

Geothermal Reservoir Volume Estimation from Gravity and Aeromagnetic Modeling Of the Steamboat Hills Geothermal Area, Reno, Nevada

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ABSTRACT

Concurrent development and production of nearby geothermal and drinking water resources in the Steamboat Hills area, Nevada require an understanding of the hydrogeologic connection between these two resources. The need to identify the structural controls for groundwater flow in this complex hydrogeologic setting prompted us to construct a detailed 3-D geologic model based on 2.75-D forward modeling of multiple gravity and aeromagnetic profiles constrained by geological data and physical properties. Data along 11 profiles allow detailed modeling of altered granodiorite and metamorphic rocks thought to represent the extent of the geothermal reservoir. This representation of the geothermal reservoir yields a volume estimate of 58 km³ and a geothermal recovery factor (R_g) of 12.5% for the system. The model also suggests thermal water may upflow along a fault flanking the western Steamboat Hills in an area not yet explored.

Introduction

In the Steamboat Hills area south of Reno, Nevada the concurrent development of drinking water and geothermal water resources necessitates thorough understanding of the hydrologic communication between these two resources. We have modeled gravity and aeromagnetic data to estimate the geologic structure within a complex hydrogeologic setting. This paper presents a methodology for geologic modeling in this setting by using potential fields data, surface and subsurface geology, and physical properties of rocks. The results of this study provide a 3-D representation of the geothermal reservoir and suggest how to identify hydrologically significant faults that may facilitate communication between the two water resources.

The study area is located along the western margin of the extensional Basin and Range province in the western United States. The Steamboat Hills are a topographically prominent NE-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 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). 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*), that in turn are overlain 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. The *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), NE-SW, and NW-SE (White *et al.*, 1964) are found in the study area. A series of five Pleistocene rhyolite domes (*Qsh*) occur along the NE-SW fault trend. The Steamboat Hills geothermal field occurs predominantly along this same NW-SE trending fault system within the *Kgd* and *pKm* rocks.

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. Using mixing trends between thermal and non-thermal waters within the alluvial aquifer, Skalbeck, *et al.*, (2002) found hydraulic connection of the drinking and geothermal water resources along north-trending faults.

Methods

Gravity data at 166 stations from a study (Carpenter, 1996) contracted by Washoe County Department of Water Resources (Washoe County) 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 3 tie lines oriented at N20E with about 5000 m spacing (DIGHEM, 1994). A cesium vapor magnetometer was towed 20 m below the helicopter and draped above ground surface at heights of 30 to 120 m. Figure 3 shows residual reduced-to-pole data derived from minimum curvature gridding. A 10 factor decimation of the aeromagnetic data resulted in 40 to 60 m data spacing for profiles that replicates the full data set.

Physical property data used in modeling were obtained from published data and laboratory measurements in the study. Fifty-eight hand samples and 36 paleomagnetic core samples of altered (*Alt*) and unaltered *Tv*, unaltered *Kgd* and *Alt Kgd*, and *pKm* were collected from the 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, 1998). Whole core magnetic susceptibility for *Alt Kgd* was measured on 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.

The 2.75-D 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. Model block strike lengths were extended perpendicular to the

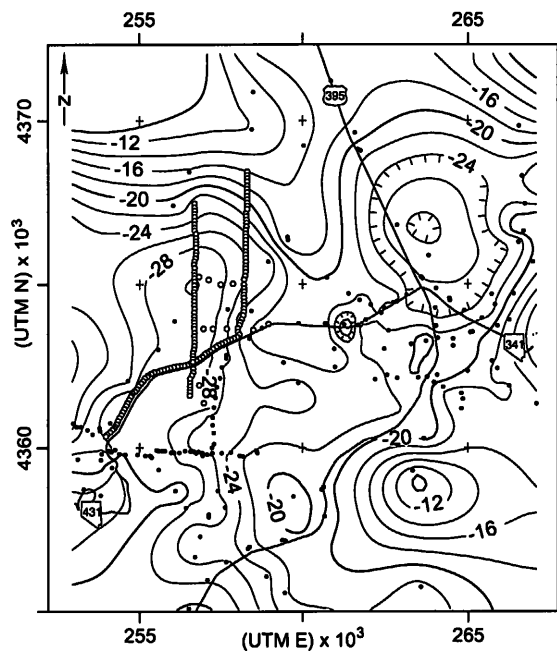


Figure 2. Residual isostatic gravity map of the Steamboat Hills area. Open circles are stations from Carpenter (1996), closed circles are from Hittelman et. al. (1994). Contour interval is 2 mGal.

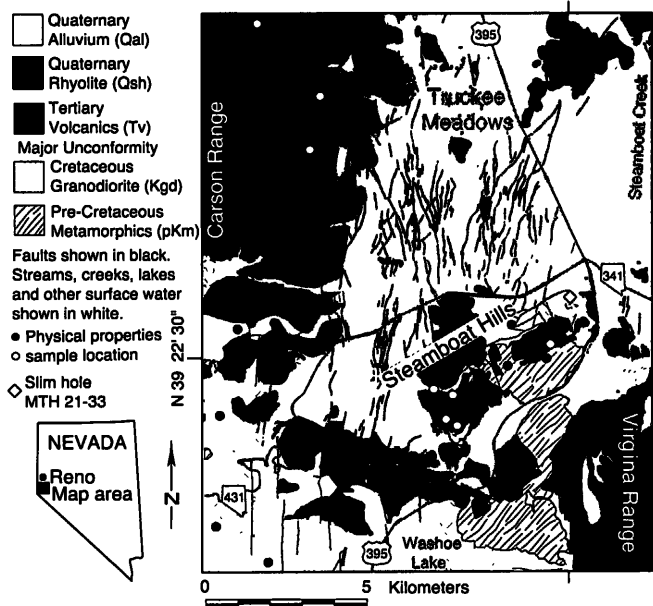


Figure 1. Generalized geologic map modified from Bonham and Rogers (1983), Bonham and Bell (1993), and Tabor and Ellen (1975). Map shows sample locations for physical properties measurements.

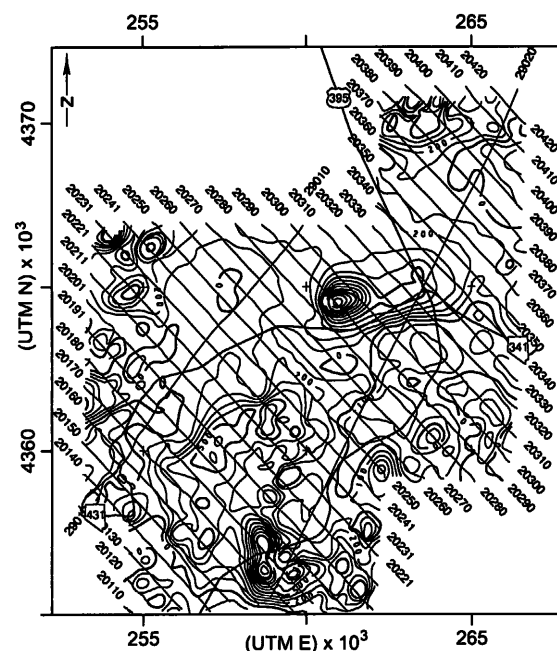


Figure 3. Residual reduced-to-pole aeromagnetic map of Steamboat Hills area shown with helicopter flight lines. Contour interval is 100 nT.

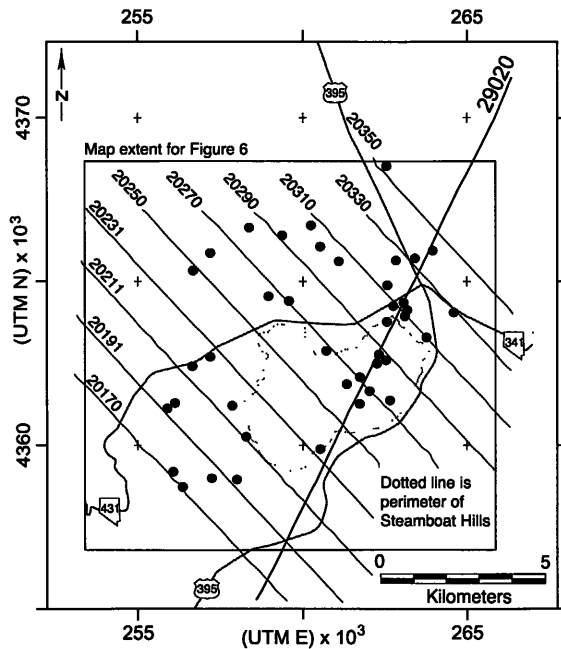


Figure 4. Locations of model profiles and wells used for vertical control in models. Bold profile (29020) is shown in Figure 5. Data for wells and other profiles are given in Skalbeck (2001).

profile based on the mapped geology. The perpendicular strike orientation was chosen based on the local 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 from domestic, Washoe County, and geothermal wells provide vertical control of model blocks. Iterative adjustments to geologic block con-

figuration, 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 the 3-D modeling. These data were computed by Kriging (Cressie, 1990) to obtain *Alt Kgd* and *pKm* thickness.

Results

Of the 11 profiles modeled for this study, Profile 29020 (Figure 5) is presented here to highlight key features within the study area. Remaining profiles are presented in Skalbeck (2001) and model fit results are summarized in Table 1. The model for Profile 29020 represents a good fit for aeromagnetic data with a %RMSE of 7.7% but the fit for gravity with a %RMSE of 7.5% is outside the target value of 5.0%. The majority of error in the gravity fit occurs from Washoe Hill (distance 12000 m) to the crest of Steamboat Hills (distance 18000 m) where very few gravity stations exist. Excellent vertical geologic control exists for this profile with data from 7 wells. Five of these wells provide data control on the depth to *Tv* and *Kgd*. Two wells include depth to *pKm* and one well includes depth to *Kgd*.

3-D Geometry of Geothermal Reservoir

The combined thickness of *Alt Kgd* and *pKm* (Figure 6) are believed to represent the geothermal reservoir beneath the 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 due to the current geothermal system. The main NE trend of this feature is aligned with NE-trending faults and associated Quaternary

Table 1. Best fit statistics for 2.75-D forward models of gravity and aeromagnetic data.

Flightline	Complete Bouguer Residual Gravity				Reduced-to-Pole Residual Magnetics			
	Range (mGal)	Anomaly (mGal)	RMSE (mGal)	% RMSE	Range (nT)	Anomaly (nT)	RMSE (nT)	% RMSE
20170	-22.7 -28.2	5.5	0.227	4.1	-634 1305	1939	106.987	5.5
20191	-20.5 -28.0	7.5	0.279	3.7	-450 850	1300	89.213	6.9
20211	-19.3 -28.9	9.6	0.359	3.7	-415 758	1173	113.339	9.7
20231	-16.9 -28.0	11.1	0.405	3.6	-598 514	1112	97.738	8.8
20250	-17.9 -28.7	10.8	0.396	3.7	-186 439	625	62.303	10.0
20270	-14.4 -25.1	10.7	0.503	4.7	-343 407	750	57.828	7.7
20290	-14.1 -24.6	10.5	0.485	4.6	-206 1603	1809	116.832	6.5
20310	-16.2 -23.0	6.8	0.215	3.2	-588 579	1167	67.847	5.8
20330	-17.9 -26.6	8.7	0.349	4.0	-258 663	921	23.991	2.6
20350	-19.1 -27.0	7.9	0.168	2.1	-211 488	699	15.341	2.2
29020	-15.1 -39.0	23.9	1.795	7.5	-1241 870	2111	161.569	7.7
Best Fit Target Value for % RMSE				5.0	10.0			

RMSE: Root mean square error mGal: Milligal nT: nanoTesla % RMSE: RMSE/Anomaly

rhyolite domes. A secondary NW-trend along the western flank of the 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 NW-trending zone with maximum thickness of 1560 m occurs beneath the alluvial deposits NE of the Steamboat Springs Fault System, which is the discharge area for the geothermal system.

Conceptual Model of Geothermal System

In general, most researchers agree with the basics of the conceptual model for the Steamboat Hills geothermal area proposed by White (1968). This model includes deep circulation (>3000 m) of meteoric water recharging primarily in the Carson Range (with some recharge from the Virginia Range) with circulation occurring in fractured and faulted Mesozoic granitic and metamorphic rocks. The water becomes heated through deep circulation, or perhaps by a magma chamber and rises by convection through a complex network of fractures and faults. The age of the Steamboat Hills geothermal system is between 100,000 and 1 My (White, et. al., 1964).

Disagreement does occur over the details of the conceptual model. The model postulated by van de Kamp and Goranson (1990) includes two separate geothermal systems while Mariner and Janik (1995) propose a single geothermal system for Steamboat Hills with differences in the temperatures due to boiling. Finger, et. al., (1994) postulate an undetected shallow rhyolite intrusion is the heat source. Some investigators believe the rhyolite is too old (1.2 my) to be the heat source (Chris Henry, personal communication, 2001). White (1968) suggests that a batholith volume of 100-1000 km³ is required to supply heat for this geothermal system over the life of this system, but a chamber has not yet been detected in this or past studies.

The potential fields modeling results from this study suggest a single geothermal system

for Steamboat Hills in agreement with basic concepts postulated by White (1968) and proposed by Mariner and Janik (1995). A schematic of the conceptual model of the geothermal system is shown in Figure 7. The geothermal system is modeled as *Alt Kgd/pKm* representing host rock containing a complex network of fractures that permit migration of thermal water. Thermo-chemical 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 further from the fracture is not likely altered. 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), which considers the geothermal reservoir as the entire volume of rock and water that host the heated water rather than just the permeable zones.

The thick zone of *Alt Kgd/pKm* along the western flank of the Steamboat Hills is coincident with a north-NW trending fault that may represent a previously unrecognized upflow zone for the geothermal 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

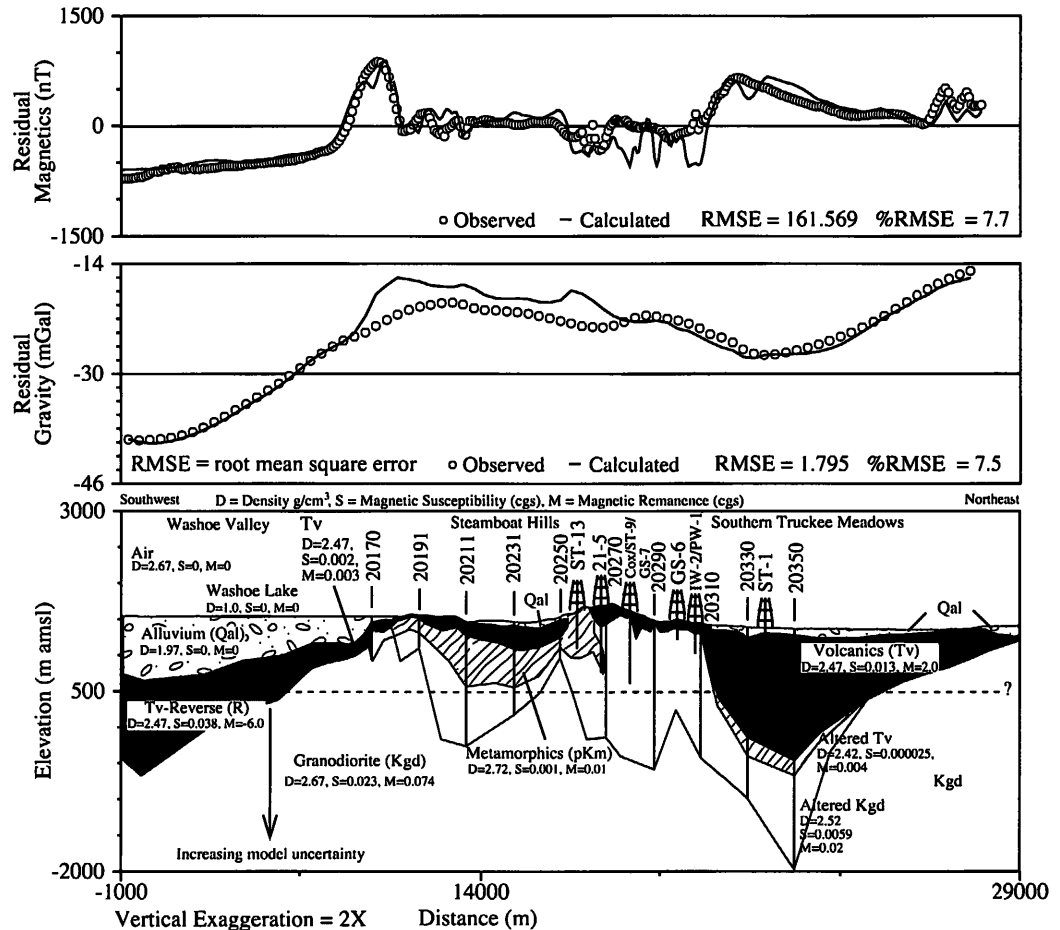


Figure 5. Profile 29020 (Tie Liine) cross-section as computed by 2.75-D forward modeling of gravity and aeromagnetic data.

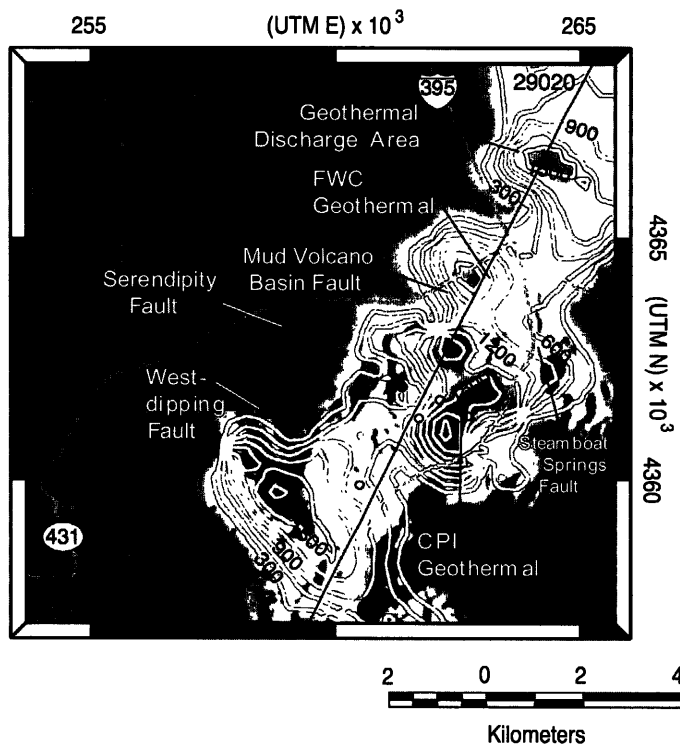


Figure 6. Altered Kgd/pKm thickness from 2.75D forward models of gravity and aeromagnetic data. ●: well constrains thickness; ○: well constrains top of unit. CI is 300 m.

and Browns Creeks. Water is heated at depth and flows upward along a west-dipping normal fault along the western flank of the Steamboat Hills. The NE-trending fault system along the axis of the 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., 2002).

Discussion and Conclusions

By modeling *Alt Kgd* and *pKm* to represent the geothermal reservoir based on recognition that the reservoir rock has lower magnetic susceptibility due to thermal alteration along fractures, we present a new method to estimate geothermal reservoir volume from potential fields modeling. According to Muffler (1975) the largest uncertainty in estimating the thermal energy of a geothermal resource is estimating the reservoir area and depth (volume), which leads to uncertainty in calculating the geothermal recovery factor (R_g) for hot-water geothermal resource determinations where R_g is the ratio of geothermal energy recovered at the wellhead (q_{wh}) to geothermal energy originally stored in the reservoir (q_r). Our method of modeling geothermal reservoir volume offers the opportunity to revise previous volume estimates and therefore recalculate R_g . Muffler (1979) estimated the mean reservoir volume for Steamboat Hills at $29 \pm 12 \text{ km}^3$ whereas our new volume estimate is 58 km^3 . Using our revised volume estimate, the R_g for Steamboat Hills

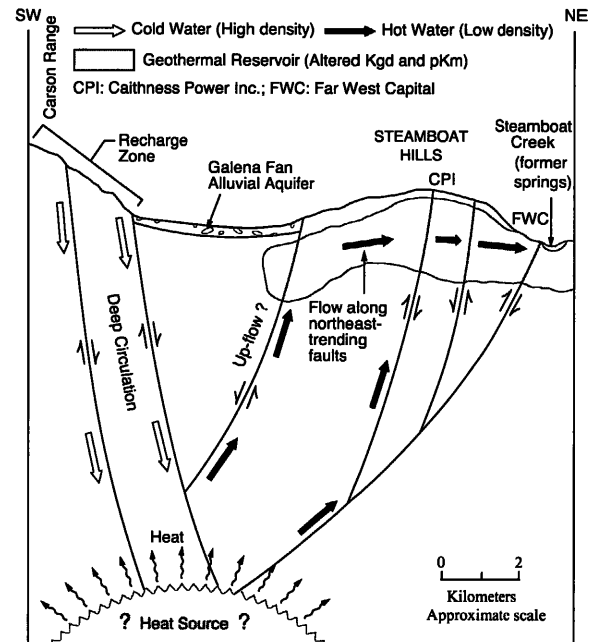


Figure 7. Conceptual model of Steamboat Hills geothermal system. Modified from White 1968), Mariner and Janik (1995), and Derocher (1996) based on this study.

is 12.5% versus the assumed 25% R_g value used by Muffler (1975). During the Joint UNR/USGS Geothermal Science Workshop on May 1, 2001, Muffler stated that the 25% R_g value is known to be high and that an R_g value of 9% has been calculated for the Geysers. The new R_g value for Steamboat Hills compares closely with the Geysers value.

Summary

We use 2.75-D forward modeling of gravity and aeromagnetic data along multiple profiles that are highly constrained by geologic data and physical properties to obtain the geologic structure for a geothermal system and present a new method to estimate geothermal reservoir volume and possibly identify upflow zones. We model altered granodiorite and metamorphic rocks to represent the geothermal reservoir based on recognition that the reservoir rock has lower magnetic susceptibility and density due to thermochemical alteration along fractures. An average magnetic susceptibility value obtained from whole rock core was a critical parameter used to represent altered granodiorite for the modeled geothermal reservoir host rock in order to match observed aeromagnetic data. A thick zone of altered granodiorite and metamorphic rocks suggests a previously unrecognized thermal water upflow zone may exist along a fault near the western flank of the Steamboat Hills. This site should be targeted for future exploration drilling in an attempt to locate an upflow zone and possibly higher temperature fluids than currently produced at CPI.

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