Structural Control of Warm Springs and Wells in the Hillsboro-Lake Valley-Palomas Basin Region of South-Central New Mexico

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ABSTRACT
Subsurface fluid flow and heat transport in the Animas graben and horst between Hillsboro and Lake Valley and in the Palomas Basin in south-central New Mexico are evaluated using older industry and new temperature gradient data and geothermometry. Thermal manifestations include warm springs (31-38°C) and a borehole with a high geothermal gradient (80°C at 74 m) near Hillsboro. In addition, three shallow water wells drilled during the past decade near Lake Valley have encountered warm water (31-38°C) at shallow depth (<24 m). These warm waters and a nearby warm spring indicate the presence of a low-temperature geothermal system north of Lake Valley along Berrenda Creek where the creek crosses the Animas horst. Three wells in the Palomas Basin tap into a 28-30°C north-striking confined aquifer at a depth of 280 m that appears to be associated with a small intra-basin graben and localized gravel deposits. Numerical hydrogeologic models of the Animas horst and graben system, using temperature as a groundwater tracer, were constructed to test the hypothesis that groundwater originating from the crest and eastern slopes of the Black Range flows eastward, circulates to depths up to 6 km to be heated, and flows upward to discharge along the western boundary faults of the Animas horst, particularly the north-striking Berrenda normal fault. Although the steady-state hydrogeologic model does produce elevated temperatures along the Berrenda fault, the temperature-depth profiles predicted by the model do not exactly match the observed data. Instead, the shapes of the measured temperature-depth profiles from the Hillsboro area are consistent with more complicated shallow and local hydrothermal processes. The maximum estimated reservoir temperatures at Hillsboro using the chalcedony and quartz geothermometers are 137°C and 161°C, respectively. The maximum estimated reservoir temperatures near Lake Valley using the chalcedony and quartz geothermometers are 83°C and 112°C, respectively.

Introduction
Hydrothermal systems in extensional settings are commonly associated with gravity-driven, deep circulation and heating of fluid in a high heat flow thermal regime; the heated fluids are discharged in the vicinity of faults or at intersections of multiple generations of structures (Witcher, 1988). Discharge can also occur in places where an aquifer is juxtaposed against an aquitard, above and within fractured horst blocks where aquitards have been removed by erosion, or in fractured intrusions penetrating aquitards (hydrogeologic windows; Witcher, 1988). Many of the hydrothermal systems in the southern Rio Grande rift, including Socorro (Barroll and Reiter, 1990; Mailloux et al., 1999), Truth or Consequences (Person et al., 2013), Rincon (Witcher, 1991), and Radium Springs (Witcher, 2002), have been described in the context of this type of conceptual model. The regional heat flow in the Rio Grande rift, a north-striking extensional province that stretches from central Colorado to west Texas, is high (75 to 110 mW/m²; Reiter et al., 1975; 1978; Decker and Smithson, 1975). Westerly-directed extension caused thinning of the crust, passive upwelling of the mantle and associated advection of heat starting at 36 to 37 Ma. The rift narrowed and the basins deepened significantly during the peak of extensional deformation between 14 and 16 m.y. ago; tectonic activity has decreased significantly through the last 5 Ma (Chapin and Cather, 1994).

This study evaluates the geothermal potential of an underexplored region within the Rio Grande rift along the Animas horst and east-dipping half-graben, which separates the Palomas basin to the east from the Black Range to the west in south-central New Mexico (Figure 1). Structures created during three major tectonic episodes - the NW-striking Rio Grande reverse fault that formed during Laramide deformation, the Emory caldera that collapsed during Mogollon-Datil volcanic field development, and north-striking, west-dipping normal faults that developed during rift extension - intersect in this area (Figure 2). Thus, this area is structurally unique and is interesting from a geothermal prospecting point of view because this area shares several significant, permeability-enhancing structural elements that are also found at the high-temperature Lightning Dock geothermal resource in southwestern New Mexico (Witcher, 2008).
Indeed, warm springs and wells have been identified in two localities on the west flank of the Animas horst, one near Hillsboro and another near Lake Valley (Figure 1). The warm springs near Hillsboro was first identified in the 1980s (Swanberg, 1984). A temperature of 80°C at 74 m was measured in a geothermal well drilled near the warm spring. Both the warm spring and the warm well are located in the hanging wall of the Berrenda fault, a north-striking, down-to-the-west normal fault bounding the west side of the 34-km long Animas horst (Figures 1 and 2). More recently, landowners with property along one of the creeks located north of Lake Valley, Berrenda Creek, have reported warm water in shallow domestic wells. Again, the warm water discharges near the Berrenda fault, although the Berrenda fault is more complicated and has a pronounced ENE-strike in this area (Figure 2). Here, the warm water is located about 2 km to the east of the main trace of the Berrenda fault and is within the Animas horst.

A conceptual model that assesses the role of geologic structures and stratigraphic units in controlling subsurface hydrothermal circulation and the location of warm springs and wells was developed as part of this investigation. In this study, we tested two hypotheses: a regional versus a local deep groundwater flow system. Regional-scale, topographically-driven, deep circulation and heating of fluid in a high heat flow thermal regime, which has been used to describe geothermal systems elsewhere in the rift, forms the basis of the first hypothesis. Water falling as precipitation on the Black Range on the west side of the study area percolates to depths of 6 km and is heated by elevated rift-related heat flow in the Hillsboro/Lake Valley area (71.1-108.4 mW/m²; Reiter et al., 1975; Decker and Smithson, 1975) before discharging in the vicinity of the Berrenda fault (Figure 3). The regional scale system is 24-27 km across in an E-W direction, stretching from the crest of the Black Range to the Berrenda fault. Here, possible flow paths cross several north-striking, west-dipping faults with stratigraphic offsets on the order of 10s to 100s of meters. Because major structures like the Berrenda fault are dipping against the flow direction, such structures could be the loci of discharge. Other factors, including the stratigraphy, the age of faulting, and mineralization and alteration along the faults could all affect fault permeability, thus enhancing or hindering groundwater flow across fault zones.

Localized flow within a single 10-km-wide fault block located between another west-dipping fault, the Lake Valley fault (Figure 2), on the west and the Berrenda fault on the east forms the basis of the second hypothesis. The second hypothesis is similar to the first hypothesis in terms of geologic/thermal setting and depth of circulation, but the postulated flow paths are shorter and possible recharge of the system is located in an area to the east of the crest of the Black Range.

Figure 1. Location map. Rivers, creeks (blue lines) and canyons in the study area. The main features include the Black Range, Animas graben and horst, Copper Flat and Palomas basin. HWS = Hillsboro warm spring; BWS = Berrenda warm springs. Red line is the location of the cross section in Figure 8.

Figure 2. Tectonic map of the area. K = Cretaceous. Map modified from O’Neill et al. (2002). HWS = Hillsboro warm spring; BWS = Berrenda warm spring.
To understand the interplay of structures, stratigraphy and hydrological windows in the vicinity of the Animas horst and graben, we compiled and measured structural, geochemical, and temperature profile data. Geologic maps (Seager et al., 1982; O’Neill et al., 2002) and structural data are used to construct regional-scale cross sections (Figure 3). A preliminary hydrogeologic model was created from the northern cross section to quantitatively evaluate temperature and hydraulic head distributions related to the topographically-driven system in the Hillsboro area. The resulting temperatures and flow lines predicted by the model are compared to measured temperature profiles and reservoir geothermometry calculated from the water chemistry data. The cross sections are used to identify hydrogeologic windows and qualitatively analyze the local-scale flow system.

Geologic Setting

Late Cretaceous to Paleogene Laramide transpressive deformation formed prominent NW- and W-striking structural fabrics controlling permeability and fluid flow in this region (Seager et al., 1986). The northeastern edge of the Laramide Rio Grande uplift lies between Silurian carbonate exposures on the hanging wall just north of Berrenda Creek and Pennsylvanian exposures on the footwall north of Sibley Mountain within the east-dipping Animas horst between Lake Valley and Hillsboro (Figure 3; O’Neill et al., 2002). The Rio Grande uplift, along with the contemporary Love Ranch basin to the north, are now primarily buried by younger rift-fill sedimentary deposits in the Palomas and Animas basins (Figure 3; Seager and Mayer, 1988). Plutons of Cretaceous age were emplaced at Copper Flat northeast of Hillsboro and in an area 8 km northwest of Hillsboro (Figure 2; Seager et al., 1982). The Cretaceous andesitic stratovolcano at Copper Flat is composed primarily of well-indurated volcaniclastic debris flows intercalated with a few andesitic lava flows.

Laramide compression was followed by slab roll-back and voluminous eruptions in the Mogollon-Datil volcanic field starting at ~37 Ma (Seager et al., 1986; O’Neill et al., 2002; Chapin et al., 2004). The 34.89 ± 0.05 Ma Emory caldera formed during this volcanic event, producing the regionally extensive Kneeling Nun Tuff (McIntosh et al, 1991). The 34.5-million-year-old Mimbres Peak Formation rhyolite subsequently filled the ring fractures of the caldera.

At least three episodes of post-Laramide faulting have been recognized in this area (O’Neill et al., 2002). The southern, NW-striking part of the Lake Valley fault (Figure 2) has a history of offset that occurred prior to middle Cenozoic volcanism because this normal fault controls the distribution of the oldest Eocene lava flows in the area. The northern, N-striking portion of the Lake Valley fault is a ring fracture fault that formed during the collapse of the Emory caldera (Figure 2). The Berrenda fault is part of the Rio Grande rift normal fault system. Generally, the rock units dip 10 to 20° to the east (O’Neill et al., 2002), which is the groundwater flow direction. The north and south splays of the Berrenda fault in the Lake Valley area have 360 and <250 m of dip-slip and right-slip, respectively. The north-striking Berrenda fault turns sharply toward the SW and breaks into two major splays south of Sibley Mountain. Rift fill deposits of the Santa Fe Group are juxtaposed against Pennsylvanian limestones and shales along the Berrenda fault north of the bend; here the amount of displacement is not constrained (O’Neill et al., 2002). South of the bend, the main splay of the Berrenda fault has 600 m of down-to-the-NW displacement and the southern splay has 300 m of down-to-the-NW offset; slickenlines on both splays are primarily dip-slip (O’Neill et al., 2002). The two major fault zones (Berrenda and Lake Valley faults) cross each other along Berrenda Creek. The origin of E-W striking faults in the Lake Valley and Berrenda Creek areas is uncertain (O’Neill et al., 2002); the faults roughly parallel the Laramide structures, but these faults offset units as young as the Eocene Rubio Peak Formation. An episode of basaltic volcanism occurred near Hillsboro at ~4.8 Ma; these lava flows are clearly faulted southwest of Hillsboro (Seager et al., 1982, 1984). Although Quaternary faults are common in the Palomas basin a few miles west of the Rio Grande, no Quaternary faults have been mapped in the Animas half-graben (Seager et al., 1982).

Methods

Temperature Measurements

Thirteen thermal logs from wells and fourteen water samples from wells and springs were collected as part of this study. In addition, thermal logs and water
chemistry data from geothermal industry sources were compiled and are available in Tewelde (2014). Presentation and analysis of industry thermal logs from Hillsboro and new logs measured along Berrenda Creek and in the Palomas Basin will be the focus of this paper. The New Mexico Bureau of Geology and Mineral Resources temperature-logging equipment uses a thermistor attached to a wireline cable to measure resistance as a function of depth. Resistance is translated to temperature using a laboratory calibration. Resistance is recorded at 1 m depth intervals using a digital multimeter and a computer. All logs reported here were measured with a sensor designed to measure resistance in water; consequently, the air readings are not in thermal equilibrium. The logging rate varied from 1 to 4 m/minute. The curvature of well temperature profiles can be used to estimate vertical flow rates. Interpretations of upflow and downflow of fluid around boreholes can be estimated using plots of dimensionless temperature versus dimensionless depth. By matching a dimensionless temperature versus depth profile with the type curves of Bredehoeft and Papadopulos (1965), a Peclet number can be assigned to the profile.

The seepage velocity ($q_z$) can be calculated:

$$q_z = \frac{\lambda}{\rho_f c_f L} \text{Peclet number} = 5.8 \times 10^{-3} (\text{Peclet number}/L) \quad (1)$$

where

- $\lambda$ = bulk thermal conductivity of unconsolidated porous sandstone (2.43 J/(s.m.oC));
- $\rho_f$ = fluid density (1000 kg/m$^3$; 969 kg/m$^3$ at 84°C)
- $c_f$ = fluid heat capacity (4.187 kJ/kg.°C);
- $q_v$ = vertical Darcy flux (m/s); and
- $L$ = thickness of the semi-confining unit in meters.

Two different values of $L$ were used. One value was calculated over the length of the well below the water table. The second value of $L$ ranges from 300 to 2000 m, which corresponds to the thickness of rift-fill sediments in the vicinity of certain wells in the Animas half-graben (Table 1). The direction and velocity of flow each the well bore were evaluated and those values were plotted on a geologic map to establish correlations among flow direction, velocity, geologic structure, and rock type.

**Geothermometry**

Geothermometers were calculated from the groundwater chemistry data using Excel spreadsheets provided by Powell and Cumming (2010). Ternary diagrams and cross-plots of the data were constructed using the program. The geothermometry calculations are based on published empirical relations of temperature relative to the ratio of dissolved cations, including K/Mg (Giggenbach, 1988) and Li/Mg (Kharaka and Mariner, 1989) and temperature-dependent equilibrium of dissolved silica for solid silica species, quartz (Fournier and Potter, 1982) and chalcedony (Fournier, 1977).

**Hydrogeologic Modeling**

The equations representing groundwater flow and heat transport were solved using a parallel version of the finite element hydrothermal model FEMOCP described by Person et al. (2008). The geologic cross-section through Hillsboro was discretized using 3770 nodes and 7275 triangular elements. The elements varied in size from about 1500 m in the low permeability crystalline rock to 200 m in the fault zone. The complex geology is simplified into six hydrostratigraphic units (Table 2; Tewelde, 2014). The model is about 58 km long and 6 km thick. Crystalline basement was represented in the model at depths of 4 to 6 km below the land surface. Isotopic fault properties were assigned to both the Berrenda and Palomas basin faults. We used a time-step size of between 1 to 10 years. The model was run for 150,000 years, which approached steady-state conditions. The depth of circulation was varied by setting the lower portion of the crystalline basement to a permeability of 0.0001 mD. Higher permeability values were assigned to the upper part of the crystalline basement. Temperature at the water table was varied from about 17 °C in the lowlands to 60 °C in the Berrenda fault zone to 15 °C in the uplands. The model was run using a variety of fault zone permeabilities (10,000 mD to 100 mD) and basal heat flow values (0.08 to 0.104 Wm$^{-2}$) to assess how temperatures changed in the vicinity of Berrenda fault. Recharge occurred at high elevations near the crest of the Black Range. In addition, the permeability of a fractured Cretaceous pluton located 8 km NW of Hillsboro was varied to investigate more localized recharge of the system. Permeability ranges and physical parameters used in the different model runs are presented in Tewelde (2014).

### Table 2. Hydrologic properties used in best-fit model.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Permeability (mD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proterozoic basement</td>
<td>200</td>
</tr>
<tr>
<td>Oligocene volcanics</td>
<td>0.1</td>
</tr>
<tr>
<td>Berrenda fault</td>
<td>1000</td>
</tr>
<tr>
<td>Paleozoic sedimentary units</td>
<td>0.01</td>
</tr>
<tr>
<td>Palomas basin fault</td>
<td>500</td>
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<tr>
<td>Rift-fill sediments</td>
<td>5</td>
</tr>
</tbody>
</table>

### Results

**Hillsboro Industry Lithologic and Temperature Logs**

Three wells northeast of Hillsboro, H1, H5 and H2 (from north to south), were drilled into middle Cenozoic volcanioclastic, rift-related debris flows of the Santa Fe Group in the hanging wall immediately west of the Berrenda fault (Figure 2). Wells H4, H6, and H8 are located two to three km west of the fault in the hanging wall. Wells H3 and H7 are on the footwall.

The temperature profile for H1, located near the HWS in the hanging wall just west of the fault, shows pronounced upwelling of 80°C water from a shallow depth of 74 m (Figure 4). For this well, temperature gradients in the interval between 20 to 74 m vary from 165 to 286°C/km (Table 1). The gradient above the water table at 20 m is apparently conductive. Based on our cross section through the area, the basin fill sediments may host a hydrothermal system to depths of 900 m; thus we use this value in our Peclet number/velocity analysis (Table 1). In contrast to H1, the maximum temperature in well H5 is 34.5°C at 152 m (Figure 4). This well has a linear high gradient of 96°C/km between 20 and 65 m and 106°C/km between 65 and 145 m (Table 1; Figure 4). The southermost well (H2w) adjacent to the fault on the hanging wall has a gentle concave-up temperature profile that may indicate a gradual decrease in conductivity or a conductive
adjustment to a zone of lateral flow of warm water below the bottom of the well (Figure 4). The geothermal gradient increases downhole from 88°C/km between 10 and 36 m to 164°C/km between 80 and 106 m (Table 1). The bottomhole temperature is 33.85°C at 106 m.

Two wells, H3 and H7, were drilled into the Cretaceous andesitic volcaniclastic debris and minor andesite lava flows on the footwall just east of the fault (Figure 4). The northernmost well, H3, has a relatively linear gradient of 76°C/km between 25 and 103 m and a maximum temperature of 26°C at 103 m (Figure 4; Table 1). This well penetrated andesitic lava flows. A subtle change in gradient at 80 m appears to coincide with the top of a lava flow and limonite and clay in the well cuttings (unpublished industry field notes), and thus could be related to a change in thermal conductivity. Upwelling of ~31°C water from depths of 150 m and a lateral flow of 31°C water at 91 m are indicated in the temperature profile of H7 (Figures 4; Table 1). Well-cemented, fractured volcanic breccia was penetrated by this well. A flow rate of 40 to 50 gpm was reported for this hole in the drillers' log.

Two wells, H4 and H6, were drilled along North Percha Creek in the hanging wall of the Berrenda fault about 2.5 km to the west of the fault trace (Figure 4). H4 has a complex thermal profile that is challenging to decipher. Overall the fluid seem to flowing upward, but the lateral flow of cold water through a fracture noted on the drillers logs at ~70 m is superimposed on the general upwelling pattern. A pronounced increase in the induration of the Santa Fe Group volcaniclastic fanglomerates was observed in H4 at 100 m, and a decrease in induration was noted at 142 m. The interval below 100 m in H4 is associated with lower geothermal gradients and possibly higher thermal conductivity near the bottom of the well. The fracture zone noted in the drillers log at 70 m in H4 could correlate with a fracture at 80 m in H6. The bottomhole temperature is 30°C at 153 m in H4 and 30.6°C at 152 m in H6. The geothermal gradient is 65°C/km between 130 and 150 m in H4 and 60°C/km between 135 and 150 m in H6 (Table 1).

**New Temperature Logs**

**Copper Flat/Palomas Basin.** Two new logs were acquired during the Spring of 2012 from water monitoring wells in the Copper Flat mine pit; the monitoring wells were drilled two years prior to measurement (CF2, CF3; Figure 5). The new logs, as well as data from Animas Peak measured by Reiter et al. (1975; CF1; Figure 5), show increasing geothermal gradient with depth, indicative of slow downward flow of water in this local recharge area on the eastern side of the Animas horst.

In addition, three logs were measured in old water production wells located 13 km east of the mine in the Palomas basin (Figure 3). The production wells, perforated between 115 to 303 m, were drilled from 1975-1980 and had not been pumped for many years prior to logging. The three production wells in the Palomas basin appear to have tapped into a ~28-30°C artesian aquifer, causing warm water to flow upward in the borehole. Well records from Quintana Mining Company, the operator of the Copper Flat mine during the 1980s, reveal that the Santa Fe Group in the Palomas basin is generally fine grained and has low permeability in the area between Copper Flat and the production wells. Furthermore, these records indicate that the coarse-grained sand-to-gravel intervals intersected by the production wells at a depth of 130 m to 200 m are restricted to a band that is narrow in an E-W direction (John Hawley, personal communication, 2012). A possible buried south-southeast oriented paleo-axial-fluvial system in the Palomas Formation of the Santa Fe Group that occupies a narrow intrabasin graben bound by Quaternary faults appears to form the aquifer for these high-capacity wells (Figure 10; Wilson et al., 1981; Seager et al., 1982).
Berrenda Creek Ranch. Eight logs were measured in the Spring of 2012 in open water wells that were drilled in 2004-2007 (Figure 6). Two holes south of the north splay of the Berrenda fault and two wells north of the same splay on the west side of the ranch were logged (Figure 7). The wells on the west side of the ranch were spudded into Eocene Rubio Peak Formation, and based on cuttings lying on the ground in the vicinity of the wells, Rubio Peak andesite lava and clasts were the only rock types intersected by the wells. Additional wells were logged in strategic positions relative to the Berrenda fault on the east side of the ranch. The geology on the east side of the ranch is more complex; the easternmost well intersected 35.17 ± 0.12 Ma Sugarlump Tuff and the younger andesite of Sibley Mountain (28.1 ± 0.6 Ma), in addition to the Rubio Peak Formation (Figure 7; O’Neill et al., 2002).

In general, the wells on the west side of the Berrenda Creek Ranch are 1°C colder than those to the east at a given depth. The deepest well, BC1, has an increasing geothermal gradient with depth (Figures 6 and 7; Table 1). Examination of the cuttings next to this hole and the relative position of the cuttings in the pile indicate that the lower part of the well encountered altered (pink) Rubio Peak Formation. The curvature of the temperature log could be due to gradually decreasing thermal conductivity related to increasing alteration and clay content down section in the Rubio Peak Formation. Alternatively, the curvature could be related to slow downflow. No systematic thermal signature was observed on either side of the E-W oriented Berrenda fault on the west side of the ranch, but temperatures are slightly warmer on the east side of the ranch in the vicinity of the bend of the Berrenda fault. Measured and reported occurrences of warm water are found along and 1.5 km east of the significant curved strands of the Berrenda fault (asterisks on Figure 7).

Central Animas Graben. Although we have little data along the Trujillo and Tierra Blanca drainages between Lake Valley and Hillsboro (Figure 1), the groundwater discharge temperatures that we do have along the Berrenda fault on the west side of the Animas horst in these two drainages are only 13 to 18 °C. Thus, along much of the length of the Berrenda fault, this structure is not acting as a barrier to flow in deep warm water aquifers that might exist in this region. One critical observation is the presence of high-volume discharge of 21 °C water at Big Spring (roughly 50 gpm; BS, Figure 3) in the Tierra Blanca drainage along the Lake Valley fault on the west side of the Animas half-graben, which forces groundwater to flow up to the surface before travelling east to the Berrenda fault. This spring, with a temperature that is 7°C above the mean annual temperature (MAT) at Hillsboro (~14°C), just barely qualifies as a warm spring using the criteria of Witcher (1981; >7.5 °C MAT). High volume warm springs discharge significant amounts of heat (e.g. Ferguson and Grasby, 2011).

Geothermometry

The estimated reservoir temperatures based on chalcedony, quartz, K/Mg, and Li/Mg for two samples from Hillsboro warm spring are above 100 °C (Teweide, 2014). The geothermometers range from 107 to 161 °C for sample 1 and 102 to 137 °C for sample 2. The best conservative estimate of the reservoir tempera-
ture at Hillsboro using chalcedony data from both the spring and well data is 82 to 137 °C (Tewelde, 2014). The Na-K-Mg ternary diagram (Giggenbach, 1988) indicates that the two samples from HWS are the only samples in partial equilibrium with a reservoir at an elevated temperature. Temperatures predicted using the Na-K-Mg ternary geothermometer method gave higher temperature values (200 and 170 °C) for HWS.

The estimated reservoir temperature at Berrenda Creek using the chalcedony geothermometer is 64 to 83 °C (Table 2). The geothermometers indicate relatively low temperature reservoirs for the Berrenda Creek area.

Hydrogeologic Modeling

Computed heads and flow patterns are indicative of a forced convection hydrothermal system analogous to the Socorro-La Jencia Basin geothermal system (Mailloux et al. 1999). We found that the crystalline basement and the fault zones needed to be relatively permeable in order to approach matching observed thermal conditions. A crystalline basement permeability of 200 mD to depths of 6-7 km produced best agreement with observed temperatures (Figure 4). The Berrenda and Palomas basin fault permeabilities also needed to be relatively high (500 and 1000 mD, respectively) in order to match field conditions. The depth of circulation within the crystalline basement had a profound affect of flow patterns. If the crystalline basement was permeable and the flow path was deep (6 to 7 km), then a regional flow system developed with high temperature discharge occurring along the Berrenda fault. This circulation depth seems unusually deep compared to other forced-convection systems (Person et al., 2008) and the predicted geothermometers are considerably higher than the measured values.

However, if the crystalline basement circulation was limited to 4 km depth (setting the boundary between low and high crystalline basement permeability at -2000 m elevation), then a more localized flow system developed with a lateral circulation of about 15 km (Figure 9). In this scenario, the Berrenda fault became an upflow zone as observed, but the temperatures are much cooler than that observed. Temperature profiles extracted from the best-fit model (dashed line) are plotted with the measured values on Figure 4; although the magnitude of the computed temperature profile is more or less correct, the simulated temperatures lack the observed curvature near the surface. This may be because the geothermal fluids are allowed to discharge at the top of the model domain when in reality, the no surface springs are present. The maximum temperature along the lowest stream line that enters the Berrenda fault had a maximum temperature of 86 °C.

Figure 8. Geologic cross-section A-A’ through Hillsboro constructed from the geologic map of Seager et. al. (1982). The bold blue and red lines are possible streamlines of regional and local groundwater flow, respectively.

Figure 9. (A) Simulated hydraulic heads (in m) and streak lines (lines with circles) along the Hillsboro Cross Section. Below -2000 m elevation, the crystalline basement permeability was set to be 0.00001 mD. (B) Simulated temperatures (in °C) along the Hillsboro cross section.
We also evaluated the effect of changing the permeability of the various stratigraphic units (Tewelde, 2014). For example, setting the permeability of the Proterozoic crystalline basement to 10,000 mD resulted in the formation of free convection cells, which seemed unrealistic. Varying the permeability of the volcanic unit was found to have a second order effect on heat flow patterns.

**Discussion**

**Temperature Profiles**

**Hillsboro.** The temperature profiles provide information about the complex nature of the shallow hydrologic system in the Animas graben northeast of Hillsboro. Thermal profile data in the Hillsboro area are located at four key localities relative to the Berrenda fault: (1) immediately west of the fault in the hanging wall with Santa Fe Group rift-fill sediments at the surface (H1, H2, H3, H5); (2) 1-2 km west of the fault in North Percha Creek in Santa Fe Group sediments (H4 and H6); (3) immediately to the east of the Berrenda fault in the Cretaceous bedrock footwall (H3 and H7); and (4) within the Copper Flat mine area 4-5 km east of the fault in the Cretaceous bedrock footwall (CF1, CF2, CF3). With the exception of the Copper Flat mine data, the temperature profiles in each area record a range of thermal regimes.

Wells located within the Santa Fe Group in the hanging wall immediately west of the Berrenda fault have high geothermal gradients (88-165°C/km) and record strong upflow in the northern well (H1w), generally conductive behavior in the middle well (H5), and possible lateral flow of hot water below the southern well (H2); these wells are located within 2.5 km of each other along the strike of the fault (Figure 4). The closely-spaced, diverse thermal regimes could be caused by spatially restricted zones of enhanced permeability inherited from NW-striking Laramide deformation or convection along the strike of the fault. These possible hypotheses could be tested with additional mapping. Wells in the Santa Fe Group hanging wall 1-2 km west of the fault have lower gradients of 60-65°C/km; these wells also penetrated different thermal regimes. Hw4 mostly shows upflow with influx of cooler water in the vicinity of a fracture at 70 m that masks the 60 to 65°C/km geothermal gradients recorded near the bottom of the well. In contrast, the thermal profile in Hw6 shows a small volume of inflow of cooler water along a fracture at 80 m superimposed on a generally conductive regime.

The geothermal gradients in the Copper Flat bedrock footwall immediately adjacent to the Berrenda fault near Hillsboro are 76 to 106°C/km and are 16-30°C/km close to the center of the Copper Flat highland. One well in the footwall block just east of the fault locally has strong upflow (H7), suggesting that here, warm fluid moved through the Berrenda fault and is upwelling against buried faults below the volcanic rocks or low-permeability layers related to complexities in the stratigraphy within the volcanic succession. In contrast well H3w is basically conductive. To the east, in the Copper Flat pit, the concave-up signature is indicative of recharge.

**Berrenda Creek.** Like Hillsboro, BWS lies in close proximity to the Berrenda fault. The main strands of the fault are not obstructing flow in the deep aquifers. Instead, a fault to the east of the Berrenda fault zone forms a barrier, perhaps in a place where low permeability units like the Percha Shale or Proterozoic basement are juxtaposed against a deep aquifer, forcing warm water to the surface. Several of the wells on the west side of Berrenda Creek Ranch (BC1, 2,3,4) could be interpreted to record slow recharge in this area that is located ~15 km east of the crest of the Black Range.

**Palomas Basin.** The Copper Flat production wells appear located in a N-S oriented high-permeability gravelly zone within the Santa Fe Group in the Palomas basin.

**Modeling and Geothermometry**

The groundwater flow system could be regional and deep, local and deep, local and shallow, or a combination of the three. The high reservoir temperatures calculated by the geothermometers are indicative of deep flow paths. The cross sectional hydrogeologic model of a groundwater flow system with a length scale of ~25 km and a depth scale of 7.5 km through the Hillsboro area does, in general, predict higher geothermal gradients and temperatures observed along the Berrenda fault in the vicinity of Hillsboro. Warm spring compared to areas to the east and west of the fault, high heat flow is not required to form thermal springs if circulation is deep (up to 5 km) and the depth-to-length ratios flow systems are 1:100 to 1:1 for HWS and 1:1 in areas of high heat flow (Ferguson and Grasby, 2011). Thermal springs can also form in systems with depth-to-length ratios of 1:1 to 1:2 flow system is too short to effectively sweep up enough heat to account for the measured temperatures and the calculated geothermometers in the Hillsboro area.

**Conclusions and Summary**

**Hillsboro**

Based on this study, we attribute the thermal waters in the Hillsboro area to the presence of deep circulation of groundwater that originated as precipitation in the Black Range and discharged along the Berrenda fault. This fault bounds the western part of the Animas horst. Reservoir temperatures predicted for chalcedony equilibrium points to thermal waters (82 to 137°C). Furthermore, the K/Mg and Li/Mg geothermometers are 107 to 137°C for HWS and 82 to 137°C for other wells in the Hillsboro area.

The hydrogeologic model predicts that the background heat flow in the area has to be elevated (104 mW/m²) to approach matching measured temperatures and the estimated geothermometry temperatures at Hillsboro. These heat flow values match the measured heat flow value at Lake Valley (Decker and Smithson, 1975). The predicted model heat flow value near Hillsboro is much higher than the measured heat flow value at nearby Copper Flat (Reiter et al., 1975), but the concave-up shape of the temperature logs at Copper Flat record show recharge on the Animas horst which could mask the elevated regional heat flow. The temperatures and geothermal gradients predicted by a flow system traveling only 10 km are low compared to the observed values at HWS.

**Palomas Basin**

Wells in the Palomas basin with rapid upflow have typical temperatures for such a shallow depth. Here again, the hydrogeologic
model shows buried and deep warm groundwater upflow along a Quaternary fault but the model did not represent the N-S oriented enhanced permeability and porosity related to buried channels and a N-striking graben. Examination of topographic maps in the area reveals the presence of several discharging wells along Las Animas Creek to the north of the study area in the Palomas basin. This area warrants further investigation that should be put into the model constraints. These wells are not unusually warm for this part of the Rio Grande rift.

Lake Valley

The Laramide Rio Grande uplift intersects the Animas horst 3 to 4 km north of Berrenda Creek. Such intersection of structures appears to control location of thermal water discharges in southwestern New Mexico, but we did not observe warm springs or wells at the intersections of the Berrenda fault and the principal Laramide structure. In contrast, the large volume 21°C Big Spring is located near the intersection of the Lake Valley fault and the Rio Grande fault.

Berrenda Creek area within the Animas horst potentially holds new geothermal prospects. All the wells with warm water drilled thus far are shallow, but they might be connected hydrologically with deeper aquifers. The Mayeux well (BC13), with a temperature of 38°C at 24 m, and the BC11 well, with a temperature of 31°C at 2 m, both indicate upwelling of water at a shallow depth along an unnamed fault zone east of the Berrenda fault. We observed fractured Rubio Peak Formation to the south of a mapped N-striking fault zone in this area (Figure 6); consequently, we would project the mapped fault southward into the area where warm water has been reported. The low silica geothermometers (41 - 78°C) in this area indicate low temperature or diluted waters from mixing. West from these warm wells, temperature logs collected on either side of the E-W striking splays of the Berrenda fault show no difference in temperature because the regional groundwater flow roughly parallels the faults.

In summary, the difference in both observed and calculated temperatures between the Hillsboro and Lake Valley areas can be attributed to variations in structure and stratigraphy. The cross sections illustrate the difference between the Hillsboro and the Berrenda Creek areas. For example, the continental divide in the Black Range coincides with the center of the Emory caldera along the northern cross-section through Hillsboro. Water circulating in a deep flow system originating at the crest of the Black Range would start out in thick silicified tuff and andesitic lavas and relatively thin Paleozoic clastic and carbonate units before encountering the Proterozoic rocks that form the caldera margin to the east of the Animas horst. Water might be in Proterozoic and volcanic rocks along much of its path, with little interaction with carbonates when the water moves up along the Berrenda fault. A long flow path and deep circulation are needed for heat sweep. At Hillsboro notable geologic features that could form a barrier to flow include the presence of low-permeability volcanoclastic sediments at Copper Flat and silicification along the fault zone just east of the warm spring. In contrast, a cross-section drawn through Berrenda Creek indicates that much of the flow path along this drainage is in shallower Paleozoic carbonates between the continental divide and the Berrenda fault (Tewelde, 2014). Along Berrenda Creek, the splayed nature of the Berrenda fault in the Lake Valley area, and possible juxtaposition of fractured basement with low-permeability Percha Shale form upflow zones.

References


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