INTERPRETIVE GEOTHERMAL GRADIENT MAP OF COLORADO
COLORADO GEOLOGICAL SURVEY

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EXPLANATION OF MAPS

The Colorado Geological Survey publication Interpretive Geothermal Gradient Map of Colorado includes a compilation of geothermal gradient data in Colorado. Thermal gradient is the change in temperature over distance. Geothermal gradient values are a way to quantify the depth-temperature relationship for use in evaluating geothermal resource potential. In geothermal resource assessment, distance is the depth into the Earth provided by a borehole or well. Geothermal gradient is commonly expressed in units of degrees Celsius per kilometer (°C/km) or degrees Fahrenheit per 100 feet (°F/100 ft) [10°C/km = 0.55°F/100 ft]. Plates 1 and 2 show zones of geothermal gradient values as interpreted from gradient data points contained in the geothermal gradient database. Plate 3 illustrates projected temperatures at various depths based upon gradient data points. Geothermal gradient is a vector that actually changes in the horizontal and vertical directions. Practically, the maximum gradient within the Earth's upper crust is generally vertically downward because most heat moves down gradient from the Earth's hot interior to its cool surface. By convention, the negative sign of the geothermal gradient is ignored and only the magnitude of the vertical gradient is reported. This is the convention used in this publication.

The new geothermal gradient map (plates 1 and 2) shows that the geothermal gradient for most of Colorado is higher than the US continental average of ~35°C/km. 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 (>100°C/km), Pagosa Springs (>100°C/km), Trinidad area (W & SW of Trinidad; >100°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. Areas of high gradient translate into higher temperatures at a given depth. As a result, similar visual patterns are apparent in Plate 3, Projected Temperatures at Depth showing these anomalies as areas of higher temperature. Many other anomalies may exist but remain undiscovered because of the uneven coverage of the existing data set. Some of the sedimentary basins in Colorado including the Raton Basin (W & SW of Trinidad), the Denver Basin (N & E of Denver), and the San Juan Basin (S of Durango) have relatively high-gradient anomalies (>45°C/km), and deep drilling for hydrocarbons confirms temperatures in the range of at least 200 to 250°F in the depth range of 8,000 to 12,000 feet in these basins.

Geothermal gradients are calculated from measurements made in drilled wells. The geothermal gradient data herein were derived from several sources - dedicated geothermal test holes, mineral resource assessment drillholes, oil, gas and CO_2 wells, and geothermal wells. Domestic water-well data were not used in this compilation because, generally, they are not logged for temperature. 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). Heat flow data compiled by Blackwell and Richards (1989) and from the International Heat Flow Commission, Global Heat Flow Database for geothermal test holes and mineral resource drill holes are also contained in the database. Heat flow data are located primarily in the mountainous central and western portion of the state, and are geographically complimentary to the oil and gas data set. By combining these data sets, a more complete and detailed picture of geothermal gradient in Colorado is produced than was previously available. These data points are shown by small black dots on the map. In some areas, such as the Denver Basin and northeastern Colorado, the map appears to show fine detail in the gradient contours: The contouring is faithful to the data, but most of this area has a gradient close to 50°C/km and small fluctuations in the gradients that are within the error limits of the data push the local averages above or below the contour cutoff. Therefore, in general, detailed contours in this region, and other regions where contours oscillate back and forth about a single value, are probably not significant.

For plates 1 and 2 showing the Interpretive Geothermal Gradient Map of Colorado, contours of equal geothermal gradient were generated by computerized interpolation from the more than 17,000 gradient data points. Upon completion of this automated contouring, contours were manually adjusted to address unrealistic contour shapes generated as artifacts of the computerized contouring process. Further contour adjustments were made to provide control along the border of the State where known gradient data from adjacent states were incorporated into the contour interpretation. The boundaries of many geothermal anomalies lack precise control because of uneven data coverage. In areas of sparse data, hot spring temperature data were used to supplement the available gradient data. A relationship between spring temperature and expected gradient value was derived by plotting hot spring temperature against nearby drill hole gradient data for the Hortense, Cottonwood, Pagosa, and Shaws hot springs. The resulting least-squares best-fit linear equation, $G = 2.181T - 24.80$, 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.

Plate 3, Interpretive Geothermal Gradient Map of Colorado: Projected Temperatures at Depth, shows contours of projected temperatures at specified depths as interpolated through a computerized process using projected temperature values for each gradient data point assuming a uniform gradient (with depth) at each location. Projected temperatures in degrees Fahrenheit were contoured for depths of 3000, 6000, and 10,000 feet. Projected depth to boiling water (212 degrees Fahrenheit) under conditions of standard atmospheric pressure was also contoured. The tiles on Plate 3 show only projected temperatures (and projected depth in the "Depth to 212 Degree Fahrenheit" tile) which were interpolated from calculations made using all available gradient values regardless of gradient reference depth. In the deeper portions of the sedimentary basins the projected temperatures may correspond to depths at which temperatures were actually measured; elsewhere the temperatures have been extrapolated from measurements at shallower depths.

GRADIENT CALCULATION METHODS

Geothermal gradients are calculated by two primary techniques. If multiple temperature-depth measurements are available from a single drillhole or well, the longest section of measurements is taken in which the data define an approximately linear plot. The gradient is calculated as a linear least-squares fit to this sub-set of the data. When a drill hole or well contained multiple long sections that were measured in this manner and for which gradients were calculated, the average gradient of the measured sections was used. This is 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 is 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. The Gradient Data Source fields of the Colorado Geothermal Gradient Database and of the Colorado Geothermal Gradient Datapoints GIS feature class indicate the source of the gradient data and the method used in its calculation.

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) 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. Other factors contributing to errors in the data are random data recording errors and heat transport by groundwater flow, but the latter is considered to be part of the signal in this map.

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 (2004) 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:

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

The second correction was proposed by Blackwell and Richards (2004) 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).

In addition to the oil and gas well data, there are 214 gradient data points from the Colorado Geothermal Heat Flow database (multiple temperature measurements) included in this gradient dataset. These comprise most of the gradient data outside the sedimentary basins. Both the corrected BHT/DST derived gradients and gradients from the heat flow dataset were used in contouring the geothermal gradient map.

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