# Sedimentary Basin Geothermal Resources in the Piceance Basin, Colorado

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***Keywords***

*Sedimentary basin, geothermal resource, Piceance Basin, Colorado, Leadville Limestone, bottom-hole temperature, temperature log, Geotherm*

## ABSTRACT

The Piceance Basin is a major oil and gas producing basin in western Colorado. More than 27,000 bottom-hole temperatures (BHTs) from oil and gas wells in the basin have been corrected for the drilling disturbance. When these data were plotted as a function of the well depth the plots indicated changes in the geothermal gradient that roughly correlated with changes in lithology and thermal conductivity. The BHTs were separated into groups based on the stratigraphic intervals in which their wells were completed and geothermal gradient maps prepared for each group. The geothermal gradient maps also indicate a change in gradient as the stratigraphic intervals increased in depth and also showed a general increase in gradient to the south of the basin. Commercial temperature logs were digitized from some of the wells in the basin, including one very deep well. The temperature logs indicated temperature in general agreement with the BHT data except the log from the very deep well. The very deep well had two very different gradients which were interpreted to result from a long-term water flow at a steady temperature in the Dakota Formation about two-thirds down the well. The most suitable formation for a geothermal reservoir is probably the Mississippian Leadville Limestone which has intrinsic porosity, fracture, and karst permeability.

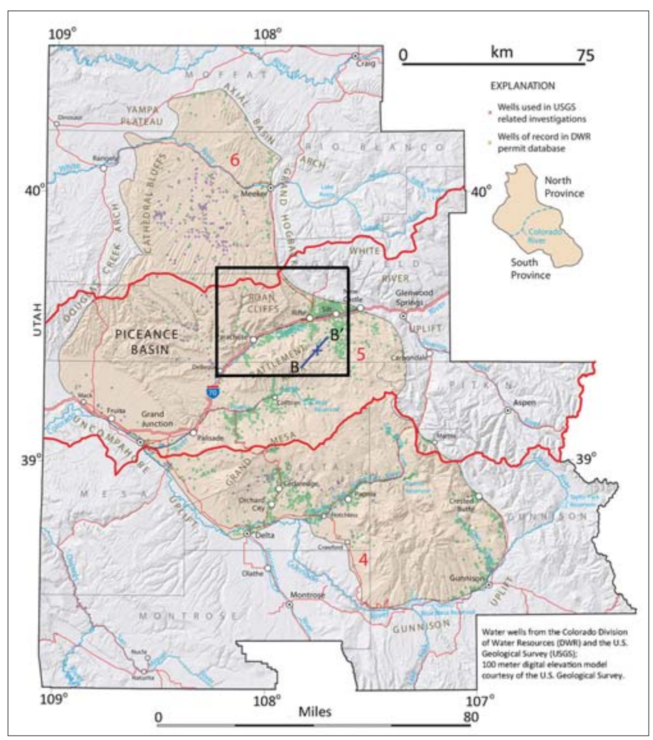


**Figure 1.** Map showing the major surface and bounding structural features, surface topography and drainage of the Piceance Basin in western Colorado. The red lines divide the three major water authorities, Districts 4, 5 and 6 in the map area. Water wells used as control points in compiling the map are shown as purple dots where the source of the wells was U.S. Geological Survey-related investigations and green dots where the source was the Colorado Department of Water Resources (DWR). The black box bounds the locations of the wells listed in Table 1 with temperature plots in Figures 5 and 6, and its sides have latitudes 39.3° and 39.7° N and longitudes 107.6° and 108.2° W. The blue cross is the location of the Mobil well discussed in the text and Figure 7, and the line B-B′ is the approximate location of the profile shown in Figure 8. Map modified from Figure 6.2-1 of Topper et al. (2003).

## Introduction

Colorado's geothermal resources include traditional geothermal resources, such as Mt Princeton Hot Springs, Waunita Hot Springs, and Poncha Hot Springs, all of which have reservoir temperatures indicated by geothermometry suitable for electrical power generation (Barrett and Pearl, 1978, Sares et al., 2009). Apart from a great reserve of heat in the crystalline basement (Tester et al., 2006), which is beyond the economic reach of current technology, the potentially greatest untapped geothermal resource in Colorado is in moderate depth aquifers in sedimentary basins. Preliminary descriptions of the geothermal potentials of some of these basins have been reported in the Transactions of the GRC (*e.g.*, Morgan, 2009; Morgan et al., 2010; Morgan and Scott, 2011). Specific areas in these basins are indicated to be more favorable as drilling targets for moderate temperature (~150°C; 300°F) geothermal fluid production as more information is being gathered concerning the temperatures and potential reservoir rocks in the basins. The present study focuses on the Piceance Basin in western Colorado, the subject of a previous study by Morgan and Scott (2011). The Piceance Basin is a deep sedimentary basin with high measured temperatures and Mississippian limestone near the base of its sedimentary section which is extremely permeable where exposed around the basin and elsewhere in Colorado and neighboring states.

## The Piceance Basin

The Piceance Basin is a major oil, gas and coal producing basin in western Colorado. It is part of the Uinta-Piceance Province, separated from the Uinta Basin in Utah by the Douglas Creek Arch (USGS Uinta-Piceance Assessment team, 2003). The basin is approximately 90 miles (145 km) east-west at its widest point and about 155 miles (250 km) in extent north-south. Its main surface structural and bounding features are shown in Figure 1. The depression that forms the Piceance Basin is Laramide in age but occupies part of the Early Pennsylvanian Maroon Trough (Quigley, 1965). Prior to 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 almost 210 m (700 feet) in thickness. The local representative of these deposits is the Leadville Limestone, which has lithologic equivalents in the Redwall and Madison Limestones in other Four Corner states and Wyoming. All three limestones are typically karst-forming.

Growth of the Ancestral Front Range and the Ancestral Uncompahgre Uplift acted as sources for clastic sediments, carbonates and evaporites for the Maroon Trough during the Late Permian. A marine transgression in the Cretaceous renewed sedimentation in the basin and it became a shallow sea with lagoonal and swamp sedimentation conditions. At the end of the Cretaceous, the trough was folded and faulted during the Laramide orogeny to form the modern tectonic Piceance Basin (Quigley, 1965). A generalized stratigraphic column for the Piceance Basin is given in Figure 2.

| AGE | | STRATIGRAPHIC UNIT | |
|---|---|---|---|
| TERTIARY | Pliocene | | |
| | Miocene | Unnamed basalt | |
| | Oligocene | Unnamed andesite | |
| | Eocene | Uinta Formation<br>Green River Formation | |
| | Paleocene | Wasatch Formation | |
| CRETACEOUS | | Mesaverde Group | Williams Fork Fm.<br>Cameo Coal zone |
| | | | Iles Formation<br>Rollins Ss. Mbr.<br>Cozzette Ss. Mbr.<br>Corcoran Ss. Mbr. |
| | | Mancos Shale<br>Niobrara Shale<br>Frontier Formation<br>Dakota Sandstone | |
| JURASSIC | | Morrrison Formation<br>Entrada Sandstone | |
| TRIASSIC | | Chinle Formation<br>State Bridge Formation | |
| PERMIAN | | Weber Sandstone | |
| PENNSYLVANIAN | | Maroon Formation<br>Minturn Formation<br>Eagle Valley Formation<br>Belden Shale<br>Molas Formation | |
| MISSISSIPPIAN | | Leadville Limestone<br>Castle Butte Mbr.<br>Redcliff Mbr. | |
| DEVONIAN | | Gilman Sandstone<br>Dyer Formation<br>Parting Sandstone | |
| SILURIAN | | Manitou Formation | |
| CAMBRIAN | | Peerless Formation<br>Sawatch Sandstone | |
| PRECAMBRIAN | | | |

**Figure 2.** Stratigraphic units in the southern Piceance Basin, Colorado. Source Wilson et al. (1998) who modified the diagram after Western GeoGraphics (1985) and Pearl (1986).

Thermal springs and heat-flow measurements in and around the Piceance Basin were summarized by Morgan and Scott (2011) and will not be repeated here. Morgan and Scott (2011) presented bottom-hole-temperature (BHT) data from 10,372 wells to present arguments that there was a high probability of an EGS resource deep in the Piceance basin. We now have BHTs from more than twice the number of wells available in 2011; we have contoured gradients for the basin based on the stratigraphic depths of the BHTs, and have a number of commercial temperature logs that allow a more detailed investigation of potential geothermal resources in the basin.

## An Expanded Bottom-Hole Temperature Database and Gradient Contours for the Piceance Basin

The current Colorado Geological Survey (CGS) database for the Piceance Basin includes 27,056 BHTs from oil and gas wells collected from well-log headers. A correction for the drilling disturbance specific to the Piceance Basin has been calculated by comparing BHTs with temperatures from drill-stem tests and cement-bond log BHTs that were measured a significant time after the completion of drilling (see also Morgan and Scott, 2011). This correction is:

$$BHT_{corr}\ (°C) = BHT_{uncorr}\ (°C) + 0.00175 * depth\ (m) + 5.07\ °C \quad (1)$$

where $BHT_{corr}$ is the corrected BHT, $BHT_{uncorr}$ is the measured BHT (from the log header), and *depth* is the vertical depth of the measured BHT. A plot of corrected BHTs versus depth is shown in Figure 3. The scatter in this plot is typical of BHT data but there is one unexpected feature of this plot, the significance of which was not recognized in the plot of the smaller sample of data presented by Morgan and Scott (2011). Although a single linear fit to the data is shown in Figure 3, there are two distinct geothermal gradients indicated by the data, a lower gradient above an average depth of about 1,830 m (1,220 to 2,240 m; approximately 6,000 feet, 4,000 to 8,000 feet), and an average temperature of about 71°C (60 to 82°C; approximately 160°F, 140 to 180°F), and a higher gradient at greater depths and higher temperatures. This basin-wide general feature of a lower geothermal gradient over a higher gradient is likely caused by the stratigraphy of the basin in which higher thermal conductivity siliceous formations overlie lower thermal conductivity coal-bearing formations and shales, such as the thick Mancos Shale (Figure 2). On a basin-wide scale, as seen in the plot in Figure 3, the geothermal gradients appear to decrease again below about 2,900 m (from 2,300 to 3,200m; below about 9,500 feet, from 7,500 to 10,500 feet; approximately) and temperatures above about 133°C (from125 to 143°C; above about 245°F, from 230 to 260°F) where shales are less abundant and the average thermal conductivities of the strata increase.

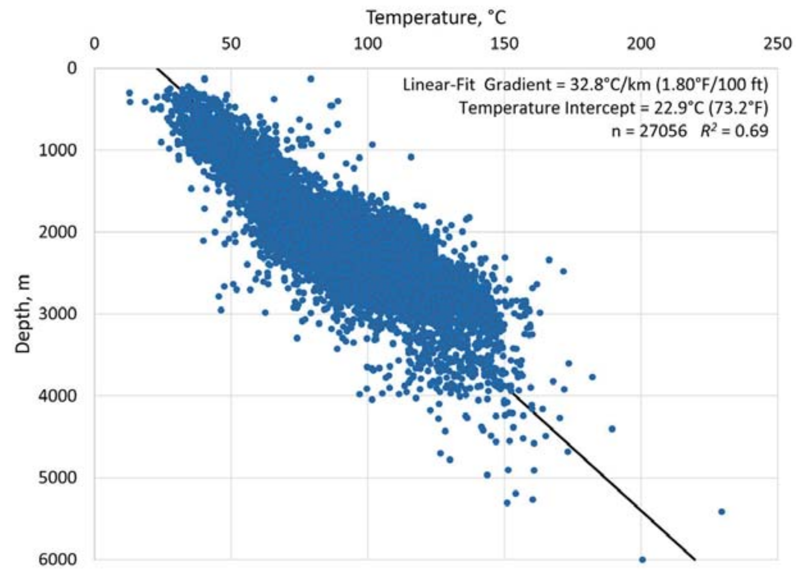


**Figure 3.** Corrected BHTs from 27,056 wells in and around the Piceance Basin in western Colorado plotted as a function of depth. Temperatures were corrected for the drilling disturbance as described in the text. A single linear fit to the complete data set is shown by the black line although the gradient probably changes with depth.

Using data from climate stations in and around the Piceance Basin and adding 3°C (5.4°F) to account for the difference in mean annual ground and mean annual air temperatures, the following formula was derived for surface ground temperature in the Piceance Basin from which geothermal gradients could be calculated for individual BHTs:

$$Ts = -0.0039254e\ (m) - 2.1903LA\ (decimal\ degrees) + 161.43\ °C \quad (2)$$

where *Ts* is the calculated surface ground temperature, *e* is the ground surface elevation of the well for which the temperature is being calculated, and *LA* is the latitude of the well. Using these ground surface temperatures and the BHTs, geothermal gradients were calculated for each of the 27,056 BHTs in the Piceance Basin dataset from the difference in the BHT and the mean surface ground temperature for the well divided by the BHT vertical depth. The result was disappointing, however, in terms of a result that showed clear geographic gradient trends. The reason why geographic gradient trends were not visible in the complete dataset is apparent in Figure 3: the geothermal gradients change significantly with depth as thermal conductivity changes with depth. In heat-flow studies, changes in thermal conductivity with depth may be accommodated by plotting temperature against thermal resistance, the quantity given by the following equation:

$$TR(z) = \sum_{i=1}^{n} \frac{dz_i}{K_i} \quad (3)$$

where *TR(z)* is the thermal resistance at depth *z*, $dz_i$ is the thickness of the $i^{th}$ layer, $K_i$ is the thermal conductivity of the $i^{th}$ layer and there are *n* layers. The thermal resistance is calculated for the depth of every temperature measurement. A plot of temperature versus the thermal resistance compensates for variations of thermal conductivity with depth and yields heat flow, *q*, as the slope ($q = dT/(dz/K)$) (Bullard, 1939). This is an excellent technique to reduced data when there are significant variations in thermal conductivity with depth, but it masks the temperature-depth information that is vital for geothermal exploration.

A compromise method of mapping geothermal gradients when thermal conductivities change with depth is to separate the BHT data according to stratigraphic depth and to make geothermal gradient maps for BHTs taken from wells that were completed in similar stratigraphic depth intervals Morgan and Scott, (2014). This technique assumes that wells completed in the same stratigraphic depth interval have similar stratigraphy and that the effective thermal conductivity of the units above the chosen stratigraphic interval should be roughly constant even if the total thickness of these units changes. This assumption is an approximation, but as stratigraphic thicknesses generally change less rapidly horizontally than lithologies change vertically, and as maps display horizontal separation of data, it allows BHTs to be separated to present geothermal gradient maps that are not overwhelmed by vertical thermal conductivity variations. Geothermal gradient maps for BHTs in eight different stratigraphic intervals for the Piceance Basin are shown in Figure 4. Lower geothermal gradients are seen with BHTs from the deepest stratigraphic intervals in the basin, consistent with the results of the BHT plot in Figure 3. The highest geothermal gradients are in the south and on the southwest margin of the basin.

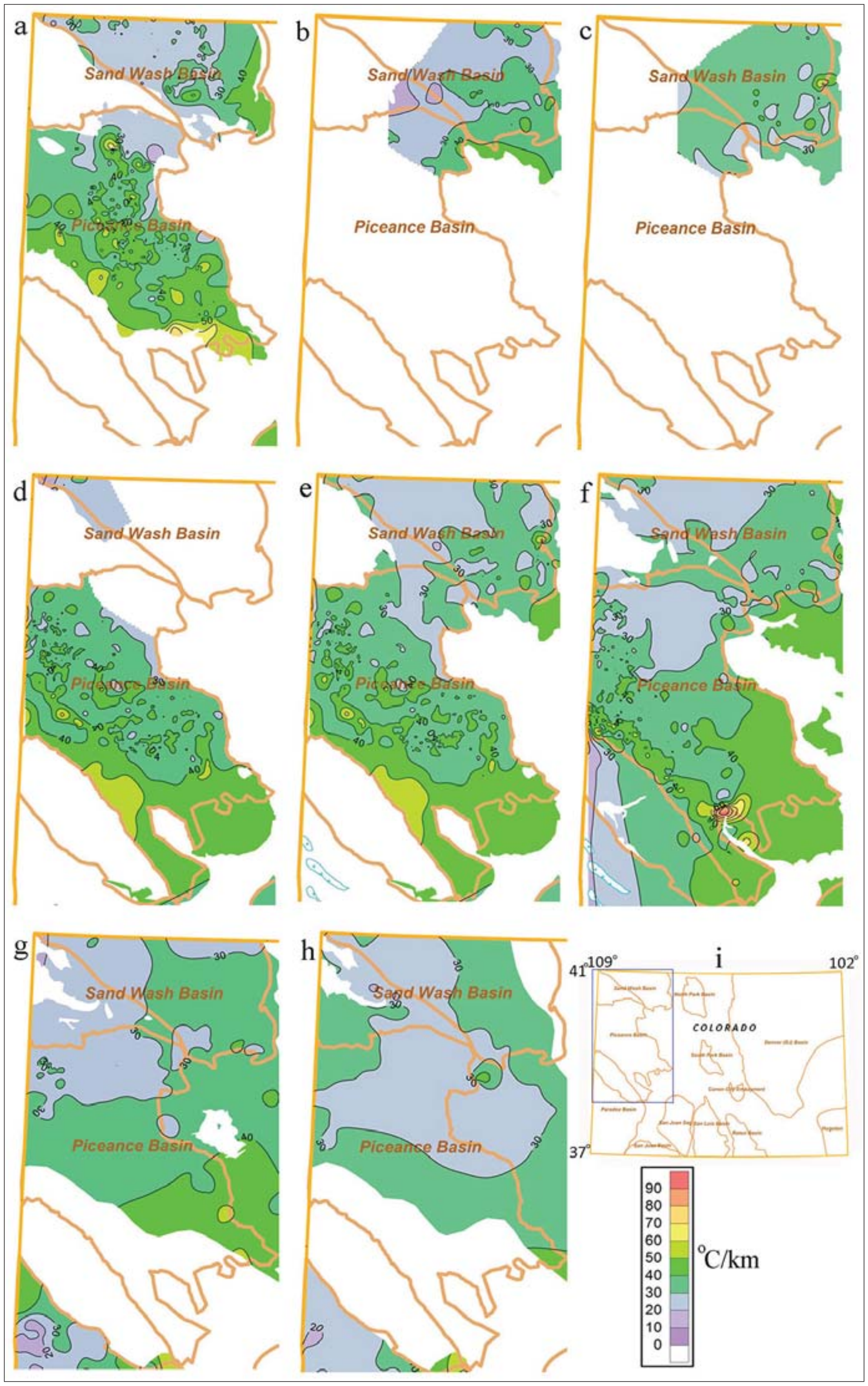


**Figure 4.** Geothermal gradient maps derived from corrected BHTs and surface ground temperatures, as described in the text. The data were separated according to the stratigraphic interval in which the well from which the BHT was taken was completed. The intervals were: a. Surface to top of Mancos or Pierre Shale; b. Top of Mancos or Pierre Shale to top of Niobrara; c. Top of Niobrara to top of Dakota; d. Top of Mancos to top of Dakota – Niobrara missing; e. Top of Mancos to top of Dakota – Niobrara present; f. Top of Dakota to top of Permian; g. Top of Permian to top of Mississippian; h. Top of Mississippian to top of Precambrian. The location of the gradient maps and color gradient scale are shown in i.

## Temperature Logs

In addition to BHTs, some wells in the Piceance Basin have commercial temperature logs available online from the Colorado Oil and Gas Conservation Commission (COGCC: https://cogcc.state.co.us/). These logs record the temperatures in the well at the time of logging but can also yield useful information about the geothermal conditions in the basin. A selection of temperature logs are shown at recorded temperatures in Figure 5, and shifted in temperature to allow individual temperature logs to be viewed in Figure 6. The temperature logs were available as scans of paper logs and were mostly hand digitized at 100 foot (30.5 m) intervals. The shallowest temperature for the logs was not always clear on the logs and for some logs this temperature was deduced from the lowermost temperature on the log (the BHT). A few logs had recorded temperatures at 7.6 m (25 feet) intervals and these temperatures were used to digitize the logs.

A few of the temperature logs, such as 12977, extrapolate back to very high surface temperature of about 30°C (85°F). Whether this is an error in the reading the temperature scale for digitization or in recording the temperature scale on the log is unknown, but such surface temperature are significantly higher than normally recorded by climate stations for Colorado (see equation 2). Therefore, absolute temperature from these temperature logs should be treated with caution. Only three of the temperature logs, 11343, 11350 (below ~900 m; ~3000 feet), and 13025 (and perhaps 21944) show an increase in gradient with depth as indicated in the BHT data (Figure 3). Most other logs indicate more complex changes in gradient with depth or have sections that are clearly disturbed. Top of cement was indicated at 1661 m (5450 feet) for log 12977, 1471 m (4825 feet) for log 13540, 419 m (1375 feet), and 2896 m (9500 feet) for log 15497, respectively, and significant positive temperature disturbances can be seen in the logs below these depths recording the curing heat of the cement. The temperature plots in Figure 5 and 6 are all from a small area in the Piceance Basin and have and not been corrected for directional drilling (Table 1). The average total depth correction for directional drilling is 0.97 and the maximum correction is 0.88.

The deepest well drilled in the Piceance Basin was a wildcat well, the Mobil O'Connell F11-34P (Wilson et al., 1998). This well was drilled to a depth of 5,629 m (18,422 feet) during 1990-1992 in the same area as the wells subsequently drilled from which the temperature logs were recorded that are shown in Figures 5 and 6, as indicated in Figure 1 and Table 1. A temperature log for this well was downloaded from the COGCC, digitized and is plotted in Figure 7 together with interval temperature gradients and the formations penetrated by this well. The interval temperature gradients show an increase in gradient starting at the top of the Cameo Coal Group (~ 1600 m; ~5259 feet) that continues to a depth of somewhere between halfway to two-third the thickness of the Mancos Shale (2,500 to 3,000 m; 8,200 to 9,850 feet). The gradient then decreases to the top of the Dakota Formation at a depth of 3,640 m (11,950 feet). These changes in geothermal gradient, including the change in gradient in the Mancos Shale, are probably caused by changes in thermal conductivity; the Mancos Shale is more siliceous in its lower half which increases its thermal conductivity (P. Morgan, unpublished core logging information, 2014). Below the top of

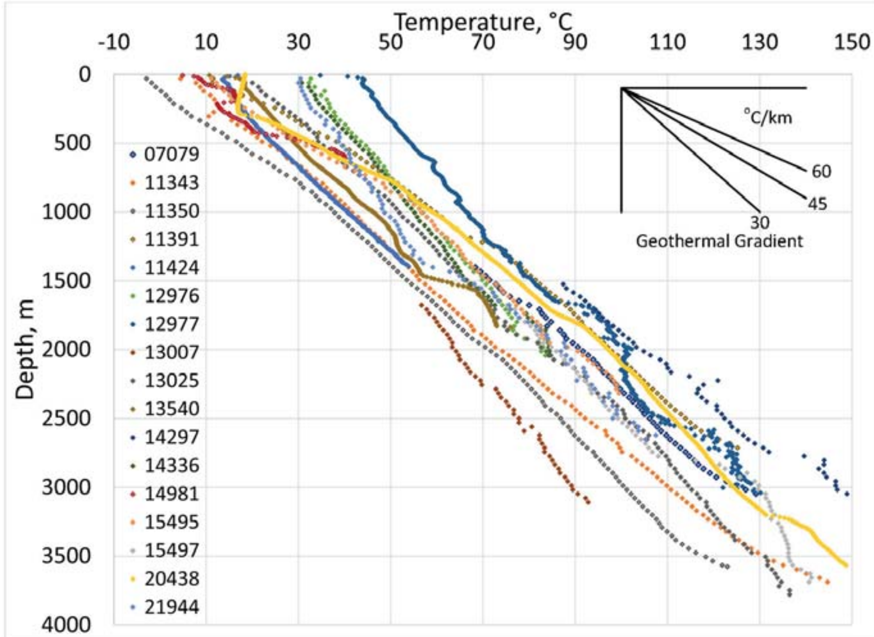


**Figure 5.** Temperature-depth plots of data digitized from commercial temperature logs from a selection of wells in the Piceance Basin. Temperatures are plotted at values digitized from logs. Locations of wells are given in Table 1 from the area indicated in Figure 1. The wells are all from Garfield County, Colorado and the well numbers given on the plot are the last five digits of the API numbers. The full API numbers may be derived by preceding these numbers by 05-045- (i.e., API # = 05-045-nnnnn).

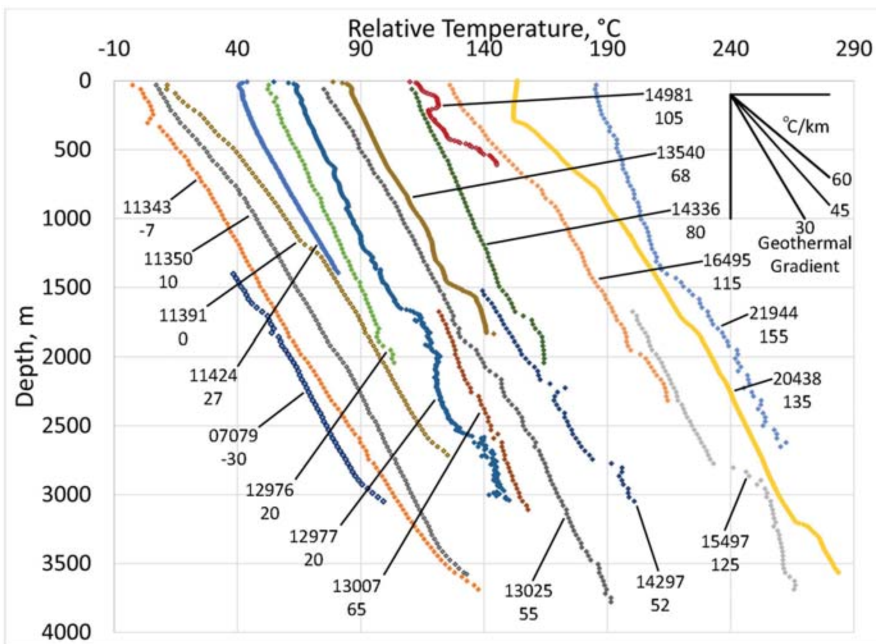


**Figure 6.** Temperature-depth plots from Figure 5 separated by adding a constant temperature to each of the temperature datasets. The constant added to the temperatures is given beneath each well number in °C. See Figure 5 caption for key to well numbers and locations.

**Table 1.** Basic Information for oil wells for which geotherms are shown in Figure 5, 6, and 7. O'Connell F11X-34P is the Mobil well shown in Figure 7. Last five digits of API numbers are used to identify wells in Figures 5 and 6. Negative longitude indicates longitude west. Depth is drilled depth, V. Dep is vertical depth. Status codes: PA – plugged and abandoned; PR – producing, AL – abandoned location; IJ – injection well for disposal or secondary recovery. Date is when status was reported is given under the Status code. The O'Connell F11X-34P was reported to be a vertical well but its true vertical depth was not reported; the value given in the table is assumed to be vertical depth.

| API # | Well name | Field | Latitude | Longitude | Depth feet | V. Dep feet | Completion Formation | Status |
|---|---|---|---|---|---|---|---|---|
| 05-045-06723 | O'CONNELL F11X-34P | WILDCAT | 39.408002 | -107.660352 | 18422 | ? | LEADVILLE | PA 7/14/1993 |
| 05-045-09079 | CHEVRON #242-20D | GRAND VALLEY | 39.606046 | -108.195236 | 10197 | 10166 | WILLIAMS FORK | PR 2/8/2010 |
| 05-045-11343 | LONG RIDGE #15B M16 595 | GRAND VALLEY | 39.608051 | -108.064124 | 12198 | 11950 | WILLIAMS FORK | PR 4/7/2007 |
| 05-045-11350 | LONG RIDGE 14B M16 595 | GRAND VALLEY | 39.607815 | -108.064127 | 9080 | 7947 | WILLIAMS FORK | PA 11/11/2006 |
| 05-045-11391 | N.PARACHUTE WF03B D23A 596 | GRAND VALLEY | 39.60558 | -108.143 | 9135 | 8980 | WILLIAMS FORK | PR 5/30/2006 |
| 05-045-11424 | BISCUIT RANCH 10-31D | WILDCAT | 39.56838 | -107.75966 | 9250 | 9247 | WILLIAMS FORK | PA 7/15/2013 |
| 05-045-12976 | N.PARACHUTE CP07C08 G08 596 | GRAND VALLEY | 39.630599 | -108.19192 | 10933 | 10931 | COZZETTE | PR 1/29/2014 |
| 05-045-12977 | N. PARACHUTE CP02D-08 G08 59 | GRAND VALLEY | 39.630598 | -108.191955 | 10055 | 9781 | WILLIAMS FORK | PR 10/11/2006 |
| 05-045-13007 | N. PARACHUTE CP14A-09 G09 59 | GRAND VALLEY | 39.632252 | -108.173752 | 10600 | 9953 | WILLIAMS FORK | PR 10/31/2006 |
| 05-045-13025 | N. PARACHUTE CP04C-02 A03 59 | GRAND VALLEY | 39.647936 | -108.147815 | 12500 | 12437 | COZZETTE | PR 1/12/2012 |
| 05-045-13540 | N. Parachute CP01D-17 E16 59 | WILDCAT | 39.616461 | -108.183269 | 6175 | 5951 | WILLIAMS FORK | AL 1/14/2013 |
| 05-045-14297 | N.PARACHUTE CP11B-09 G09 596 | GRAND VALLEY | 39.632252 | -108.173823 | 10200 | 9922 | WILLIAMS FORK | PR 6/20/2007 |
| 05-045-14336 | N. PARACHUTE CP11D-8 G08 596 | GRAND VALLEY | 39.630598 | -108.191988 | 9900 | 9702 | WILLIAMS FORK | PR 2/1/2014 |
| 05-045-14981 | N. PARACHUTE CP02B-16 B16 59 | GRAND VALLEY | 39.620961 | -108.172258 | 10730 | 10713 | WILLIAMS FORK | PR 2/1/2011 |
| 05-045-15495 | SGU CP01B-27 M23 49 | GRAND VALLEY | 39.681302 | -108.14277 | 9253 | 9048 | WASATCH | IJ 8/16/2010 |
| 05-045-15497 | SGU CP12D-23 M23 49 | UNNAMED | 39.681356 | -108.142794 | 12160 | 11975 | WILLIAMS FORK | PR 1/9/2009 |
| 05-045-20438 | DW 8616A-28 P28496 | GRAND VALLEY | 39.687912 | -108.165737 | 11755 | 11685 | SEGO | PR 1/14/2013 |
| 05-045-21944 | HMU 6-15D (J6SEB) | MAMM CREEK | 39.387387 | -107.706099 | 8843 | 8601 | NOT COMPLETED | PR 5/20/2014 |

the Dakota, however, the average geothermal gradient increases by a factor of three or more to a gradient of about 70°C/km (3.8°F/100 feet). This is a much greater increase than can be explained by a change in thermal conductivity and is inconsistent with the lithologies of sandstone, evaporite, and carbonate formations below the Dakota with relatively high thermal conductivities. The abrupt change in geothermal gradient at the depth of the Dakota must indicate a change in vertical conductive heat flow.

The Dakota Sandstone is a widespread aquifer in Colorado with permeability commonly in the form of fracture rather than intra-grain porosity. The geothermal gradients in the Mobil hole do not vary in a systematic way with vertical distance from the Dakota formation as would be expected if the change in conducted heat flow at the Dakota were a recent event: changes in gradient appear to be random, as would be expected, either from random noise in the temperature measurements or from small-scale vertical variations in thermal conductivity. None of the wells, from which the temperature plots shown in Figures 5 and 6 were derived, were drilled to the Dakota (Table 1). These plots do not provide information about an increase in thermal gradient below the Dakota. On average, however, they indicate a temperature of about 140°C (285°F) at a depth of about 3,640 m (11,950 feet), the depth of the top of the Dakota in the Mobil well (Figure 5). The temperature at this depth in the Mobil well is only 101°C (214°F), however, suggesting that the Mobil well could be about 40°C (~70°F) below its temperature predicted from the other logs at this depth. Unfortunately, there is a break in the Mobil hole temperature logs available from the COGCC between 3,962 m (13,000 feet) and 5,060 m 16,600 feet). If a simple linear gradient is calculated from temperatures at the bottom of the hole and temperatures at the top of the hole the interpolated temperature at 3,640 m (11,950 feet) is about 160°C (320°F). This temperature is about 20°C (35°F) higher than the average extrapolated temperature at the same depth from the temperature plots shown in Figure 5. Neither of these analyses is rigorous, but both approaches indicate that there has been significant effective cooling of the measured geotherm at the depth of the Dakota in the Mobil hole. From the lack of curvature in this geotherm above and below the Dakota, the cooling is interpreted to be caused by a long-term constant-temperature flow of water in the Dakota that removes about two-thirds of the conducted heat entering the base of the Dakota.

There is significant structure in the formations that comprise the pre-Laramide Piceance Basin. An example of this structure is shown in Figure 8. At least one fault penetrates the Dakota Sandstone in the proximity of the Mobil well, but there is insufficient published information to constrain models of water-flow in the Dakota to explain the abrupt change in gradient in this well.

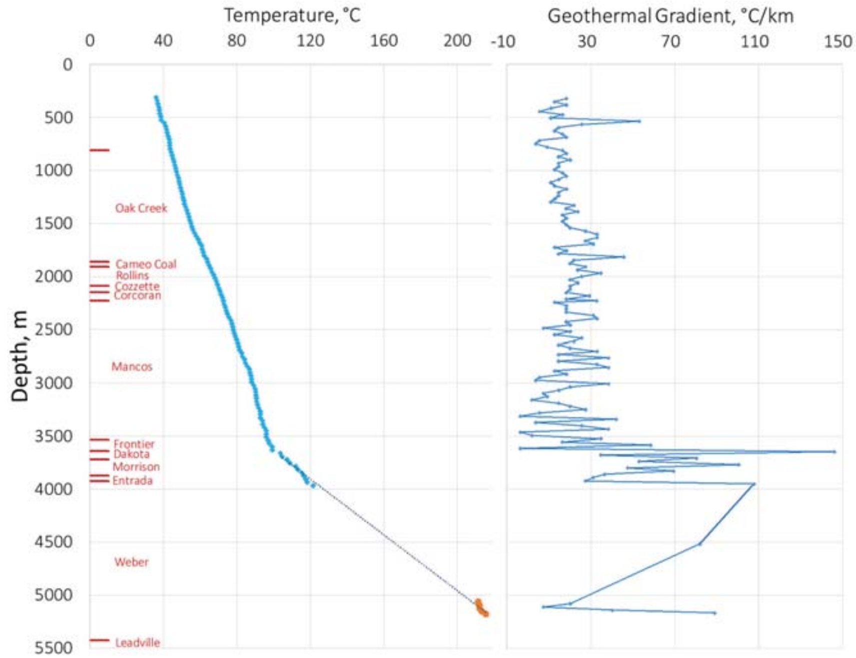


**Figure 7.** Temperature-depth and geothermal gradient-depth plots for data digitized from commercial temperature logs from Mobil well O'Connell F11-34P. The stratigraphy indicated on the plot was taken from the COGCC scout card for the well. Gradients were calculated from adjacent pairs of digitized temperatures.

## The Leadville Limestone: A Potential Geothermal Reservoir

Corrected bottom-hole temperature data indicate that temperatures in the Piceance Basin are consistently 120 to 175°C (250 to 350°F) and higher below about 3,950 m (~13,000 feet). The measured temperature at the bottom of the Mobil well was 215°C (420°F) at 5,175 m (16,980 feet). These are sufficient temperatures for geothermal power generation if an aquifer can be found that can produce large quantities of water at these temperatures (and if pumping costs are not prohibitive). There are a number of sandstone units in the lower portion of the Piceance Basin (Figure 2) but the formation with the greatest potential for producing very high water flows is the Mississippian Leadville Limestone.

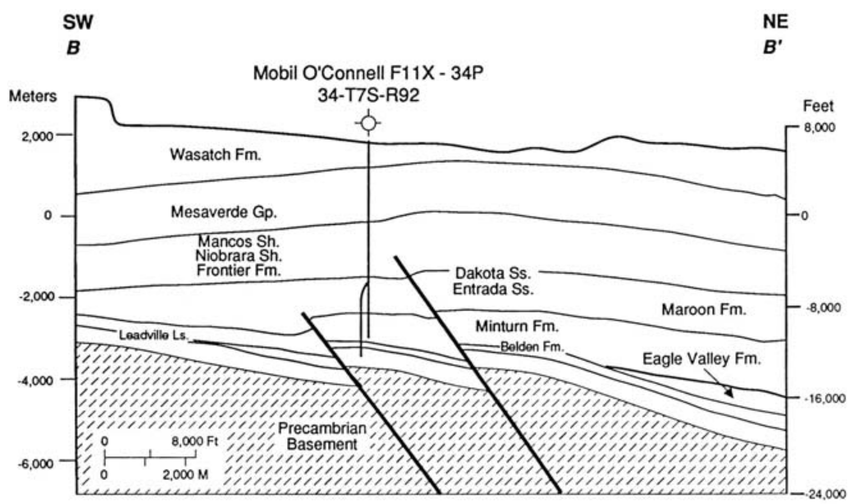


**Figure 8.** Interpretive cross section extending from southwest to northeast through the Mobil well showing tilted fault-block structure derived from seismic reflection data (see Wilson et al., 1998). The approximate location of this line is shown by the blue line and the location of the Mobil well is shown by the blue cross on Figure 1.

The Leadville Limestone is briefly described by Wilson et al. (2003). Pertinent observations are that it has two members, the Redcliff member overlain by the Castle Butte Member, both deposited in tidal and intertidal environments. The 12 to 24 m (40 to 80 foot) Redcliff member includes coarse crystalline and sucrosic dolomite layers, and median porosity in the dolomites is 6%. The Castle Butte Member includes 24 to 37 m (80 to 120 feet) of massive, micritic, fossiliferous limestone. The shoreline that deposited these beds was uplifted in late Mississippian time resulting in erosion, incision of paleo-valleys, and karst formation. A combination of intrinsic permeability, karst, and fracturing gives the Leadville Limestone an excellent potential for very high permeability. Wherever the Leadville Limestone, or its lateral equivalents the Redwall and Madison Limestones, are observed today, high permeability is characteristic of these formations, typically in the form of karst structures. The Leadville Limestone takes its name from the town of Leadville where mineralization, paleo-geothermal systems, was often formed in karst structures. The most favorable areas in which to find high permeability in the Leadville Limestone in the Piceance Basin will probably be where faults intersect the limestone. Wells may need to be stimulated or drilled a short distance horizontally to connect with karst permeability. However, once connected, the main impedance to pumping is likely to be the diameter of the well.

## Concluding Remarks

Morgan and Scott (2011) proposed the Piceance Basin as a sedimentary basin EGS resource. With an increase in the quantity of BHT data by almost a factor of three and examination of data from commercial temperature logs, including a very deep Mobil O'Connell F11-34P well, the thermal structure of the basin is now clearly defined with vertical changes in geothermal gradient correlated to basic changes in lithology and thermal conductivity. The BHT data and data from the temperature logs indicate that temperatures suitable for geothermal electricity generation are generally present in the basin at depths greater than 3,950 m (13,000 feet), perhaps shallower in the southern portion of the basin. There are no obvious candidates for high permeability aquifers in the siliceous rocks at these depths through most of the basin, but from its lithology and observations its karst structure in outcrop and mines, the Mississippian Leadville Limestone is an excellent candidate for a geothermal aquifer in the lower stratigraphic section of the basin.

The next steps in exploration for sedimentary geothermal resources in the Piceance Basin are to compile information on the deep structure of the basin and to combine this information with BHT-gradient data to determine the optimum location for locating fractured Leadville Limestone with a trade-off between the highest possible temperature and the shallowest depth. As multiple oil and gas wells in the Piceance Basin are now commonly drilled from a single pad, if there is oil and gas drilling close to the optimum location for drilling to the Leadville Limestone, a practical and economic proposal to drill the first wildcat geothermal exploration well in the Piceance Basin could be to drill it in conjunction with oil and gas drilling.

## Acknowledgements

Anna Crowell is thanked for a careful review of a draft of this manuscript.

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