Where the Barnett Ends— A Study of the Geothermal Potential in Dallas County, Texas

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ABSTRACT

North Eastern Texas has been identified as an area of high geothermal potential given the subsurface temperatures at economic drilling depths.

The object of this paper is to present new geothermal data to evaluate and identify the geologic formations in North Texas, particularly in Dallas County, that hold the most potential for industrial geothermal electrical production, and that would also potentially be able to support same-site co-production of natural gas along with geothermal energy.

Data were collected and analyzed from existing oil, gas, and deep-water wells in the North Texas area; and was subsequently correlated with existing geologic data. The results indicate very favorable geologic conditions for geothermal energy in North Texas, with the major conclusions being:

1) The Ellenberger Limestone Formation has the required temperatures and flow rates to sustain geothermal energy production in North Texas.
2) To reach the Ellenberger, it is necessary to drill through the Barnett Shale, the most productive gas producing formation in Texas, which is virtually untapped in central Dallas County.
3) Depending on the extent of the Ouachita Fracture Zone in the Paleozoic rocks, there may be even higher potential for geothermal fluid flow than imagined, as well as untapped natural gas reserves entrapped in the subsurface.

Despite the fact that these areas remain predominantly uncharted and unforeseen challenges may arise during resource development, the results still hold tremendous economic and political significance, as geothermal energy is a clean, sustainable, base-load power source that can be locally produced. Furthermore, if properly harnessed, this resource could cost-effectively meet energy needs, as well as spur the local economy. By all accounts, North Texas appears to have a unique resource of tremendous potential value, which at the very least, merits more research to be properly understood, so that it can be properly harnessed.

Introduction

At the Southern Methodist University (SMU) Geothermal Energy and Utilization Conference in June of 2008, Bernie Karl of the Chena Hot Springs Geothermal Plant publicly asked why SMU was not geothermally powered.

This question was posed in light of studies done in and through the SMU Geothermal Laboratory indicating that there is sufficient heat flow and geothermal potential in the South-Central United States to utilize geothermal energy production (Negraru et al., 2008). Furthermore, it was asked against the political and

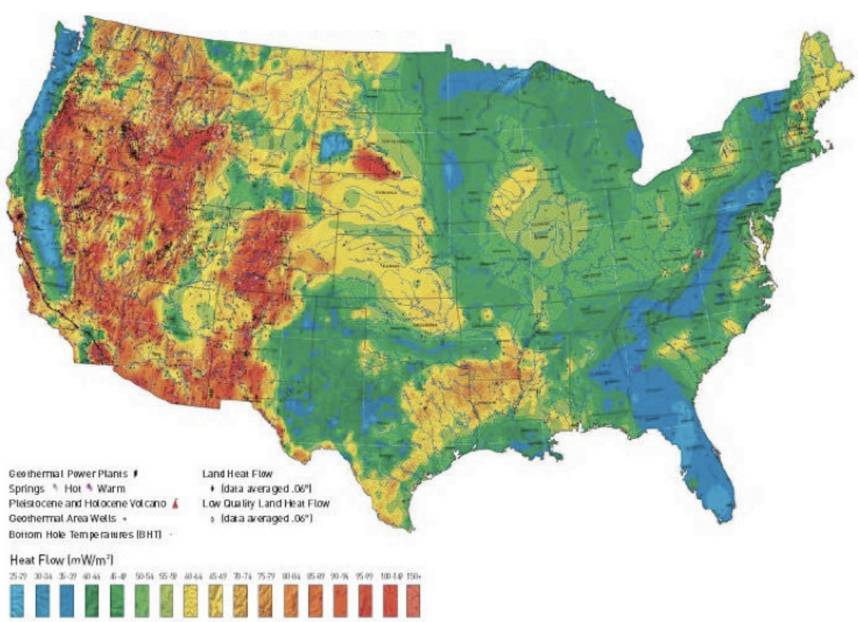


Figure 1. Heat-flow map of the conterminous United States- a subset of the Geothermal Map of North America (Blackwell & Richards, 2004).

economic backdrop of climate change, rising oil prices, and a renewed importance placed on U.S. energy independence, thus creating an ever-increasing demand for renewable energy. These are challenges that will have to be dealt with by this generation, and geothermal energy presents itself as an important part of the long-term sustainable solution.

Although it was known that there is geothermal potential in the North Texas area at depth, as seen in Figure 1. (Blackwell & Richards, 2004), a more concrete geologic analysis was necessary if geothermal is to become part of the solution for Dallas. It is for this reason that our objective was to evaluate and identify the formations underlying Dallas that have potential for large-scale industrial geothermal electrical production, and that would also ideally be able to support same-site co-production of natural gas along with geothermal energy.

Methods

In identifying which geologic formation held the key to unlocking geothermal potential in Dallas, our major task was to correlate geologic, hydrogeologic, and geothermal data. However, this would prove a far more daunting task than originally thought in all cases, primarily due to out-dated and incomplete public information, and in contrast, a tremendous wealth of modern, state of the art information that happened to be the proprietary information of various Barnett Shale operating oil & gas companies.

Another major challenge to identifying the geothermal potential has been the lack of reliable flow rate data from the water bearing formations. Flow rates data is extremely important as the rate of fluid flow from the earth, directly affects that amount of heat available for power production on the surface. It is important to note that water production is a major liability for those oil & gas companies operating in the Barnett Shale Fields, ergo, they take great lengths to produce as little water as possible, and when water is produced, flow rates are generally not measured.

The fluid geochemistry data of water bearing formations is another very important set of data that is very poorly documented. This is important for looking at geothermal potential as the amount of total dissolved solids (TDS) will dictate specifications of infrastructure and equipment in building the power plant systems, and also give an idea of how often the power plant will need to be shut down for maintenance to address issues of scaling and buildup.

Geologic Data

The geologic information quintessential to the study was the stratigraphic and structural data specific to North Texas, with a particular focus on the Dallas County area.

The data for the stratigraphy of the Cretaceous rocks came predominantly from water well logs from the Dallas area, which yielded information to slightly below 3,200 ft (~0.98 km) from the surface. These data were generally complete and well documented, and yielded an accurate account of the Cretaceous stratigraphy in Dallas County. In this part of the study, the goal was to create a stratigraphic column of what lies directly below SMU from the location of the 1925 SMU Water Well Site, which has a total depth of 2,850 ft (~0.87 km).

Collecting the data for the sub-Cretaceous (which would prove to be entirely Paleozoic) rock stratigraphy would prove more challenging. Most of the data were considered proprietary by various oil & gas companies, however, after explaining the purpose of the project, many of the companies would go on to disclose select information from oil, gas, and primarily injection wells in Dallas County. The well logs collected provided us with invaluable stratigraphic information down to 10,500 ft (~3.4 km).

Of particular importance, are the findings from the analysis of two oil & gas type wells that, seem to be the only existing deep wells drilled in the heart of the Ouachita Over-thrust Belt. For the moment, more study is needed before a definitive conclusion can be reached. However, the preliminary findings seem to indicate that the massive Ordovician age Ellenberger limestone defines the fault planes along which the Pennsylvanian Ouachita Over-thrust occurred. These movements seem to have subsequently caused the Mississippian age Barnett Shale to turn over on itself and double in thickness in certain areas under the Ouachita Over-thrust Belt.

In order to ensure accuracy, as some of the well sites were miles apart, accredited published findings were referenced for each unit and subsequently compared with its respective unit in the well log data. This would yield a detailed account of the average thicknesses of each of the stratigraphic units in our 10,500 ft column, ranging from the uppermost (Austin Chalk) to the lowermost (Ellenberger Limestone). This cross-referencing ensured consistency and accuracy, as well as provided a deeper

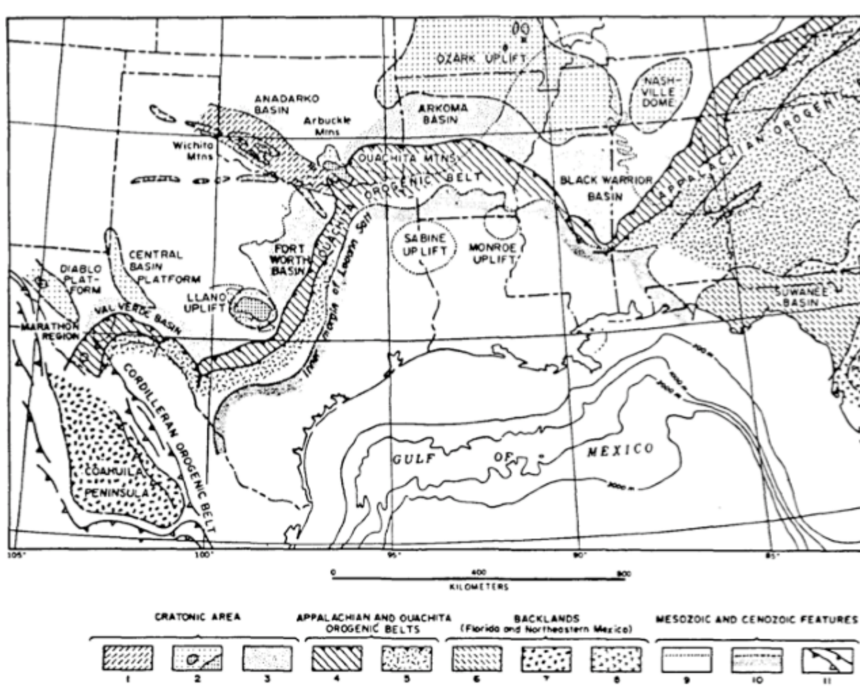


Figure 2. Tectonic Provinces of the Southern United States (Williams, 1975).

understanding of lithologic units in the column.

As the topography of Dallas County lacks major relief and is overwhelmingly flat, with the exception of a few flood planes, the geologic structure of Dallas does not make itself readily obvious. Similar to the stratigraphic data, the structural data would also come in two parts: Cretaceous and Paleozoic. Fortunately however, there exists a wealth of public information regarding the large-scale structural and tectonic setting in the area, which would prove vital to the study. Of particular importance was information regarding the area of the Permian-Triassic Ouachita Orogenic Belt, which illustrates that Dallas County straddles the Ouachita Belt and the Fort Worth Basin as shown in Figure 2. (Williams, 1975).

The Cretaceous rocks in the area are generally flat lying, with a general dip of about 2 degrees southeast (Winton & Adkins, 1919). There is an unconformity at the base of the Trinity Sands, where the Cretaceous and Paleozoic rocks meet, and the structure becomes unknown to public sources.

The structure in the Paleozoic rocks could be yielded by seismic data taken of Dallas County, however as it is strictly propriety, no information could be accessed. However, given the tectonic setting of Dallas County, we expected to find a triangle zone region, a typical habit of thrust faults, in the Paleozoic Rock structure. This implied that the structure should be quite similar to triangle zones of Alberta's Turner Valley (MacKay et al., 1994) or the Valley and Ridge geologic province of the Eastern United States (Grotzinger et al., 2007). This would later be confirmed by Bill Kerrigan, manager of exploration and development for Amarillo-based Llano Royalty Corp., who described the structure under Dallas as having a, "saw-toothed pattern" (Bowker, 2008) characteristic of triangle zones.

Geothermal Data

The bulk of the heat flow and thermal conductivity data for the various lithologies encountered in the well logs could be found in the files and databases of the SMU Geothermal Laboratory. However, in the case of geothermal gradients, they had to be calculated from the depth (ft) and the bottom hole temperature (BHT in °F) at that depth. The following formula was used on the BHT data from the 146 Dallas County water, oil, gas, and injection wells analyzed for the study:

$$\text{Geothermal Gradient} = \left[\frac{(\text{Corrected Bottom Hole Temperature} - \text{Ambient Temperature})\ °F}{(\text{Depth of BHT})}\right](1{,}000\,ft)$$

where,

- *Geothermal Gradient is in °F per 1000 ft*
- *Ambient Temperature value used was 68°F*
- *Corrected BHT = BHT + 40°F, which accounts for the temperature loss at the time of the temperature measurement from drilling mud and circulating drilling fluids.*

The Texas Rail Road Commission served as a useful source for identifying wells drilled in Dallas County over the years, but other than that it supplied no useful temperature or flow rates for Dallas County oil & gas wells. To obtain this data, the well logs would need to be pulled from the Bureau of Economic Geology Well Log Library at the University of Texas in Austin, Texas. The information was subsequently obtained by various calls and e-mails to different companies with the end result of some disclosure of data.

Another important source of information and reference was the paper, "Heat Flow and Geothermal Potential in the South-Central United States" by Negraru, Blackwell, and Erkan, 2008.

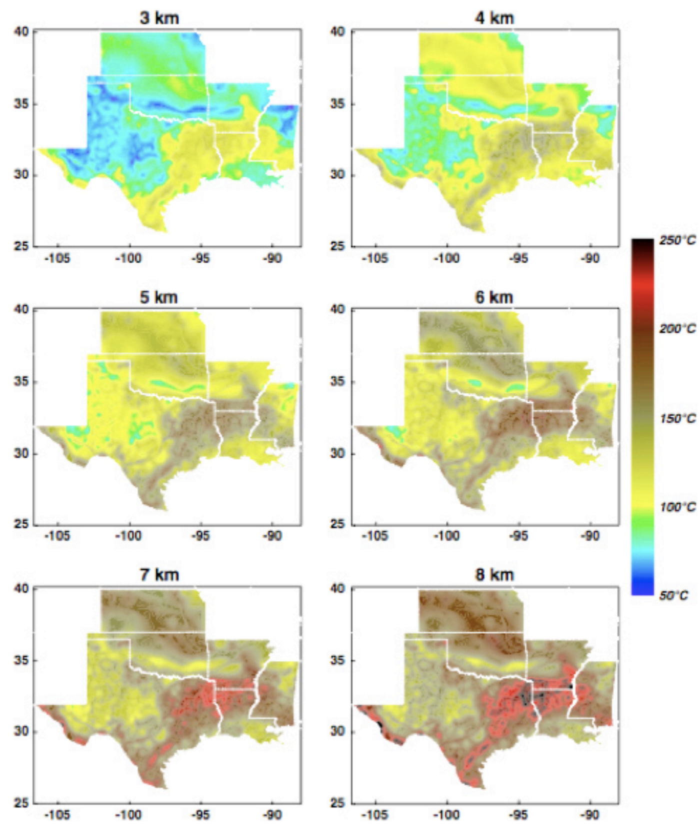


Figure 3. Temperature at depths of 3-8 km used in computing geothermal resource assessment (Negraru, Blackwell, & Erkan, 2008). [Figure has been slightly modified to display both Metric and Imperial Units]

Results

Data collection was completed by phone calls, e-mails and site visits with various Dallas area oil & gas companies. It should be made note of that some of the data collected were discarded due to incoherent values that were most likely a result of simple human error such as typos or incorrect units. After piecing together the reliable data, the results presented us with a clearer picture of the geology under Dallas County.

The results pertaining to the geologic structure of Dallas County indicated that below the relatively flat-lying Cretaceous sediments, there exists a primary sedimentary Paleozoic triangle zone within the Ouachita Orogenic Belt between the Fort Worth Basin and the igneous and metamorphic Ouachita assemblages, as seen in Figure 4, overleaf. Please note, that data recently acquired calls for changes to the cross section. These changes will be addressed in a subsequent paper.

The stratigraphic data allowed for the creation of a stratigraphic column for Dallas County, assuming that the surface location is

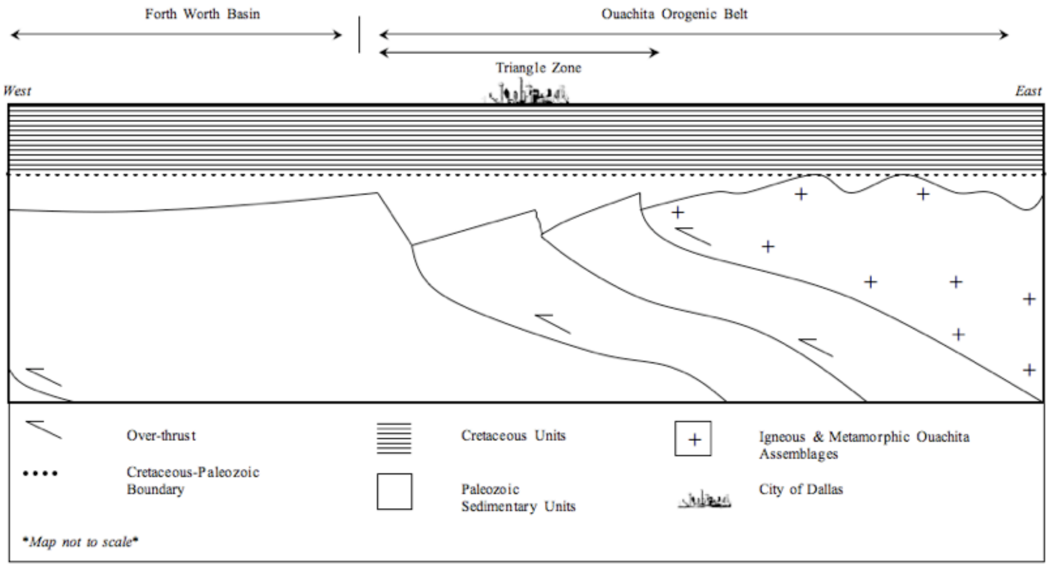


Figure 4. Idealized cross section map across Dallas County displaying over-thrusts.

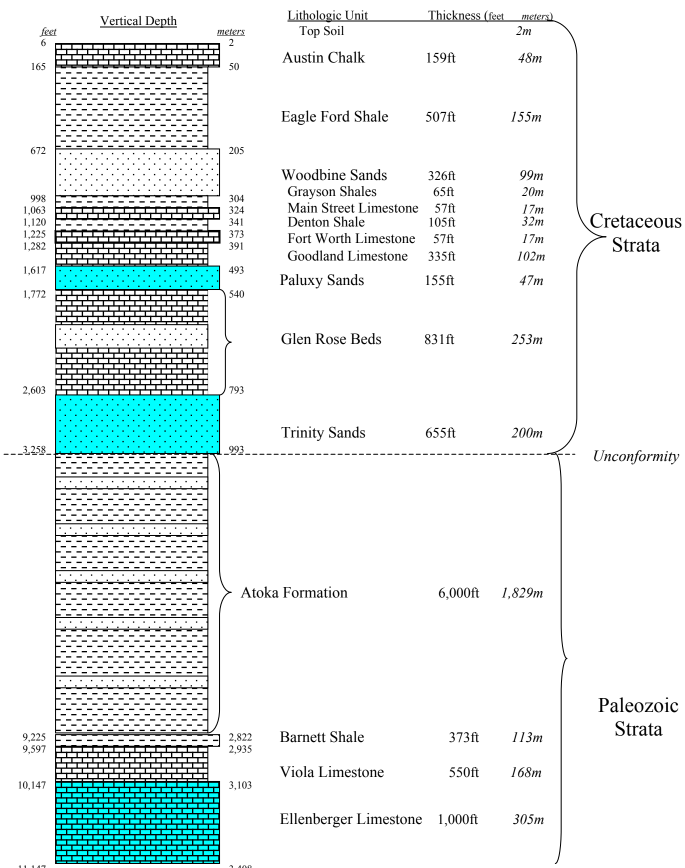


Figure 5. Predicted stratigraphic column of Dallas County from the site of the 1925 SMU Water Well of the SMU campus. Water bearing formations shown in blue.

the 1925 SMU Water Well on the SMU campus. The column starts from the surface and descends to the bottom of the Ellenberger, (Figure 5).

Analyzing the geothermal gradients of various oil, gas, and water wells from the North Texas area also yielded valuable data that would further shed light on the geothermal potential of Dallas County. Figures 6. shows the maps of the wells in the Dallas County area that were used in this study. The water wells are shown by green and blue tabs, while the oil & gas wells are denoted by the yellow tabs. Maps of the locations of the water wells and the oil & gas wells, along with their corresponding Temperature-Depth Curves for the wells analyzed and the average geothermal gradient (in °F per 1000 ft) can be found in Figures 7-a,b,c and 8-a,b,c.

In the process of gathering the geothermal data from Dallas County oil & gas wells, we came across an unexpected finding– the Barnett Shale extending into central Dallas County. This finding would also go on to reflect itself primarily in the stratigraphic column.

Although discovered in the 1980's, it was not until around 1999 that advancements in hydraulic fracturing and horizontal drilling allowed for economic production in the Barnett Shale, which is now the largest natural gas producing formation in Texas.

Individuals involved in the Barnett Shale play, reported that the Barnett Shale, in fact, did extended into central Dallas County, however it was deeper and in "more complicated geology" resulting in higher drilling costs. Also, given isopach data, there should be approximately 372 feet of Barnett Shale under central Dallas (Figure 9, overleaf).

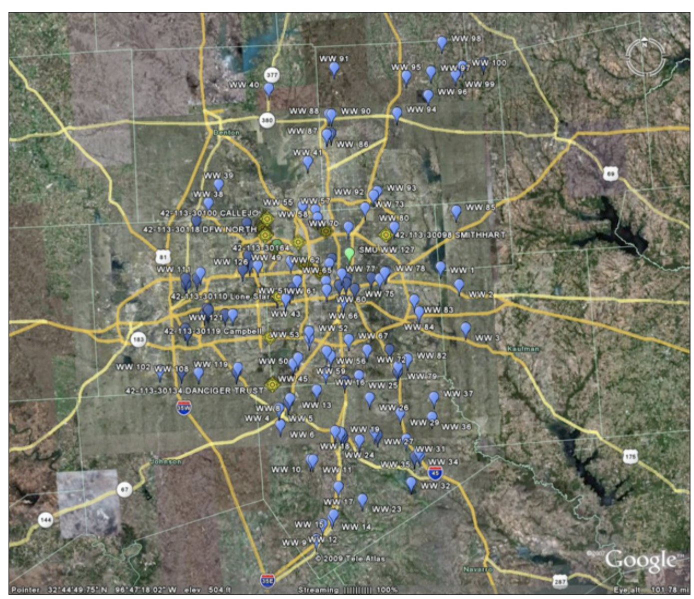
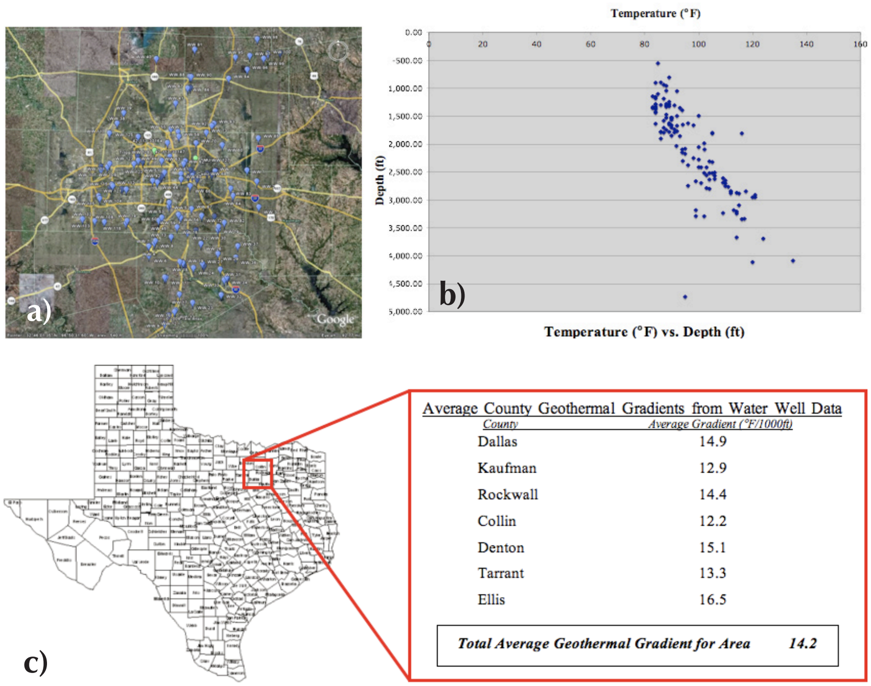
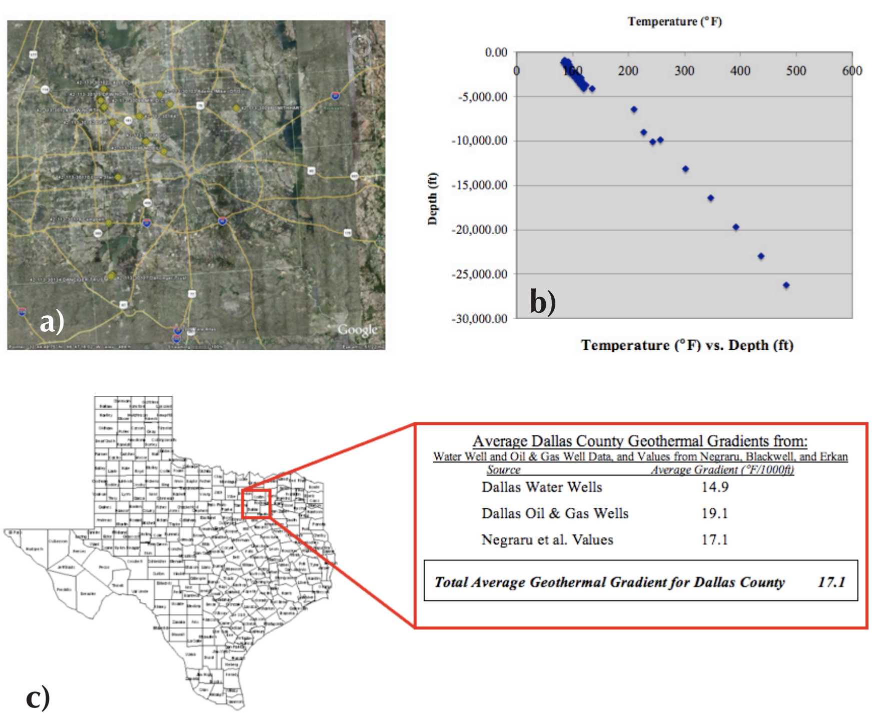


Figure 6. Map of the oil, gas, and water wells in Dallas County used in this study. *Please note, that there exist oil & gas wells from this area, whose logs provided valuable data for this study, but that are not shown on the map. The reason I have omitted the locations, API numbers, and other information regarding these wells is because I still lack written permission to publish this data. However, I do hope to obtain the necessary permissions and publish the results in my next paper.



Average County Geothermal Gradients from Water Well Data	
County	*Average Gradient (°F/1000ft)*
Dallas	14.9
Kaufman	12.9
Rockwall	14.4
Collin	12.2
Denton	15.1
Tarrant	13.3
Ellis	16.5
Total Average Geothermal Gradient for Area	***14.2***

Figure 7. a) Google Earth Projection of Water Wells in Dallas County Area: Dallas, Kaufman, Rockwall, Collin, Denton, Tarrant, and Ellis Counties: Location Map for the 128 water wells analyzed. b) Temperature vs. Depth Plot for the 128 water wells analyzed in the Dallas County Area: Dallas, Kaufman, Rockwall, Collin, Denton, Tarrant, and Ellis Counties. Depth denotes depth from surface. c) Average geothermal gradient by county for the Water Wells in the Dallas County Area: Dallas, Kaufman, Rockwall, Collin, Denton, Tarrant, and Ellis Counties. Also shows a generalized location Map for the 128 water wells analyzed.



Average Dallas County Geothermal Gradients from: Water Well and Oil & Gas Well Data, and Values from Negraru, Blackwell, and Erkan	
Source	*Average Gradient (°F/1000ft)*
Dallas Water Wells	14.9
Dallas Oil & Gas Wells	19.1
Negraru et al. Values	17.1
Total Average Geothermal Gradient for Dallas County	***17.1***

Figure 8. a) Google Earth Projection of oil & gas wells in Dallas County. Certain Dallas County Area oil & gas wells have been omitted from this map to comply with disclosure issues. b) Temperature vs. Depth Plot for the Dallas County oil & gas wells analyzed, as well as the hypothesized value points from Negraru, Blackwell, & Erkan, 2008. c) Average geothermal gradient for the Dallas County Area from the Dallas County Area oil, gas, and water wells analyzed, as well as the hypothesized values from Negraru, Blackwell, & Erkan, 2008.

As previously mentioned in this paper, well log analysis of certain deep wells drilled into the heart of the Ouachita Over-thrust Belt yielded preliminary findings that seem to indicate that the Barnett Shale has turned over on itself and can be found in thicknesses of up to 1,000 feet in certain areas underneath the Ouachita Over-thrust Belt.

Assuming that the Barnett Shale is in fact overturned on its Northeastern edge, south of the point where the Muenster Arch and the Ouachita Over-thrust belt meet, this means that the thickest sections of Barnett Shale, that are also the deepest lying sections remain totally untouched by oil & gas drilling. The major concern from an oil & gas point of view is how fractured the Barnett is underneath the Ouachita Thrust-belt. This information requires further study, and will also be addressed in a future paper.

Another major concern for Barnett Shale players is that a highly fractured zone, the Ouachita Fracture Zone, may extend deep into the Ellenberger Limestone. The Ellenberger is a deep water-bearing formation that underlies the Barnett Shale. It is an issue of constant concern for Barnett Shale players, as water flow rates high enough to "flood" wells and cause them to be junked due to excessive water flow are routinely observed. This however, is generally a result of accidentally over fracturing into the Ellenberger (Figure 8.).

Although no reports of average Ellenberger flow rates could be gathered, as most wells are simply capped as soon as too much water is encountered. An interesting point to note is that in no instance were oil & gas companies ever looking for high water shows, in fact, great lengths are taken and costly studies are preformed to keep the Barnett Shale wells as free of Ellenberger waters as possible. In the cases where over fracturing has occurred, the Ellenberger waters must be pumped back into the formation. This occurs at various injection sites in the Barnett Shale play area, where at least 100,000 barrels of water per day are into the Ellenberger Formation.

Other data collected from sources in the Barnett Shale play indicate that the waters from the Ellenberger are in fact very "dirty" and contain a high amount of total dissolved solids. At this point we are waiting to hear back from various companies to whom requests have been made for water samples.

Furthermore, we know from drilling in the Fort Worth Basin that the Ellenberger is highly karsted and faulted in various places. From data collected regarding the recent earthquakes in the Dallas County area, there seems to be a local fault system running from East to West in Tarrant and Dallas Counties. Also of particular interest are reports of a vast and intricate water-flooded Ellenberger cave system to the south of Dallas in Johnson County.

Figure 9. Barnett Shale Isopach Map (Pollastro, 2004).

Discussion

To be able to support a standard model binary-cycle geothermal power plant, two main conditions need to be met: there must be hot water and there must be high flow rates. In light of the new results of this study, it appears that Dallas County has even more geothermal potential than originally thought.

The average gradient from Dallas County oil & gas wells was shown to be higher than both the expected linear values (Negraru et al., 2008) and the average gradient of the Dallas County water wells, which may indicate that the function of temperature and depth may be exponential rather than linear. The hypothesized reason for this within the zone of current oil & gas drilling and production, is the Ouachita Fracture Zone, an extensive system of faults and fractures that resulted from the Ouachita over-thrust.

This information coupled with the results of the structural and stratigraphic data, which identify the water well data being measured in Cretaceous rocks, and the oil & gas measurements in Paleozoic rocks may imply that the Ouachita Fracture Zone exists extensively in the Paleozoic rocks underneath Dallas County. Such a fracture zone may serve as a superhighway for sub-surface thermal waters.

The results further imply that the Ellenberger Limestone underlies Dallas County at approximately 10,147ft (3,103m) below the surface. Furthermore, we know that in situations where the Ellenberger was slightly fractured into, water volumes sufficient enough to junk multi-million dollar drilling investments were observed. Also, on average 100,000 barrels of saline water are re-injected into the Ellenberger per day. From the Paleozoic geothermal gradient, a temperature could be projected to the top of the Ellenberger, which is expected to be approximately 262°F (128°C).

Using Figure 11, we can estimate approximately how much power could be produced by drilling a geothermal well into the Ellenberger Formation from the site of the 1925 SMU Water Well. Using an approximate 262°F, 128°C water temperature estimate, and a flow rate of 20,000 barrels per day flow rate, an estimated 1.2 megawatts of clean, base load electricity could be produced. The flow rate in this example is an estimate based on how much individual injection wells pump into the Ellenberger, and assuming that a well was drilled specifically looking for hot water.

As a point of reference, the Southern Methodist University Campus uses between 3 to 15 megawatts depending on the time

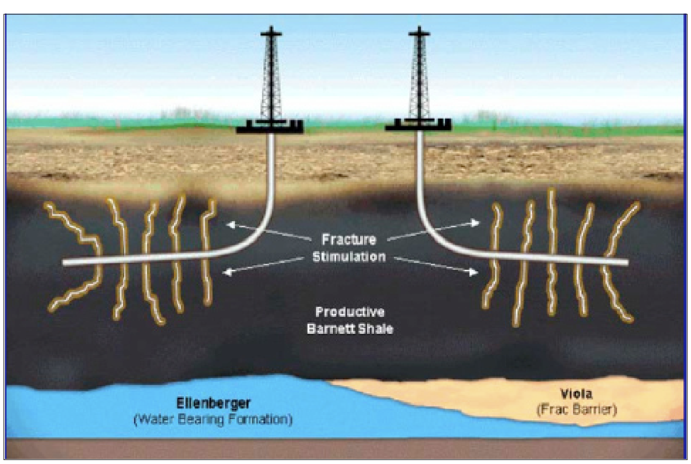


Figure 10. Fracture Stimulation in Productive Barnett Shale Wells displaying the Ellenberger as a Water Bearing Formation (Quicksilver, 2005)

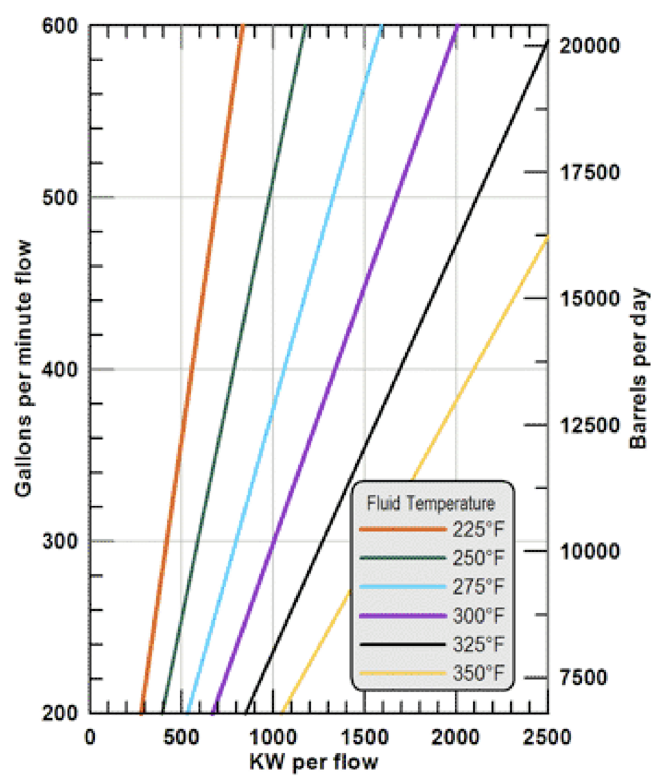


Figure 11. Approximate kW production from given temperatures and flow rates. Courtesy of SMU Geothermal Laboratory Presentation and Information Files

of year. Presumably it is feasible that between 1/3rd to 1/15th of SMU energy consumption could be produced from a small off the shelf type geothermal unit.

It is important to note that these estimates deal solely with the case of the Ellenberger Limestone being tapped for its geothermal potential. However, there also exists the possibility of co-produced natural gas from the untapped Barnett Shale under Dallas, County. Such co-production is currently being done near Casper, Wyoming at the Rocky Mountain Oilfield Test Center (RMOTC), a joint project of the U.S. Department of Energy and Ormat Technologies.

The potential for co-production makes the project even more enticing, as the returns from natural gas production, which lasts about 2 years in the average Barnett Shale well, could potentially pay for the geothermal investment that could produce at least 30 years of clean, geothermal energy. Yet, what is most attractive about such a co-production system in the heart of Texas, is that as of September 1st 2009, Texas Senate Bill 44.33 all hydrocarbons co-produced from a energy producing geothermal well are considered tax free.

Another important factor to consider is the extent of the Ouachita Fracture Zone, which could result in higher temperatures at shallower depths, as well as higher fluid flow through the subsurface. Furthermore there is a chance that the gas from the natural fracturing of the Barnett Shale may have followed the faults and fractures to a point of entrapment in the Dallas County subsurface underneath the Ouachita Over-thrust Belt.

There are some foreseeable issues that may arise with the project. The first is scaling on the casing of the wells, due to the Ellenberger being a "dirty" saline-aquifer. This is a minor issue, as oilfield and geothermal geochemical technology exists that could resolve this problem.

Another issue is the high initial capital costs of undertaking such a project. This issue will be addressed in a Financial Analysis of the SMU Geothermal Project, which will be completed through the Maguire Energy Institute and the SMU Cox School of Business.

The final issue that has often been mentioned regards the permitting and zoning laws required to drill a well in developed urban areas. Fortunately, there exists a very well established methodology and precedent to procure the necessary permits for such a project through the Texas Rail Road Commission. Evidence of urban drilling can be found in the near by oil & gas drilling in downtown Forth Worth, Texas. It should also be noted that drilling can even be observed in downtown Los Angeles, California.

In conclusion, the geothermal potential of Dallas County, and the rest of North Texas appears to be found in the Ellenberger Limestone Formation. To properly explore and value this potential resource, acquiring seismic data well be essential in identifying the highly karsted and fractured zones that could yield the highest water volumes. Also, a test well needs to be drilled to test the three conclusions of this paper, and so potentially usher in a new era for North Texas energy production.

So to answer Bernie Karl's question of why SMU is not run, in-part or entirely, on geothermal power—I still don't have the slightest idea, and I can only hope that SMU will look right beneath out feet to find our energy solution.

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References

Blackwell, D. D.; Richards, M. 2004. *"Geothermal Map of North America"*. American Assoc. Petroleum Geologist (AAPG), 1 sheet, scale 1:6,500,000.

Richards, M., *"Chart: Approximate kW production from given temperatures and flow rates"*. Geothermal Laboratory Presentation and Information Files. SMU Geothermal Laboratory

Bowker, Kent. *"Barnett Shale Drilling Moves East"*. Fort Worth Star-Telegram. July 27th 2008. Accessed Fall 2008. http://www.tradingmarkets.com/.site/news/Stock%20News/1784219/

Grotzinger, John; Jordan, Thomas H.; Press, Frank; Siever, Raymond. "Understanding Earth: Fifth Edition". W.H. Freeman and Company. New York, New York. 2007. (The Appalachian Fold Belt Pg. 218)

MacKay, P.A.; Spratt, D.A.; Soule, G.S.; Lawton, D.C.. *"The triangle zone of southern Alberta – geometry, lateral variations and associated oil and gas fields: Field Trip Guidebook, Canadian Society of Exploration Geophysicists/ Canadian Society of Petroleum Geologists Joint Annual Convention"*. Calgary, Alberta. 1994. (Turner Valley Pg. 46)

Negraru, Petru T.; Blackwell, David D.; Erkan, Kamil. *"Heat Flow and Geothermal Potential in the South-Central United States"*. Natural Resources Research. 2008.

Pollastro, Rich. *"USGS Province 50 Boundary Bend Arch – Fort Worth Basin Regional Isopach Data, Barnett Shale"*. 2004. Accessed Fall 2008. http://www.barnettshalenews.com/documents/Barnett%20ShaleThickness%20Map%20by%20County%202004.pdf

RMOTC (Rocky Mountain Oilfield Test Center) Website. U.S. Department Of Energy. Ormat Technologies. Accessed Nov. 2nd 2008. http://www.rmotc.doe.gov/

Quicksilver. *"Barnett Shale: A 25 Year "Overnight" Success"*. Ellison Miles Geothechnology Institute at Brookhaven College - Barnett Shale III Symposium Presentation. June 2005. Accessed Fall 2008.

Williams, Thomas. *"Regional Geology of the United States"*. Department of Geological Sciences, Southern Methodist University. Textbook as prepared for GEOL 3340 Face of the Earth. [No date given, most likely in 1970's] (Structure and tectonic history of the Ouachita Mountains, Arkansas Pg. 86)

Winton, W.M.; Adkins, W.S.. *"University of Texas Bulletin No. 1931: June 1, 1919: The Geology of Tarrant County"*. University of Texas Bureau of Economic Geology and Technology. Division of Economic Geology. Austin, Texas. June 1, 1919. (Possibilities of Oil and Gas Pg. 95)