Geothermal Gradients and Geothermal Opportunities in the Piceance Basin, Colorado

Paul Morgan, with an average depth of 2103 ± 685 (± standard deviation) m. For a preliminary statistical analysis, the data were combined in 0.4 by 0.4 degree blocks by their geographic coordinates and average geothermal gradients calculate

d for each block. Gradients ranged from 22.7 to 41.8°C/km. Block gradients corrected for the disturbance caused by drilling ranged from 27.3 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. Alterna

tively, impermeable strata could be hydrofractured to produce an enhanced/engineered geothermal system (EGS). In addition to power production, geothermal systems are being investigated in northern Alberta, Canada, as a source of thermal energy for *in situ* extraction of hydrocarbons from oil sands. The Piceance Basin is one of the largest know reservoirs of oil shale in the world and geothermal energy could be used to preheat the oil shale prior to extraction of hydrocarbons from this resource. Geothermal energy is an Creek, the Roan Creek, and the Parachute Cr

eek 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 Upper Cretaceous Cameo Group, shown in Figure 2. It is generally designated as a Laramide-age basin but it occupies part of the Early Pennsylvanian Maroon Trough (Quigley, 1965). Before the Maroon Trough, the area was a marine seaway. Mississippian shelf and 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 Uncompahgre Uplift continued to act as sources for clastics, carbonates, and evaporites in the trough from Late Permian through the Jurassic. 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 complete BHT data set compiled from 10,372 oil and gas wells is plotted as a function of depth in Figure 4. 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 other units in the table. These rocks have a higher proportion of high thermal conductivity limestone, dolomite and evaporates and shallower formations and the drop in thermal gradient is probably associated with a change in thermal conductivity. These data are not corrected for the transient temperature disturbance caused by the circulation of drilling fluid. Temperature data from drill-stem tests (DST data) are often taken to be a close approximation to the undisturbed, or virgin rock temperatures (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*.

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	WILLI1.470Td<0003>Tj/TT01Tf0.0014Tc4.8960Td(39)T7Td<0003>Tj/TT01Tf0.pe				

For the Piceance Basin, limited DST and 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 the DST and CBL data sets overlap geographically but cover different areas. They 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 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:

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

where T_{corr} is the correction in °C, and z is depth in meters. As a

3. Calculation of Geothermal Gradients

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:

$$T_{sa} = 20.085 - 0.007027e \text{ °C} \quad (2)$$

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:

$$T_s = 23.085 - 0.007027e \text{ °C} \quad (3)$$

where T_s is the surface ground temperature

Coal Canyon near Palisade with Williams Fork Formation on the north flank and Rollins Sandstone in the foreground
Photo credit: Ralph Topper, CGS

4. Interpretation of Results

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 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.

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. 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 [illegible] 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

ypes)Tj /TT0 1 Tf -0.0004 Tc 0.225 0 Td (through)Tj /C2_0 1 Tf 0 Tc 3
030003>Tj /TT08 Tf -0.0001 Tc -37.685 -1. Tf 0 Tc <0003>Tj /TT0 1 Tf 0.0002 Tc 1.555 0 Td (approximately)Tj /C2_

5. Geothermal Resources in the Piceance Basin

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. 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 Mississippi213.0161.405Td[(o)2(ne)]TJ/C201Tf0.2250Td(inL

6. Geothermal from Co-Produced Water in the Piceance Basin

In common with most oil and gas production in Colorado (the exception is coalbed