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Origins and Geothermal Potential of Thermal Springs in Archuleta County, including Pagosa Springs, Colorado, USA (Revisited)

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Thermal Springs, Geothermal Potential, Origins, Archuleta County, Pagosa Springs, Colorado

ABSTRACT

Archuleta County, is located on the southwest margin of the San Juan Mountains, south-central Colorado, USA. Several thermal springs and wells in the county follow a NW-SE trend that is roughly parallel to the margin of the San Juan Mountains to the northeast. Most previous studies of these thermal features have focused on the town of Pagosa Spring, the location of the largest spring in the county, Big Spring. These studies have concluded that the source of the thermal springs and wells is deep circulation of groundwater into crystalline Precambrian basement with hot water rising along faults and/or fractures.

I have collected a small amount of new subsurface temperature data and reexamined existing temperature gradient and heat-flow data from the county. Through this analysis I have re-contoured heat-flow data in and around the town of Pagosa Springs which has revealed a circular heat-flow anomaly centered on Big Spring. This anomaly does is not consistent with previous interpretations of geophysical data indicating faults controlling geothermal fluids in the area or shallow fault of fracture control of the geothermal systems associated with Big Spring. The anomaly suggest that the hot water rises through a pipe-like conduit to the Dakota Formation at a depth of 72 to 133 m where it spreads laterally in all directions. The origin of the pipe-like conduit is not known. Other thermal springs in the NW-SE trend may have similar plumbing systems. Wells that penetrate the Precambrian basement along the trend provide artificial pipe-like conduits but their casing prevent the spread of hot water in shallow aquifers to form circular thermal anomalies.

1. Introduction

Archuleta County, is located on the southwest margin of the San Juan Mountains, south-central Colorado, USA (Figure 1). The San Juan Mountains are the erosional remnant of a very large, mid-Tertiary magmatic event that was initially dominated by intermediate composition central volcanoes followed by large-scale, upper-crustal, batholith growth (Lipman and Bachmann, 2015). Geophysical data and geological constraints are consistent with the presence of vertically extensive (> 20 km) intermediate to silicic batholiths. Ignimbrite volcanism and caldera formation dominated the period from 32 to 27 Ma, and isotopic and other evidence indicates voluminous mantle-derived magmas and lengthy periods of near-solidus, crystal mush in the crust (Lipman and Bachmann, 2015). The locations of thermal springs in Archuleta County follow a NW-SE trend that is roughly parallel to the adjacent margin of the San Juan Mountains (Figure 2).

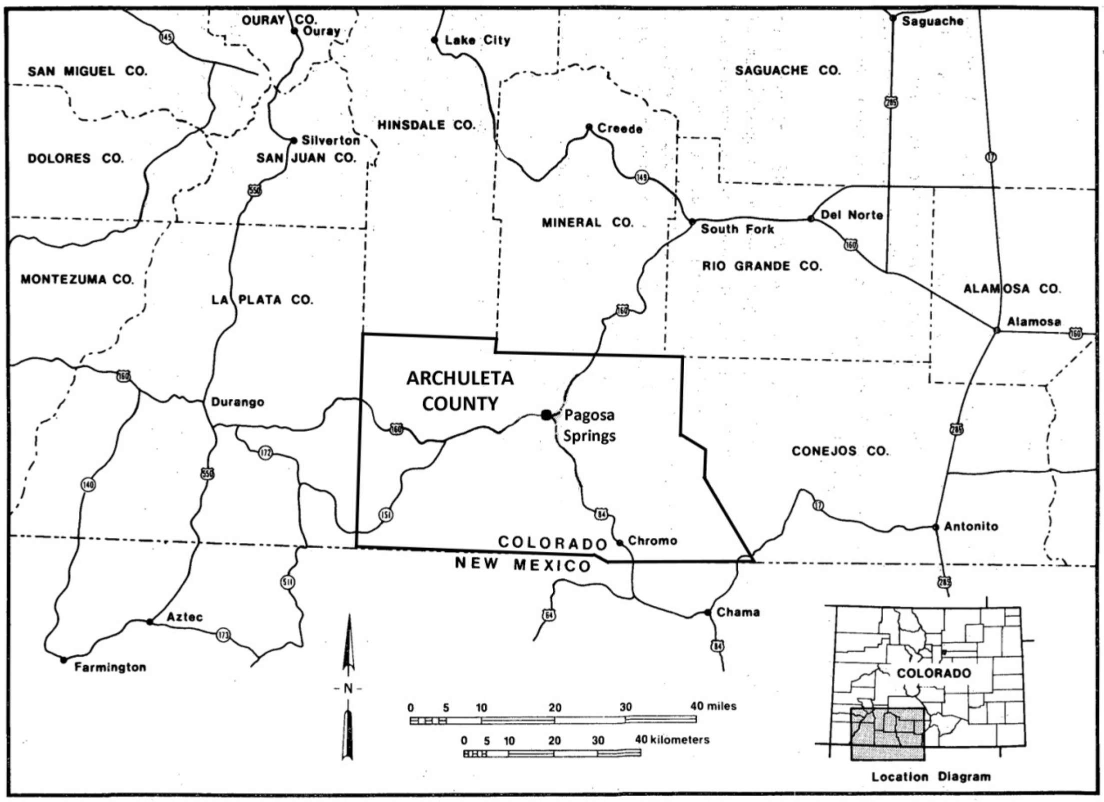


Figure 1: Location map for Archuleta County (modified from Galloway, 1980).

The largest thermal spring in the county is Big Spring in Pagosa Springs: The area around this spring has been the subject of several studies, including a study for the drilling of a well to supply a district heating system for the town (Galloway, 1980), and three geophysics summer field camps (Field Camp, 2012, 2013, 2016). Two geophysics field camps studied the Chromo area toward the southeast end of the trend of thermal springs (Field Camp, 2014, 2015). Goff and Tully (1994) made a thorough geothermal assessment of the main aquifers in the county associated with thermal springs.

In late 2014 and 2015 new temperature gradient wells were drilled under the leadership of Pagosa Verde, LLC (Mink et al., 2015). Temperature gradient data from these wells, combined with the data reported in Galloway (1980), and a few new measurements by the Colorado Geological Survey provide critical constraints in understanding the geothermal systems in

Archuleta County. I review these data here and present my current understanding of the geothermal systems in the county.

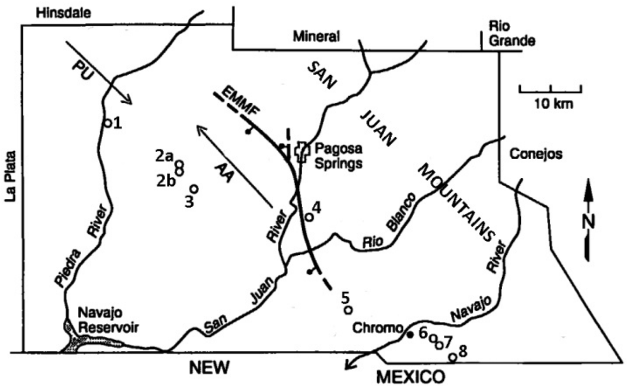


Figure 2: Map of Archuleta County showing locations of major thermal springs and wells, and structural features. EMMF = Eight Mile Mesa Fault; AA = Archuleta Anticlinorium (plunge NW; PU = Piedra Uplift anticlinorium (plunge SE). Key to wells and springs given in Table 2. (Modified from Goff and Tully, 1996).

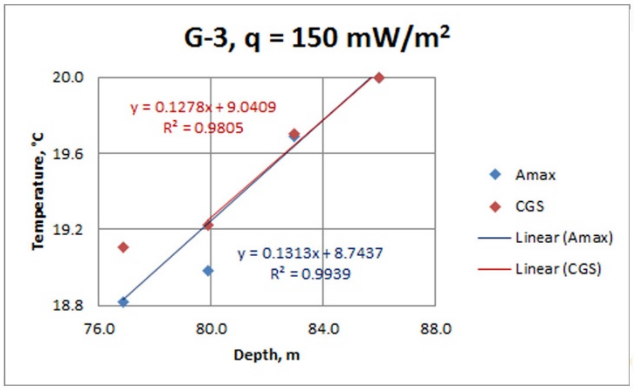
2. Geothermal Gradients, Heat Flow and Subsurface Temperatures Around Pagosa Springs

Galloway (1980) presented the first geothermal map of the Pagosa Springs area. This map includes isothermal contours of groundwater temperature in the center of town and heat-flow contours that extend approximately 1 km west, and 1.75 km NE and SE of the town center. The groundwater temperature contours indicate a closed thermal anomaly just south of the town center; the heat-flow contours indicate that the center of the anomaly is more than 1 km west of the town center and slightly south of the latitude of the town center, The heat-flow contours are based on very few, and widely-spaced data. These heat-flow data were based on temperatures measured in shallow drillholes by both Amax Inc. and the Colorado Geological Survey. Thermal conductivities were estimated. An example of the data is given in Figure 3, and the data are summarized in Table 1. Although the quality of the data is low, the variations in heat flow among the sites, and the consistency in these variations, gives confidence that the data are mapping a real shallow thermal anomaly, as will be demonstrated below.

Table 1. Summary of heat-flow data derived from Galloway (1980, Table 6, p. 22) from shallow drillholes around Pagosa Springs. Thermal conductivities used to calculate heat flow in original publication were estimated by Arthur L. Lange of Amax Inc. Mean thermal conductivities given here were back-calculated from mean geothermal gradients and heat-flow values.

Hole #	[1]Depth Range, m	Geothermal gradient, ^{o}C/km			Formation	Mean Thermal Conductivity, W/(m K)	Heat Flow, mW/m^2
		Amax	CGS	Mean			
G-1	38.9-45.0	143	145	144	Dakota	1.38	199
G-2	74.9-87.0	125	123	124	Mancos	1.41	174
G-3	76.9-86.0	128	131	129.5	Dakota?	1.16	150
G-4	74.9-84.0	110	95	103	Dakota?	1.21	124
G-5	85.0-88.0	83	83	83	Mancos	1.53	127
G-6	80.9-87.0	69	65	67	Mancos	1.34	90

[1] Depth ranges were back-calculated from total depths (m) and number of gradient intervals given in Galloway (1980), assuming that each gradient interval spans 3 m (10 feet).



z, m	Amax Grad	T, °C	CGS Grad	T, °C
74.9	110.7	19.0	99.8	19.1
77.9	66	19.3	59	19.4
81.0	153.8	19.5	128	19.6
84		20		20

			K
Amax gradient	110.1	Mancos	1.13
CGS gradient	95.3		1.30
	102.7		1.21

Figure 3: Example of reconstructed temperature-depth data for site G-3 from Galloway (1980). Left graph shows temperature-depth plot with Amax Inc (blue), and Colorado Geological Survey (CGS, red) data. Right table gives Amax and CGS gradient data with reconstructed depths and temperatures. Lower table gives temperature gradients derived from plots and back-calculated thermal conductivities with means of Amax and CGS values in black.

When Galloway contoured these heat-flow data (Galloway, 1980, Plate 2) he omitted two data that could have constrained the contours, the two deeper wells in the town center that were primary focus of his study, O-2 and P-1. The temperatures in both of these wells start to overturn at a depth of about 34 m (110 feet), but linear geothermal gradients may be determined above these depths. These gradients are higher than the gradient in the drillhole to the west, G-1, 790 and 520°C/km versus 144°C/km. One might argue that the P-1 and O-2 gradients are shallow high anomalies over a convective warm-water plume. However, other nearby high geothermal gradients have a similar origin, and contouring the shallow O-2 and P-1 gradients into the same shallow heat-flow map is logical. Thus, rather than leave the heat-flow contours open to the west, the heat-flow contours are probably closed around the Big Spring in the town center.

In 2013 and 2014 Pagosa Verde, LLC, primarily with funding from the Department of Energy Geothermal Technology Office and the Colorado Energy/Mineral impact Assistance Fund, drilled three additional deep (~450 m) and one shallow (~100 m) geothermal gradient exploration holes in the vicinity of Pagosa Springs (Figure 4). The background to the philosophy and preliminary results from these holes was reported by Mink et al. (2015a, b). Final temperature data from these holes, and temperature data from the deep temperature wells P-1 and O-2 from the Galloway (1980) are shown in Figure 5. One of the new, deep, temperature gradient holes, TG-1, is close to one of Galloway's (1980) shallow heat-flow holes, G-2, and the geothermal gradients from the two holes are similar. This comparison supports the validity of the data from Galloway's (1980) shallow heat-flow holes. Geothermal gradients from the other two new, deep, temperature gradient holes are relatively low, indicating that the heat-flow anomaly is closed to the south. The new, shallow, temperature gradient hole has an anomalously low gradient of 30°C/km over the bottom 12 m (40 feet) of the hole, but it has an anomalously deep (~60 m) apparent penetration of the annual wave (Figure 5), indicating that the hole is not in conductive equilibrium. As this hole has a much lower thermal gradient than the holes to the east and west, it is not considered suitable for inclusion in heat-flow or gradient contouring until the cause of its anomalous temperature profile is resolved.

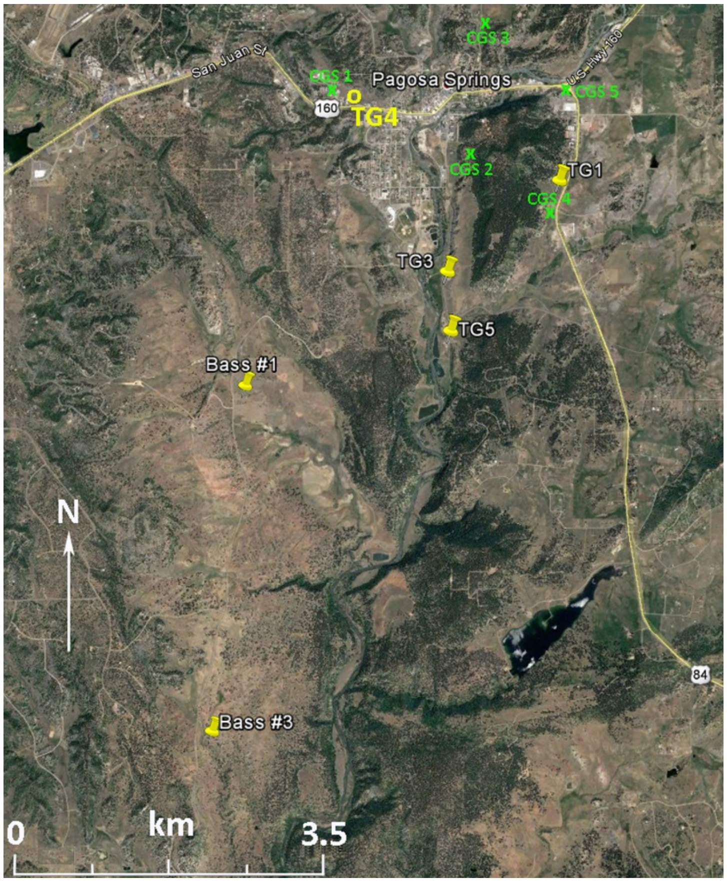


Figure 4: Google image of central Archuleta County showing locations of Pagosa Verde temperature gradient sites (TG1, TG3, TG4, and TG5), Galloway (1980) heat-flow sites (G-1 to G-5), and shallow Bass Well sites (Bass #1 and #3).

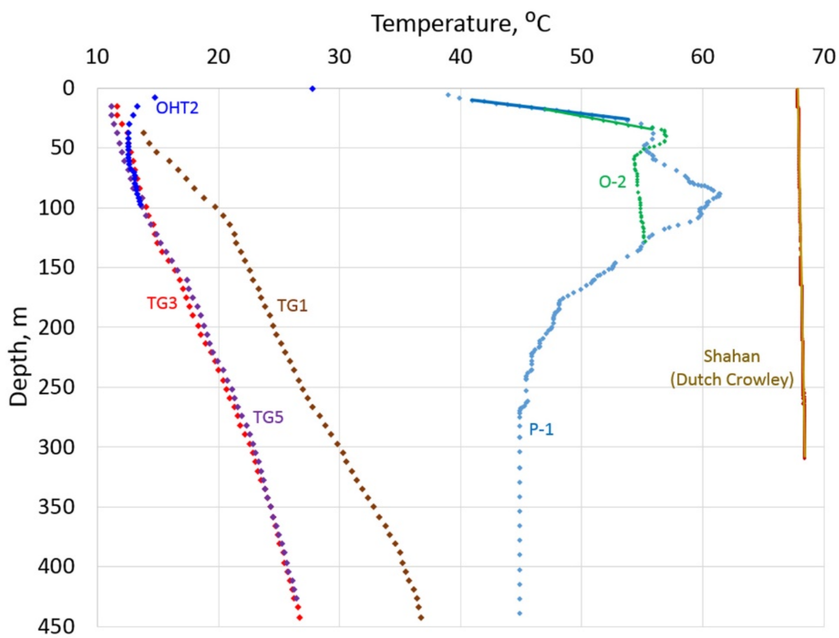


Figure 5: Temperature-depth plots for the deep wells discussed in text in Archuleta County. See text for explanation.

3. Regional Geothermal Exploration and Geothermometry in Archuleta County

Galloway (1980) presented an inventory of thermal springs and wells, and their chemistry, including stable isotopes, in the Pagosa Springs area. This work was expanded to Archuleta County by Goff and Tully (1994). Temperatures and silica and ionic geothermometry results from the main thermal springs in Archuleta County are listed in Table 2, with locations keyed to Figure 2. Results from the geothermometry are unimpressive indicating that either the thermal waters do not originate from hot reservoirs (probably less than 100°C, almost certainly less than 150°C), and/or there is major mixing and dilution of the thermal waters with shallow, cold waters before sampling. Goff and Tully (1994) reached similar conclusions based on a more extensive study of the chemical and isotopic data from the thermal waters in the county.

The Colorado School of Mines (Mines) Geophysics Department held their summer geophysical field camp in the vicinity of Pagosa Springs in 2012, 2013, and 2016, and in the area around Chromo in southern Archuleta County in 2014 and 2015. In 2012 and 2013 they were joined by students from Imperial College, London, UK. Reports of their data collection and interpretations are on line at Field Camp (2012, 2013, 2014, 2015, and 2016). They mapped many structures in the subsurface using geophysical exploration techniques. Interpretations focused on geothermal features. New faults and other structures were interpreted from their data, and these structures were hypothesized to be controls for geothermal fluids in the Pagosa Springs area. However, there is no direct evidence that any of the postulated faults or other structures provide conduits, or have any other control on geothermal fluids in the immediate area of the town. One of the deep, temperature gradient wells (TG-3) drilled by Pagosa Verde was located to intercept one of the Mines faults but did not have an elevated gradient or intercept hot water. In addition, there is no evidence from the heat-flow map of Galloway (1980), and its subsequent modifications from new data, that indicates fault control of the local geothermal system.

4. Minor Contributions from New Subsurface Temperature Data

I have been able to make three small additions to the direct subsurface temperature data. The first contribution is a partial temperature log of the Dutch Crowley well, well # 8 on Figure 2. This well was drilled as an oil test to 530.7 m (1741 feet) and reached Precambrian basement quartzite at 527.9 m (1732 feet). The well started producing water to the surface under artesian pressure upon completion and has continued to flow steadily at a temperature of about 70°C for several decades. I made a temperature log in this well using a portable hand winch and reached a depth of 306.9 m (~1007 feet) before I concluded that the well was open beyond the depth capabilities on my winch and that I should find a winch with greater depth capabilities to log the well to total depth. The temperature data in the log were noisy because of rapid water flow in the hole: smoothed temperature data are shown in Figure 5. There is a small, positive gradient in the hole of about 1.9°C/km which is approximately the adiabatic gradient for fresh water (Caldwell and Eide, 1980).

Temperature measurements were also made in two very shallow water wells south of Pagosa Springs, Bass Well # 1 (37.23606°N, 107.03603°W) and Bass Well #3 (37.20043°N, 107.03876°W). Temperature data from these wells are shown in Figure 6. In both wells there was an abrupt change in the temperature profiles at about 4.5 m which corresponded to the water table. Below about 9 m reasonably linear gradients were measured in both wells. A low gradient of 27°C/km was measured in Bass Well #1, a gradient thought to be representative of the regional background. The gradient in Bass well #3 was very high, however, 214°C/km. This hole was only 14 m in depth, but was about 25 m from a warm water seep, giving direct evidence of thermal water at shallow depth in the vicinity of the well. Unfortunately there are currently no other subsurface temperature data from the immediate area of Bass Well #3 from which to investigate this thermal anomaly.

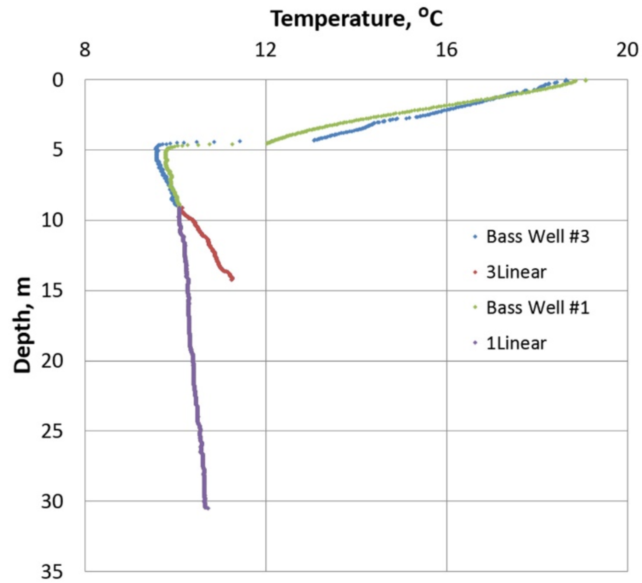


Figure 6: Temperature-depth plots for Bass Well #1 and Bass Well #3. Sections of plots with colors keyed "NLinear" were used to calculate temperature gradients. See text for explanation.

5. Pagosa Springs, a Spring Without Faults – How Common in Archuleta County?

Previous interpretations of the geothermal system at Pagosa Springs have concluded that hot water rises along fractures or faults from Precambrian basement, where it is heated by the regional geothermal gradient. Many faults have been mapped in Archuleta County and student geophysical studies have added more faults. Figure 7 shows my re-contouring of Galloway's (1980) heat-flow data with the addition of shallow temperature data from P-1, O-2, and the new wells TG-1, TG-3, and TG-5. The pattern of the re-contoured heat-flow map is approximately concentric circled, increasing in magnitude toward the center, and roughly centered on Big Spring. From the interpretation of the temperature data from P-I (Figure 5) by Galloway (1980), a reasonable interpretation is that the Dakota Formation (sandstone) acts as permeable aquifer for horizontal flow of hot water. The heat-flow pattern suggests that hot water rises through a pipe-like structure at Big Spring to the Dakota Formation in the depth range of about 72 to 133 m (237 to 435 feet) where it spreads laterally in all directions. The approximately circular pattern in the heat-flow contours indicate that there is no linear fault or fracture control of the flow in the Dakota Formation. The origin of the pipe-like structure that acts as a conduit for the hot water to rise to the Dakota Formation is not known. Whether this structure originated as a fault or fracture, or as an intersection of faults and/or fractures is one possible hypothesis, but no evidence of these speculated parent structures is apparent at the surface or in subsurface geophysical structures. Big Spring is a large thermal pool at the surface, approximately 8 m in diameter, with no visible bottom.

Pagosa Springs is the only area in Archuleta County with sufficient temperature-gradient/heat-flow values from which to make contour maps of these data associated with a thermal spring or well. Thus, whether the pipe-like structure that acts as a conduit to bring hot water to the surface at Big Spring is a common feature, or very rare, is currently unknown. Where wells have penetrated to basement, the wells mimic the behavior of Big Spring, but as the wells are cased, thermal waters cannot escape laterally into permeable aquifers at shallow depths to form circular thermal anomalies.

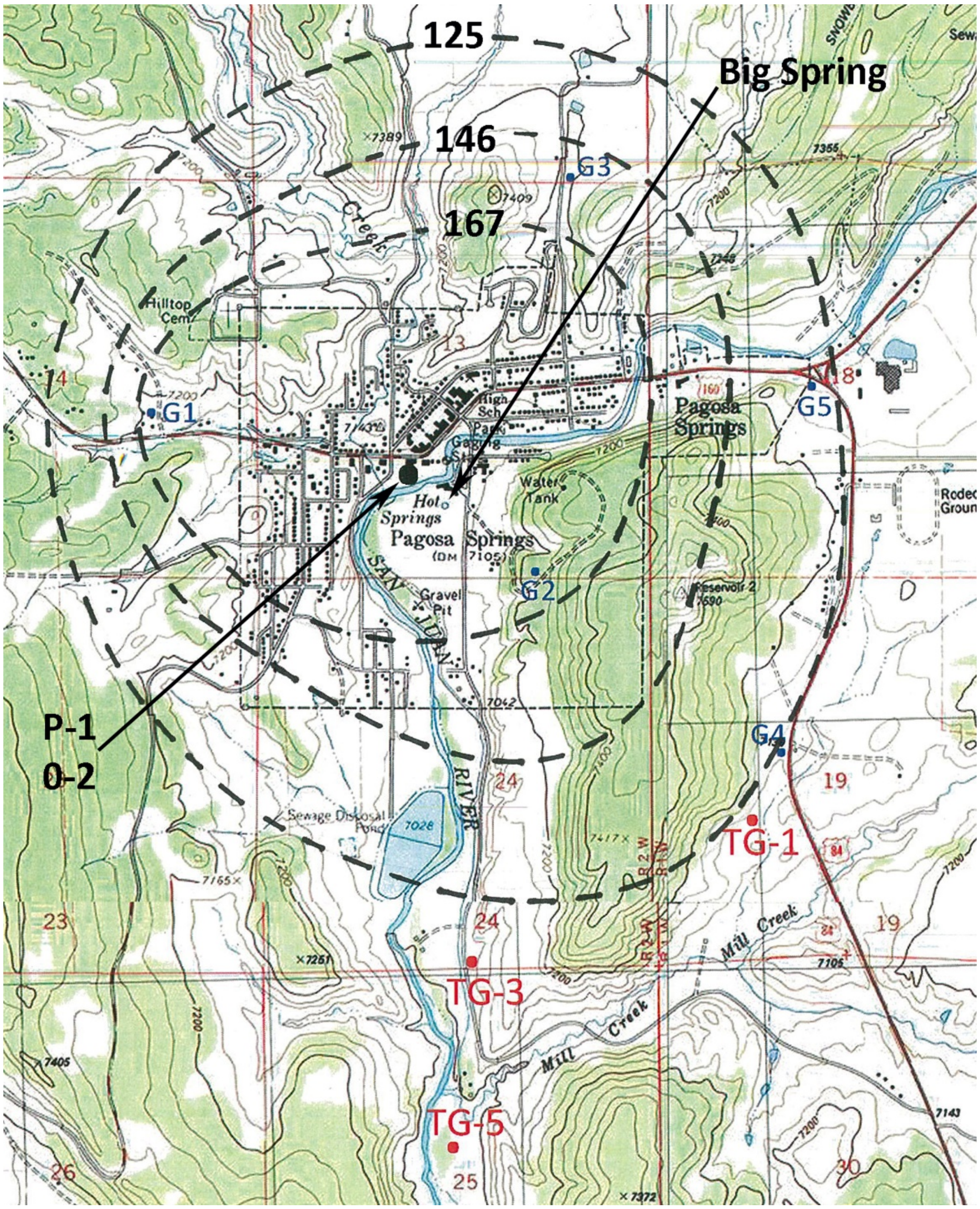


Figure 7: Revised heat-flow contours for the Pagosa Springs area. Heat flow contours are in mW/m^2. Locations of control points for contouring, G1-G5, TG-1, TG-3, TG-5, P-1, O-2, and Big Spring are shown. Topographic contours are in feet – contour interval 20 feet. Large grid pattern defines sections in the Township and Range land division system – each square is approximately 1.6 km (1 mile) on a side.

Faults may or may not be associated with the northwest to southeast trend of thermal springs and wells that cross Archuleta County parallel to the southwestern edge of the San Juan Mountains. The hydraulic gradient, created by topography and uneven precipitation drives groundwater from the mountains to the southwest through central Archuleta County. Basement structural highs (Hemborg, 1996), and/or anticlines (Goff and Tully, 1996) that are roughly parallel to the trend of thermal features roughly coincide with the general areas of the thermal springs and wells contribute to force deep circulating groundwater back toward the surface.

5. Concluding Remarks

Archuleta County, Colorado, has several of thermal springs and wells in a roughly linear northwest to southeast trend, roughly parallel to the to the southwestern edge of the San Juan Mountains. The maximum surface temperature of these features is ~70°C. Geothermometry calculations indicate that they probably rise from maximum reservoir temperature of ~100°C, with absolute maximum temperatures of 150°C. There is no evidence that there is a recent magmatic source of heat for these geothermal resources. Even a surface temperature of 70°C requires that the waters are heated by circulation into the Precambrian basement, probably driven by hydraulic gradients derived from the topography of the San Juan Mountains to the northeast.

A new heat-flow map has been contoured for the areas around Pagosa Springs that indicates a roughly circular anomaly centered on Big Spring in the center of town. This circular pattern indicates that hot water rises through a pipe-like structure at Big Spring and then spreads laterally in all directions in the Dakota Formation in the depth range of about 72 to 133 m. There is no evidence for shallow control of the flow by linear fault of fractures. The origin of the pipe-like conduit forming Big Spring is unknown. Whether similar structures exist elsewhere in Archuleta County is also currently not known.

Acknowledgements

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