NOTICE CONCERNING COPYRIGHT RESTRICTIONS

This document may contain copyrighted materials. These materials have been made available for use in research, teaching, and private study, but may not be used for any commercial purpose. Users may not otherwise copy, reproduce, retransmit, distribute, publish, commercially exploit or otherwise transfer any material.

The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted material.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specific conditions is that the photocopy or reproduction is not to be "used for any purpose other than private study, scholarship, or research." If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of "fair use," that user may be liable for copyright infringement.

This institution reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve violation of copyright law.
Geothermal Opportunities of Southeastern United States

Nicole Sica, David Blackwell, Zachary Frone, and J. Park

Huffington Department of Earth Sciences
Southern Methodist University, DallasTX
nsica@smu.edu

ABSTRACT

This paper discusses Kentucky, Tennessee, northern Alabama and northern Mississippi, with concentration on Kentucky. The object of the overall project was to build an eastern US heat flow map. Variables studied included conductivities, bottom hole temperatures, existing heat flow data, lithologies and thicknesses, stratigraphic correlation, calculated resistances, depth and calculated heat flow. Purpose of study is for future development of Enhanced Geothermal Systems in the eastern United States. Kentucky was the focus for this study due to the amount of information available. With this focus there are three areas of interest that are shown to exhibit anomalies and are in need of further research to understand the geothermal significance of these anomalies. Along the Rough Creek fault zone high gradients are associated with deep wells. Although the heat flow map does not reflect this, the thick shale sections within this area may be the reason. Mid state has areas of high heat flow and don’t seem to be affected by the fault system (Cincinnati Arch) within the area. This mid state area does not have large beds of shale. The area of the Pine Mountain thrust fault has intermediate to high heat flow values and gradients. Ongoing research from others show that the West Virginia fault system that is a conjunction of the Pine Mountain fault system has high heat flow values as well. One conclusion is that with further information, research may also show high heat flow values from fault systems going into Tennessee along the eastern border of Tennessee and Kentucky.

Introduction

The purpose of this study is to develop a resource basis for future development of geothermal systems in eastern United States. Geothermal power is cost effective, reliable, sustainable, and is a baseload resource. Due to this, geothermal energy has been developed worldwide. This study focuses the construction of a new eastern United States heat flow map. Of the four major geothermal resource categories, hydrothermal, geopressured, magma, and conduction-dominated (Hot Dry Rock (HDR)/Enhanced Geothermal Systems (EGS)), this paper highlights two possibilities: hydrothermal and conduction-dominated (Hinze, 1986).

Geology

Stratigraphy

An understanding of the stratigraphy and hydrogeology of Illinois, Indiana, Ohio, Kentucky and Tennessee area is needed to understand the underlying basement and heat flow effects. In the Blue Ridge Providence of the eastern Tennessee, Precambrian igneous, metamorphic and sedimentary rocks are at land surface. Elsewhere, these rocks are buried beneath younger rocks with a thick sequence of Paleozoic consolidated sediment above them. The Precambrian rocks have been warped due to tectonic forces, creating arches, domes, structural basins and fracture systems. Within the arches and domes, freshwater can be obtained from water-accruing rocks at land surface or at shallow depth. On the contrary, deeply buried water-accruing rocks within the basins, mostly contain saltwater or brine. In consideration of the underlying aquifers of the major fault systems of interest, vertical displacements/faults could cause upward migration of hot water. As groundwater is heated by deep circulation and then is trapped by an impermeable barrier, a potential hydrothermal resource could form.

In the study area, the distributions of Paleozoic rocks are controlled by positioning of the arches, domes, structural basins and faults. Ordovician rocks are at land surface or at tops of arches and domes. Pennsylvanian strata are present within the Appalachian Basin in SE Ohio and within the Illinois Basin in central and southern Illinois, SW Indiana, and NW Kentucky. Also, within the Appalachian Basin of Ohio, Permian strata are found. Where as in the eastern part of Kentucky and east-central part of Tennessee, within the Appalachian Basin, only Pennsylvanian aged strata exists. The Mississippi Embayment, in the western parts of Kentucky and Tennessee and in southern Illinois, contains Paleozoic rocks that have been covered by sedimentary rocks of late Mesozoic and Cenozoic age. These deposits vary in thicknesses from 100-3,000 feet from the northern and eastern end to the southwestern tip of Tennessee.
Structure

Kentucky includes parts of four major structural provinces, the Illinois Basin, Appalachian Basin, Cincinnati Arch and Mississippi Embayment. These structures are said to initiate before the mid-Paleozoic and are broad, shallow, crustal warps; except for the Appalachian Basin, with its extensive structural relief of ~1-2 miles. These structural provinces locally have been contorted into smaller gentle folds and cut high-angle faults & grabens. Kentucky, physiographically speaking, can be characterized as a series of dissected plateaus and gently rolling plains separated by scarps (Newell, 2001). Locally, the most important of the several major fault systems are the Kentucky River, Irvine-Paint Creek, Lexington, and Rough Creek fault systems.

The Illinois basin is a major structural downwarp taking up large parts of Illinois, Indiana, and Kentucky. Within the basin, major structural features include the Rough Creek and Pennyrile fault systems, the Moorman syncline and the Illinois-Kentucky flurospar district. Of specific interest to this study, the Rough Creek fault zone is made up of numerous high angle faults, some reverse faults, horsts and grabens.

The Cincinnati Arch, a pronounced regional uplift, expands from the Nashville Dome in central Tennessee through central Kentucky to NW Ohio. This structural province separates the Appalachian Basin from the Illinois and Michigan Basins. Major structural elements include the Jessamine/Lexington dome, Cumberland saddle, and the Lexington, Kentucky River & Irvine-Paint Creek fault systems. This structural province is dominated with numerous minor normal faults and grabens.

Appalachian Basin forms a part of the Cumberland Plateau and is denoted at the surface mainly by strata of Pennsylvanian age. The basin’s sedimentary rocks are of Precambrian to Early Permian age and can reach thicknesses of about 35,000 feet in some places. Sedimentary thicknesses can cause altering affects on calculated heat flow. The basin contains many structural features. Those including, Cumberland Plateau in Kentucky and Tennessee, Pine Mountain thrust fault, Kentucky River and Irvine-Paint Creek fault systems, and the Waverly Arch. Specifically, the Kentucky River fault system (a concealed system that extends into West Virginia) and Pine Mountain overthrust fault (a ramp on a bedding plane thrust that underlies the Middleboro syncline, as well as, a fault that brings Devonian and younger rocks over the Pennsylvanian rocks with a total displacement of ~7.5 miles (McDowell, 2006)).

Mississippi Embayment is comprised of mostly NE-trending, high angle normal faults that displace Paleozoic rocks along the east and northeast borders of the Jackson Purchase. Concelled within the embayment, specifically beneath the Cretaceous and younger sediments, are faults of the New Madrid and Ste. Genevieve fault zones. The axis of the embayment coincides with the Mississippi River and Jackson Purchase.

Tennessee contains five major structural features: Unaka Mountains; Valley & Ridge; Cumberland Plateau; Eastern Highland Rim, Central Basin & Western Highland Rim; and the Mississippi Embayment/Coastal Plain.

Precambrian Basement

Across most of Kentucky, Tennessee, northern Mississippi and northern Alabama, is the Eastern granite-rhyolite province (1.5-1.4 Ga). It extends just slightly east of the Grenville thrust fault. Although most of the northern part of Mississippi is the Eastern granite-rhyolite province, a younger province (1.4-1.35 Ga), Southern granite-rhyolite province protrudes it (Figure 1A & B). Ranges represent areas of high heat flow, while sedimentary heat flow depends on underlying basement.

![Figure 1. A. Precambrian basement geology with basement structures overlying a gravity & magnetic map. B. Shows same map with a blown up concentration of study area. Colored dots represent SMU heat flow points.](image)

Data

Data have been collected from various sources including: American Association of Petroleum Geologists (AAPG)/Geothermal Survey of North America (GSNA), Correlation of Stratigraphic Units of North America Project (COSUNA), Spicer, Kentucky Geology Survey (KGSweb), United States Geological Society (USGS) and Southern Methodist University (SMU) internal databases. Figure 2 shows a data density map, as well as color coded origins of data.

The type of data analyzed were that of calculated thermal conductivity and resistance, bottom hole temperature, existing heat flow data, lithologies and thickness, stratigraphic correlation, and calculated heat flow. For each COSUNA area, there are temperature-resistance curves (Figure 3A), temperature-depth curves (Figure 3B) and histograms of heat flow. Data for bottom hole temperatures were gathered from various sources: AAPG/GSNA, KGSweb, and published USGS well data. BHT values used have been applied with our correction. Resistance values were calculated using COSUNA stratigraphic data (lithologies, thicknesses and conductivities). This was then used for the making of the heat flow map.

The temperature versus depth chart shown in Figure 3B, shows high bottom hole temperatures with depth. These KGSweb bottom hole temperatures get higher closer to the fault system (Pine Mountain). Figures shown represent data within COSUNA SA-19...
area (Figure 2). SA-19 is in the Pine Mountain overthrust fault system. Other COSUNA areas (ie. SA-18, SA-20, & SA-21) reflect higher temperatures with depth in this fault system. Further into Tennessee it becomes harder to demonstrate due to lack of data. It is presumed to have the same outcome, since SA-19 is near the border of Kentucky and Tennessee.

Another constituent to these potential anomalies are the high gradients with depth. Rough Creek fault system shows very high gradients with depth, but give low heat flow values. This may be due to the very thick shale beds in the region skewing the heat flow data. Shale leads to low conductivities which lead to low heat flow values. Meaning, that what is shown is not necessarily correct. Heat flow is not only a determinant on structure but it is on lithology as well.

Heat Flow

Within Kentucky, there are three areas that exhibit anomalies. Identification of these anomalies is preliminary and is in need of further research to see whether or not they stand true or not. Along the Rough Creek fault zone the results indicate high gradients with deep wells. The heat flow map does not reflect this, the very large shale beds within this area may be the cause. Mid state Kentucky show areas of high heat flow and don’t seem to be skewed by the fault system (Cincinnati Arch) within the area. This mid state area does not have large beds of shale. The Pine Mountain thrust fault shows intermediate to high heat flow values and gradients. Ongoing research from others shows that the West Virginia fault system that runs into this Pine Mountain fault system, has high heat flow values as well. One conclusion is that with further information, research may also show high heat flow values from fault systems going into Tennessee along the north central-northeastern of Tennessee.

The Grenville thrust fault system exhibits interesting and promising characteristics. The fault system starts in Michigan and extends to northern Alabama. At fault intersections with this N-S structure, high heat flow appears. Hence, heat flow is related to the Grenville fault structure and these affects in the north could quite possibly be running down dip. Figure 4, designated areas (shown in black...
circles) show where such anomalies may occur along the Grenville thrust fault. The limited data that we do have along this fault system shows the wells to have high temperatures with depth. Again, in order to be sure of this hypothesis, more data is needed.

**Geophysics**

**Seismology**

Two significant intraplate seismic zones impact the Tennessee Valley, the New Madrid Seismic Zone (NMSZ) and the Southern Appalachian Seismic Zone (SASZ). The New Madrid Seismic Zone envelops most of the central Mississippi Valley, as well as parts of the lower Ohio River Valley and the Wabash River Valley. It is related to the Reelfoot rift. The Southern Appalachian Seismic Zone is an intraplate seismic zone that is caused by reactivation of Precambrian age faults in the crystalline basement beneath the younger sedimentary rocks. The tectonic stress regime for both seismic zones is oriented nearly horizontal and trends east-northeast to west-southwest (Munsey, J.W.).

**Gravity and Magnetics**

Figure 1A & B, provide maps showing gravity and magnetic anomalies across mid-eastern United States with heat flow points. Areas of importance are shown in blue and yellow. Blue represents corresponding negative gravity and negative magnetic anomalies, thus indicating possible high heat flow. Yellow, represents negative gravity and positive magnetics, possible high heat flow as well, but less certain in every case, due to the type of lithology and sediment thickness. The yellow is variable. Green indicates low heat flow. Positive magnetic anomalies don’t necessarily indicate mafic rocks, which give low heat flow values, just mafic minerals. The yellow and blue areas indicate potential high heat flow areas. Figure 5, shows that in areas with few data points, specifically mid Kentucky and all of Tennessee, proposed areas correlate with the assumption of high heat flow. With further data such could be concluded or disproved? The proposed fault structures present on this figure correlate with the potential high heat flow areas.

**Temperature at Depth**

Shown in the next two figures, Figure 6A and Figure 6B, are maps of temperature variation at 10 km depth. Figure 6B, also shows the major fault systems of Kentucky, Tennessee and Alabama. The Pine Mountain thrust fault system shows warmer temperatures with depth. Propose with further research that there could be even higher temperatures with depth, due to fault leakage from the upper connecting fault systems in West Virginia. This could also lead to further fault leakage downdip to the fault system in Alabama. Also in Figure 6B, proposed areas along the Grenville thrust fault shown in Figure 4, show a lot of promise with the higher temperatures carry on throughout 10 km depth.

![Figure 5. Gravity and Magnetic map with fault structures and basement structures. Also indicated are the fault systems discussed throughout paper.](image)

**Summary**

The purpose of this study is for future development of Enhanced Geothermal Systems in eastern United States. Various types of geophysical and geological data used throughout this study have given promising outlooks for the specified areas of interest. The proposed high heat flow starting in West Virginia, along the Pine Mountain thrust fault system, into fault systems
in Tennessee, could be true with further data and research. The study shows the same amount of potential in the Cincinnati Arch throughout mid Tennessee, upper Alabama, mid Kentucky, and the arch’s surrounding fault systems (i.e. Lexington fault system) in mid Kentucky. With the Grenville thrust fault interaction with these fault systems being a major constituent to this potential. With further data and research, this potential vision could become a reality.

References


Kentucky Geological Survey, University of Kentucky, 2006, Beneath the Surface (Geologic Structures) http://www.uky.edu/KGS/geology/beneath.html

KGSweb, Kentucky Geological Survey, University of Kentucky, Data Searching, Oil & Gas


Sass, J. H., and Robert J. Munroe, Basic Heat-Flow Data from the United States, United States Department of the Interior Geological Survey, USGS open file number 74-9, 6-56-6-59, 7-6, 1974


