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Quantifying How Errors in Thermal Conductivity Estimates Affect Geothermal Production Models

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ABSTRACT

Thermal conductivity can vary significantly within a rock type, sometimes by as much as +/- 50% of published values. The large range for thermal conductivities can be caused by variations in composition, laminations, impurities, fractures, compaction, grain orientations, temperature, fluid content, and other factors. If published values for thermal conductivity are used in geothermal production models, rather than actual measurements, it is easy to overestimate or under estimate production temperatures over the life of a geothermal well. In a low temperature 3D model of paired geothermal injection and production wells, altering the thermal properties of only one rock layer resulted in production well temperature changes of over 5°C, ranging from +3% to -5% from the baseline production temperature.

Introduction

It has been shown that although thermal conductivity varies within a formation there are methods for obtaining more accurate estimates than just using a published "average thermal conductivity" for each rock type or even for a whole basin (Crowell & Gosnold, 2013). Quantifying how changes in the thermal conductivity values used affect production model results shows how important accuracy is. Modeling a paired geothermal injection and production well in a sedimentary basin allows individual input values to be altered to quantify how much error could be introduced to a production model if incorrect thermal conductivities are used.

Methodology

A simplified stratigraphic column, representing a hypothetical section of the Williston Basin is shown in figure 1. The column was constructed using average formation rock types and average formation thicknesses from the North Dakota Stratigraphic Column and (Murphy et. al., 2009). The result was a 3360 meter column with 19 layers, of varying thicknesses. Each layer represents either a single formation or a series of formations with similar bulk composition. Seven rock types were used in the model, shown in Table 1. Water was used as the geothermal fluid, rather than brine, to further simplify the model.

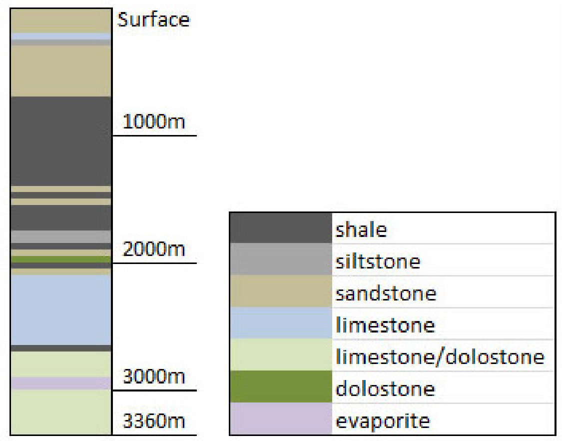


Figure 1. Stratigraphic column used in the model.

The model used was a finite difference model that calculates temperature for each cell in the model approximately once every

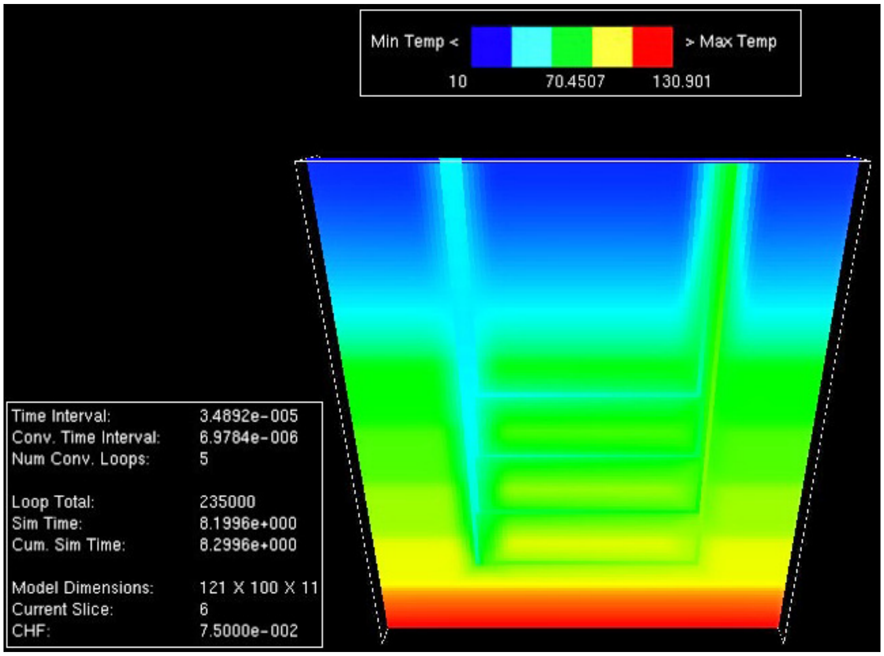
Table 1. Rock types and thermal conductivities used in the model, thermal conductivities are averages of core samples I measured using a divided bar apparatus.

Rock Type	Thermal Conductivity (W/mK)
Shale	1.20
Siltstone	1.60
Sandstone	1.60
Limestone	2.50
Limestone/Dolostone	3.10
Dolostone	4.00
Evaporite	4.00
Water	0.58

two minutes of the model duration and the model was run for 30 years in each iteration, simulating the expected 30 year lifespan of a power plant. Thermal capacity, thermal conductivity, radiogenic heat production, starting temperatures, water flow speed, water flow direction and cell size are set for each individual cell in the model. A 100 x 121 x 11 cell model was built representing a 73m thick slice, 794m long and 3360m deep. The model ground surface was held at a constant 10°C. Heat flow at the lower boundary of the model was held constant at 75mW/m^2, which is slightly higher than most of the heat flow measurements in the Williston Basin, but still lower than the highest recorded value of 87 mW/m^2 (NGDS, 2015).

Radiogenic heat generation was set to zero for all the layers in the model except the shales. Specific measurements of radiogenic heat production from cores from the basin were not available, other than a few shale samples, which were found to produce about 2.0 μW/m^3. This heat production value was applied to all the shale layers in the model since it fell within published ranges for shale in general (Rybach, 1986; Keen and Lewis, 1982). Heat generation in other sedimentary rocks can vary from almost zero up to a few μW/m^3 (McKenna and Sharp, 1988). The heat flow at the lower boundary of the model was adjusted to make up for zero values for heat production in most of the layers. The heat flow value of 75 mW/m^2 was chosen by repeatedly running the model for 10,000 years with different heat flow values until one was found which maintained a steady state temperature of 130°C at the base of the model. The temperature of 130°C was chosen because it is the median temperature 3km deep in the Williston Basin (Crowell et. al. 2011).

The injection and production wells, although not circular in the model, equate to a pipe with a 22.6cm (9 inch) diameter. Injection and production rates were held constant at 2280 L/min (600 gal/min) over each 30 year run. The water was injected at a constant 40°C (104°F) into a limestone aquifer extending from 2,100m at its top to 2,660m deep at its base. The injection and production wells were located 400m apart, centered in the 73m x 794m ground surface of the model. For simplicity of modeling, and to be presenting a worst case scenario, water flow paths were designed as four short-circuits rather than an extensive crack network. The short circuits were four large linear 'cracks' that were 10cm tall x 10cm wide x 400m long. Cells near the injection and production wells, as well as cells near the 'cracks,' were given reduced width and height and thickness to improve model accuracy by reducing the error introduced by the decimal place limits and rounding in the software. Cell size was gradually increased moving away from the pipes and 'cracks', with most of the cells in the model being 10m wide and 50m tall. The thickness of the 11 slices, and therefore the cells in each slice, decreased from 20m thick in the front and back slices down to 10cm thick in the slice containing the wells and cracks. Figure 2 shows the center slice, containing the wells and 'cracks' after eight years of pumping. Because every cell is visually the same size, despite representing different dimensions, it gives the appearance that the reservoir is about half of the basin rather than less than one sixth.



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Time Interval:          3.4892e-005
Conv. Time Interval:    6.9784e-006
Num Conv. Loops:        5

Loop Total:             235000
Sim Time:               8.1996e+000
Cum. Sim Time:          8.2996e+000

Model Dimensions:       121 X 100 X 11
Current Slice:          6
CHF:                    7.5000e-002
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Figure 2. Center slice of the 3D model, showing the injection and production wells and the 'cracks' through which the water is flowing.

For each rock type in the model, an average thermal conductivity was used, although the averages were from my measurements of core samples from the Williston Basin rather than from published lists. Water flow was then initiated in the injection and production wells, as well as through the short circuits and the model was run for 30 years to obtain a baseline production temperature. Thermal conductivity values for three of the rock types in the model were then altered incrementally to determine the effect on a 30 year production run. The model reached a quasi-steady state production temperature within the first few months of the 30 year run with production temperatures changing less than 2 degrees from year 1 to year 30. Table 2 shows each run and what thermal conductivities were changed. In each model run, any rock types not listed for that run in table 2 were using thermal conductivity values from Table 1.

Limestone was chosen to be one of the rocks varied because it was the reservoir rock and because of the rock types in the basin, limestone and sandstone tend to have the most thermal conductivity variability. Limestone can vary tremendously based on parameters such as the presence or absence of silty laminations, varying amounts of the calcite turning into dolomite or varying porosity. The thermal conductivity of sandstone can vary based on mineral content, cement type, compaction and other factors. Shale was varied in one run to see if changing the conductivity of an insulating layer above a reservoir had more or less effect than changing the conductivity of the reservoir itself.

Results

Table two shows the changes to thermal conductivity and resulting changes in production temperature for each run of the model. As expected, when the reservoir rock has higher thermal conductivity it results in higher production temperatures and when the reservoir rock has lower thermal conductivity then production temperatures are lower. When rock layers above the reservoir have lower thermal conductivity the production temperature is increased, due to the insulating effect. The increase in production temperature does not increase linearly with the increase in thermal conductivity of the reservoir rock, as shown in Figure 2.

Table 2. Thermal conductivities changed in each run and the resulting production temperature changes.

Run #	Rock Type(s) Changed	Thermal Conductivity Used (W/mK)	TC % Change From Average	Production Temp (°C)	% Change in Temp
1	none (base line)	-	-	66	(base line)
2	Limestone	3.50	+ 40%	68	3.03%
3	Limestone	3.00	+ 20%	67.1	1.67%
4	Limestone	2.00	- 20%	64.45	-2.35%
5	Limestone	1.50	- 40%	62.3	-5.61%
6	Limestone and Sandstone	3.50 and 2.24	+ 40%	67.2	1.82%
7	Limestone and Sandstone	3.00 and 1.92	+ 20%	66.7	1.06%
8	Limestone and Sandstone	2.00 and 1.28	- 20%	64.9	-1.67%
9	Limestone and Sandstone	1.50 and 0.96	- 40%	63.2	-4.24%
10	Shale	0.96	- 20%	66.3	0.45%

Discussion

The assumptions and simplifications of parameters in the model are intended to be conservative and better isolate the effects of varying the thermal conductivity, so that the results are not overstating the effect being tested. One thing which was not done, but may seem like an oversight, is the system was not brought to a new equilibrium by running it for 10,000 years with no pumping after each new thermal conductivity value was added. The reasoning behind this is that often a temperature profile is known, or at least estimated from a bottom hole temperature. So no matter what thermal conductivities are used in a geothermal production model, the initial temperature profile will be based on measured values and will not change even if incorrect thermal conductivity estimates are chosen. I therefore kept the same initial temperature profile for every test run and only altered the conductivities, to better represent how an error in thermal conductivity could affect the results even if all other model parameters were accurate.

As thermal conductivity of the reservoir was changed the temperature of the water at the production well head changed in the direction expected, but it is important to note that there was not a linear relationship between the thermal conductivity and the production temperature. Figure 3 shows the relationship between thermal conductivity and output temperature. When considering the thermal conductivity of the reservoir rock, each increase resulted in a smaller and smaller increase in modeled production temperature, meaning that a larger error is introduced by under estimating reservoir thermal conductivity than by over estimating it. The reverse trend applies when considering the thermal conductivity of layers above the reservoir, as seen by how changing the conductivities of the sandstone layers above the reservoir affected the modeled production temperature. When they were increased with the limestone, or decreased with it, the change in modeled production temperature was dampened slightly. If the sandstone conductivity was reduced when the limestone conductivity was increased then a larger increase in predicted production temperature would result.

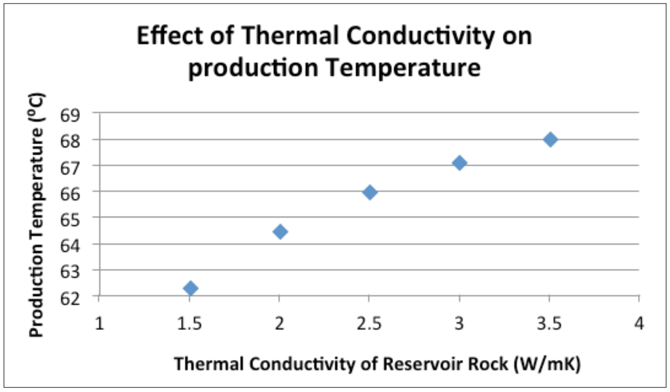

Figure 3. How production temperature changed when just the thermal conductivity of the reservoir was changed; run #s 1 through 5 from Table 2.

Although this model was run at low temperatures, such as are seen in the Williston basin, it is assumed that the same trends will hold for high temperature resources.

More work needs to be done to test if errors in thermal conductivity have a greater or lesser effect as resource temperature increases by running similar models with higher temperature gradients. It is expected that the effect will be greater as temperature increases. If multiple layers in a model have incorrect thermal conductivities assigned it is possible that the errors will cancel each other out or that they will enhance the effect, like constructive or destructive wave interactions, potentially resulting in errors greater than the 5.6% observed in this model. In reservoirs with temperatures in excess of 250°C, it is not unreasonable to assume errors in thermal conductivity estimates could result in models with production temperature errors of 10°C (4%), or more.

Conclusion

This work shows that using inaccurate thermal conductivity values when modeling a geothermal system can result in substantial errors in geothermal well production temperature estimates. When production temperatures are under estimated it could result in project cancelation, with investors incorrectly assuming the resource is not worth developing. When production temperatures are over estimated it could waste time and money developing a site that will never be profitable. Having more thermal conductivity measurements publicly available and having better methods of estimating thermal conductivity in specific places is vital, otherwise large levels of error and uncertainty are introduced to geothermal production models.

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