiltration in the Carson Range and flows eastward toward Steamboat Creek (Cohen and Loeltz, 1964). Depths to groundwater range from 80 m near the center of the alluvial fan to land surface at Steamboat Springs. Sorey and Colvard (1992) note that similarities in chemical characteristics and decreases in hydraulic head suggest that the geothermal reservoir and alluvial aquifer are hydrologically connected; however, the study does not detail locations of this connection. Using mixing trends between thermal and nonthermal waters within the alluvial aquifer, Skalbeck et al. (2002b) found a hydraulic connection of the drinking and geothermal water resources along north-trending faults. Results of potential-fields modeling from this study support the connection along north-trending faults.

A number of recent publications illustrate the application of potential-fields modeling for a variety of geologic studies. Berger et al. (1996) used 2D forward modeling of magnetic and gravity data along three profiles to obtain basin-fill thickness as part of a numerical groundwater model of Spanish Springs, Nevada. Mankinen et al. (1999) constructed 2.5D forward and inverse models of gravity and aeromagnetic data for 13 profiles in the Pahute Mesa and Oasis Valley region in Nevada to provide information for groundwater models of the Nevada test site. Blakely and Stanley (1993) modeled a profile of gravity and aeromagnetic data using 2D forward and inverse techniques to assess the possible presence of a partial-melt magma chamber at the Geysers geothermal area. In assessing heat sources in the Geysers–Clear Lake geothermal area, Stanley and Blakely (1995) modeled a profile of gravity and aeromagnetic data using 2.5D forward and inverse techniques. Langenheim and Hildenbrand (1997) constructed 2.5D inverse models of two gravity and aeromagnetic profiles to evaluate the Commerce geophysical lineament, extending from central Arkansas to southern Illinois. Zeng et al. (2000) used 2D forward modeling of gravity data to evaluate emplacement mechanisms of the Linglong granitic complex in the Shandong Province of east China. As part of a seismic hazard evaluation of basins in the Reno and Carson City, Nevada, area, Abbott and Louie (2000) constructed a 2.5D forward model of residual gravity from a profile located approximately 10 km north of the Steamboat Hills area and tied it into a basinwide gravity analysis.

These model profiles are highly constrained by mapped geologic data, well-log data, and physical (density and magnetic) properties measured within the study area. We model asymmetric strike lengths about the profile (2.75D) based on mapped geology, and we include remanent magnetization data from the study area in addition to induced magnetization to represent the total magnetic field. A 2.75D model better represents the off-profile geology with variable strike lengths than a 2D model (infinite strike length) and a 2.5D model (symmetric strike length about the profile). The use of multiple 2.75D forward-model profiles of gravity and aeromagnetic data to obtain a 3D representation of alluvial basins and an adjacent geothermal system undergoing concurrent development greatly increases understanding of the hydrogeologic connections between these important water resources. This 3D characterization yields a much more detailed delineation of the alluvial basins, which is important for future development of the drinking-water resource and an indication of a possible unexplored upflow zone of thermal water that could be important for future development of the geothermal resource.

METHODS

Gravity data at 166 stations from a study contracted by Washoe County Department of Water Resources was merged with existing gravity coverage (Hittelman et al., 1994) for total coverage that included 503 points. The nearest-neighbor distance between stations ranged from 100 to 4000 m. Figure 2 shows the northern portion of the residual isostatic gravity contour map derived from minimum curvature gridding (Briggs, 1974). Values for each forward-model profile were extracted at 300-m intervals from the gridded data along aeromagnetic flight lines.

Washoe County contracted a draped airborne geophysical survey consisting of 41 helicopter flight lines oriented at N45W with 609-m spacing and three tie lines oriented at N20E with about 5000-m spacing. The northern portion of the data used for this study is shown in Figure 3. A cesium-vapor magnetometer was towed 20 m below the helicopter and draped above ground surface at heights of 30 to 120 m. The total field data were international geomagnetic reference field (IGRF) corrected using the IGRF95 model (IAGA Division V, Working Group 8, 1995) and reduced to pole using a 2D fast-Fourier transform algorithm. A 10-factor decimation of the original aeromagnetic data resulted in a subset for the profiles with 40- to 60-m data spacing that replicates the full data set. Figure 3 shows residual reduced-to-pole data derived from minimum-curvature gridding (Briggs, 1974).

Physical-property data used in modeling were obtained from published data and laboratory measurements in the study (Table 1). Fifty-eight hand samples and 36 paleomagnetic core samples of hydrothermally altered (Alt) and unaltered Tv, unaltered Kgd and Alt Kgd, and pKm were collected from 15 locations in Steamboat Hills and the adjacent Carson Range (Figure 1). Densities, magnetic susceptibilities, and remanent magnetic measurements were made using standard methods at UNR laboratories (Skalbeck, 2001). Whole core magnetic susceptibility for Alt Kgd was measured along 155 m (61 to 216 m depth) of rock from core hole MTH 21-33 drilled in the Far West Capital (FWC) area of the Steamboat Hills geothermal reservoir. Density and magnetic susceptibility results from this study compare closely with published density data (Thompson and Sandberg, 1958; Thompson and White, 1964; Krank and Watters, 1983) and magnetic susceptibility data (Hendricks, 1992) obtained regionally (Table 1). The results of remanent magnetic measurements provide confirmation of antipodal (south- and north-seeking) directions in volcanic rocks and provided constraint for assigning remanent magnetization intensity in the forward models.

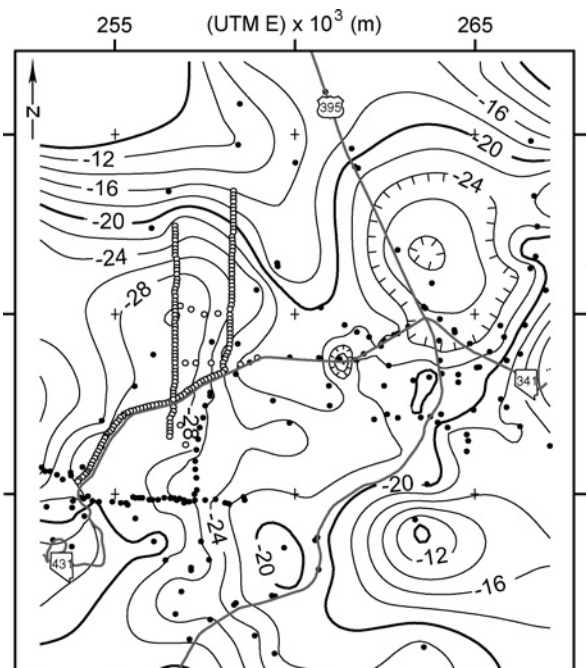

Figure 2. Residual isostatic gravity map of the southern Truckee Meadows and Steamboat Hills area. Open circles are stations from the Washoe County study and black dots are from Hittelman et al. (1994). Contour (solid line) interval is 2 mGal.

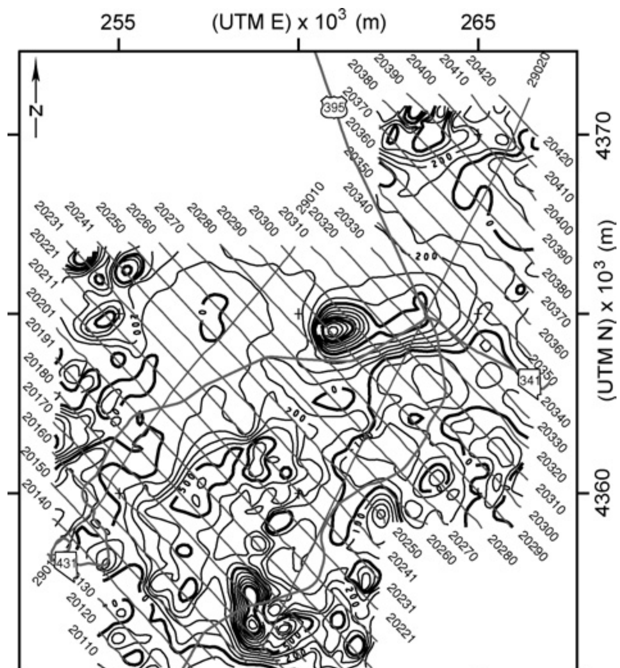

Figure 3. Residual reduced-to-pole aeromagnetic map of southern Truckee Meadows and Steamboat Hills. Helicopter flight lines are indicated with line numbers (e.g., 20270) at each end. Contour (solid line) interval is 100 nT.

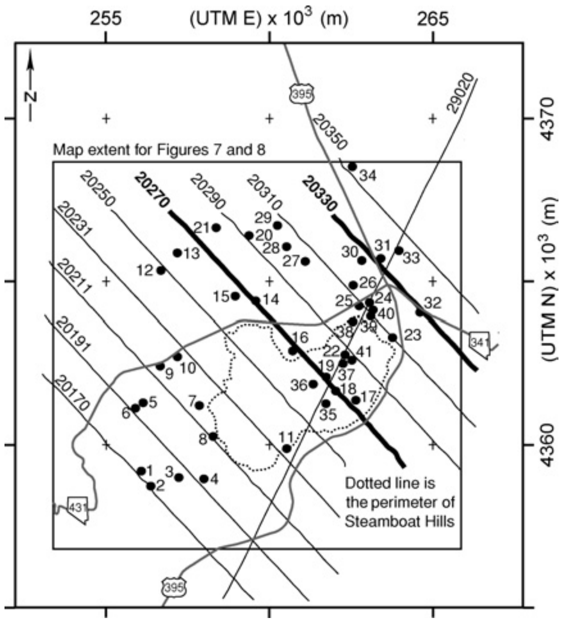

Figure 4. Locations of forward model profiles and wells (black dots) used for vertical control of geologic blocks in models. Bold flight lines (20270, 20330) indicate profiles shown in Figures 5 and 6. Well numbers correspond to Table 2.

The 2.75D-coupled forward 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™ by Northwest Geophysical Associates based on Talwani et al. (1959) and Talwani and Heirtzler (1964). Model block strike lengths were extended perpendicular to the profile based on the mapped geology. The perpendicular strike orientation was chosen based on the local northeast–southwest structural trend. Density and magnetic properties within a given model block were assumed constant. The mapped surface geology provides horizontal control of model blocks. Well-log data (Table 2) provide vertical control of model blocks. Iterative adjustments to geologic block configuration, density, and magnetic properties were made to minimize the root-mean-square error (rmse) between observed and calculated gravity and aeromagnetic anomalies. Top and base elevations for each geologic unit were extracted at 300-m intervals along the model profiles for creating 3D surfaces computed by kriging (Cressie, 1990) to obtain unit thickness.

RESULTS

Of the 11 profiles modeled for this study, Profiles 20270 (Figure 5) and 20330 (Figure 6) are presented here to

Table 1. Summary of physical properties data used in 2.75D forward models.

	Mean physical properties measurements Steamboat Hills and Carson Range			Density[1,2,3] and k[4] from previous studies near the study area			Density and magnetic properties used in 2.75D forward models		
Rock type	Number of samples	Density range (g/cm^3)	Mean density (g/cm^3)	Number of samples	Density range (g/cm^3)	Mean density (g/cm^3)		Density range (g/cm^3)	
Qal	NA	NA	NA	NA	NA	NA		(1.97)[5]	
Sr	1	NA	1.94	NA	1.32–2.56	2.02		1.97	
Tv	15	2.22–2.69	2.49	38	1.84–2.69	2.42		2.27–2.47	
Kgd	8	2.55–2.84	2.72	11	2.62–2.73	2.67		2.67	
pKm	3	2.61–2.78	2.71	6	2.69–2.75	2.69		2.57–2.77	
Alt Tv	NA	NA	NA	21	2.07–2.72	2.50		2.42	
Alt Kgd	1	NA	2.52	6	2.46–2.62	2.55		2.52	
Rock type	Number of samples	k Range (SI × 10^3)	Mean k (SI × 10^3)	Number of samples	k range (SI × 10^3)	Mean k (SI × 10^3)	k Range (SI × 10^3)	M_r Range (A/m × 10^3)	Q Range
Qal	NA	NA	NA	NA	NA	NA	0	0	NA
Sr	NA	NA	NA	NA	NA	NA	0	0	NA
Tv	14	8–25	20	13	NA	16	13–38	1000–9000	1.2–11
Kgd	8	6.3–32	22	3	NA	38	23	74	0.1
pKm	3	0.2–21	7.2	3	NA	0.6	1.3–13	10–1700	0.2–5.9
Alt Tv	5	0.02–0.03	0.025	NA	NA	NA	0.025	4	4.9
Alt Kgd	See notes	–0.25–35	5.9	3	NA	0.3	5.9	20	0.1

Qal = alluvium, Sr = sinter, Tv = volcanics, Kgd = granodiorite, pKm = metamorphics, Alt = altered
k = Magnetic susceptibility
(g/cm^3) = grams/cubic centimeters
NA = Not measured, not available, or not applicable
Alt Kgd k values = From core of MTH 21-33, 1-cm intervals from depth of 9 to 216 m.
M_r = Remanent magnetization
Q = Koenigsberger ratio, Q = Remanent magnetization/Induced magnetization
[1]Thompson and Sandberg (1958)
[2]Thompson and White (1964)
[3]Krank and Watters (1983)
[4]Hendricks (1992)
[5]Grant and West (1965)

highlight key features within the study area. Remaining profiles and model fit results are presented in Skalbeck (2001).

Profile 20270 crosses the Washoe County drinking-water-production field in the Mount Rose Fan alluvial basin, the production area of the Caithness Power, Inc. (CPI) geothermal field located at the crest of Steamboat Hills and the southern extent of Steamboat Valley. Excellent vertical geologic control data is provided from six wells. Qal and underlying Tv show maximum thickness of 190 m and 370 m, respectively, near distance 2350 m. Shallow Tv creates two subbasins in the alluvial fan near well STM-TH10, where Qal thickness is 30 m and Tv thickness is 135 m. Profile 20330 is located in the northeast portion of the study area near the discharge zone of the geothermal system. The minimum thickness of Qal in the center of the model is constrained by

Table 2. Well-log data used in 2.75D forward models and 3D model depth to bedrock.

Well Number	Profile Number	Well ID	Surface geologic unit	Surface elevation (m)	Depth to Tv (m)	Depth to Kgd (m)	Depth to pKm (m)	Total depth (m)	3-D model depth to bedrock (m)	Reference
1	20170	SJ-1	Qal	1737	90			110	60	PN 59330
2	20170	SJ-2	Qal	1747	52			183	40	PN 59631
3	20191	SJ-MW2	Qal	1662	70			195	65	PN 59303
4	20191	SJ-MW1	Qal	1662	79			240	70	PN 59632
5	20191	MR-5	Qal	1765	172			242	175	PN M/O-334
6	20191	MR-6	Qal	1770	192			231	180	PN 65364
7	20211	MR-3	Qal	1652	67			104	65	PN 35149
8	20211	ST-12	Tv	1626			390	539	0	NA
9	20211	Tessa 1	Qal	1763	73			242	75	PN 61267/61268
10	20231	Tessa 2	Qal	1715	79			224	80	PN 61269/61270
11	20231	ST-7	Qal	1429	65		414	506	55	21772
12	20250	AC-3	Qal	1732				335	315	PN 43607
13	20270	AC-2	Qal	1638				216	200	PN 35159
14	20270	STM-PW4	Qal	1579	43	98		253	45	LN 22665
15	20270	STM-TH10	Qal	1600	30	165		215	25	NA
16	20270	ST-5	Qal	1525		113		518	110	LN 21795
17	20270	ST-6	Qal	1513			18	515	15	LN 21768
18	20270	32-5	pKm	1650				897	0	NA
19	20270	28-32	Tv	1713	30			805	20	NA
20	20290	STM-MW1	Qal	1528	164			189	180	NA
21	20290	AC-1	Qal	1556	149			233	150	PN 57160
22	20290	COXI-1	Tv	1497		25		1058	0	LN 22782
23	20310	GS-5	Sr/Qal	1423	41	166		175	25	White et al. (1964)
24	20310	IW-3	Sr/Qal	1433	69	152		158	15	NA
25	20310	Old IW-1	Qal	1432	53	213		499	45	NA
26	20310	PTR-2	Qal	1423	21	51		132	25	LN 4532
27	20310	STM-MW3	Qal	1439	122			134	135	PN 47066
28	20310	STM-PW3	Qal	1444				207	185	LN 2571
29	20310	STM-PW11	Qal	1469				156	200	PN 65080
30	20330	Herz Domestic	Qal	1386				34	170	4061
31	20330	Brown School	Qal	1387				116	165	NA
32	20330	Steinhardt	Qal	1387				41	170	NA
33	20350	ST-1	Qal	1371	70			599	115	LN 21792
34	20350	DD-1	Qal	1370				130	150	NA
35	29020	ST-13	Tv	1608			17	520	0	LN 23431
36	29020	21-5	Sr	1682	49	893	100	930	0	LN 21769
37	29020	GS-7	Sr	1622	77	100		122	0	White et al. (1964)
38	29020	GS-6	Sr	1534		30		289	0	White et al. (1964)
39	29020	PW-1	Sr	1453	28	54		64	0	NA
40	29020	IW-2	Sr	1439	30	108		192	15	NA
41	29020	ST-9	Tv	1606	88	149		427	0	NA

Qal = alluvium, Sr = sinter, Tv = volcanics, Kgd = granodiorite, pKm = metasediments and metavolcanics.
Reference = LN refers to DWR log number; PN refers to DWR permit number.
NA = No DWR log number or permit number indicated on log; State of Nevada, Division of Water Resources.
Zero value for 3D model depth indicates bedrock at ground surface.

the total depth data from three domestic wells that did not encounter volcanics. Thermal water is known to migrate along the Herz and Sage Hill Road faults and is also known to exist in the Curti Barn and Steinhardt domestic wells, which are both completed in the alluvial aquifer (Skalbeck et al., 2002b). Subtle aeromagnetic low anomalies near these two wells are modeled as vertical zones of Alt Tv to represent faults that conduct thermal water. Including these model faults improves model fit nearly twofold for aeromagnetic data along Profile 20330 (rmse = 23.991 A/m with faults versus rmse = 47.839 A/m without faults).

The Qal thicknesses derived from the forward models and well-log data are shown in Figure 7. The Galena Fan appears as a southeast-trending basin west of Steamboat Hills with maximum Qal thickness of 210 m near Nevada Highway 431. The Mount Rose Fan consists of two subbasins more than 200-m thick within an east-trending trough that is generally parallel to slope of the alluvial fan and the groundwater flow direction. The maximum Qal thickness (315 m) is found in the western subbasin, near the base of the Carson Range. The saddle of thinner Qal (165 m) that divides the Mount Rose Fan occurs along the Serendipity Fault. An eastern subbasin reaches maximum Qal thickness of 270 m near US Highway 395. A small circular subbasin adjacent to Nevada Highway 431 north of Steamboat Hills reaches maximum Qal thickness of 270 m. A northwest-trending basin with maximum Qal thickness of 195 m occurs along Nevada Highway 341 east of Steamboat Hills.

The combined thickness of Alt Kgd and pKm (Figure 8) are believed to represent the geothermal reservoir beneath Steamboat Hills because the modeled altered zone generally coincides with the known resource area (although larger than the currently exploited area) and is assumed to be caused by the current geothermal system (Skalbeck, 2001; Skalbeck et al., 2002a). The main northeast trend of this feature is aligned with northeast-trending faults and associated Quaternary rhyolite domes. A secondary northwest trend along the western flank of Steamboat Hills reaches a maximum thickness of 1300 m near a mapped rhyolite dome. A minimum thickness of 330 m is found near the southern extent of the Serendipity fault. The CPI and FWC geothermal fields show maximum thickness of 2540 m and 1700 m, respectively. A north-trending thick zone (1200 to 2400 m) from the CPI to FWC production areas is coincident with the Mud Volcano Basin fault. A northwest-trending zone with maximum thickness of 1560 m occurs beneath the alluvial deposits northeast of the Steamboat Springs fault system, which is the discharge area for the geothermal system.

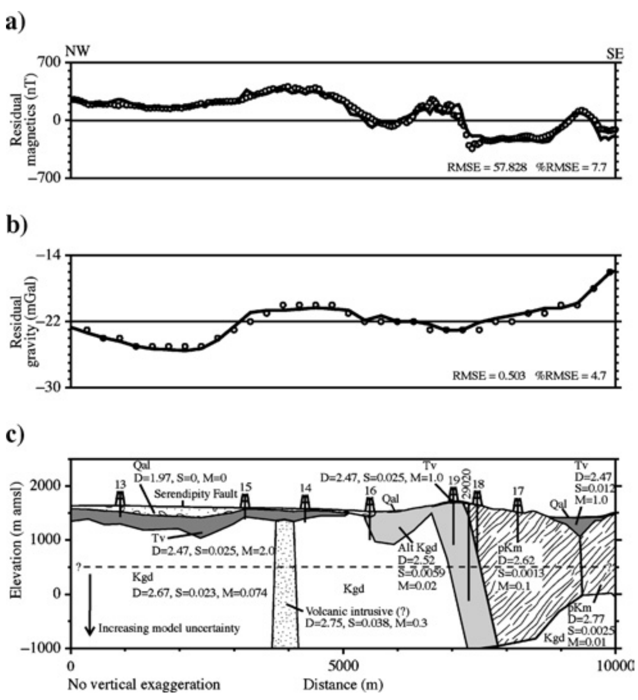

Figure 5. Profile 20270 cross section as computed by 2.75D forward modeling of gravity and aeromagnetic data. (a) Observed (dots) and fitted (solid line) residual reduced-to-pole aeromagnetic anomalies. (b) Observed (dots) and fitted (solid line) residual Bouguer anomalies. (c) Geologic cross section with model block properties. D = density (g/cm^3), S = magnetic susceptibility (SI), M = magnetic remanence (A/m), Qal = alluvium, Tv = volcanics, pKm = metamorphics, Kgd = granodiorite, Alt = altered. Derrick symbol indicates well with number corresponding to Table 2 and Figure 4. RMSE = rms error between observed and model calculated anomaly, %RMSE = rmse/anomaly range.

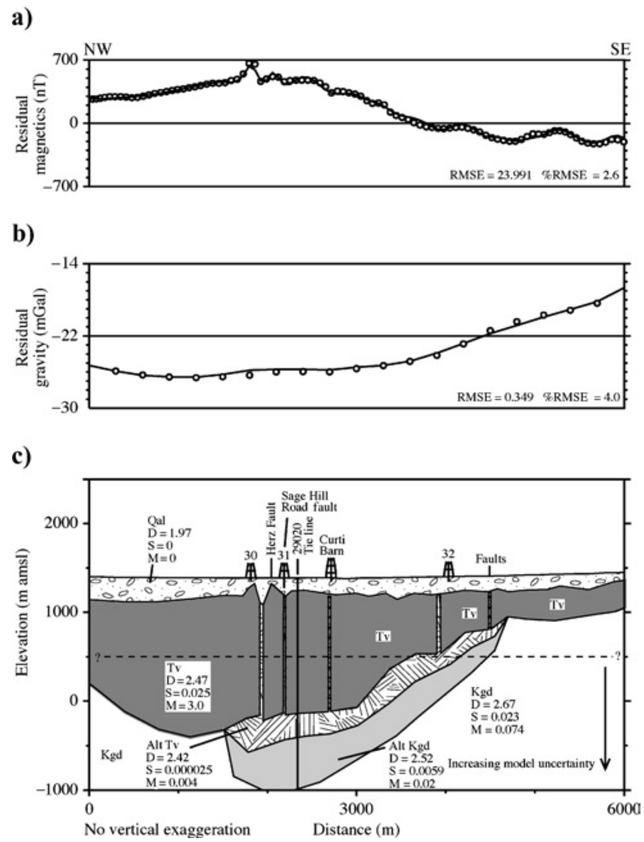

Figure 6. Profile 20330 cross section as computed by 2.75D forward modeling of gravity and aeromagnetic data. (a) Observed (dots) and fitted (solid line) residual reduced-to-pole aeromagnetic anomalies. (b) Observed (dots) and fitted (solid line) residual Bouguer anomalies. (c) Geologic cross-section with model block properties. Key as in Figure 5.

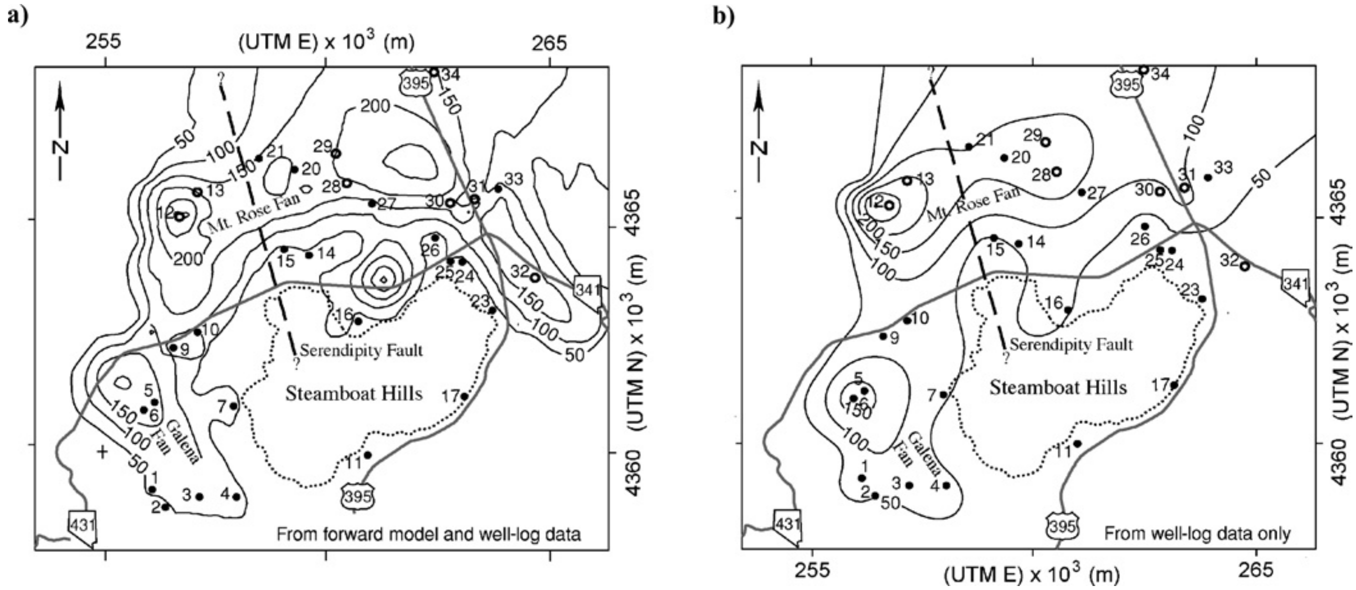

Figure 7. Alluvial thickness in basins surrounding Steamboat Hills: (a) derived from 2.75D forward models of gravity and aeromagnetic data and well-log data, and (b) derived from only well-log data. Contour interval is 50 m. Black dots indicate wells that constrain alluvial thickness, and open circles indicate wells that yield minimum thickness because bedrock was not encountered. Well numbers correspond to Table 2.

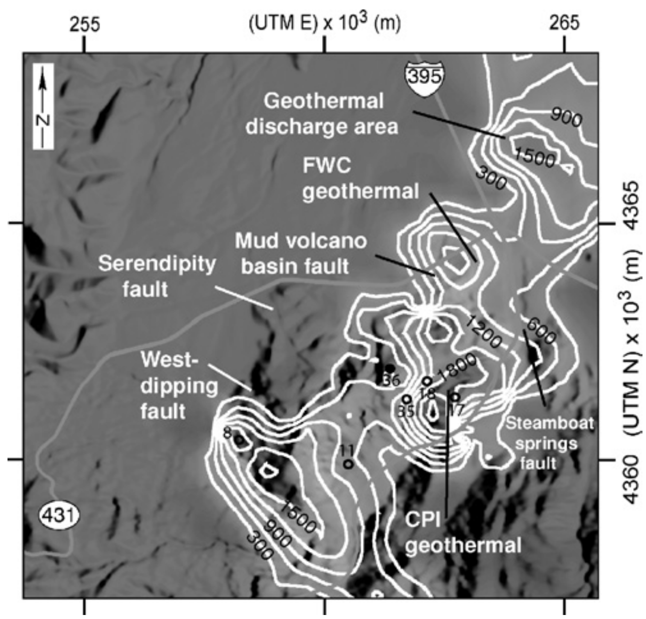

Figure 8. Combined thickness of altered granodiorite and metamorphics from 2.75D forward models of gravity and aeromagnetic data. Black dot (36) indicates a well that constrains thickness, and open circles indicate wells that constrain top of metamorphic unit. Contour interval is 300 m. Well numbers correspond to Table 2. CPI = Caithness Power, Inc.; FWC = Far West Capital.

DISCUSSION AND CONCLUSIONS

The subsurface geology along 11 profiles derived from 2.75D forward modeling of gravity and aeromagnetic data is constrained by geologic, physical property, and well-log data. The large amount of surface and vertical geologic data used for this study allows for a detailed delineation of the geologic units found in the Steamboat Hills area. The physical property values assigned to yield the best-fit forward models are consistent with data measured from samples collected in the area and published regional data. Reasonable consistency in the geologic structure and assigned physical property data between each profile model was built into this study by modeling a tie line. The high degree of constraint and the good-to-excellent fit between the observed and calculated gravity and aeromagnetic data for the 2.75D forward models yield reliable depth data for the 3D representation of geologic units, which, in turn, allows for a confident interpretation of the geologic structure of Steamboat Hills and surrounding alluvial basins. The methods of modeling gravity and aeromagnetic data presented in this study provide a new approach for characterizing the hydrogeologic connection between the alluvial aquifer and the geothermal system. Good understanding of the hydrogeology is a vital component in the planning process for regarding current operation and future development of drinking-water and geothermal resources.

The good match between observed and 3D representation of Qal thickness (derived only from profiles) illustrates that the well-log data were used appropriately in the model profiles even though adherence was subjective at times because of the projected distance between the well and profile locations. The match also indicates that 3D representation accurately represents between-profile variations. Combining well-log data with model-profiles data obviously improves the match but, more importantly, increases the constraints on the 3D representation. Our Qal thickness results in the Mount Rose Fan area agree quite well with the gravity results from Abbott and Louie (2000), which use fewer data (no magnetic data and fewer well-log and gravity data). The maximum Qal thickness (depth to bedrock) from our study is within 25% of the maximum depth to bedrock from their study. We consider these two study results to agree closely, since Abbott and Louie (2000) report a potential depth error of 50% because of highly speculative density values. We note that our Qal thickness results were obtained from multiple profiles of 2.75D-coupled forward modeling of gravity and aeromagnetic data, while Abbott and Louie (2000) calculated depth to bedrock using an infinite slab approximation. It is also noteworthy that the density contrast range (-0.30 to -0.65 g/cm^3) between basin fill and bedrock used by Abbott and Louie (2000) is similar to the density contrast (-0.30 to -0.50 g/cm^3) between Qal and Tv used in our 2.75D models. The close agreement of these independent results provides validation for both studies. However, because of higher resolution caused by greater data density and the use of aeromagnetic data, our results provide better definition of the alluvial basins adjacent to Steamboat Hills. Since we have vertical geologic control from numerous well logs, we can confidently model 50-m contours for the Qal thickness that yield definition of the alluvial basins. The results also delineate subbasins within the Mount Rose Fan resulting from the Serendipity fault and a small, deep subbasin at the northern flank of Steamboat Hills.

To evaluate the delineation of the alluvial basins surrounding Steamboat Hills from this study, we compare Qal thickness derived from the 2.75D forward modeling of gravity, aeromagnetic, and well-log data with Qal thickness obtained only from well-log data (Figure 7). Although the general configuration of the alluvial basins is similar, the additional data derived from the potential-fields data increase the definition of these basins. The three subbasins located north and northeast of Steamboat Hills are not fully defined with well-log data alone. Also, the maximum depths in both the Mount Rose and Galena Fans are greater for the map derived from the potential-fields data than the map from well-log data alone. The volume of the basins defined by only the well-log data is 7 km^3 compared with a volume of 11.5 km^3 defined by potential-fields modeling and well-log data — a 64% increase. The more detailed alluvial basin configuration and increased basin volume estimate based on the Qal thickness results obtained from this study indicate that potential-fields modeling adds valuable information for water-resource investigations in the southern Truckee Meadows area.

The geothermal system is modeled as altered granodiorite and metamorphic basement rock (Alt Kgd/pKm) containing a complex network of fractures that permit migration of thermal water. Thermochemical alteration of original magnetic minerals reduces the magnetic properties of the rock adjacent to the fractures. Although nearly complete demagnetization of the rock occurs near the fractures, the rock matrix farther from the fracture is likely not altered (Skalbeck, 2001). Thus, magnetic properties assigned in the model for Alt Kgd/pKm units represent an average for the geothermal host rock. This concept is consistent with Muffler (1979), who considers the geothermal reservoir as the entire volume of rock and water that host the heated water, rather than just the permeable zones.

A thick zone of Alt Kgd/pKm along the western flank of Steamboat Hills is coincident with a north–northwest-trending fault. We suggest that this zone may represent a previously unrecognized upflow zone for the geothermal system. Skalbeck et al. (2002a) present a detailed discussion of this conceptual model for this system. For this model, precipitation in the Carson Range is circulated deeply along east-dipping, normal range-front faults, and, perhaps, faults associated with Galena and Browns Creeks. The recharge water is heated at depth and flows upward along a west-dipping normal fault along the western flank of Steamboat Hills. The northeast-trending fault system along the axis of Steamboat Hills likely conducts the thermal water toward the CPI and FWC production areas and eventually discharges to the alluvial deposits northeast of Steamboat Hills along north-trending faults (Skalbeck et al., 2002b).

ACKNOWLEDGMENTS

The authors thank Colin Goranson and James Combs for freely sharing their knowledge of the Steamboat Hills area. J. Skalbeck was supported by the Washoe County Department of Water Resources, Utility Services Division, under a joint agreement with SB Geo, Inc. (Far West Capital, now Advanced Thermal Systems, Inc.) and Steamboat Development Corporation. Additional funding was provided by a scholarship from the Women's Auxiliary to the Association of Mining, Metallurgical, and Petroleum Engineers. Comments from John Louie, Gary Oppliger, and Jane Long improved the manuscript.

REFERENCES

Abbott, R. E., and J. N. Louie, 2000, Depth to bedrock using gravimetry in the Reno and Carson City, Nevada, area basins: Geophysics, **65**, 340–350.

Ayers, J. F., 1989, Application and comparison of shallow seismic methods in the study of an alluvial aquifer: Ground Water, **27**, 550–563.

Berger, D. L., W. C. Ross, C. E. Thodal, and A. R. Robledo, 1996, Hydrology and simulated effects of urban development on water resources of Spanish Springs Valley, Washoe County, west-central Nevada: United States Geological Survey Water-Resources Investigations Report 96-4297.

Blakely, R. J., R. L. Morin, E. H. McKee, K. M. Schmidt, V. E. Langenheim, and G. L. Dixon, 1998, Three-dimensional model of Paleozoic basement beneath Amargosa Desert and Pahrump Valley, California and Nevada: Implications for tectonic evolution and water resources: U. S. Geological Survey Open File Report 98-496.

Blakely, R. J., and W. D. Stanley, 1993, The Geysers magma chamber: Constraints from gravity data, density measurements, and well information: Geothermal Resources Council Transactions: **17**, 227–233.

Bonham Jr., H. F., and D. K. Rogers, 1983, Geologic map, Mt. Rose NE quadrangle: Nevada Bureau of Mines and Geology, Map 4Bg.

Bonham Jr., H. F., and J. W. Bell, 1993, Geologic map, Steamboat quadrangle: Nevada Bureau of Mines and Geology, Map 4Fg.

Briggs, I. C., 1974, Machine contouring using minimum curvature: Geophysics, **39**, 39–48.

Cohen, P., and O. J. Loeltz, 1964, Evaluation of hydrogeology and hydrochemistry of Truckee Meadows Area, Washoe County, Nevada: U. S. Geological Survey Water Supply Paper 1779-S.

Cressie, N. A., 1990, The origins of kriging: Mathematical Geology, **22**, 239–252.

Grant, J. S., and G. F. West, 1965, Interpretation theory in applied geophysics: McGraw-Hill Book Co., Inc.

Haeni, F. P., 1986, Application of seismic refraction methods in groundwater modeling studies in New England: Geophysics, **51**, 236–249.

Hendricks, J. D., 1992, Total-intensity magnetic-anomaly map of the Reno 1° by 2° quadrangle, Nevada and California: U. S. Geological Survey Miscellaneous Field Studies Map MF-2154-C.

Hittelman, A. D., D. Dater, R. Buhmann, and S. Racey, 1994, Gravity CD-ROM and user's manual National Oceanic and Atmospheric Administration, National Geophysical Data Center.

IAGA Division V, Working Group 8, 1995, International Geomagnetic Reference Field, 1995, adopted by the International Association of Geomagnetism and Aeronomy (IAGA) during the XXI

General Assembly of the International Union of Geodesy and Geophysics: http://www.ngdc.noaa.gov/seg/potfld/igrf95.html.
Krank, K. D., and R. J. Watters, 1983, Geotechnical properties of weathered Sierra Nevada granodiorite: Association of Engineering Geologists Bulletin, **XX**, 173–184.
Langenheim, V. E., and T. G. Hildenbrand, 1997, Commerce geophysical lineament — Its source, geometry, and relation to the Reelfoot rift and New Madrid seismic zone: Geological Society of America Bulletin, **109**, 580–595.
Mankinen, E. A., T. G. Hildenbrand, G. L. Dixon, E. H. McKee, C. J. Fridrich, and R. J. Laczniak, 1999, Gravity and magnetic study of the Pahute Mesa and Oasis Valley region, Nye County, Nevada: U. S. Geological Survey Open File Report, 99-303.
Muffler, P., 1979, Assessment of geothermal resources of the United States — 1978: U. S. Geological Survey Circular 790.
Skalbeck, J. D., 2001, Geophysical modeling and geochemical analysis for hydrogeologic assessment of the Steamboat Hills area, Nevada: Unpublished Ph.D. dissertation, University of Nevada.
Skalbeck, J. D., R. E. Karlin, L. Shevenell, and M. C. Widmer, 2002a, Geothermal reservoir volume estimation from gravity and aeromagnetic modeling of the Steamboat Hills geothermal area, Reno, Nevada: Geothermal Resources Council Transactions, **26**, 443–448.
———, 2002b, Mixing of thermal and non-thermal waters in the Steamboat Hills area, Nevada: Geothermics, **31**, 69–90.
Sorey, M. L., and E. M. Colvard, 1992, Factors affecting the decline in hot-spring activity in the Steamboat Springs area of critical environmental concern, Washoe County, Nevada: U. S. Geological Survey, Administration Report for U. S. Bureau of Land Management.
Stanley, W. D., and R. J. Blakely, 1995, The Geysers–Clear Lake geothermal area, California — An updated geophysical perspective of heat sources: Geothermics, **24**, 187–221.
Tabor, R. W., and S. Ellen, 1975, Geologic Map, Washoe City Folio: Nevada Bureau of Mines and Geology Environmental Series.
Talwani, M., and J. R. Heirtzler, 1964, Computations of magnetic anomalies caused by two-dimensional bodies of arbitary shape, *in* G. A. Parks, ed., Computers in the mineral industry, Part I, Stanford University Publications: Geological Sciences, **9**, 464–480.
Talwani, M., J. L. Worzel, and M. Landisman, 1959, Rapid gravity computations for two-dimensional bodies with application to the Mendocino Submarine fracture zone: Journal of Geophysical Research, **64**, 49–59.
Thompson, G. A., and C. H. Sandberg, 1958, Structural significance of gravity surveys in the Virginia City–Mt. Rose area, Nevada and California: Geological Society of America Bulletin, **69**, 1269–1282.
Thompson, G. A., and D. E. White, 1964, Regional geology of the Steamboat Springs area, Washoe County, Nevada: U. S. Geological Survey Professional Paper 458-A.
White, D. E, G. A. Thompson, and C. H. Sandberg, 1964, Rocks, structure, and geologic history of the Steamboat Springs thermal area, Washoe County, Nevada: U. S. Geological Survey Professional Paper 458-B.
Zeng, H., T. Wan, C. Teyssier, C. Yao, and B. Tikoff, 2000, The 3-D geometry of the Linglong granitic complex from 2-D gravity forward modeling, Shandong Province, east China: Geophysics, **65**, 421–42.