Statewide Geothermal Resource Mapping in Colorado

Matthew A. Sares, Frederick E. Berkman, and Nicholas A. Watterson

Colorado Geological Survey

Keywords

Geothermal map, heat flow, gradient, Colorado

ABSTRACT

The Colorado Geological Survey (CGS) has compiled existing geothermal data with oil and gas well data, and a number of new geothermal data points to produce new statewide maps of heat flow and geothermal gradient. These maps are being used to help focus new data development efforts, providing the geothermal community with basic data to identify exploration targets.

Heat Flow Map of Colorado

Heat flow is a measure of heat moving from the Earth's interior to its surface. Areas of high heat flow are capable of providing sustained heat energy to specific areas of the upper crust and, therefore, are prospective for economic geothermal resources. Heat flow data and the mapping thereof, are important in assessing the geothermal development potential of an area. Blackwell and Richards (2004a) mapped the heat flow of the United States (Figure 1). Based on this map, Colorado has a significant high heat flow anomaly and compares favorably with other areas of the west experiencing accelerated geothermal development. In order to assist in geothermal exploration efforts in Colorado, the Colorado Geological Survey has built on this earlier work to provide a more detailed heat flow map of Colorado at 1:500,000 scale (Figure 2; Berkman and Carroll, 2008).

The Colorado heat flow map is based on a compilation of heat flow data from Southern Methodist University (SMU) (Blackwell and Richards, 1989), University of North Dakota (UND) (International Heat Flow Commission, 2006), and University of Michigan (UM) (Pollack and others, 1993) with additional heat flow data collected and calculated from temperature-depth logs. These data are predominantly derived from mineral resource assessment drill holes, geothermal

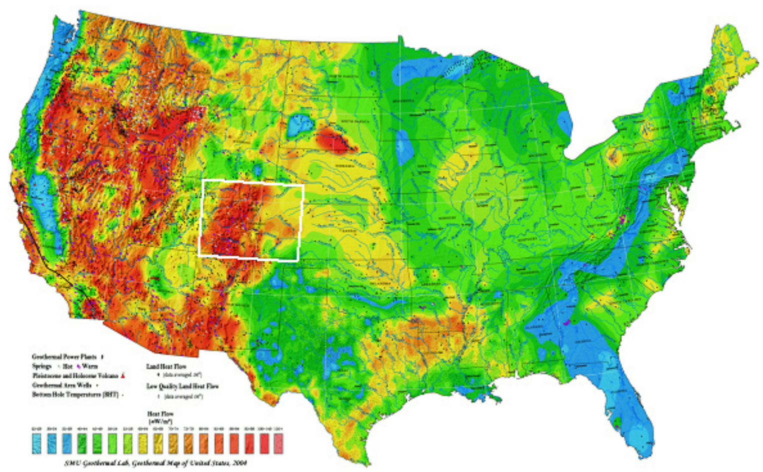

Figure 1. Geothermal Map of the United States (Blackwell and Richards, 2004). Heat flow indicated by color shading with warmer colors representing higher heat flow. Colorado outlined in white.

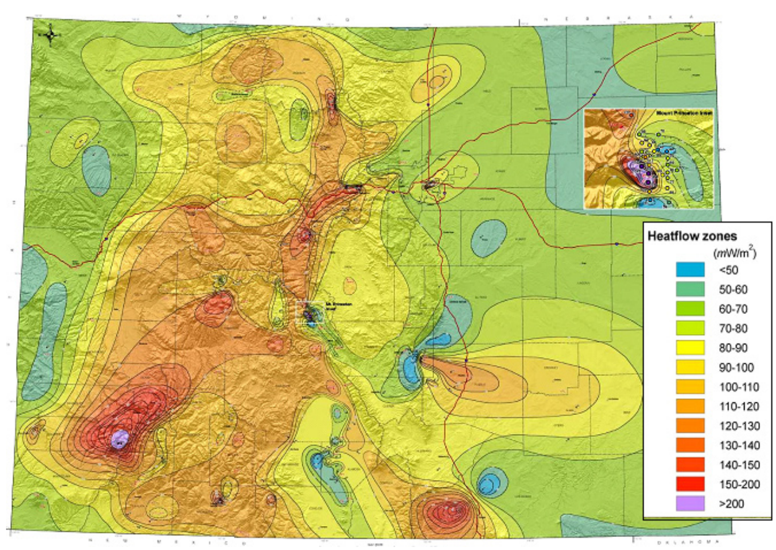

Figure 2. Interpretive heat flow map of Colorado (Berkman and Carroll, 2008). Inset map is close up of the Mt. Princeton area, the highest known heat flow location in Colorado, having heat flow measurements up to 378 mW/m^2.

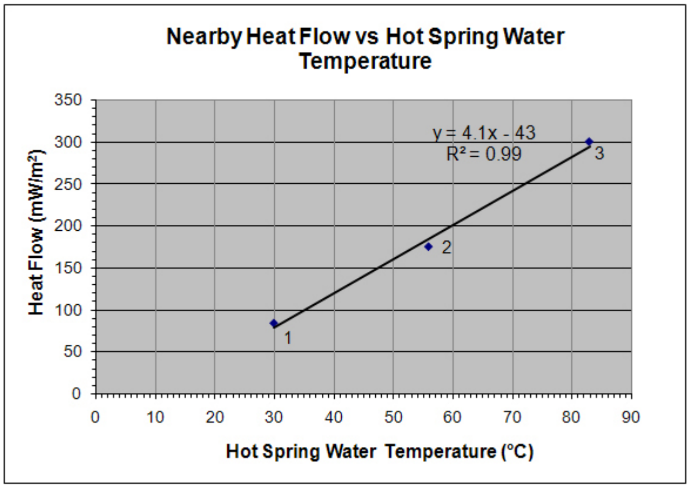

Figure 3. Graph of heat flow vs hot spring temperature for springs with nearby heat flow data points. The best fit line expresses a relationship between spring temperature and heat flow that was used to estimate heat flow near hot springs without nearby heat flow data. Data points are 1=Shaw's Warm Spring, 2=Pagosa Hot Spring, 3=Hortense (Mt Princeton) Well

test holes, and geothermal wells. The SMU, UND, and UM datasets include geothermal gradient, thermal conductivity, heat flow value, and other parameters for each drill hole; however, they do not include the original down hole temperature-depth numbers. CGS augmented these data by calculating heat flow values for 40 additional sites from temperature-depth logs and other published data.

Thermal spring and well water temperature data were used to supplement available heat flow data. A relationship between thermal spring and well temperature and expected heat flow value was derived by plotting spring temperature against nearby drill-hole heat flow data for three specific areas where these were in close proximity. The areas used for this analysis were Hortense Hot Spring Well near Mt Princeton in Central Colorado, Shaw's Warm Spring in the San Luis Valley of south-central Colorado, and Pagosa Hot Spring in the town of Pagosa Springs, southwest Colorado (Figure 3). The resulting linear regression to these data is,

$$Q = 4.1*T-43$$

where Q = heat flow (mW/m^2) and T = hot spring temperature (°C), allows a rough estimate of heat flow using thermal spring/well temperatures in Colorado's mountainous areas where down-hole heat flow values are not available. The contour lines are dashed where values derived from thermal springs and wells influence the contour placement.

The resulting interpretive heat flow map of Colorado compiled from the three major heat flow datasets, newly calculated heat flow data, and heat flow derived from thermal springs or well temperatures indicates that several areas of Colorado have high heat flow anomalies. These areas include the Mt. Princeton-Buena Vista area (300-400 mW/m^2) in central Colorado, Rico-Ouray trend (200-300 mW/m^2) in southwest Colorado, Trinidad and eastern San Luis Basin area (up to ~200 mW/m^2) in south-central Colorado, and Leadville-Georgetown area (up to 200 mW/m^2) in north-central Colorado.

The heat flow data are not distributed evenly across the state. Small areas with clustered data surrounded by wide areas containing sparse data are characteristic of the heat flow map. As such, the contours are well constrained in areas of clustered data and more interpretive in areas of sparse data.

High heat flow can result from various geologic situations, such as 1) an area of relatively thinner crustal rock above the mantle, 2) resident heat from geologically recent igneous activity, 3) upwelling of deep, heated groundwater, or 4) a concentration of radioactive minerals within the crust. In Colorado it is likely that situations 3 and 4 above are the primary reasons for high heat flow. Upwelling of deep heated groundwater is driven by the hydrodynamic effects of large topographic changes and the opportunity for deep plumbing systems associated with geologically young faults. Colorado has 93 verified Quaternary faults, but doubtless many more than that number are unidentified because of the difficulty of verifying movement on faults that juxtapose the same Precambrian crystalline rocks on each side of a fault. The abundance of crystalline rock in Colorado with its radioactive mineral content is also likely to contribute to Colorado's overall high heat flow anomaly.

Geothermal Gradient Map of Colorado

A new interpretive geothermal gradient map of Colorado (Figure 4; Berkman and others, *in prep*) was compiled from several data sources. The gradient data inherent in the Colorado heat flow dataset and temperature data from oil, natural gas, and carbon dioxide production wells were combined for this task.

Not all oil and gas well data were used in compiling the map. Bottom-hole temperature data for the major oil and gas producing areas of Colorado were used as compiled by Dixon (2002, 2004). In oil and gas production areas not covered by the Dixon compilations, the database was augmented by selecting oil and gas wells that had drill-stem test temperature data from the PI/Dwights dataset (IHS Energy) and temperature log data from LogSleuth (M.J. Systems).

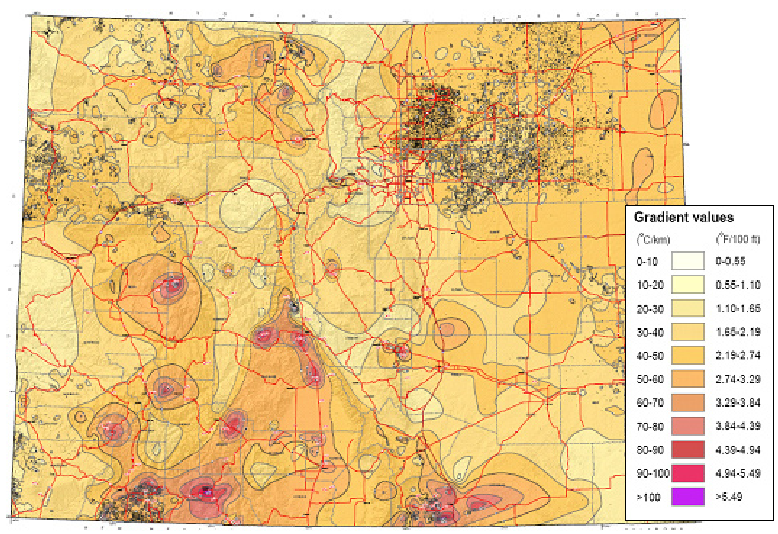

Figure 4. Interpretive geothermal gradient map of Colorado (Berkman and others, *in prep*).

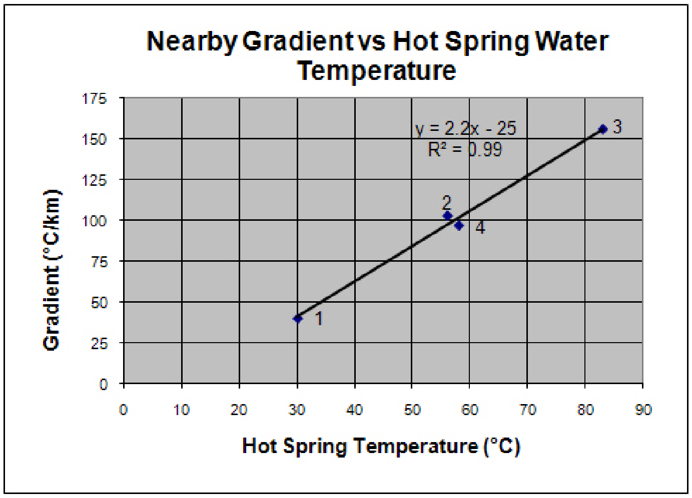

Figure 5. Graph of geothermal gradient vs hot spring temperature for springs with nearby gradient data points. The best fit line expresses a relationship between spring temperatures and geothermal gradient that was used to estimate the gradient near hot springs lacking nearby data. Data points are 1=Shaw's Warm Spring, 2=Pagosa Hot Spring, 3=Hortense (Mt Princeton) Well, 4=Cottonwood Hot Spring.

Data from the heat flow dataset are located primarily in the mountainous central and western portion of the state and are geographically complimentary to the oil and gas data, which are located predominantly in sedimentary basins on the eastern plains and western slope of Colorado. The combined dataset comprises gradients from more than 17,000 wells and drill holes.

Some areas of sparse data persist in spite of the large number of data points. In these areas, hot spring temperature data were used to supplement the available gradient data. A relationship between spring temperature and expected gradient was derived by plotting hot spring temperature against nearby drill hole gradient data for the Hortense, Cottonwood, Pagosa, and Shaws hot springs (Figure 5). The resulting linear regression to these data,

$$G = 2.2T - 25$$

allows a rough estimate of geothermal gradient, G. using hot spring temperatures, T, in Colorado's mountainous areas where down-hole temperature values are not available. Contour lines are dashed where values derived from hot springs influence the contour placement.

The resulting interpretive geothermal gradient map of Colorado presents a more complete and detailed picture of geothermal gradient distribution in Colorado than was previously available. The map reveals that the geothermal gradient for most of Colorado is higher than the Western U.S. continental average of approximately 34°C/km (Nathenson and Guffanti, 1988). Several areas of Colorado have significant high gradient anomalies that may be indicative of economically viable geothermal resources. These areas include: Mt. Princeton Hot Springs (up to 167°C/km), Trinidad area (up to 141°C/km), Pagosa Springs (up to 119°C/km), Somerset area (>100°C/km), Bayfield (E of Durango; >90°C/km), Waunita Hot Springs (>90°C/km), Poncha Springs (>90°C/km), Mineral Hot Springs (>90°C/km), Rico (>80°C/km), Wagon Wheel Gap (SW of Creede; >80°C/km), Florence (>80°C/km), Wetterhorn Peak (Between Ouray and Lake City; >80°C/km), Delaney Butte (W of Walden; >80°C/km), Buffalo Creek (S of Walden, E of Steamboat Springs; >80°C/km), and numerous other anomalies of lower magnitude. Many other anomalies may exist but remain undiscovered because of the uneven coverage of the existing data set.

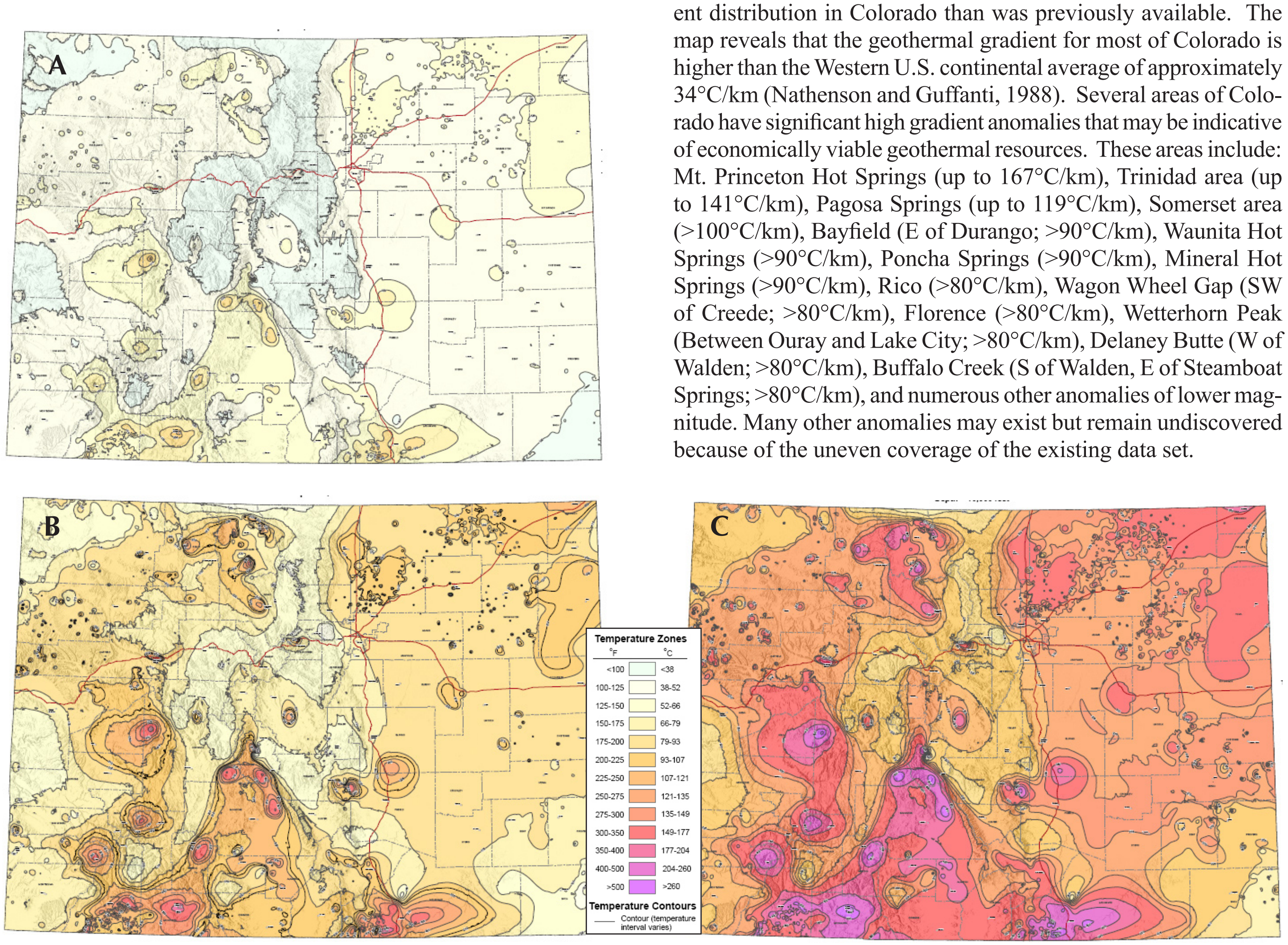

Figure 6. Projected temperature at three depths: A = 3,000 ft, B = 6,000 ft, and C = 10,000 ft (Berkman and others, *in prep*).

The geothermal gradient data were also used to produce "projected temperature at depth" maps for depths of 3,000, 6,000, and 10,000 feet (Figure 6). These maps were created by projecting temperature values for each gradient data point assuming a uniform gradient (with depth) at each location regardless of gradient reference depth.

Gradient Calculation Methods

Geothermal gradients were calculated by two primary techniques. If multiple temperature-depth measurements were available from a single drill hole or well, the longest section of measurements was taken in which the data define an approximately linear plot. The gradient was calculated as a linear least-squares fit to this sub-set of the data. When a drill hole or well contained multiple long sections for which gradients were calculated, the average gradient of the measured sections was used. This was the preferred method of gradient calculation and was used on a limited number of wells for which temperature log data was acquired. For most wells only one down-hole temperature was available. In these cases some estimate of the surface ground temperature must be made to derive geothermal gradient. The average geothermal gradient in the hole was then given by the difference between the down-hole temperature and the surface temperature, divided by the depth below the surface of the down-hole temperature measurement point.

Most single down-hole temperatures used for this map were bottom-hole temperature measurements (BHTs) made during well logging, typically at the completion of drilling, and recorded on the well logs. The remainder was data from drill-stem tests (DSTs). For wells with multiple DST's (~1000 wells) the temperature of the deepest DST was used and the depth was assumed to be the midpoint of this test interval. The temperatures measured in wells with only one DST (~2500) were also assumed to be located at the midpoint of the DST. About 94 percent of the selected DST intervals were located within 5 percent of the total depth of the bottom of the hole.

Air surface temperatures at each well 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. 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.

Mud circulation during drilling usually cools a volume of the formation surrounding the hole. Ten to twenty times the drilling time is required for a well to thermally readjust (equilibrate) to the undisturbed formation temperature (Bullard, 1947). When holes are logged specifically for temperature (multiple temperature measurements), time is usually allowed for the drilling disturbance to dissipate. BHT and DST temperature measurements made during or soon after drilling need to have the temperatures corrected to yield the undisturbed formation temperature. Corrections are approximate as they are primarily based on data outside Colorado but should yield more accurate geothermal gradients than the uncorrected data.

Two corrections were applied in sequence to BHT and DST data. Harrison et al. (1983) derived the first correction by comparing average BHTs from Oklahoma with reliable temperatures at the same depths, determined from the temperature readings from pressure tests, temperature logs, and (or), interpolations from reliable temperature gradients. This correction, T_{corr1} °C, was given as a function of depth, z, by Blackwell and Richards (2004b) as:

$$T_{corr1} = -16.51213476 + 0.01826842109z - 0.000002344936959z^2.$$

The correction, T_{corr1} °C, was added to the BHT recorded on the well log, so that the intermediate corrected temperature, T_{int} °C was given by:

$$T_{int} = BHT + T_{corr1} \text{ or } T_{int} = DST + T_{corr1}$$

The second correction was proposed by Blackwell and Richards (2004b) for differences between Oklahoma and other areas, and is based on the average geothermal gradient, ABG °C/km, in each basin, calculated after application of the Harrison formula. This second correction, T_{corr2} °C, is given by:

$$T_{corr2} = ((1.361609905ABG) - 33.21973078),$$

(M. Richards, pers. comm., 2008). The final corrected temperature, T_{final} °C, is then given by:

$$T_{final} = T_{int} + T_{corr2}.$$

The ground surface temperature was subtracted from this temperature, T_{final} (°C), and the result was divided by the depth of measurement, z (km), to determine the final geothermal gradient (°C/km).

Conclusions

The statewide geothermal heat flow and gradient maps of Colorado can be used to focus new exploration efforts in the state. The combination of various datasets available from other researchers, newly derived data points, and the oil and gas well industry have produced maps that are more complete and detailed than previous geothermal maps of Colorado. A review of the maps herein reveal the potential for conventional hydrothermal resources in several areas, but also the potential for enhanced or engineered geothermal resources in a much wider area, including a few warm sedimentary basins.

Acknowledgements

Funding for the this work was provided by the Colorado Governor's Energy Office (C900537, PO No. 06-34) through grants from the U.S. Department of Energy. The Colorado Geological Survey provided funding from Severance Tax Operational Account. Severance tax funds come from the production of natural gas, oil, coal, and metals.

Paul Morgan gave invaluable help through his review of this manuscript and collegial discussions of all things geothermal.

References

Berkman, F.E. and C.J. Carroll, 2008, Interpretive Geothermal Heat Flow Map of Colorado, Colorado Geological Survey Map Series 45 [CD-ROM].

Blackwell, D.D., and M. Richards, 2004a, Geothermal Map of North America, American Association of Petroleum Geologist (AAPG), 1 sheet, scale 1:6,500,000.

Blackwell, D.D., and M. Richards, 2004b, Calibration of the AAPG Geothermal Survey of North America BHT Data Base, American Association of Petroleum Geologists (AAPG) Meeting, Dallas Texas, 2004, Southern Methodist University Geothermal Lab Poster on BHT Calibration.

Blackwell, D.D., and M. Richards, 1989, Regional Heat Flow Database (Colorado), SMU Geothermal Lab - Geothermal Data Files, data file: Color89.csv, <http://www.smu.edu/geothermal/georesou/colorado.htm> Accessed May 3, 2006.

Bullard, E.C., 1947, The Time Taken for a Bore Hole to Attain Temperature Equilibrium., Monthly Notices of the Royal Astronomical Society, Geophysics Supplement, no. 5 p.127-130.

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>, accessed, 2008-09-03.

Dixon, J., 2002, Evaluation of Bottom-Hole Temperatures in the Denver and San Juan Basins of Colorado: Colorado Geological Survey Open-File Report 02-15, 41 p.

Dixon, J., 2004, Evaluation of Bottom-Hole Temperatures in the Canon City Embayment, Hugoton Embayment, North Park, Paradox, Piceance, Raton, and Sand Wash Basins of Colorado: Colorado Geological Survey Open-File Report 04-1, 44 p.

Harrison, W. E., M. L. Prater, and P. K. Cheung, 1983, Geothermal Resource Assessment in Oklahoma, Oklahoma Geological Survey, Special Publication 83-1, Norman, OK, 42 p., 3 plates.

International Heat Flow Commission, Global Heat Flow Database, International Association of Seismology and Physics of the Earth's Interior, site maintained by the University of North Dakota, data file: USA.xls, <http://www.heatflow.und.edu> Accessed May 3, 2006.

Nathenson, M., and M. Guffanti, 1988, Geothermal Gradients in the Conterminous United States, *J. Geophys. Res.*, 93(B6), p. 6437–6450.

Pollack, H. N., S. J. Hurter, and J. R. Johnson,1991, New Global Heat Flow Compilation, Univ. of Michigan, Dep. of Geol. Sciences, Ann Arbor. Michigan 48109-1063, USA.

Pollack, H.N., S.J. Hurter, and J.R. Johnson, 1993, Heat Flow from the Earth's Interior: Analysis of the Global Data Set, Reviews of Geophysics 31(3), pp. 267-280.