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Evaluation of EGS Resources in the Eastern United States: Illinois, Michigan, Indiana, Western Ohio and Western Kentucky

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ABSTRACT

The large amounts of data from oil and gas wells include bottom-hole temperature and depth of measurement. But these temperatures need to be corrected because of drilling disturbances and these data alone are not sufficient for heat flow calculation. The temperature data after correction may be used to determine the well gradient. In order to calculate heat flow the thermal conductivity of the lithologic section encountered in the well is also necessary. The stratigraphic columns from the AAPG COSUNA data set were used to determine the lithology of each well along with the AAPG sediment thickness map. Thermal conductivities were assigned for each different rock type based on previously published values. The thermal section data were used to calculate mean conductivity for each well and by combining this value with the BHT data, heat flow was calculated. A comparison of the calculated heat flow to published values gives an accuracy of ±20 in percent for most borehole groups. After filtering, this method has added approximately 800 data points in the states of Illinois, Indiana, Michigan, and Ohio. The new heat flow map shows some interesting correlations to geophysical data (gravity and magnetics) that may identify the lithology of the basement. The results support the hypothesis that heat flow variations can be inferred based on some characteristics of the geophysics of a given area. The new heat flow map is more detailed and has shown that areas of the Midwest for focused future research and geothermal development can be defined.

Introduction

The most recent version of the Geothermal Map of North America (GMNA) published by Blackwell and Richards (2004), defined in detail the heat flow of the Western United States, yet the Eastern United States only had a few tens of points for all the area east of the Mississippi River. This sparse data meant that a heavy weight was placed on the few existing heat flow measurements. In areas such as the Illinois and Michigan basins, where there were very little detail, general trends were used. The increased interest in renewable energy resources has given the opportunity to acquire funding to fine tune the process of using well log data from the oil and gas industry, and other existing data sets not previously considered to calculate heat flow for the Eastern United States. This lack of data and the goal of enhanced geothermal systems (EGS) development nationwide have fueled a search for additional thermal data in the Eastern United States.

The study area presented herein focuses on the Midcontinent Basin and Arches Region of the Correlation of Stratigraphic Units of North America (COSUNA) project. No new data were collected for Wisconsin, Iowa and Missouri due to shallow sediment cover and lack of hydrocarbon exploration drilling. The Illinois and Michigan basins have data from the petroleum industry that can be used with proper corrections to explore the geothermal potential of the region. Temperature-at-depth maps have been calculated and these maps show greater variation in temperatures than calculated previously for the MIT Future of Geothermal Report (Tester et al., 2006). This paper is a subset of the overall research focusing on the the states of Illinois, Indiana, Michigan, western Ohio, and western Kentucky.

Data

The primary source of information used in this geothermal assessment for the Midcontinent (primarily focused on Michigan, Illinois, Indiana, Ohio, and western Kentucky) was oil and gas well data compiled by the AAPG Geothermal Survey of North America (AAPG, 1994) (Figure 1). This compilation included a selected sampling of wells drilled for oil and gas exploration up to about 1972. Bottom-hole temperatures (BHT) data were also collected from Indiana, Kentucky and Ohio Geological Surveys where there has been extensive drilling since the 1970s. The increase in data is obvious, especially in the Illinois and Michigan basins. An explanation of the steps taken to correct BHT data, as well as other rediscovered data and the results follow. The process is discussed in detail in Blackwell et al. (2010).
Starting with the BHT from a well log header, a correction was made. Raw BHT data represent a rudimentary temperature measurement, because logs are usually collected soon after drilling and the well has not had enough time to equilibrate from drilling disturbances. The Harrison correction curve is applied to BHT data in this study as a first attempt to correct temperature (Harrison et al., 1983). After the Harrison correction is applied, there is still an issue with shallow (<600 m) and deeper wells (4 km) because of the parabolic form the Harrison correction curve makes. Any point less than 700 m was removed from this study to account for seasonal and drilling near surface effects. The corrected BHT is assumed to represent a near equilibrium temperature and is used to calculate geothermal gradient. When there are multiple BHT values for one well, the average gradient for the well is calculated.

BHT is a large data resource but the accuracy is less than desired as discussed by Blackwell et al. (2010); the better resource are high resolution - equilibrium temperature logs. These are very rare in this Midcontinent area. A temperature log has two primary purposes for this study: it provides a more accurate data site and is used as a calibration check for BHT data points in the nearby area. The Illinois and Michigan basins are the regions enclosed by the dashed lines labeled IL and MI, respectively.

Thermal conductivity measurements were calculated for each individual BHT point to calculate heat flow. The average conductivity of the well would be calculated as follows: the thermal conductivity of a formation is multiplied by the percentage of depth that layer occupies within the well giving it a weighted value. This calculation was done for every individual lithologic layer in an area based on the COSUNA stratigraphic section and lithology information available in the literature. This value was used as the mean thermal conductivity for BHTs according to the depth of the temperature measurement. In determining the lithology and thickness, the COSUNA stratigraphic charts were used within an area and sections were normalized to the local sediment thickness map (AAPG, 1978). This was necessary because the two data sets were not co-located. This process should give a better estimation of conductivity in wells by constraining the thickness of different layers; however, a better approach would be to have cross-sections or lithology logs specific for each well. Time and lack of access to digital logs precluded this more detailed approach. Average conductivities for individual rock types were collected from previous literature for similar age rocks in the Midcontinent and used in the calculation for average conductivities of each well (Gallardo and Blackwell, 1999 and Carter et al., 1998). Any conductivity for a specific rock unit would be used when it could be found and correlated to a unit in the respective COSUNA section (e.g. the Salina Formation in the Michigan Basin) (Leney, 1955). This same conductivity determination method was used for both data sets, BHT and existing temperature logs.

Figure 2 shows the new heat flow map for the study area including interpolations for the areas surrounding the focused areas. The most notable change from the Geothermal Map of North America (2004) is the increase of detail in the parts of the map occupied by the Michigan and Illinois basins. The heat flow values range from about 30 mWm² to over 70 mWm², typical for the eastern 2/3’s of North America.
Basement Information

Basement geology can have an effect on the heat flow of a region because of the variance of radioactivity due to different crustal compositions. This information would have great importance for interpolations between existing heat flow data. This becomes a problem, however, when basement is also unknown. Previous attempts have been made to correlate heat flow with other geophysical maps, primarily gravity and magnetics and a combined approach is described in Blackwell et al. (2010) and applied for this study. In comparing the calculated heat flow to the gravity-magnetic map, two areas of interest were seen in Michigan and Ohio with the geophysical maps.

The basement depth below the Michigan Basin varies from near surface on the edges to over 5000 m at the center. Some assumptions about the basement composition can be made from well data, but are not conclusive since there are not core samples to the basement throughout the basin (Brewster and Pollack, 1976). It is also known to vary because of the location of the Mid-Continent gravity high (also a magnetic high) running through Michigan associated with mafic rocks. The established position of this feature makes Michigan a good area to examine the hypothesis of a correlation between gravity and magnetics and heat flow. The general thought is that a gravity high and magnetic high would be associated with mafic to ultramafic rocks. These rock compositions have low levels of the radioactive elements uranium, thorium and potassium and should then be associated with a low heat flow; likewise the opposite, a low gravity and low magnetics pattern could be associated with a large sediment thickness or felsic igneous bodies, either of which (but especially the latter) might have higher radioactive element concentrations. A map correlating gravity and magnetics was compiled and this correlated gravity-magnetics map was compared to the new heat flow map of the Eastern US (Blackwell et al., 2010).

One correlation example is a well drilled in Ohio. The bottom of the drill hole enters a gabbro intrusion in the Eastern granite-rhyolite province (Ryder et al., 2008). The position of this well is shown with its position on the gravity and magnetic correlation map and in the subset map on the right (Figure 3). It correlates with a small positive gravity and positive magnetic anomaly as shown by the green color. This well supports the idea of using the correlation map to determine small geothermal areas within a region as a starting point for data collection.

To further test this hypothesis Michigan has been evaluated in detail. Figure 3 shows the heat flow data overlaid on the gravity-magnetic map. The higher heat flow measurements are seen to follow the diagonal yellow trend in the south-central region of Michigan. There is a less defined relationship in the northeast section of the state where there are the high heat flow points with a broad yellow area symbolizing a low gravity and a high magnetic signature. These relationships are clear and follow the stronger anomalies shown in the map. Consequently, gravity and magnetic data appear to be a valid estimation tool in areas where heat flow data are limited and if the geophysical anomalies reflect the crustal composition assumed as shown in the model used in this project (Blackwell et al. 2010). There will however, be areas where the basement geophysical anomalies will not give such definitive results.

Temperature Data and Interpretations

New temperature at depth prediction and the analysis of the potential for EGS were the primary goals of this study. Temperature calculations were modified slightly from the technique described in the Future of Geothermal Energy report (Tester et al., 2006; and Blackwell et al., 2007). These calculations assume a one or two layer model and make generalized assumptions of conductivity. The conductivity calculations for this study are thought to be more accurate because of the use of the COSUNA for more site specific thermal conductivity averages for the sediment section. Figure 4 is an example of the changes between the previous and updated temperature maps. There is a general increase in temperature when comparing equal depths, except for Illinois. This overall temperature rise implies more EGS potential in some of the Midcontinent states assessed in this project. Most notable areas in this section are Louisville, Kentucky, and Cincinnati, Ohio. Temperature anomalies have been calculated in the region around these two cities with the potential to enter the energy market because of the nearby population centers. Northeastern Michigan is another area to be considered for further review.
Comparison of the two models reveals the increase in detail of the new map. This increased detail can be attributed to the increase in data of this region. Previous assumptions were made and interpretations given in a very broad manner, but now smaller scale anomalies can be identified. The correlation between gravity and magnetic data with heat flow can be directly applied to the contouring of temperature maps where data are still sparse.

Conclusions

This study has improved the resolution of the Geothermal Map of the United States (2004) by increasing the number of data points using BHT data where available. In general inferred temperature-at-depth has increased in the study area implying more potential for EGS resources. Small scale anomalies are now visible on the map providing evidence that site specific EGS resources are available in the Eastern United States. Temperatures, however, are still an issue. Even at a depth of 7.5 km the highest temperatures are still below 250°C. This implies that the primary inhibitors are technology for low temperature reservoir electricity production, drilling costs, and no near surface resources.

The results have verified that BHT is a viable resource for heat flow calculations. Both temperature and conductivity are still problematic when only a depth and temperature are given. The drilling disturbances affecting temperature are appropriately accounted for by the Harrison and SMU Geothermal Laboratory corrections although these are not exhaustive and can be improved; likewise, accuracy was increased for conductivity estimates using COSUNA sections and previous research. Accuracy will be improved further when well cores are collected and the thermal conductivity measurements of lithologies are available for detailed stratigraphic sections.

Geophysical measurements of the gravity and magnetic anomalies can be a good proxy to interpolate heat flow trends where measurements are scarce. The most correlated are two positive anomalies and two negative anomalies following low and high heat flows, respectively. These major trends can be used for almost all points, even when it is a single intrusive, as seen in Ohio. Less correlated are the smaller anomalies resulting in mixed gravity and magnetic highs and lows. These could represent intermediate rock types where radioactivity can be more site specific, or is more precise than current measurement techniques will allow. The best way to find a better correlation is more research into these subtle anomalies with more heat flow data. In the same regard, more research needs to be done in areas where correlations to the gravity-magnetic map were not as clear so a better understanding can be gained. Future research for this project specifically will include further data collection from entities like the Illinois State Geological Survey, and the Ohio Geological Survey. The goal of this continued research will be to increase detail to the Geothermal Map of the United States, identification of more potential geothermal systems, a procedure for transforming BHT into a reliable heat flow data point, and an increase in knowledge of the correlation between gravity, magnetics, and heat flow.

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References


