Bottom-Hole Temperature Data from the Piceance Basin, Colorado: Indications for Prospective Sedimentary Basin EGS Resources

Paul Morgan and Brian Scott

Colorado Geological Survey, Denver CO, USA

Keywords

Exploration, Piceance Basin, Colorado, sedimentary basin, EGS, bottom-hole temperature, drilling-disturbance correction, limestone aquifer

ABSTRACT

In addition to relatively shallow geothermal resources associated with the structurally controlled deep circulation of groundwater, significant geothermal resources exist in Colorado's sedimentary basins. One basin previously unexplored for geothermal resources is the Piceance Basin, a Laramide-age structural basin, which includes a sedimentary rock foundation of Mississippian and older platform deposits and basin deposits of the broader Maroon trough that preceded the Piceance Basin. The modern Piceance drainage basin comprises four smaller drainage basins and is much smaller than the structural basin. A few thermal springs occur on the eastern margin of the structural basin, and high heat-flow values have been reported near the southeastern salient of the basin, but no significant geothermal manifestations occur in the basin.

Bottom-hole temperature (BHT) data have been compiled from 10,372 hydrocarbon wells in the Piceance basin with an average depth of 2103 ± 685 (± standard deviation) m. The data were combined in 0.4 by 0.4 degree blocks by their geographic coordinates and average geothermal gradients calculated for each block. These gradients ranged from 22.7 to 41.8°C/km. A correction for the effect of the circulation of drilling fluid on the BHTs was estimated from BHTs from second cement bond logs and fluid temperatures from drill stem tests. Block gradients calculated from corrected BHTs ranged from 27.3 to 51.5°C. km. A general increase in gradients from the north to the south of the basin was observed. No significant correlation was found between block geothermal gradient and well depth or well collar elevation, tentatively suggesting that neither basin-wide thinning of formations toward the basin margins nor basin-wide thermal convection by groundwater flow were the primary cause of the regional distribution of geothermal gradients. Increased gradients to the south correlate with Quaternary faulting in the Uncompahgre uplift to the southwest and Tertiary volcanism to the southeast.

Uncorrected BHTs indicate geothermal resources at temperatures of 100 to 250°C in the depth range of 2.5 to 5 km. Corrected BHTs reduce this range to 1.7 to 4.2 km. General permeability at these depths is likely to be low. The Leadville Limestone, a Mississippian karst-forming limestone is likely to underlie most of the basin, shallowing on the southwest margin of the basin. Observations of this limestone at other locations indicate that it is a very permeable aquifer. Production from similar fractured karst limestone aquifers in Germany has generated ≥3.0 MWe from single wells. Alternatively, impermeable strata could be hydrofractured to produce an enhanced/engineered geothermal system (EGS). An analogous sedimentary basin EGS project is currently in the early stages of development in the Raton basin of southern Colorado.

Introduction

The intra-mountain basins of Colorado have many hot springs in structures similar to hosts for producing geothermal fields in Nevada, such as Dixie Valley. Looking beyond these traditional resources, however, larger quantities of geothermal energy may be extracted from deep sedimentary basins, at a higher cost than from shallow hydrothermal resources, but significantly cheaper than from crystalline rock enhanced/engineered geothermal systems (EGS). One such basin is the Piceance Basin in northwest Colorado, a basin that may be evaluated from thousands of bottom-hole temperature (BHT) data collected during hydrocarbon operations in the basin.

The physiographic Piceance Basin is shown in Figure 1 and comprises four drainage basins, the Yellow Creek, the Piceance Creek, the Roan Creek, and the Parachute Creek Drainage Basins. The structural basin is significantly larger in area, as shown by a map of the generalized depth to the base of coal in the Upper Cretaceous Cameo Group in Figure 2. It is generally designated as a Laramide-age basin but occupies part of the Early Pennsylvanian Maroon Trough (Quigley, 1965). Before the Maroon Trough, the area was a marine seaway. Mississippian shelf and

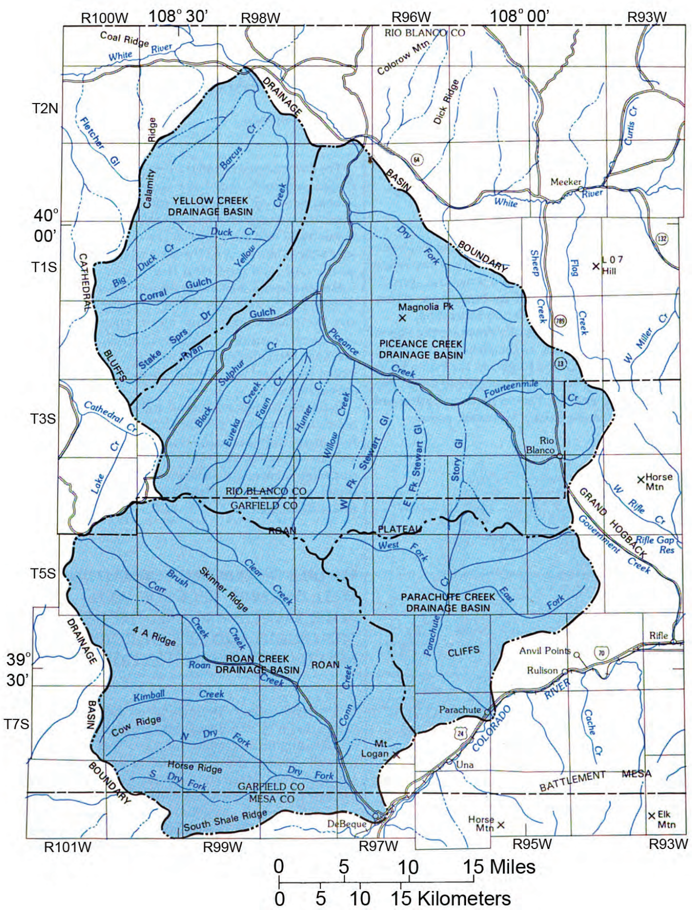

Figure 1. Piceance Drainage Basin showing component drainage basins. Modified from Taylor (1987, Figure 3).

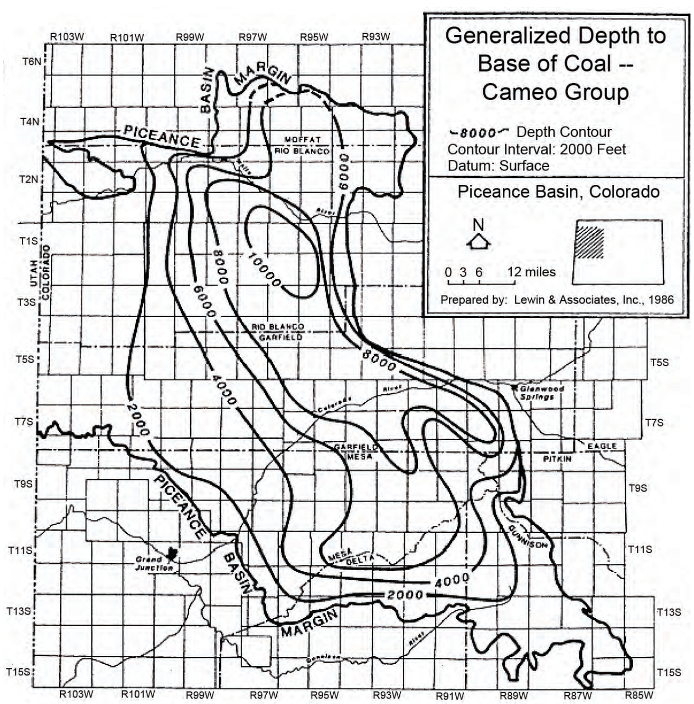

Figure 2. Piceance Basin – generalized depth to base of coal – Cameo Group. Modified from EPA (2004, Attachment 3, Figure A3-3).

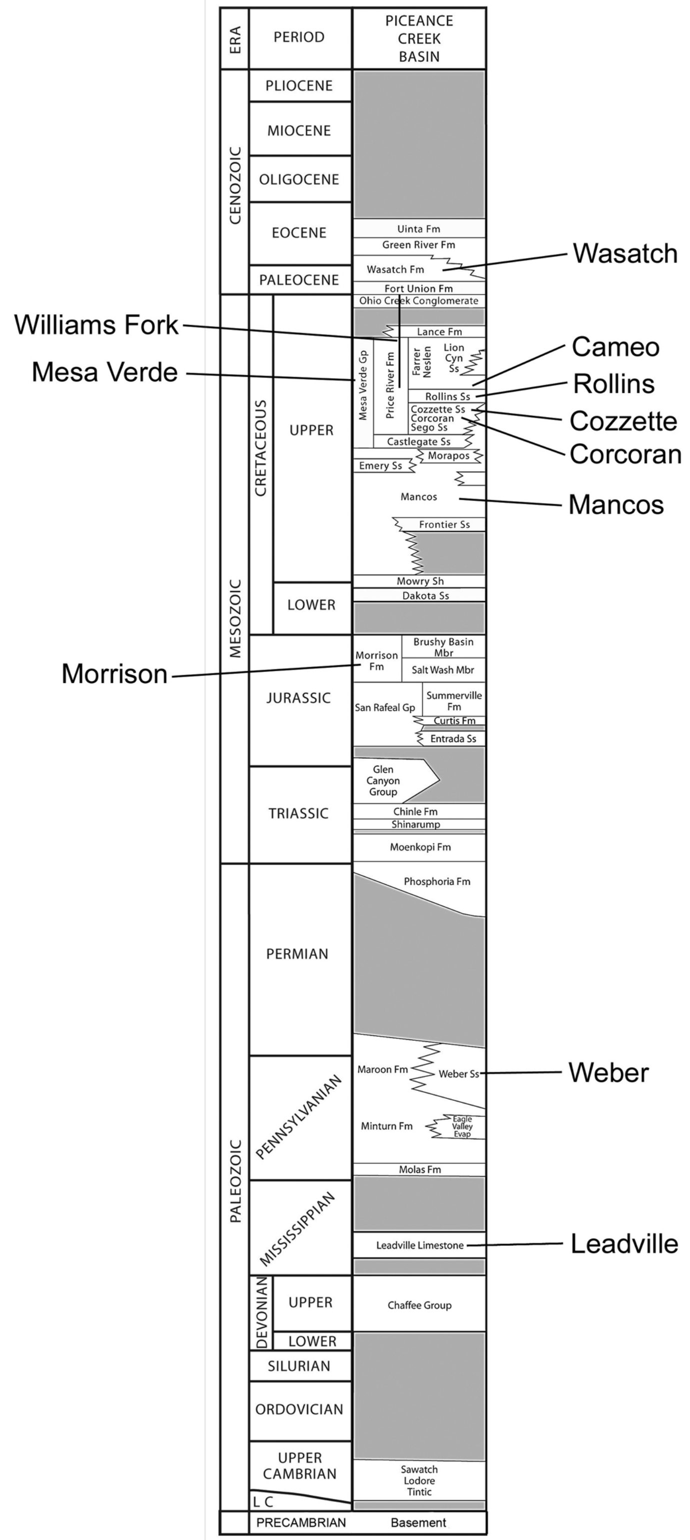

Figure 3. Generalized stratigraphic column for the Piceance basin. Modified from Colorado Geological Survey, unpublished.

platform limestone and dolomite of this seaway in northwestern Colorado range from zero to 210 m in thickness. These rocks are the local representative of the Leadville Limestone which has equivalents in the Four Corner states and Wyoming and are typically karst-forming limestones. Continued growth of the Ancestral Front Range and Ancestral Uncompahgre Uplift continued to act as sources for clastics, carbonates, and evaporites in the trough from Late Permian. A marine transgression in the Cretaceous resulted in renewed sedimentation and the basin became a shallow sea with lagoonal and swamp sediments. At the end of the Cretaceous the basin was folded and faulted during the Laramide orogeny forming the present tectonic Piceance Basin (Quigley, *op. cit*.). A generalized stratigraphic column for the Piceance basin is shown in Figure 3.

The eastern margin of the structural Piceance Basin is a few kilometers west of Glenwood Springs (Figure 2), the site of Yampa Hot Spring, the highest volume hot spring in Colorado (143 l/s, 2,263 gpm, 50°C; Barrett and Pearl, 1976). Another small group of hot springs, South Canyon Hot Springs, is approximately 11 km west of Glenwood Springs on the eastern margin of the Piceance Basin. These springs are similar in temperature to Yampa Hot Spring (48-49°C), but their combined flow is less than 1.6 l/s (25 gpm). However, there is only one reported warm spring and one hot artesian well within the margins of the structural Piceance Basin. Both are in the extreme southeast of the basin. The spring is Sylvester Gulch Warm Spring at the western end of Gunnison County (38° 54.80'N, 107° 26.37'W) with a temperature of 25°C (Cappa and Hemborg, 1995). The artesian well is the Colonel Chinn well at the eastern edge of Delta County (38° 50.37'N, 107° 38.05'W) with a temperature of 42°C (Barrett and Pearl, 1978). Barrett and Pearl (*op. cit.*) state that the depth of this well is reported to be 1371 m (4499 feet) and calculated a silica geothermometer mixing temperature for the water of 43°C. Cappa and Hemborg (*op. cit.*) give a depth of 20.0 m for the well, which seems more likely. Water rising from a temperature of 43°C at a depth of 1371 m would indicate a temperature gradient below the regional average. The close agreement between the surface temperature and the calculated, silica-mixing geotemperature for the well suggests that this water is heated by circulation of groundwater to a depth of about 1 km in the crust. One well is reported as "thermal" near the center of the Piceance drainage basin on the Roan Plateau (East Willow Creek; Cappa and Hemborg, 1995). However, it has a temperature of only 22°C and is not of significance to the deeper thermal structure of interest in this study.

Heat-flow measurements from three sites in the southeast salient of the Piceance Basin have been published (Reiter *et al*., 1975; Decker *et al*., 1988). Average values from these sites are all high: 100 (depth range 300-740 m), 129 (depth range 90-280 m), and 150 (depth range 200-1500 m) mW m^{-2}. They will be discussed further with the BHT data.

Although there are only geothermal manifestations associated with eastern margin of the Piceance Basin, there are two factors that suggest geothermal resources may exist at depth: 1) the basin is in excess of 3 km in depth and a linear fit to all the BHT data from the basin yields a temperature gradient of 33.6°C/km with an intercept temperature of 11.8°C: this fit projects a temperature of 112.6°C (235°F) at 3 km and 134.4°C (274°F) at 4 km; 2) The Leadville Limestone is a formation underlying the basin and is likely to have very high fracture and karst permeability. Thus, there is a good probability of finding moderately high temperatures and high permeability at depth in the Basin.

Bottom-Hole Temperature Data from the Piceance Basin

Bottom-hole temperature (BHT) data have been compiled from 10,372 oil and gas wells in the Piceance Basin with a depth range from 125 m to 5415 m and an average depth of 2103 ± 685 (± standard deviation) m. These data were compiled using LogSleuth© to read log headers and Petra© and the Colorado Oil and Gas Conservation Commission web site (URL: http://cogcc.state.co.us/, last accessed 2011-5-11) to compile other well information. Depths from Petra© were checked with depths recorded on log headers and small disagreements were common but sometimes disagreements were as large as hundreds or even thousands of feet. "Logger" depths from log headers were taken to indicate the depth of all measurements. Where possible, BHT values were read from induction logs. When induction logs were not available other electrical logs were used as a first alternative. If no electrical log were available the BHT was read from any other available log. Multiple logging runs were available for many wells, but the same BHT or maximum temperature was recorded on all logging runs indicating that the BHT was measured only once. There was no indication from repeated BHTs or linear arrays of BHTs that a proxy for BHT measurements was used and all BHT data are believed to be records of actual measurements, with the exception of repeating the first measurement on multiple logging runs in the same well. The complete BHT data set are plotted as a function of depth in Figure 4. There are significant changes in geothermal gradient with depth with low gradients at shallow and deep depths and high gradients in middle depth ranges. The higher gradients are probably associated with low thermal conductivities in Upper Cretaceous shales, particularly in the Mancos Formation. Table 1 lists average geothermal gradients from the surface for wells terminating in different units: the only unit that has a gradient that is statistically significant is the Lower Permian/Upper Pennsylvanian Weber unit. This unit has a greater thickness of Upper Paleozoic sedimentary rocks than all

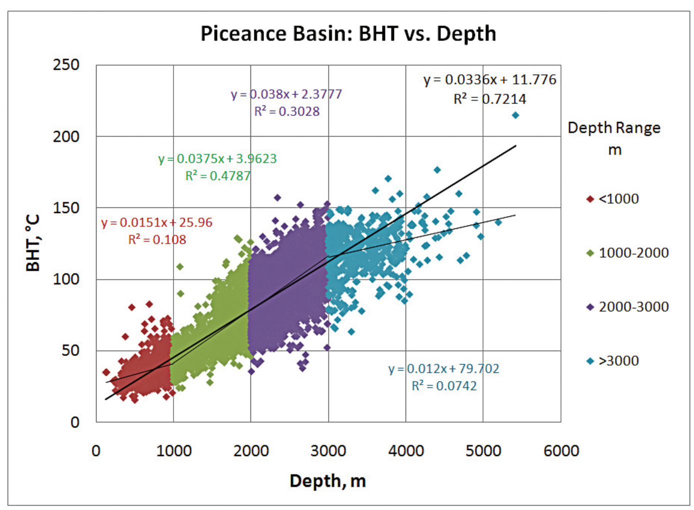

Figure 4. Plot of uncorrected bottom-hole temperature values versus depth. Above 3000 m data are divided by depth intervals of 1000 m (size of plotting symbols causes overlap of groups). Trendline fits are given for each group and parameters of fit are given with color keys to data group color. Trendline fit for complete dataset is given in black.

other units in the table. These rocks have a higher proportion of high-thermal-conductivity limestone, dolomite and evaporites than shallower formations. The drop in thermal gradient is probably associated with a change in thermal conductivity.

Table 1. Depth, BHT and geothermal gradient data for different units.

Stratigraphic Age	Name	Average Depth, m	Average Temperature, °C	Geothermal Gradient °C/km	n
Paleocene/Eocene	WASATCH	917 ± 471	44 ± 15	39 ± 15	181
Upper Cretaceous	WILLIAMS FORK	2183 ± 549	89 ± 24	36 ± 12	664
Upper Cretaceous	MESA VERDE	1756 ± 772	65 ± 25	33 ± 11	238
Upper Cretaceous	CAMEO	2320 ± 432	93 ± 19	35 ± 6	477
Upper Cretaceous	ROLLINS	2367 ± 401	99 ± 19	37 ± 6	4605
Upper Cretaceous	COZZETTE	2139 ± 568	89 ± 23	38 ± 7	68
Upper Cretaceous	CORCORAN	2287 ± 745	88 ± 24	35 ± 6	956
Upper Cretaceous	MANCOS	1353 ± 589	55 ± 25	34 ± 8	563
Upper Jurassic	MORRISON	1622 ± 642	63 ± 20	34 ± 7	255
Lower Permian/Upper Pennsylvanian	WEBER	1985 ± 213	64 ± 9	26 ± 3	464

Circulation of drilling fluid causes a transient temperature disturbances in wells that do not dissipate before BHTs are measured on normal logging runs as these are typically run within a few hours to a couple of days after the cessation of circulation of the drilling fluid. BHT data recorded on well-log headers are almost always lower than the undisturbed, or "virgin rock temperature" (VRT). The transient temperature disturbance caused by the circulation of drilling fluid is commonly called the *drilling disturbance*. Algorithms to correct for the drilling disturbance go back to at least Bullard (1939). Hermanrud et al. (1990) made a study of the biases and errors of 22 different correction methods for the drilling disturbance. A more recent comparison of correction methods was given by Beardsmore and Cull (2001, p. 59-67). Most correction algorithms for individual wells require a series of BHTs at the same depth measured at different times, and/or a detailed record of drilling circulation times and temperatures. Alternatively, approximate basin-wide corrections may be calculated if subsurface temperatures that are not perturbed by the drilling disturbance are available. Temperature data from drill-stem tests (DST data) are often taken to be a close approximation to the VRTs. DSTs pull fluid from a formation under test which is generally assumed to be outside the region of thermal (and fluid) disturbance by drilling). In some wells, a second cement-bond log (CBL) is run days, weeks, or months (rare) after normal logging operations and a BHT may be measured on this log. These second cement bond log temperatures may also be a close approximations to the VRTs. In this study, data from DSTs and CBLs will be referred to as *proxy VRTs*. Examples of calculations of basin-wide corrections were given by Harrison et al. (1983), and Blackwell and Richards (2004). In the geothermal industry, the method to determine equilibrium temperatures (VRTs) is to log a well for temperature 60 to 90 days after being static. Hydrocarbon wells do not remain static for that length of time – they are generally either put into production or plugged and abandoned shortly after completion.

For the Piceance Basin, limited DST and second cement bond log (CBL) temperature data are available, and these are plotted together with normal BHT data from the same wells in Figure 5. The wells sampled by these two data sets overlap geographically but cover different areas and have different average mean temperatures and average thermal gradients. Both data sets show that the BHTs are cooler than the proxy VRTs, but do not indicate a common correction. When the averages from each data set are examined, however, there is remarkable agreement in the

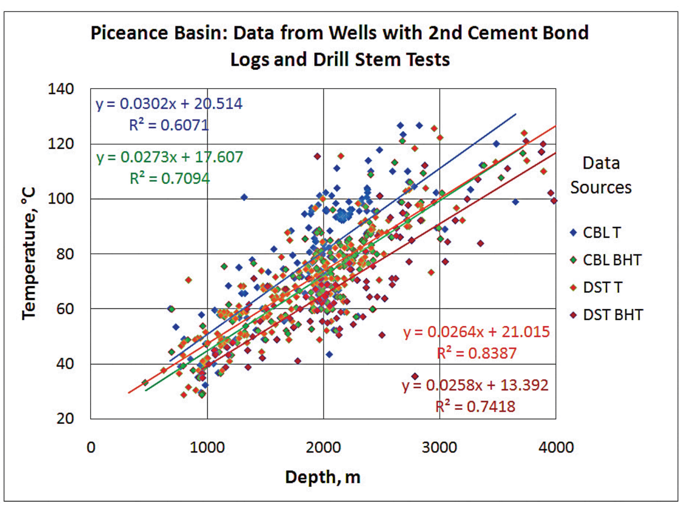

Figure 5. Temperature data from wells with second cement bond logs and drill stem tests (see text for details). CBLT are BHT data from 2nd cement bond logs; CBL BHTs are regular BHT data from wells with 2nd cement bond logs. DST Ts are fluid temperature data from drill stem tests; DST BHTs are temperature data from wells with drill stem tests. Trendline fits are given for each group and parameters of fit are given with color keys to data group color.

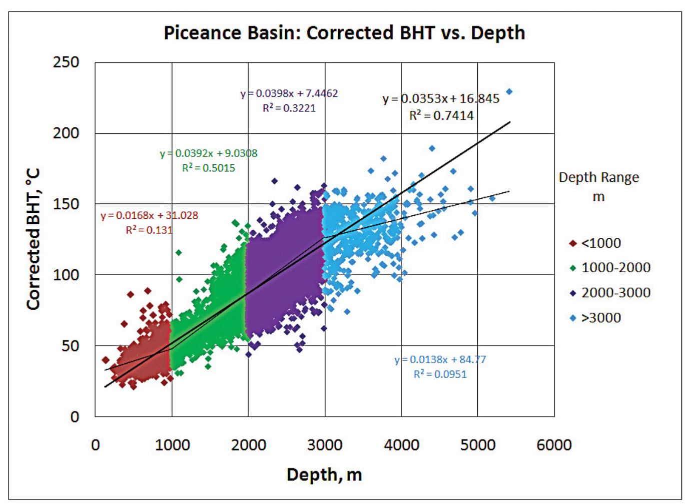

Figure 6. Plot of corrected bottom-hole temperature values versus depth. Above 3000 m data are divided by depth intervals of 1000 m (size of plotting symbols causes overlap of groups). Trendline fits are given for each group and parameters of fit are given with color keys to data group color. Trendline fit for complete dataset is given in black.

disturbances indicated by the two data sets. For each data set the average temperatures and depths were calculated and then the temperatures were corrected to 2000 m using the temperature gradients calculated from the linear fits to the data shown in Figure 5.

The difference was then calculated between the proxy VRTs at 2000 m and the normal BHT temperatures at 2000 m. For both the CBL and the DST data sets this difference was calculated to be 8.7°C. This agreement is perhaps fortuitous, but the magnitude of the correction is consistent with the BHT corrections for other basins (*e.g.*, Harrison *et al.*, 1983, Blackwell and Richards, 2004). A BHT correction has therefore been calculated from the average of the differences of the pairs of the CBL and DST lines, and this correction is:

$$T_{corr} = 0.00175z + 5.0685\ °C \qquad (1)$$

where T_{corr} is the correction in °C, and z is depth in meters. As a rough check on this crude estimate of the correction, the calculated correction at 2000 m is 8.6°C. All values calculated using this correction are indicated as "corrected" values below. Corrected BHTs are plotted as a function of depth in Figure 6.

Willett and Chapman (1987) calculated a drilling disturbance correction for the adjacent basin to the west in Utah, the Uinta Basin. In its simplest form their correction may be described by the equation:

$$T_{corr}=6.93Z-1.67Z^2+0.101Z^3+0.0026Z^4 \qquad (2)$$

Where Z is depth in km. This correction is 0.6°C lower than the correction calculated for the Piceance Basin at 2,000 m, but 5.1°C at the surface and 4.0°C at 4,000 m. These differences are considered to be within the errors of both corrections.

For calculation of temperature gradients, an estimate of the surface ground temperature is required. For this study surface air temperature data were compiled from the Western Regional Climate Center (URL: wrcc@dri.edu, last accessed 2011-5-11). Temperature data were collected from twenty one climate stations in and around the Piceance Basin and a linear fit was made to the temperature versus elevation data from these stations with the following result:

$$T_{sa} = 20.085 - 0.007027e\ °C \qquad (3)$$

where T_{sa} is the surface air temperature in °C and e is elevation in m. The goodness of fit parameter (R^2) for this fit was 0.8. The data were also analyzed in terms of a dependence on latitude and/or longitude, but no significant correlation with these parameters was found. Previous studies have found that, on average, surface ground temperature are 3°C higher than surface air temperature, and therefore the following formula was used to calculate surface temperatures for each well:

$$T_s = 23.085 - 0.007027e\ °C \qquad (4)$$

where T_s is the surface ground temperature in °C.

Geothermal gradients were estimated by two methods. The first method used trendline fits to plots of temperature vs. depth using Microsoft Excel®: gradients calculated by this method are given in Figures 4, 5 and 6. The second method calculated gradients for individual wells as:

$$\partial T/\partial z = (T - T_s)/z \qquad (5)$$

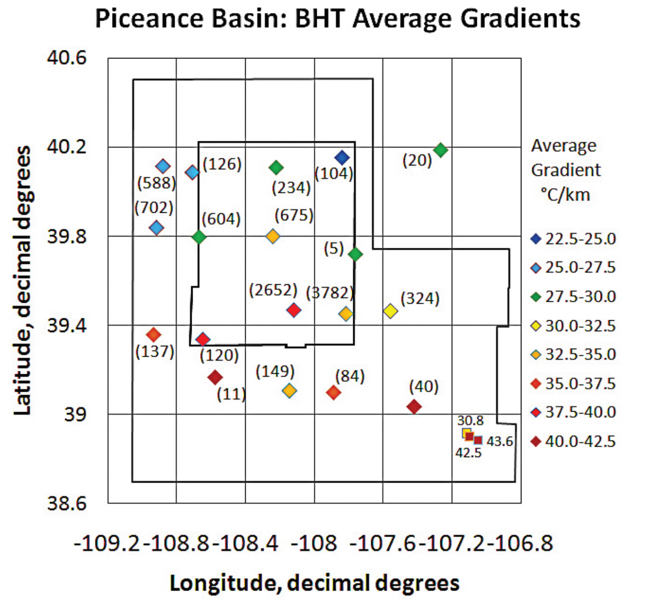

Figure 7. Plot showing locations of 0.4 by 0.4 degree block averages of BHT geothermal gradients. Symbols are plotted at the geographic average coordinate of each block data set. Symbol color indicates gradient magnitude. Numbers in parentheses indicates the number of wells in each block. Square symbols in lower right are gradients calculated from heat-flow data (see text). Inner polygon is the outline of boundary of Figure 1. Outer polygon is the outline of the boundary of Figure 2.

where $\partial T/\partial z$ is the geothermal gradient and T is temperature at depth z: gradients calculated by this method are displayed in Figure 7. With z in km, the units for geothermal gradient are °C/km.

The BHT data are impossible to display individually on a small map. They have been averaged in 0.4 by 0.4 degree blocks and plotted at their average geographic coordinate location in Figure 7. The number of data in each block is indicated in parentheses by

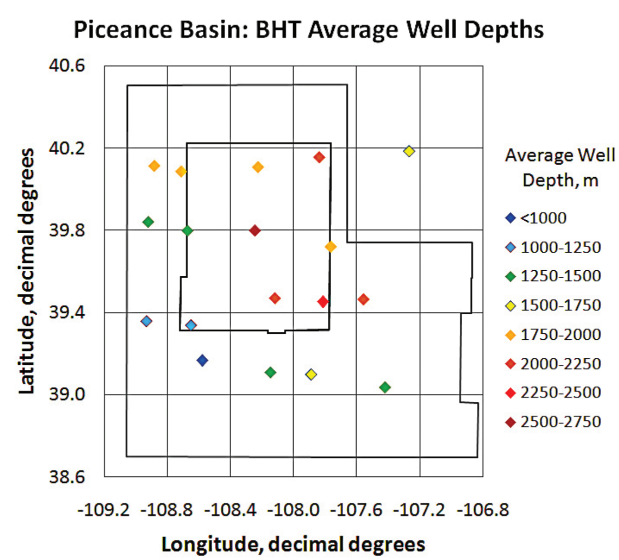

Figure 8. Plot showing locations of 0.4 by 0.4 degree block averages of BHT well depths. Symbols are plotted at the geographic average coordinate of each block data set. Symbol color indicates range of average well depth. Inner polygon is the outline of boundary of Figure 1. Outer polygon is the outline of the boundary of Figure 2.

the symbol that indicates the average geothermal gradient in each block. The outlines of the physiographic and structure Piceance Basins from Figures 1 and 2, respectively, are also shown on Figure 7. There is a clear trend of increasing gradients from north to south. Figure 8 is a plot of average well depths corresponding to Figure 7. Comparing Figures 7 and 8 suggests an imperfect inverse correlation between average geothermal gradient and average well depth. Lower geothermal gradients tend to be found where the basin is deeper, although a very well established uncorrected gradient of 39.2°C/km was calculated in the second most populated block (n = 2652) with an average depth of 2170 m. Uncorrected average block gradients ranged from 22.7 to 41.8°C/km; corrected average block gradients ranged from 27.3 to 51.5°C/km.

BHT geothermal gradient data have been supplemented in the southeastern salient of the structural basin by average geothermal gradients calculated from the published heat-flow values. For each site, the best heat-flow value was divided by the mid-point of the range of thermal conductivities given for the site to give a representative geothermal gradient. These geothermal gradients are plotted as square symbols with the average BHT geothermal gradients in Figure 7, using the same color key to indicate gradient magnitudes. The numerical values of calculated heat-flow geothermal gradients are given by the symbols. The heat flow gradients are consistent with the BHT gradients and give confidence to the BHT results as they were derived from detailed equilibrium temperature logs.

Interpretation of BHT Geothermal Gradient Results

An interpretive geothermal gradient map of Colorado, including the Piceance Basin, has been published by Berkman and Watterson (2010). This map was based on about 17,070 BHTs and 1,000 DSTs. The BHTs were corrected by first applying the corrections derived for the Anadarko basin in Oklahoma:

$$T_1 = -16.51213476+1.826842109\text{x}10^{-2}z-2.344936959\text{x}10^{-6}z^2 \qquad (6)$$

where T_1 is the temperature correction to be added to the BHT and z is depth in m. After this correction was applied, geothermal gradients were calculated using equation 5 above and the average basin gradient, *ABG*, of 31.89°C/km was calculated. A second correction to the BHTs was then calculated based on the work of Blackwell and Richards (2004):

$$T_2 = ((1.361609905ABG)-33.21973078) \qquad (7)$$

where T_2 is the second correction to be added to the BHT. These corrections are significantly different from the correction calculated for the Piceance Basin in this study and for the Uinta Basin to the west by Willett and Chapman (1987) in that they are negative at shallow depths and much larger at greater depths. Surface temperature values for the Colorado map were derived from the PRISM model data from Oregon State University (Daly and Gibson, 2006). This model was used to generate contours of mean annual air surface temperature for Colorado at intervals of 2ºF (1.1°C). The air surface temperature at each well site was then determined from these contours using GIS techniques and the geographical coordinates of each well. Three degrees Celsius was added to each calculated air temperature to give the ground surface temperature at each site to compensate for the difference between air and ground temperatures associated with radiative ground heating and other effects.

The interpretive geothermal gradient map is based on an order of magnitude fewer BHTs in the region of the Piceance Basin than the present study. It shows an average corrected geothermal gradient of about 40°C/km with a very large positive anomaly in the southeast. This is a one-point anomaly and was based on unpublished data from a coal mine (M. Sares, personal communication, 2011). The heat-flow data discussed above, while indicating a high geothermal gradient at this site, indicate that it is about 40% of the peak value shown on the interpretive gradient map (*N.B.* the heat-flow gradient is an equilibrium value, measured after the drilling disturbance has had time to dissipate, and does not need correction). In general, the interpretive geothermal gradient map with the exception of the anomalous high value in the southeast of the basin, has very few data in Mesa, Delta, western Pitkin, and western Gunnison Counties (*i.e*., in the Piceance Basin south of latitude 39.4°N), and does not show the general increase in geothermal gradient from the north to the south shown in the new analysis of the expanded BHT data set in Figure 7. While in general agreement in the northern Piceance Basin, the general scatter in the enlarged BHT data do not support the fine detail in contouring in the interpretive geothermal gradient map.

There is a weak inverse correlation between average geothermal gradient and average well depth (R^2 = 0.11), as shown in Figure 9. The large scatter in this plot strongly suggests that geothermal gradient is not controlled by changes in mean thermal conductivity associated with lithologic changes, for which well depth is a proxy. Assuming that the main production horizons are similar across the basin, average well depth is a function of the depths to the main production layers. If thinning of sedimentary rocks overlying the main production horizons as their depths change is partially by pinching out of some horizons, then the lithologic column above the main producing horizons would be expected to change. Changes in the lithologic column are likely to be accompanied by changes in the mean thermal conductivity

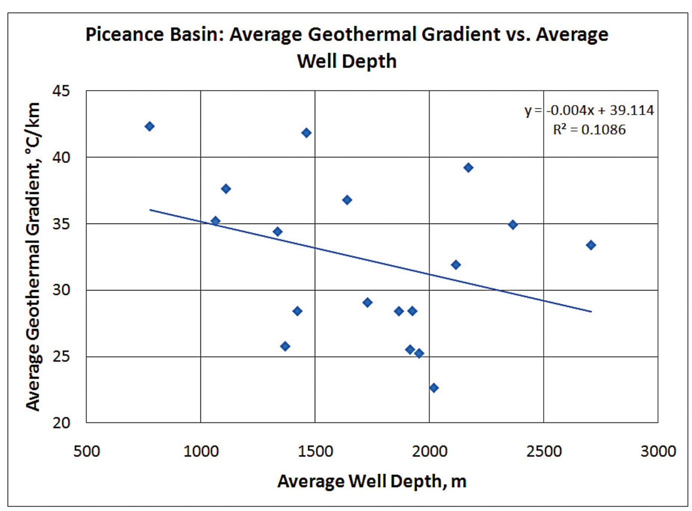

Figure 9. Plot of average BHT geothermal gradients calculated in 0.4 by 0.4 degree geographic blocks, as shown in Figure 7 versus average well depth, as shown in Figure 8. Trendline fit is shown with parameters of fit.

of the column resulting in changes in geothermal gradient even for uniform heat flow. However, as there is no simple relation between average geothermal gradient and average well depth, factors other than changes in mean thermal conductivity with depth may be assumed to dominate.

Heat is redistributed by groundwater flow in many sedimentary basins (*e.g.*, the Raton Basin, Colorado; Morgan, 2009). An indication that groundwater thermal convection may be occurring is that there is a general inverse correlation among geothermal gradients calculated for individual wells and the collar elevations for the wells. A more accurate indicator is to plot the elevation of the water table at each well, but well collar elevation is a useful proxy for water table elevation if the number of wells is large. A plot of geothermal gradients versus collar elevation for individual wells is shown in Figure 10. For the Piceance Basin the correlation is weak (R^2 = 0.16) but it is positive rather than negative. The plot of geothermal gradient versus well collar elevation does not indicate large-scale thermal convection driven by regional groundwater recharge.

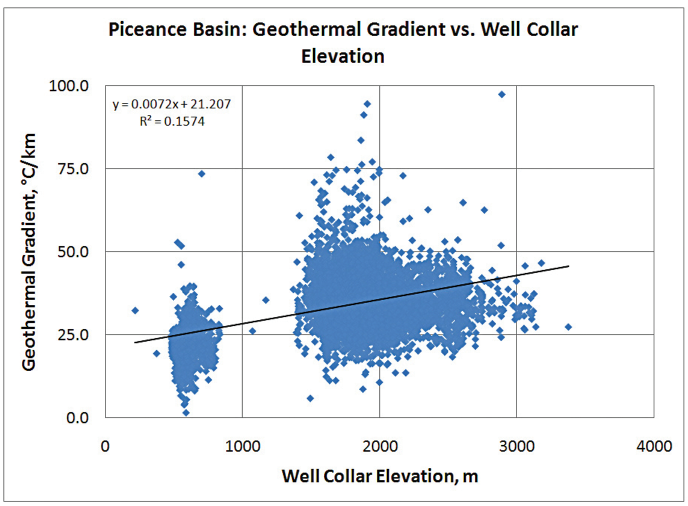

Figure 10. Plot of geothermal gradients calculated from uncorrected BHT data versus well collar elevation for individual wells. Trendline fit is shown with parameters of fit.

The general increase in geothermal gradient from north to south in the Piceance basin cannot be explained by a general lithologic change associated with well depth or with groundwater convection. The Upper Cretaceous depocenter of the basin is to the north (Figure 2). The depocenter is relatively narrow to the north, and locally higher geothermal gradients are where this depocenter is relatively deep north of latitude 39.4°N (Figure 7). However, south of latitude 39.4°N the higher geothermal gradients do not spatially correlate with the depocenter. High geothermal gradients from equilibrium heat flow measurements are in the southeast corner of the study area at the extreme edge of the depocenter and indicate that the high gradients are a regional anomaly, not a result of thermal refraction associated with basin structure.

A conspicuous source of the regional, high geothermal gradients at the southern end of the Piceance basin is not obvious. However, other geological features commonly associated with elevated heat flow are observed. A northwest trending system of late Tertiary and Quaternary faults follows the northeastern margin of the Uncompahgre Uplift on the southwest of the Basin, as shown in Figure 11. Basaltic lava flows are exposed approximately 40 km east-southeast of Grand Junction, also shown in Figure 11. The flows include Grand Mesa, a flat-topped mountain over 1,500 km^2 in area. The flows are approximately 10 Ma old. Individual flows range from about 60 to more than 180 m in thickness. Although basaltic lavas typically rise through the upper crust rapidly, transferring little heat, such a major series of flows indicates that there must have been a significant energy source in the upper mantle responsible for their generation. Heat dissipates from shallow igneous intrusions in a much shorter time interval than 10 Ma, but a heat source at lower crustal or upper mantle depths could still have an effect at the surface after 10 Ma. Thus the very young faulting and Miocene volcanism support the hypothesis of a deep origin for the elevated geothermal gradients in the southern Piceance basin. High gradients, modified as appropriate by thermal conductivity changes with lithology, may be expected to continue beneath the measured BHT depths.

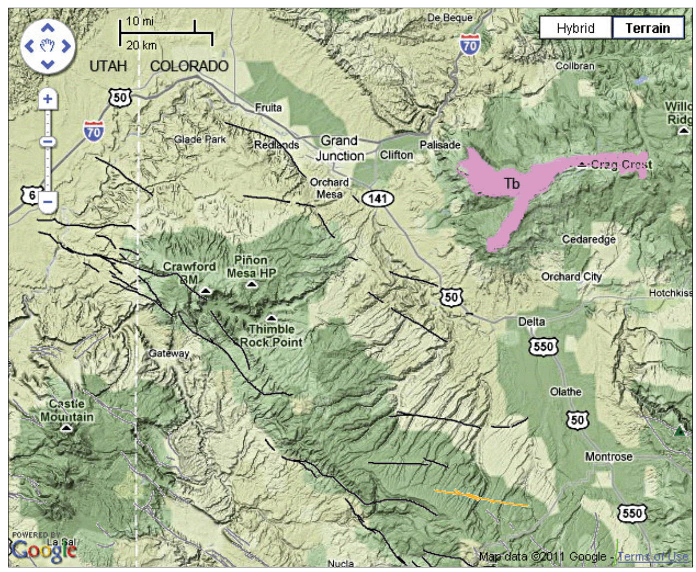

Figure 11. Map showing locations of Quaternary faults and approximate remains of Tertiary lava flows at southern end of Piceance Basin. For reference, coordinates of center of Grand Junction are 39.077°N, 108.554°W. Faults are shown by black and orange lines. Remains of lava flows are shown in pink (Tb). Base map and faults taken from USGS (2010). Tertiary volcanic rocks added by hand from Colorado Geological Survey public handout, "Generalized Geology of Colorado' (2008).

Geothermal Resources in the Piceance Basin

The concept of tapping low-temperature (≤ 150°C) geothermal resources in sedimentary basins has been suggested previously (*e.g.*, Erdlac and Swift, 2004; Alkhasov and Alkhasova, 2011), including tapping sedimentary basins in Colorado (*e.g.*, Morgan, 2009; Morgan *et al.*, 2010). Active projects are currently being pursued in Europe and Australia (*e.g.*, Bertani, 2005; Long *et al.*, 2011). The country with the greatest power production from low-temperature geothermal resources in sedimentary basins is Germany (Schellschmidt et al., 2010). The two most productive geothermal power plants in Germany tap naturally fractured, karst limestone aquifers, and each generate ≥3MWe. These two power plants generate power from geothermal systems at 150°C (Landau) and 122°C (Unterhaching). Thus, producing power from low-temperature geothermal resources is a viable proposition.

From the average uncorrected geothermal gradients of 30 to 40°C/km in the southern Piceance Basin (south of latitude 39.6°N) a temperature of 100°C is expected in a depth range of 2.5 to 3.3 km. A temperature of 150°C is predicted in an extrapolated depth range of 3.75 to 5.0 km. With the correction for the drilling disturbance, the range of average corrected geothermal gradients for the southern Piceance Basin is raised to 36 to 51.5°C/km: a temperature of 100°C is expected in a depth range of 1.96 to 2.78 km. A temperature of 150°C is predicted in an extrapolated depth range of 2.94 to 4.17 km. Many existing wells already penetrate these depth ranges. Uncorrected and corrected BHTs exceed 100°C: a few uncorrected BHTs exceed 150°C. A larger number of corrected BHTs exceed 150°C and a large number of corrected BHTs cluster just below 150°C (Figures 4 and 6). Sufficient temperature for geothermal resources is demonstrated to exist in the southern Piceance basin at depths currently penetrated by hydrocarbon wells. Gas wells in the Piceance Basin generally require hydrofracturing stimulation for production which indicates that at the depths that temperatures exist suitable for geothermal power production, permeability is likely to be low.

There are two options for producing high volumes of geothermal fluid from depth in the Piceance Basin, 1. find a naturally permeable aquifer or 2. stimulate permeability. The two ≥3 MWe geothermal power plants in Germany use natural permeability in a fractured limestone that has significant karst (cave) permeability. A shallow-water limestone was deposited across most of the Four Corner states and into Wyoming during the Mississippian period, and wherever this limestone is exposed today it is observed to have karst permeability. It has different names in different states: the Redwall Limestone in Arizona, the Redwall or Leadville Limestone in Utah, the Leadville Limestone in Colorado and northwestern New Mexico, and the Madison Limestone in Wyoming. Large caves are observed where the Redwall Limestone crops out as a steep cliff-forming formation in Arizona's Grand Canyon, but its cave-forming properties may be observed in the neighboring Colorado Plateau by depressions as the overlying strata have collapsed into voids in the buried Redwall to form sedimentary breccia pipes. From these indications of subsurface caves in the Redwall, we may assume that the Mississippian limestone is likely to have karst structure throughout the region. Regional structural contours on the top of the Mississippian by Casillas (2004, Figure 50), based on the modeling of gravity and seismic data, indicate that this surface shallows from a maximum depth of about 3,000 m below sea level in the Piceance Basin to about 300 m below sea level on the southwestern margin of the basin. These contours lack sufficient detail to make predictions concerning the depth of the Leadville limestone at specific locations relative to the geothermal gradients, but they indicate that the limestone is a reasonable drilling target as a geothermal aquifer.

Increasing permeability in sedimentary rocks by hydrofracturing is common practice in hydrocarbon production and is very common in Colorado gas production. Attempts to create artificial geothermal systems were first made in the 1970s at Fenton Hill New Mexico by hydrofracturing crystalline rock (Enhanced or Engineered Geothermal Systems, EGS, formerly known as Hot Dry Rock, HDR). Experiments have continued at other locations with limited success (e.g., Tester *et al*., 1976). The Raton Basin in south-central Colorado has an unusually high regional geothermal gradient and has temperatures in the sedimentary section of about 150°C at a depth of about 2.5 km. Proposals have been made to create an EGS system in this basin (Morgan, 2009; Macartney, 2010). A major advantage that this experiment would have over previous attempts is that the vast experience of the hydrocarbon industry in drilling and hydrofracturing in sedimentary rocks will be available for the experiment, in contrast to the limited experience of drilling and hydrofracturing in crystalline rocks that has been available for the other experiments. If the Raton basin experiment is a success, the technique could be extended to tapping geothermal resources in other sedimentary basins, including the Piceance Basin.

Concluding Remarks

New BHT data presented in this study demonstrate that temperatures sufficient for a geothermal resource are present at reasonable drillable depths in the southern Piceance Basin of Colorado. This result is apparent in the BHT data uncorrected for the effects of the effect of drilling fluid. Temperatures are likely to be higher than suggested by the uncorrected BHT data, and a correction based on drill stem test temperatures and second cement bond log BHTs indicates that gradients are about 20% higher when calculated with corrected BHTs.

Formations at depth in the Piceance Basin are likely to be generally low in permeability. However, the widespread Leadville Limestone is highly likely to have very high permeability through karst structures, locally increased by fracturing. Such natural permeability has provided aquifer conditions for successful geothermal systems in Germany where two power plants are generating ≥3.0 MWe each from single production wells with temperatures ≤ 150°C. The Leadville Limestone may provide similar aquifer conditions on the southwestern margin of the Piceance Basin. Alternatively, artificial permeability stimulated by hydrofracturing could provide sufficient permeability for enhanced geothermal systems in the Basin. An experiment to test this technology is currently in development in the Raton Basin in southern Colorado.

Acknowledgements

We thank Matt Sares, Vince Matthews, and the GRC reviewer, Dave Meade for an earlier version of this manuscript. Any errors, however, remain the responsibility of the authors.

References Cited

Alkhasov, A. B. and D. A. Alkhasova, 2011. "Harnessing the geothermal resources of sedimentary basins for electricity production." *Thermal Engineering*, v. 58, p. 153-161.

Barrett, J. K., and R. H. Pearl, 1976. "Hydrochemical Data of Thermal Springs and Wells in Colorado." Colorado Geological Survey, Denver, CO, *Information Series 6*, 124 pp.

Barrett, J. K., and R. H. Pearl, 1978. "An Appraisal of Colorado's Geothermal Resources." Colorado Geological Survey, Denver, CO, *Bulletin 39*, 224 pp.

Berkman F. E. and N. A. Watterson, 2010. "Interpretive Geothermal Map of Colorado." Colorado Geological Survey, Denver, CO, *URL:* http://geosurvey.state.co.us/energy/Geothermal/Pages/GradientMap.aspx, last accessed 2011-5-10.

Blackwell, D. D. and M. Richards, 2004. "Calibration of the AAPG geothermal survey of North America BHT data base." American Association of Petroleum Geologists Meeting, Dallas Texas, April 2004, Southern Methodist University Geothermal Lab Poster on BHT Calibration, *URL:* http://smu.edu/geothermal/BHT/BHT.htm, last accessed 2011-5-10.

Cappa, J. A. and H. T. Hemborg, 1995. "1992-1993 Low-Temperature Geothermal Assessment Program. "Colorado, Colorado Geological Survey, Denver, CO, *Open File Report 95-1*, 34 pp., 1 plate, 1 CD-ROM.

Casillas, H. A., 2004. "An Integrated Geophysical Study of the Uncompahgre Uplift, Colorado and Utah." University of Texas at El Paso, Dept. Geological Sciences, *M. S. Thesis*, 137 pp.

Daly, C., and W. Gibson, 2006. United States average monthly or annual minimum, maximum, and mean temperature, 1971-2000, http://www.climatesource.com/us/fact_sheets/meta_tmin_us_71b.html#7, last accessed 2011-06-08.

Decker, E. R., H. P. Heasler, K. L. Buelow, K. H. Baker and J. S. Hallin, 1988. "Significance of past and recent heat-flow and radioactivity studies in the Southern Rocky Mountain region." *Geol. Soc. Am. Bull.*, v.100, p.1851-1885.

EPA, 2004. "Evaluation of Impacts to Underground Sources of Drinking Water by Hydraulic Fracturing of Coalbed Methane Reservoirs Study (2004)." Environmental Protection Agency, Washington, D. C., Cover Documents, 7 chapters, 2 Appendices, Master References, 11 attachments, *URL:* http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/wells_coalbedmethanestudy.cfm, last accessed 2011-5-10.

Erdlac, R. J., and D. B. Swift, 2004. "Deep permeable strata geothermal energy (DPSGE): tapping giant heat reservoirs within deep sedimentary basins – an example from Permian Basin carbonate strata, Geothermal Resources Council." *Transactions*, v. 28, p. 327-331.

Harrison, W. E., M. L. Prater, and P. K. Cheung, 1983. "Geothermal resource assessment in Oklahoma." Oklahoma Geological Survey, Norman, OK, *Special Publication 83-1*, 42 pp., 3 plates.

Macartney, H. H., 2010. "An enhanced geothermal systems prospect in the Raton Basin of southern Colorado, USA." *Geol, Soc. Am., Abstracts with Programs*, v. 42(5), p. 379.

Morgan, P., 2009. "A preliminary analysis of geothermal resources in the central Raton Basin, Colorado, from bottom-hole temperature data." Geothermal Resources Council, *Transactions*, v. 33, p. 509-513.

Morgan, P., P. Barkmann, C. Kluth, and M. Sares, 2010. "Prospects for Electricity Generation in the San Luis Basin, Colorado, USA." Geothermal Resources Council, *Transactions*, v. 34, p. 615-620.

Quigley, M. D., 1965. "Geologic history of Piceance Creek-Eagle Basins." *Bull. Am. Assoc. Petrol. Geol.*, v. 49, p. 1974-1996.

Reiter, M., C. L. Edwards, H. Hartman and C. Weidman, 1975. "Terrestrial heat flow along the Rio Grande rift, New Mexico and southern Colorado." *Geol. Soc. Am. Bull.*, v. 86, p. 811-818.

Schellschmidt, R., B. Sanner, S. Pester and R. Schulz, 2010. "Geothermal energy in Germany." *Proceedings World Geothermal Congress, Bali Indonesia, 25-29 April 2010*, p. 1-15.

Taylor, O. J., 1987. "Oil shale, water resources, and valuable minerals of the Piceance Basin, Colorado: the challenges and choices of development." *U. S. Geological Survey, Prof. Pap.*, 1310, 15 pp.

Tester, J.W., B.J. Anderson, A.S. Batchelor, D.D. Blackwell, R. DiPippo, E.M. Drake, J. Garnish, B. Livesay, M.C. Moore, K. Nichols, S. Petty, M.N. Toksoz, R.W. Veatch, Jr., C. Augustine, R. Baria, E. Murphy, P. Negraru, M. Richards, 2006. "The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century." Massachusetts Institute of Technology, *DOE Contract DEAC07-05ID14517 Final Report*, 374 pp.

USGS, 2010. "Colorado Quaternary Faults." In cooperation with Colorado Geological Survey. Modified from *URL:* http://geohazards.usgs.gov/qfaults/co/Colorado.php, last modified 2010-4-12, last accessed 2011-5-10. Reproduced under restricted use of U.S. Government data with some commercial content.

Willett, S. D., and D. S. Chapman, 1987. Analysis of temperatures and thermal processes in the Uinta Basin. In Sedimentary Basins and Basin-Forming Mechanisms. C. Beaumont and A. J. Tankard, eds. *Canadian Journal Petroleum Geologists*, Mem. 12, p. 447-461.