
Year 1 Progress Report
July 1, 2005 – June 30, 2006

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Executive Summary

The first year of a proposed 3-year resource assessment has been completed that covers an eight county region within the Delaware and Val Verde Basins of West Texas. This project has developed databases in Excel spreadsheet form that list over 8,000 temperature-depth recordings. These recordings come from header information listed on electric well logs recordings from various shallow to deep wells that were drilled for oil and gas exploration and production. The temperature-depth data is uncorrected and thus provides the lower temperature that is be expected to be encountered within the formation associated with the temperature-depth recording. Numerous graphs were developed from the data, all of which suggest that a log-normal solution for the thermal gradient is more descriptive of the data than a linear solution. A discussion of these plots and equations are presented within the narrative. Data was acquired that enable the determination of brine salinity versus brine density with the Permian Basin. A discussion on possible limestone and dolostone thermal conductivity parameters is presented with the purpose of assisting in determining heat flow and reservoir heat content for energy
Subsurface maps of temperature either at a constant depth or within a target geothermal reservoir are discussed, but have yet to be completed.

**Project Background**

This geothermal research project was begun in 2005 as a projected 3-year exploration and resource assessment for developing geothermal energy in western Texas. The premise upon which this research is based is that significant amounts of heat have been encountered by the oil and gas industry when drilling deep wells in sedimentary basins. This heat has been considered a liability for drilling, requiring higher temperature steels for the various tools used by the industry. The purpose of this project is to develop the needed subsurface databases and maps to enable the energy industry to expand their activities to acquiring the subsurface heat for generating renewable electrical power from sedimentary basins.

**NOTE:** The reader must recognize the importance of this project being three years. No detailed industry-directed geothermal resource assessment in West Texas had been previously undertaken other than preliminary investigations in 1999 by the West Texas Earth Resources Institute (WTERI) in Midland, Texas. Thus the findings reported here, that comprise work conducted at WTERI, data from an existing UTPB/CEED database, as well as this past year of investigation, are incomplete and will remain so unless this project is fully funded for the second and third years of the study. The cumulative time spent in building all three of these databases is on the order of 3 to 3.5 years. This report should be considered only as an interim 1-year report, contingent upon the project’s continuation.

**Differences Between ‘Deep Permeable Strata Geothermal Energy’ And The Traditional Geothermal Energy Approach**

The concept of ‘deep permeable strata geothermal energy’ (DPSGE) was first proposed in late 1999 by Swift and Erdlac (1999) as part of a preliminary investigation being carried out through the West Texas Earth Resources Institute (WTERI) in Midland, Texas. We recognized that a large number of wells drilled within the Delaware and northern Val Verde Basins of Texas covering Pecos, Reeves, Terrell, and Loving Counties had encountered bottom hole temperatures (BHT) that were sometimes in excess of 204°C (400°F). These high BHT readings have been known within the oil and gas industry for many decades. Depths for these high temperatures were often within the 8,534 to 9,144 meter (28,000 to 30,000 foot) range, far deeper than geothermal energy was being produced. Nevertheless, we felt that as large amounts of data already existed, as well as numerous deep well bores, it would be possible to develop this geothermal potential using the existing oil and gas infrastructure, and expanding upon this infrastructure when needed. Thus we began to develop a preliminary database of temperature-depth (t-d) information from wells existing within the WTERI offices and to seek outside funding for expanding this preliminary work.

The differences between DPSGE and the traditional approach to geothermal energy extraction were several. Conventional geothermal extraction has been exclusively related to shallow heat plumes near volcanic and geyser activity (DOE, 1999a, b; IGA, 2003). Geothermal energy was thus spatially variable and site specific. Existing geothermal fields are only a few 10’s of square km in size, controlled by the extent of the plume, and are of limited lifetime (IGA,
Finally, geothermal energy fields are generally less than 4 km depth due to high drilling and heat extraction costs. These costs have only escalated as the cost of oil and gas has increased worldwide. Further development opportunities for geothermal resources have thus been hindered.

This proposal sought to alter the existing geothermal paradigm by investigating an unconventional approach to geothermal power development that would tap into the heat found within deep sedimentary basins. Such an investigation would have several accomplishments. First, the investigation would expand the energy (O&G and geothermal) industry awareness of an untapped source of heat energy in sedimentary basins. The oil and gas and the geothermal industries are like brothers who rarely speak to each other. Although many of the same subsurface engineering and geoscience techniques are used in both, each industry has focused upon specific geological environments for entirely different energy goals. Thus the geothermal industry tends to be unaware of high temperatures and thermal gradients, documented permeability, porosity, and abundant formation brine that exist within deep sedimentary basins, as recognized by the oil and gas industry. Similarly the oil and gas industry has not seen the abundance of high temperatures and hot brine as an asset in energy production.

Second, this proposal sought to identify and target specific geographic areas, such as within a carbonate basin, where deeper heat sources can be developed. This goal would be accomplished as databases of temperature, porosity, permeability, and formation fluid salinity were created, graphs of t-d from various sources, well temperature profiles, and fluid salinity versus temperature were generated, and maps of subsurface temperature and formation types were developed.

Third, the results of this proposal would allow for the development of future geothermal field size to increase from 10 km$^2$ to many 100 km$^2$ to 1,000 km$^2$. The databases, graphs, and maps would provide the needed information to identify target reservoirs and the aerial extent over which geothermal development would be possible.

The final component of this project would be to increase the productive depth range for economic geothermal energy extraction below the current 4 km limit. The conversion of deep depleted and abandoned gas wells and fields into geothermal energy extraction wells is one approach to be employed to reduce cost. This would require drilling out any shallow plug and perforating hot water zones that are enclosed behind pipe. An individual company paradigm shift is also required for such deepening geothermal production. A geothermal energy company must be willing to expand its business plan to enter new geographical regions and understand the geology in order to acquire the subsurface heat resources. The geothermal energy company must also develop a plan to produce local amounts of oil and gas that might be produced along with the hot water. Similarly, an oil and gas company must incorporate the potential for hot water production within its economic analysis of areas being drilled for oil and gas production. This triad energy approach – oil, gas, and geothermal – would improve the economic picture for drilling and allow for smaller oil and gas plays to be developed with the understanding that geothermal energy could be developed in tandem or after the oil and/or gas has been produced. Presently, these energy industries act independent of each other, with economics based solely on the commodity being developed. Heat energy production from sedimentary basins will foster a coordinated exploration program by both industries, with national and international implications.

Texas Historic Geothermal Database Background
While the focus of this project was on the Delaware and Val Verde Basins of West Texas, information was also gathered about other regions in the state in order to define focus areas for future Texas geothermal development. Additionally, understanding the past history of Texas geothermal investigations is helpful in mounting strategies for fully developing this resource in the future.

In 1976, the USGS and the AAPG published two subsurface temperature and temperature gradient maps of North America (Kehle, 1973; DeFord and Kehle, 1976). This study used BHT data from over 10,000 wells provided by 23 organizations comprising oil and gas companies, logging societies, and universities. The central states east of the Rocky Mountains and west of the Mississippi River comprised the densest coverage of BHT measurements. Texas in particular displayed large areas where BHT measurements were $\geq 143^\circ C$ ($\geq 290^\circ F$) (Figure 1).

Attempts were made to apply corrections to the BHT readings due to the effect that drilling has on formation temperature. Much of this correction was based on comparing equilibrium and well log BHT readings from 602 wells from West Texas and Louisiana. A 3rd order polynomial was found to be the best statistical fit. In Louisiana, the maximum correction was $<11.7^\circ C/km$ at 1,524 m ($<0.4^\circ F/100 ft$ at 5,000 feet), and for Texas the maximum correction was $<5.8^\circ C/km$ at 5,182 m ($<0.2^\circ F/100 ft$ at 17,000 feet). Corrections for wells $>3,658$ m ($>12,000$ ft) were negligible. More recently, Blackwell and Richards (2004) reported on efforts to improve upon the calibration of the North American AAPG database.

Grisafi and others (1974) and Vaught (1980) questioned the usefulness of the North American temperature and gradient maps on the basis of arbitrary corrections applied to calculated temperature gradients. They indicated that any gradients values more than two standard deviations from the mean were excluded because of suspected error. Because of these deletions, these authors suspected that some geothermal anomalies might not be displayed on the published maps. Though possibly of satisfaction for regional efforts, the local accuracy was questionable. Vaught (1980) pointed out that differentiation between shallow-hole data and deep-hole data is of importance in interpreting the geothermal potential of an area. Vaught suggested that projecting shallow-hole gradients to greater depths might not result in temperatures sufficiently high to provide economically usable thermal fluids. Additionally, Vaught indicated that these data, while important for regional work, were not conclusive indicators of geothermal potential unless other geologic data substantiated these data.

Attempting to determine corrections for BHT data is tricky and probably as much art as it is science. At least three methods have been available for measuring temperature within the oil industry. The oldest approach is a maximum mercury thermometer that can give the maximum temperature at the deepest point reached. Assuming that the thermometer was properly used and care was taken in its use, BHT readings for mid-depth to deep well are generally too low due to the short time between drilling the well and recording the temperature data. A second means of acquiring temperature data is from drill stem tests (DST) that are run at a specific depth and within a specific formation over a period of time. DST temperatures generally give more reliable temperature data from deeper within the target formation. Finally, a continuous temperature log can provide measurements to every foot as the temperature probe is pulled up hole from the deepest point in the hole. These readings can be valuable when making vertical comparisons across formation boundaries, especially if water is moving within a given formation. Thus depending upon the methodology used, the temperature correction may vary widely.
Figure 1. This scanned image of a portion of the original 1976 North American Subsurface Temperature Map displays the variations in temperatures recorded in the subsurface across Texas. Red dots represent temperatures \( \geq 143^\circ C \geq 290^\circ F \), green dots for temperatures from \( 82^\circ \) to \( 143^\circ C \) (180°F to 289°F), blue dots for temperature from \( 66^\circ \) to \( 82^\circ C \) (151°F to 179°F), and black dots for temperatures \( \leq 66^\circ C \leq 150^\circ F \). The dark gray area represents an area where the contoured isotherm is \( 150^\circ C \) (302°F) and the medium gray region represents an area where the contoured isotherm is \( 100^\circ C \) (212°F).

Gretner (1981) indicated that there were numerous aspects of drilling and completion of oil and gas wells that can alter the true formation temperature near the borehole annulus. In fact he argued that the exact configuration of the disturbed temperature depends on factors such as the mud circulation rate, the surface temperature of the mud, the drilling rate, and the thermal
properties of the surrounding rock. The length of time between drilling completion and acquiring the temperature reading has a profound affect due to the time required to reach thermal equilibrium. For example, formation temperatures may be 12-40°C higher than temperatures reported on electric log headers, based upon opportunities to log several deep wells in the Gulf Coast after being shut-in for at least one year (Bullard, 1947; Gretner, 1981; Jam et. al., 1969). The cementing of casing in a well, being an exothermic process, can temporarily heat the area immediately surrounding the casing. Temperature logs taken within a few hours of cementation can determine the top of the cement with good accuracy but invalidate formation temperature data in that region for a period of time. Finally, the reader must remember that the reason for drilling these wells was for oil and gas exploration and production, not for temperature data recovery. It is known among older geologists that have been active in the industry for several decades that some logging companies took short cuts in data acquisition and would ‘boiler house’ their BHT record. This has also been reported in the literature by other researchers (Vaught, 1980). Even with all of these uncertainties, raw uncorrected BHT data points can provide useful information when used to define a lower temperature limit and when in conjunction with additional data points from other wells in a defined geographic area. The larger the statistical set or subset, the less error in defining the minimum expected temperature in a given geographical region and at a given depth.

Texas geothermal investigations further built upon this 1976 North American study by a long-term investigation of the geopressured-geothermal potential along the Texas and Louisiana Gulf Coast. This program began in the mid-1970’s and continued for 17 years with the Department of Energy providing about $200 million for various types of research and well testing to investigate this energy resource. Three forms of energy recovery were being investigated, including 1) chemical energy from dissolved methane within the pressurized brine, 2) thermal energy from brine with temperatures over 225°F that could be used either for further oil recovery or for electrical power generation, and 3) mechanical energy in the form of high water flow rates (>20,000 bbls/day) and high well head pressures that could be used to drive turbines. Of these three forms of energy, only the chemical and thermal energy was captured and used in a successful demonstration project located in Brazoria County, Texas.

If the reader is willing to seek it out, information regarding this Gulf Coast study and project can be found. For example, the University of Texas Bureau of Economic Geology published a number of reports about Gulf Coast sandstones and their geothermal potential. Bibb and Associates has at least a few copies of the final 2-volume engineering report on the Brazoria geopressured-geothermal hybrid plant. The DOE has made some 75 reports available through online acquisition as pdf files discussing the ‘geothermal legacy’ in Texas. In 1998 Louisiana State University produced a paper report regarding the geological investigations and findings in the Gulf that was made available over the Internet as pdf files.

In 1995, Virtus Energy Research Associates conducted a ‘Texas Renewable Energy Resource Assessment’. In their report they discussed the Texas geothermal potential in a broad manner. They indicated the information about the Texas geopressed resources had been gathered at the now closed Geopressed-Geothermal Information Systems (GCIS) under the auspices of the Center for Energy Studies at the University of Texas at Austin. This information purportedly contained digitized well logs, well header information, salinity data, sand profiles, and a bibliography. Virtus indicated that the UT Department of Petroleum Engineering had what was left of this database, but that the lack of funding had not allowed the data to be taken from its rough format and put it into a more accessible format. Queries by Erdlac to the PE
department to date of this writing has resulted in determining that most of this data resides in digital form on over 100 15” reel to reel tapes from a main frame and that they have no way of converting the tape data to more a modern electronic format. There is also some question as to how well the tape has maintained its integrity. Apparently each tape contained the digital data for a single well. There was also a database of some 3,000 to 4,000 wells across the state to which this original study had access. I suspect that the 1976 North American study described above, though the individual with whom I spoke did not know, represents this data. Thus the availability of this digital data for future operations is in serious doubt.

At the 2006 Annual AAPG meeting in Houston, one of the vendors attending the meeting was International Paper. In addition to information regarding oil and gas leasing, they had a heat flow map produced by the SMU Geothermal Lab on top of which they were indicating geothermal mineral acreage that they held in the Texas and Louisiana Gulf Coast region (Figure 2). The amount of interest generated by their booth towards geothermal energy is unknown, but it is significant that such a presentation had been made available by IP and was available to the oil and gas industry at large.

Texas Areas For Deep Geothermal Resources

The report by Virtus in 1995 provided a summary map of areas in Texas where different forms of geothermal energy might be acquired for various applications (Figure 3). Erdlac (this report) adapted this map in two ways. First, the Virtus map indicated that the geopressured region in West Texas was just east of its location shown in Figure 3. Their original location for geopressed zones, along the crest of the Central Basin Platform, was in error. This map corrects this error. Additionally, Erdlac added areas of known oil and gas data (in pink) that can be used to assist in developing regions for electrical energy production. One such area that was not shown on Figure 3 is called the Maverick Basin in the Maverick and Zapata County region along the border with Mexico.

A simpler map was created (Figure 4) that focused on those geographical areas most likely to be targeted for geothermal electrical production. Five major regions, and a sixth minor region, are presently proposed for consideration and in-depth study. The Anadarko Basin of Oklahoma has wells to depths of around 30,000 feet. Temperatures well in excess of 212°F have been documented in Oklahoma from these wells. As the basin extends to the northwest, it enters the eastern Panhandle of Texas. The 1976 North American Geothermal Map (Figure 1) does show wells that are in within the proper temperature range (>100°C) for electrical power generation using binary technology. However, no concerted effort is known to have been undertaken to investigate this basin for geothermal production.

Both the East Texas and Gulf Coast regions have had past investigations by the DOE, resulting in the Brazoria County, Texas demonstration power plant. However, the digital component of this study is in a format that was not updated to a more modern format, and the equipment needed to conduct such a transfer may no longer exist. The good news is that there are companies that have digitized logs for sale and several do have databases of log header information at various levels of detail. Thus it is possible, through the right industry contacts, to begin redeveloping a modern digital database within this region. This is important because the Brazoria geothermal power plant proved that geopressed-geothermal electrical power generation is possible.
Figure 2. This scanned image shows geothermal mineral acreage reportably held by International Paper in the Texas and Louisiana Gulf Coast.

The Maverick Basin is small basin, compared to some basin standards, that exists along the Texas-Mexico border between Maverick and Zapata Counties (Figure 4). To our knowledge
no geothermal investigations have been done within this basin, unless it was incorporated within the Gulf Coast study. This basin has Upper Cretaceous serpentine plugs that have produced oil (Lewis, 1989), but the relationship between this volcanism, local tectonism, and basin temperature data is unknown by us. The Maverick Basin was not part of this study and thus was not investigated in detail. However public information was provided to Erdlac from Wagner and Brown in Midland regarding several wells in the Maverick Basin within Zapata County (Table 1). The wells were deemed of sufficient importance to be included within this report. These 12 wells were drilled to depths ranging from around 3,962 m (13,000 feet) to a little over 5,182 m (17,000 feet).

Temperatures within these wells range from a low of 160° to 224°C (320°F to 435°F). These temperatures are among highest in wells drilled to these depths found so far in Texas and thus are important for establishing high temperatures at these shallow depths. The t-d values for these wells were plotted on a graph in order to determine a best-fit trend line (Figure 5). Both a log-normal and a linear solution were chosen for testing. The coefficient of determination $R^2$ for both the straight line and the log-normal curve were identical. As no shallower data was provided there was not way to determine if these two trend lines diverged from each other at shallower depths or remain the same. Thus by taking the straight-line function, taking the first derivative as $dt/dz$, we can solve for the average temperature gradient, giving a value of $dt/dz = 0.0551 °C/m$ or $55.1 °C/km$. This is a high temperature gradient, one that merits further investigation as to its nature in this region. The amount of water present within the sandstones within the Maverick Basin is also unknown and should be further investigated.

The last two areas for geothermal electrical power generation interest are within the West Texas region. Focus of the remainder of this report will be within the Delaware and Val Verde Basins, both of which are part of the larger Permian Basin complex. Additional mention will also be made about the Trans-Pecos region and its potential.

**Delaware And Val Verde Basins: Background Geologic Information**

Much of this discussion comes from an unpublished manuscript developed by Swift and Erdlac (1998) as part of a 3-year regional oil and gas study of the Delaware and Val Verde Basins in Texas. This study was supported by 18 major and independent companies, with the final copies of the manuscripts and data being provided to the 12 companies that supported the entire three years of the study. This data and information can now be used in other studies of the same region, such as this geothermal study.

The Delaware and Val Verde Basins are features within the much larger Permian Basin that encompasses Southeastern New Mexico and much of West Texas (Figure 6). The Permian Basin covers the Delaware and Midland Basins, the northern part of the Val Verde Basin, the Central Basin Platform, the Northwestern Shelf, and the Eastern Shelf (Figure 6). The older Cambro-Ordovician age Tobosa Basin also encompasses much of the younger Permian Basin complex (Galley, 1958). Delaware and Val Verde Basin stratigraphy is comprised of varying lithologies that include limestones and dolostones, sandstones of carbonate debris as well as quartz sand, black, brown, green, and red shale, local clay seams that are of suspected volcanic origin, and various salt and anhydrite layers in the shallowest section (Figure 7). Numerous investigations have provided vast amounts of information regarding the subsurface stratigraphy of the region.
Figure 3. Summary map of Texas Geothermal Resources that was produced by Virtus Energy Research Associates. The location and boundaries of the geothermal areas is approximate. Adapted by Erdlac, 2006.
However, a comprehensive understanding of the history of tectonic activity within the Permian Basin is distinctly lacking. This statement is not meant to detract from many of the fine investigative efforts made by researchers in the past, but instead reflects the difficulty of defining a complete tectonic history of the Permian Basin. While many regions of the world have localized outcrops of rock to assist in unraveling their geology, the tectonic history of the Permian Basin is buried under thousands of feet of varying age sedimentary rock, capped by recent caliche and wind blown sand deposits. Understanding this history is, therefore, dependent upon access to subsurface geologic and geophysical information from cuttings, core, well logs, seismic, gravity, and magnetic data, much of which has resided in oil company files. In more recent years some of this data has been preserved in log and core libraries in Texas and other states where O&G operations have occurred. Unfortunately a large amount of data has also been permanently lost as companies merged and multiple data files were purged. Even with availability of data, interpretations of Permian Basin history vary considerably.
### Table 1 – Zapata County, Texas

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<th>Meters</th>
<th>Temp Data (F)</th>
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![Graph](image)

**Zapata County, Texas**

\[
z = 3416 \ln(t) - 13273
\]

\[
R^2 = 0.8158
\]

\[
z = 18.137t + 1172.8
\]

\[
R^2 = 0.8158
\]

Figure 5. A graph depth-temperature (t-d) values from 12 wells located within Zapata County and the Maverick Basin of Texas.
Historically, those early petroleum geologists who first came to the West Texas region came from East Texas. As such, when faults were encountered in the subsurface, these faults were described as vertical with normal movement. Because of the virgin nature of the Permian Basin, early wells needed only to be drilled on structural highs (i.e. the Central Basin Platform) to find oil. Later on, outcrop work of the exposed Ouachita and Marathon Mountains in Oklahoma and Texas suggested a genetic tectonic relation between the two areas. This interpretation appeared to be supported by seismic data and wells drilled which encountered highly deformed strata along the trend of the buried Ouachita/Marathon deformation zone.

With this discovery, two elements had come together to provide a tectonic model for the Permian Basin. First, it was suggested (Galley, 1958) that all tectonic deformation in the Permian Basin, and the accompanying structures, had occurred during the Ouachita-Marathon deformational event. This was the limit of tectonic activity, which was supported by earlier regional stratigraphic analyses reported by Galley (1958) and often given out by oil companies to young, newly hired petroleum geologists. Galley’s concept began with an older Tobosa Basin (Figure 6), initiated in Cambrian time, which was altered during the Marathon-Ouachita orogeny into the various geologic subdivisions forming the more recent Permian Basin. This concept existed relatively intact in this form well into the 1980’s, and is adeptly represented by Figure 8, showing an interpretation by Frenzell and others (1988) that reflects this tectonic view.
Additionally, it was believed that all faults in the Permian Basin were vertical with normal throw. Although this idea had its roots in the history of the oil industry in West Texas, from transplanted East Texas and Gulf Coast geologists, this view received few challenges even up through the early 1980’s. As some wells along the western margin of the Central Basin Platform had encountered repeat section, which could not be easily denied, variations in this tectonic interpretation began to occur. Hills (1970) suggested that repeat section along the western margin of the Platform was a direct result of strike-slip faulting due to northwestward compression of the Marathon Orogeny (Frenzel et. al., 1988). This model, however, did not explain other fields, such as Rojo Caballos, whose wells had also encountered repeat section. For these findings the concept of a gravity slide block was developed, whose origin was from the western flank of the Central Basin Platform (Hanson and Guinan, 1975; Font and Sayre, 1984).

Other tectonic models have been suggested for the entire Permian Basin, and the interested reader can find a good review of these concepts in Ewing and Garrett (1984). Unfortunately this document was part of a seminar held in Midland that did not get published by the University of Texas Bureau of Economic Geology. Copies of this text do exist at the Midland Technical Library. Ewing and Garrett also contributed to the tectonic picture by suggesting that true horizontal compression was the dominant driving impetus behind Permian Basin tectonics. They suggested that subsurface evidence supported a strong west-directed compression of the entire crust across the Permian Basin, which regionally was linked to northwestward movement of the Llano Uplift from plate-margin forces.

In the tectonic models that have been suggested the single most consistent underlying concept is that all the deformation affecting the Permian Basin is directly related to the Marathon-Ouachita orogeny, or have at least formed during Permo-Penn time. This implies that the Tabosa Basin existed as a basin along a passive southern margin of the North American craton from Late Precambrian to Late Mississippian time (810-310 Ma) (Hill, 1996), a span of 500 million years without any tectonic activity affecting the basin. In spite of this interpretation, a generalized stratigraphic chart of the Permian Basin (Figure 7) shows at least three unconformities within the Delaware Basin during the Phanerozoic time period.

Swift and Erdlac (1988) believed that horizontal compressional shortening oriented in a general east-west direction, similar to the concept of Ewing and Garrett (1984), has created much of the structural grain in the Permian Basin. However, their work also suggests that multiple periods of deformation have affected all or a significant part of the Permian Basin. The unconformities shown in Figure 7 are probably a direct result of this tectonic activity. A tectonic events chart (Figure 9) was devised based upon subsurface regional seismic data and well call data, and suggested at least 7 separate deformation periods within the Phanerozoic that affected the southern Delaware and northern Val Verde Basins. Evidence for each of these orogenic events is variable in amount, but is sufficient to support this multiple tectonic hypothesis for the Permian Basin.

Understanding this history, from tectonics to sedimentation, is important for future geothermal energy acquisition. Location of faults and folds, fracture and fault patterns, sedimentary depocenters and erosional remnants, and the number of tectonic events impacting the region define the past geothermal history of the region as well as determine the manner in which heat moves through the subsurface. Differences in the basement complex will alter the heat flow pattern from deeper within the crust. Movement of subsurface water, its salinity, and variations in rock conductivity under differing temperature and pressure regimes will alter the ability to extract heat from these sedimentary rocks.
Figure 7. Generalized stratigraphic column of the principal units of the Permian Basin. Several unconformities are present throughout the region. Tectonic activity is one possible interpretation for these unconformities. Adapted from Frenzel et. al. (1988).
Figure 8. This tectonic history of the Permian Basin follows the overall concept established by Galley (1958). Adapted from Frenzel et. al. (1988).
Figure 9. At least 7 tectonic events have had varying affects on the structural and stratigraphic history of the Delaware Basin. These events are derived from either subsurface observation made from data worked by Swift and Erdnac (1988), or from tectonic studies conducted by other researchers. Ages used are from Hills and Kottlowski (1983).

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<td>Grenville Orogeny</td>
<td>Compression</td>
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**Literature Findings Pertinent To Sedimentary Basin Geothermal Energy**

Literature investigations for this project have focused to date on three broad categories that include thermal carrying capacity of rock, thermal conductivity, and thermal advection/convection as related to sedimentary rock and geothermal energy recovery. Much of this literature search has been conducted through Internet access as well as through published books and papers. The numbers of papers available that reference these three broad categories
are numerous. Thus only a few will be mentioned here as related to sedimentary rock and their importance for subsurface geothermal evaluation. Similarly this discussion lays the theoretical groundwork for this sedimentary basin geothermal investigation.

**Thermal Carrying Capacity**

To evaluate the various sedimentary rocks in the Delaware and Val Verde Basins as to their resource potential for heat extraction requires determining the heat carrying capacity within each of the target reservoirs. This is equivalent to determining maximum estimated volumes of oil and or gas within an exploration or production interval. The volumetric method for determining available geothermal energy is given by

\[ E_T = \rho c_p V (T_{\text{prod}} - T_{\text{ref}}) \]

and has been used as a standard method to provide an estimate of the amount of heat that is stored in the subsurface (Muffler and Cataldi, 1978; Kohl et. al., 2005; Williams, 2005). In this equation \( E_T \) is the thermal energy stored in the subsurface, \( \rho c_p \) is the heat capacity of the rock, \( V \) is the volume, \( T_{\text{prod}} \) is the temperature of the produced water, and \( T_{\text{ref}} \) is a reference temperature, which could be the temperature of the reinjected fluid as in the case of a binary plant.

Vosteen and Schellschmidt (2003) showed that in general the heat capacity of sedimentary rocks at a constant pressure tends to increase with temperature (Figure 10a). Their experiments are important because the temperatures ranged up to 300°C, covering the range of temperatures that this DOE project was investigating. Their work showed that with the representative samples that were used, sedimentary rocks have the highest heat capacity. They regarded the density as constant within this temperature range. Similarly the thermal capacity (Figure 10b) increased as a function of temperature, with the two figures differing by a constant factor (density) only.

Although this approach is fine for general analysis, each sedimentary rock strata must be investigated independently of the other formations in order to obtain a realistic appraisal of the heat stored in the formation. This is due to the difference in the heat carrying capacity that each rock type possesses. Thus the volume will be the thickness of the target formation times the expected area from which the heat would be extracted. The heat capacity of the target volume is in reality a combination of both the solid rock and any liquid that may be present within the rock, especially water. This aquifer thermal capacity is defined as

\[ \rho_a c_a = (1 - \phi) \rho_r c_{pr} + \phi \rho_w c_{pw} \]

where \( \rho_a c_a \) is the specific heat of the aquifer, \( \rho_r c_r \) is the specific heat of the rock, \( \rho_w c_w \) is the specific heat of the water, and \( \phi \) is the porosity (Gringarten, 1978; Vance, 2003).

Determining the exact parameters for density, specific heat, and porosity is a combination of laboratory and in-situ field measurements using logging equipment. The varying nature of oil field brine waters has resulted in chemical companies conducting particulate analyses on these brines in order to develop chemicals that can be used to reduce corrosion and scale development in subsurface and surface tubing. Very often the density of the brine is also determined, allowing the development of a relation between salinity and density in a basin. Thus knowing the brine salinity contained within a target formation can allow the calculation of \( \rho_w \) for equation 2. A
Figure 10. Mean values and the ranges of variation of the a) specific heat capacity at constant pressure, and b) the thermal capacity as a function of temperature for magmatic, metamorphic, and sedimentary rocks. The sample rate of the measuring device is $\Delta T = 0.05 \, \text{K}$. For best visualization the mean values of data points and the minimum and maximum values are displayed in an interval of 30 K.

discussion of brine density versus salinity will be presented in the general discussion on Delaware and Val Verde Basin data. However, in most cases the heat capacity of the brine has not been determined. Arranging to acquire samples of brine to determine their $c_{pw}$ in the
laboratory will provide the ability to then determine the specific heat of the formation brine water.

Although generalized values for rock density are available from several sources, determining the heat carrying capacity for a target formation for economic investment will require determining the heat capacity $c_{pr}$ for that rock strata. Discussions with several laboratories that analyze Permian Basin rock strata parameters revealed that heat capacity testing has not been conducted. Thus it will be necessary to secure appropriate reservoir rock samples to conduct laboratory testing under various confining pressures and temperature to determine real world values of rock heat capacity.

The porosity and rock density can be determined either from laboratory investigations or more likely log determinations from wells that have drilled into the target formation. The oil and gas industry developed various well logging techniques to determine in-place porosity. Common porosity logs include sonic, density, neutron, and resistivity techniques. These logs, either individually or in cross-plots can provide significant information as to the porosity within a formation. For example, the density log gives a value of bulk density, that is the density of the rock matrix, porosity, and fluid combined. If the fluid is a brine of known salinity then the density can be determined. Similarly the density of the rock matrix can be determined in the laboratory. With these values the porosity can be calculated using the equation

$$
\phi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_{fl}}
$$

where $\phi_D$ is the density derived porosity, $\rho_{ma}$ is the matrix density, $\rho_b$ is the formation bulk density read from the log, and $\rho_{fl}$ is the fluid density. Not all wells have the same log suites, and different techniques will need to be applied locally. However the well logs will be able to provide significant information that can be used towards determining the in-place thermal capacity of a given formation. The amount of recoverable heat will depend upon the internal permeability, the ability to move fluid through the formation, and the resulting recovery factor that is appropriate to the rock formation system.

Variations in heat capacity of water as a function of temperature and density must also be considered. The heat capacity of water can be written as

$$
c_{pw} = \frac{k_w}{\rho_w K_w}
$$

where $k_w$ is the thermal conductivity of water, $\rho_w$ the density of water, and $K_w$ the thermal conductivity of water. Abramson and others (2001) looked at how diffusivity and conductivity changed as a function of pressure and density at varying temperatures. They noted that as pressure or density increased the diffusivity tended on average to increase, and that as density increased the conductivity also tended to increase. Thus the specific heat of the water can alter depending upon the density and pressure, as well as temperature, of the water.
Thermal Conductivity
If water is introduced into a formation and moves through rock that has stored heat, the water will incrementally extract a limited amount of heat from the rock by way of the conduction process. As the water continues moving further through the rock, the rock and fluid will reach a thermal equilibrium in which the heat is stored in both the rock and the fluid and the temperature of the rock and the water should be identical. In the case where the formation does not receive water from a deeper formation but rather from a distant surface recharge center, the heat initially stored within the formation and its fluid has reached that particular level in the earth primarily through vertical conduction from deeper, hotter sources. Thus understanding the conduction process involved with initially charging these deeper formations is important for determining the sustainability of heat extraction versus heat replacement within the target formation.

Subsurface conductivity is a function of several parameters that include temperature, pressure, fluid type, and anisotropy. In the simple one-dimensional vertical case, Fourier’s law of heat conduction says that

\[
\frac{dT}{dz} = -\frac{q}{k}
\]

where \(\frac{dT}{dz}\) is the temperature gradient over a distance, \(q\) is the heat flux (flow of heat/area/time), and \(k\) is the thermal conductivity (Turcotte and Schubert, 1982). The minus sign is to show that heat flows in the direction of decreasing temperature. A discussion of the temperature gradient as related to this study will be presented in a later section.

A landmark paper directed at thermal conductivities within various rock types describes a series of experiments that investigated the dependence of thermal conductivity on temperature and rock composition (Birch and Clark, 1940a, b). For example they demonstrated that for some minerals such as quartz, the thermal conductivity varied according to the crystallographic axis, with conductivity being 30% to 60% higher parallel to the optic axis compared to perpendicular to the axis. Calcite displayed a similar anisotropy for conductivity though not at as high of percentages (Figure 11). They also showed that because of this, quartz displayed a lower heat flow parallel to the quartz optic axis. Finally, as temperature increased, in their experiments to 400°C, this crystal anisotropy decreased.

Birch and Clark looked at a number of rock types including dolomite, limestone, halite marble, and slate (Figure 11). Dolomite (dolostone) had a far higher thermal conductivity when compared to limestone. This suggests that the higher conductivity found when substituting Mg for Ca in dolostone is related to the higher velocity and density of the dolostone over limestone. The two limestones (Penn. and Solenhofen) display differences in their thermal conductivity, demonstrating that it is equally important to determine the local basin conductivities of the rocks being targeted for geothermal heat extraction. Of equal importance was the higher thermal conductivity of limestone parallel to bedding when compared to perpendicular to bedding in the same type of limestone. As these experiments were conducted under dry conditions, this anisotropy suggests that microlaminations often found in association with limestone, and that can be comprised of insoluble materials, lower the cross-bed thermal conductivity relative to parallel orientations. Although marble is a metamorphic rock its Ca composition places its conductivity within the range of limestone conductivity. And while the slate is metamorphosed shale, the generally higher density of slate over shale would suggest a much lower conductivity of shale.
Figure 11. Thermal conductivities of calcite, marble, limestone, dolomite, halite, and slate as presented by Birch and Clark (1940a, b).  SL⊥ = Slate, Penn., perpendicular to bed plane.  L⊥ = Limestone, Penn., perpendicular to bed plane,  L∥ = Limestone, Penn., parallel to bed plane.  L = limestone, Solenhofen.  M⊥ = Marble, Vermont, perpendicular to bed plane.  M∥ = Marble, Vermont, parallel to bed plane.  Ca⊥ = Calcite, single crystal, perpendicular to optic-axis.  Ca∥ = Calcite, single crystal, parallel to optic-axis.  Do = Dolomite, Penn.  NaCl = Halite.
over slate. In all of these experiments it was demonstrated that both anisotropy and temperature affect the thermal conductivity, with higher temperature causing a lowering of conductivity.

The work of Birch and Clark suggests that in temperatures ≤500°C thermal conductivity will decrease from a maximum at the lowest T to some threshold value that remains constant. This appears to be confirmed by others, such as Vosteen and Schellschmidt (2003) and Clauser and Huenges (1995). It is also striking that Birch and Clark noted that thermal conductivity was higher parallel to limestone beds than when perpendicular to bedding planes. At the lowest T (0°C), thermal conductivity parallel to beds was 35% higher than perpendicular to beds. At 200°C this difference was down to 28%. Work by Popov and others (2003) has also documented this anisotropy of thermal conductivity depending on whether the conductivity is parallel or perpendicular to bedding.

Several authors have used various means to establish equations relating thermal conductivity k as a function of temperature, as reported by Clauser and Huenges (1995). For example, Zoth and Hanel (1988) suggested a relation of the form

$$6) \quad k(T) = A + \frac{B}{350 + T}$$

where \(k(T)\) is given in W m\(^{-1}\) K\(^{-1}\), \(T\) in °C, and the empirical constants \(A\) and \(B\) are determined from a least-squares fit to measured data from various rock types. They reported that from limestones within the temperature range of 0-500°C the constants \(A\) and \(B\) were evaluated at 0.13 and 1073 respectively.

Birch and Clark (1940) also referenced experiments by Bridgman (1923) on compression and thermal conductivity k. There is a general rise in k with hydrostatic pressure amounting to 0.5%/1000 atm (0.5% /14,400 lb/in\(^2\)) for hard limestone versus 1.5% to 3% for “softer” compacted materials (talc, pipestone). Birch and Clark (1945) indicated that for their dolomitic limestone, they have a 7-8% increase in k for a dry sample at 45°C and going from 500 to 10,000 lbs/in\(^2\) (3.5 to 69 MPa). For a wet, saturated rock, the increase in k from its saturated value ranges from 1.5% to 4.6% at 45°C. The percent increase in k for dry sample due to pressure increase is greater than the percentage decrease in k for parallel and perpendicular measurements of conductivity in their earlier limestone experiments.

Clauser and Huenges (1995) also indicated that an increase in pressure would cause an increase in thermal conductivity at the onset due to closing of fractures and pore space. They indicated that when overburden pressure reaches 15 MPa, this process comes to an end, and that further pressure increases to 40 MPa does not change the conductivity significantly. While experiments demonstrated that a 10% increase in conductivity occurred within the pressure range of 0-500 MPa, most of this increase occurred within the first 50 MPa of pressure increase. Using the equation for Lithostatic stress

$$7) \quad z = \frac{\sigma}{\rho g}$$

and choosing an average \(\rho = 2.5\) gr/cc = 2500 kg/m\(^3\), with \(g = 9.8\) m/sec\(^2\), the depth \(z\) can be solved for varying amounts of stress. At pressures of 15, 40, and 500 MPa, equivalent depths are about 2000, 5400, and 67,000 feet respectively. Thus the overall affect of pressure on thermal
conductivity may not be as important as the temperature at the depths of interest in West Texas, though a detailed investigation of target Delaware and Val Verde Basin rocks would be appropriated.

Various other investigators have also looked at determining rock thermal conductivity measurements using various well log data. These investigators include Vacquier and others (1988), Brigaud and others (1990), Demongodin and others (1991), Doveton and others (1997), and Hartmann and others (2002) to name a few. While we have been collecting literature on this approach to thermal conductivity determination, this approach has not yet been applied to this West Texas geothermal study.

**Thermal Advection/Convection**

Heat moves through sedimentary rock by way of both conduction and advection or convection. Heat advection is the transport of heat (a scalar quantity) in an aquifer as the water (a vector field) moves through the aquifer. By contrast heat convection is the transfer of heat (potential energy) by currents within a fluid, and generally occurs when there is a temperature difference either within the fluid or between the fluid and its boundary.

This is an important distinction between advection and convection. Some hydrology books, such as de Marsily (1986), treat convection and advection the same, especially in a porous medium. In water saturated strata, a difference must be made between water that is locked up within pore space due to molecular adhesion, and the free water that is able to circulate under the influence of the hydraulic head. Other authors (Chapman, 1984) define convection as the term applied to one portion of a fluid mixing with another portion due to gross movements of the mass of the fluid. As such, convection is then described at either forced or free (natural) convection. Forced convection is cause by external mechanical means and might be the equivalent of an influx of water into an aquifer that has access to surface water. Free or natural convection occurs if the fluid motion is caused by density differences created by temperature differences existing in the fluid mass. Forced and free convection thus sound identical to advection and convection as used above.

At the present time, we have not investigated the aspects of advection/convection as related to this research project. We have purchased thermal modeling software that will have both conduction and advection components, and anticipate using this software in the future to develop a better understanding of heat movement in target Delaware and Val Verde Basin rock strata.

**Delaware And Val Verde Basins: Interim Analysis And Discussion**

The generalized location of the Delaware and Val Verde Basins is shown in Figures 3 and 4. A more detailed map of the region (Figure 12) shows lands that belong to the University of Texas System (UT Lands) and the three areas of these lands that fall within the study area. In initiating this geothermal study, efforts began by collecting data from ‘Regions 1, 2, and 3’ of the UT Lands acreage. The study then expanded into other areas of these basins. This project was originally devised to assemble resource assessment data on the geothermal resources available within the deep Permian Basin (Delaware and Val Verde Basins) that are drilled for oil and gas extraction with the idea of expanding geothermal extraction into this area as hydrocarbons are depleted. The study would take advantage of the huge in place
infrastructure of data, equipment, and personnel for the potential expansion of geothermal energy extraction from the region.

The project itself, defined as a 3-year investigation, was designed around a 5-phase approach. Phase I would generate detailed databases containing bottom hole temperatures from a variety of sources (well logs, scout tickets, drill stem tests), permeability and porosity

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Figure 12. Map of West Texas showing the location of University of Texas Lands (UT Lands) and the three regions (1, 2, and 3) of these lands that lie within the Delaware Basin and northern part of the Val Verde Basin. These 2 million acres cover all surface and subsurface water and mineral rights.

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information, and formation water analyses. Phase II would conduct evaluation of these data through subsurface graphs and maps of these data. Phase III would identify and discuss likely subsurface target reservoirs for heat extraction. Phase IV would conduct economic analyses, focusing on operations cost and estimated long-term sustainability. Phase V would involve information transfer by written and oral means to both the geothermal and oil and gas industries. Due to funding being provided for only one year, aspects of each of these five phases were included into the project in the attempt to begin to address the geothermal potential of the basins.

**Database Development**

The heart of this project is the database. Thus our initial efforts focused on developing the temperature-depth (t-d) database for the various counties within the study area. A detailed framework or template was established for the database that consisted of five spreadsheets: general, basic, drill stem tests (DSTs), temps, and engineering. The ‘general’ sheet contained well name and operator, location information, logging and completion date, elevation
information, drillers and loggers information, along with other pertinent well information. The basic sheet included well name and operator and location information (found on all five sheets), log types available, drillers and loggers information that included casing depth and size, scout card and scout ticket information, individual drilling runs that included date, TD, bit and casing size, and fluid type information, and columns for various formation calls. The ‘DSTs’ sheet was designed to contain information on perforations, detailed formation tops information, and drill stem test (DST) information. The ‘temps’ sheet was for depth, temperature, formation, viscosity, fluid resistivity information, and circulation data on a run-by-run basis. Finally, the ‘engineering’ sheet was to hold information on completion treatments and 4 point testing that might have been conducted on the well. An example of this database template is provided under the Excel name “DOE_County Data Template.xls”, and Appendix 1 gives a brief working description of the definitions of each column. Two additional spreadsheets are included as a general description of activities and definitions. The files labeled “@DOE index.xls” and “@duplication.xls” provided additional discussion on how the database spreadsheets are set up and what the various columns mean as far as their definition.

Initially we attempted to fill as many of the individual cells within each spreadsheet as we had data available from the well logs, scout cards, and scout tickets to which we had access. However, we soon realized that this would not be possible and focused our attention on the ‘temps’ sheet to build as large a t-d spreadsheet as possible. We subdivided the study region into various surveys and blocks and assigned these to each student. We then focused on inputting log header data into the ‘temps’ sheet.

During the last 3 months, we also began to coordinate information from three separate databases. These included the database initiated by this project, a previously existing partial database of wells at the Center for Energy and Economic Diversification (CEED), and a database from the West Texas Earth Resources Institute (WTERI) whose data, that also included well logs, scout cards, and 2D seismic data, was donated to the CEED. The CEED database is a list of several thousand wells that have been donated to CEED. In generating this database, only the deepest of the bottom hole temperatures (BHTs) were listed. The WTERI database contained around 2,500 wells but listed all of the t-d points that were provided on the well log headers. Thus a well with six different runs at varying depths that had multiple temperature recordings at each of these depths were recorded in the WTERI data. All temperature data is in an uncorrected form, and no attempts to make corrections were conducted as per the earlier discussion on correction uncertainties as found in the “Texas Historic Geothermal Database Background” section of this manuscript.

**County Database Discussion**

**Loving County**: Loving County is in the northern part of the Delaware Basin in Texas, with its northern border forming the Texas-New Mexico state boundary (Figure 13). Two databases are provided for this county. The first copy is entitled “@Copy of Loving_DOE.xls”. Information on 80 wells scattered within the county are provided within this database. The second database is called “@Loving CEED & WTERI.xls”, and includes all of the t-d data from wells listed in the first xls file and wells from the WTERI database (column A).

A total of 103 t-d points are presently in the Loving database. These wells were plotted in both normal-normal and log-normal distribution (Figure 14 A, B). In both plots a linear and a logarithmic trend line was determined for these t-d points. Both lines scored in the 90+% in their
coefficient of determination, though the log-normal curve was just slight better at $R^2 = 92.93\%$.
For the log-normal function the equation derived was

\[ y = 3315.1 \ln(x) - 10429 \]

and with $y = z$ (depth) and with $x = T$ (temperature), solving for $T$ results in the equation

\[ T = e^{0.00030165(z+10429)}. \]

By taking the first derivative of this equation gives the temperature gradient as

\[ \frac{dT}{dz} = (3.0165 \times 10^{-4}) e^{0.00030165(z+10429)} = -\frac{q}{k}. \]

Finally by substitution we have
\[
\frac{dT}{dz} = (3.0165 \times 10^{-4})T = -\frac{q}{k}.
\]

By contrast a pure linear equation for the thermal gradient in Loving County takes the form of

\[
\frac{dT}{dz} = 0.022482 = -\frac{q}{k},
\]

which is the equivalent of a constant 22.482°C/km.

We also tested the possibility that the t-d data points could be subdivided into a shallow to intermediate depth range versus a deeper set of t-d points (Figure 15 A, B). To conduct this test, paired linear equations were generated as shallow and deep subsets. The best two straight lines were defined by multiplying their coefficient of determinations to maximize the value of
Figure 14. Plots of 103 t-d points in Loving County. Blue represents straight line and red represents logarithmic function. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

\[ R^2_{s}R^2_{d} = R^4_{\text{max}} \] for the shallow and deep lines respectively. This resulted in two linear equations shown in Figure 15 for the ‘shallow’ and ‘deep’ t-d points that intersected at a mutual temperature and depth of about 76.5°C and 3,900m. These two equations were then differentiated to determine shallow and deep linear thermal gradients of the form

\[ \frac{dT_s}{dz} = 0.0146 = -\frac{q}{k} \]
Figure 15. Plots of 103 t-d points in Loving County. Light green represents points that are considered shallow to intermediate based on statistical analysis, while dark green points are the deeper t-d values. Each plot has two best fit straight lines shown in black with a red curve representing a logarithmic function. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

\[
\frac{dT_D}{dz} = 0.031933 = -\frac{q}{k},
\]

where the T_S and T_D represent temperature in the shallow and deep realm respectively. This suggests that in this model approach the shallow and deep linear thermal gradients in Loving County are 14.6°C/km and 31.9°C/km, the deeper gradient being twice that of the shallow data.

In addition to these t-d graphs, the data were taken and average temperatures were calculated over 1,000 foot intervals (Table 1). Thus for Loving County, we see that in the depth range of 0 to 1,000 feet, there were no t-d measurement. From 5,001 to 6000 feet, there were 41 t-d points with an average temperature of 101°F. Six depth ranges are shaded in color and represent depth intervals from 4.3 km to 6 km.

We also decided to determine what would be a representative curve for the average t-d pairs with a defined depth interval. Based upon Table 1, we chose the same 1,000-meter intervals so that we could make a direct comparison to the log-normal distributions defined in Figures 14 and 15. A total of seven t-d average pairs were calculated (see "@Loving CEED & WTERI.xls" file) and then plotted along with the 103 t-d measured pairs (Figure 16 A, B). Four separate curves were then defined: 1) log-normal curve on all 103 points; 2) log-normal curve on the seven t-d average pairs; 3) a 2nd order polynomial on the 103 data points; and 4) a 2nd order polynomial on the seven t-d average pairs.
Table 1
Loving Interval and Average Interval T

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Figure 16. Plots of 103 t-d points in Loving County. Red represents the log-normal curve as applied to all 103 t-d measurements. The purple defines the log-normal curve for the average t-d pairs for each 1,000 m of depth. The blue represents a 2\textsuperscript{nd} order polynomial applied to all 103 t-d data points, and the green represents the 2\textsuperscript{nd} order polynomial applied to the average t-d pairs. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

Although the shape of the two log-normal curves were different, they were very similar in their coefficient of determination values (Figure 16). The two 2\textsuperscript{nd} order polynomials had higher $R^2$ values than the log-normal curves, with the 2\textsuperscript{nd} order polynomial for all 103 point being over 98%.

\textit{Winkler County:} Winkler County is in the northeast part of the Delaware Basin in Texas. It is located immediately east of Loving County and forms the corner of the state border with
New Mexico (Figure 17). Two databases are provided for this county. The first is entitled “@DOE_Winkler.xls” and represents the initial database started within this county. The second spreadsheet is entitled “@DOE Winkler statistics.xls” and represents a listing of around 500 wells, although not all of these well have temperatures recorded on the log header or in the database. This second database also included combined data from three separate databases.

A total of 274 t-d points are presently in the Winkler database. These wells were plotted in both normal-normal and log-normal distribution (Figure 18 A, B). In both plots a linear and a logarithmic trend line was determined for these t-d points. The straight line had $R^2 = 87.39\%$ while the logarithmic function had an $R^2 = 88.61\%$. For the log-normal function the equation derived was

\[ y = 3666.2 \ln(x) - 11841 \tag{15} \]

and with $y = z$ (depth) and with $x = T$ (temperature), solving for $T$ results in the equation

\[ T = e^{0.00027276(z+11841)}. \tag{16} \]

By taking the first derivative of this equation gives the temperature gradient as

\[ \frac{dT}{dz} = (2.27276 \times 10^{-4}) e^{0.00027276(z+11841)} = \frac{q}{k}. \tag{17} \]

Finally by substitution we have

\[ \frac{dT}{dz} = (2.27276 \times 10^{-4})T = \frac{q}{k}. \tag{18} \]

By contrast a pure linear equation for the thermal gradient in Winkler County takes the form of

\[ \frac{dT}{dz} = 0.019653 = \frac{q}{k}, \tag{19} \]

which is the equivalent of a constant $19.653^\circ$C/km.
Figure 17. Image from the 1993 Producing Zone of The Permian Basin showing the boundary of Winkler County. The area outlined in orange defines Winkler County. Yellow represents production from Permian formations, blue from Pennsylvanian, purple from Mississippian, green from Devonian and Silurian, and red from Ordovician. Map is courtesy of Midland Map Company.
We also tested the possibility that the t-d data points could be subdivided into a shallow to intermediate depth range versus a deeper set of t-d points (Figure 19 A, B). To conduct this test, paired linear equations were generated as shallow and deep subsets. The best two straight lines were defined by multiplying their coefficient of determinations to maximize the value of $R^2_s R^2_d = R^4_{\text{max}}$ for the shallow and deep lines respectively. This resulted in two linear equations shown in Figure 19 for the ‘shallow’ and ‘deep’ t-d points that intersected at a mutual temperature and depth of about 64.4°C and 3,534m. These two equations were then differentiated to determine shallow and deep linear thermal gradients of the form

20) \[
\frac{dT_S}{dz} = 0.01395 = -\frac{q}{k} ,
\]

and

21) \[
\frac{dT_D}{dz} = 0.023793 = -\frac{q}{k} ,
\]

where the $T_S$ and $T_D$ represent temperature in the shallow and deep realm respectively. This suggests that in this model approach the shallow and deep linear thermal gradients in Winkler County are 13.95°C/km and 23.79°C/km, the deeper gradient being 1.7 times that of the shallow data.

In addition to these t-d graphs, the data were taken and average temperatures were calculated over 1,000-foot intervals (Table 2). This statistical table is more robust than the table produced for Loving County, and is developed using feet and degrees F. Within each 1,000-foot
interval, the minimum and maximum temperatures recorded are listed along with the mean, median, and mode for the temperature data. The same statistical data was also determined for the depths within each interval. Of greatest interest were the wells that had temperatures around 93°C (200°F) and above. Eight depth ranges are shaded in color and represent depth intervals from 4.5 km to 6.7 km, with mean temperature from 83.3°C to 146.7°C (191°F to 296°F). An average temperature of 102.2°C (216°F) is reach within the 5,182 to 5,486-m (17,000 to 18,000-foot) interval.

Figure 19. Plots of 103 t-d points in Winkler County. Light orange represents points that are considered shallow to intermediate based on statistical analysis, while dark orange points are the deeper t-d values. Each plot has two best-fit straight lines shown in black with a red curve representing a logarithmic function. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.
Table 2
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**Ward County:** Ward County is in the east central part of the Delaware Basin in Texas. It is located south of Loving and Winkler Counties (Figure 20). Two databases are provided for this county. The first is entitled "@Copy of Ward County.xls" and represents the database started for this county at the beginning of the study. The second database is called "@DOE Ward statistics.xls". This database represents a combination of multiple databases for temperature only and includes statistical and graphical information.

A total of 331 t-d points are presently in the Ward database. These wells were plotted in both normal-normal and log-normal distribution (Figure 21 A, B). In both plots a linear and a logarithmic trend line was determined for these t-d points. The straight line had $R^2 = 88.65\%$ while the logarithmic function had an $R^2 = 90.39\%$. For the log-normal function the equation derived was

\[
y = 3666.2 \ln(x) - 11841
\]

and with $y = z$ (depth) and with $x = T$ (temperature), solving for $T$ results in the equation

\[
T = e^{0.00028666(z+11195)}. 
\]

By taking the first derivative of this equation gives the temperature gradient as

\[
\frac{dT}{dz} = (2.8666 \times 10^{-4}) e^{0.00028666(z+11195)} = -\frac{q}{k}.
\]
Finally by substitution we have

$$\frac{dT}{dz} = (2.8666 \times 10^{-4})T = -\frac{q}{k},$$

25)

By contrast a pure linear equation for the thermal gradient in Ward County takes the form of

$$\frac{dT}{dz} = 0.022093 = -\frac{q}{k},$$

26)

which is the equivalent of a constant ~22.1°C/km.

We also tested the possibility that the t-d data points could be subdivided into a shallow to intermediate depth range versus a deeper set of t-d points (Figure 22 A, B). To conduct this test, paired linear equations were generated as shallow and deep subsets. The best two straight lines were defined by multiplying their coefficient of determinations to maximize the value of $R^2_sR^2_d = R^4_{\text{max}}$ for the shallow and deep lines respectively. This resulted in two linear equations shown in Figure 22 for the ‘shallow’ and ‘deep’ t-d points that intersected at a mutual temperature and depth of about 61.1°C and 3,246m. These two equations were then differentiated to determine shallow and deep linear thermal gradients of the form
Figure 21. Plots of 331 t-d points in Ward County. Blue represents straight line and red represents logarithmic function. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

27) \[
\frac{dT_S}{dz} = 0.014007 = -\frac{q}{k},
\]

and

28) \[
\frac{dT_D}{dz} = 0.0251 = -\frac{q}{k},
\]
Figure 22. Plots of 331 t-d points in Ward County. Light pink represents points that are considered shallow to intermediate based on statistical analysis, while dark pink points are the deeper t-d values. Each plot has two best-fit straight lines shown in black with a red curve representing a logarithmic function. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

where the $T_S$ and $T_D$ represent temperature in the shallow and deep realm respectively. This suggests that in this model approach the shallow and deep linear thermal gradients in Winkler County are $14.007^\circ C/km$ and $25.1^\circ C/km$, the deeper gradient being 1.79 times that of the shallow data.

In addition to these t-d graphs, the data were taken and average temperatures were calculated over 1,000-foot intervals (Table 3). Calculations were done in feet and degrees F. Within each 1,000-foot interval, the minimum and maximum temperatures recorded are listed along with the mean, median, and mode for the temperature data. The same statistical data was
also determined for the depths within each interval. Of greatest interest were the wells that had temperatures around 93.3°C (200°F) and above. Eight depth ranges are shaded in color and represent depth intervals from 4.5 km to 6.7 km, with mean temperature from 101.7°C to 152.8°C (215°F to 307°F). An average temperature of 101.7°C (215°F) is reached within the 4,572 to 4,877-m (15,000 to 16,000-foot) interval.

**Reeves County:** Reeves County is in the northcentral part of the Delaware Basin in Texas. Reeves sits immediately west of Loving and Ward Counties and has about 3 miles of its northern boundary next to Eddy County, New Mexico (Figure 23). Three databases are provided specific to this county. The first is entitled “@DOE_Reeves County Data Template.xls” and represents well data that was being entered into this database during this project. A second database called “@Reeves DOE + WTERI.xls” represents a combination of project well data and data from the previously developed West Texas Earth Resources Institute (WTERI) database that was deeded to UTPB/CEED in early 2006. The third file called “@Reeves statistics.xls” represents statistical data calculated for the combined database file.

A total of 1,295 t-d points are presently in the Winkler temperature database. These wells were plotted in both normal-normal and log-normal distribution (Figure 24 A, B). In both plots a linear and a logarithmic trend line were determined for these t-d points. The straight line had $R^2 = 90.01\%$ while the logarithmic function had an $R^2 = 92.15\%$. For the log-normal function the equation derived was

$$y = 3206.6\ln(x) - 10327$$
and with \( y = z \) (depth) and with \( x = T \) (temperature), solving for \( T \) results in the equation

\[
T = e^{0.00031186(z+10327)} .
\]

By taking the first derivative of this equation gives the temperature gradient as
Figure 24. Plots of 1,295 t-d points in Reeves County. Blue represents straight line and red represents logarithmic function. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

\[ \frac{dT}{dz} = (3.1186 \times 10^{-4}) e^{0.00031186(z+10327)} = -\frac{q}{k}. \]

Finally by substitution we have
Figure 25. Plots of 1,295 t-d points in Reeves County. Light purple represents points that are considered shallow to intermediate based on statistical analysis, while dark purple points are the deeper t-d values. Each plot has two best-fit straight lines shown in black with a red curve representing a logarithmic function. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

\[
\frac{dT}{dz} = (3.1186 \times 10^{-4})T = -\frac{q}{k}.
\]

By contrast a pure linear equation for the thermal gradient in Reeves County takes the form of
\[ \frac{dT}{dz} = 0.023393 = \frac{-q}{k}, \]

which is the equivalent of a constant \(-23.4^\circ\text{C}/\text{km}\).

We also tested the possibility that the t-d data points could be subdivided into a shallow to intermediate depth range versus a deeper set of t-d points (Figure 25 A, B). To conduct this test, paired linear equations were generated as shallow and deep subsets. The best two straight lines were defined by multiplying their coefficient of determinations to maximize the value of \(R^2_sR^2_d = R^4_{max}\) for the shallow and deep lines respectively. This resulted in two linear equations shown in Figure 25 for the ‘shallow’ and ‘deep’ t-d points that intersected at a mutual temperature and depth of about 72\(^\circ\text{C}\) and 3,536m. These two equations were then differentiated to determine shallow and deep linear thermal gradients of the form

\[ \frac{dT_S}{dz} = 0.015421 = \frac{-q}{k}, \]

and

\[ \frac{dT_D}{dz} = 0.03251 = \frac{-q}{k}, \]

where the \(T_S\) and \(T_D\) represent temperature in the shallow and deep realm respectively. This suggests that in this model approach the shallow and deep linear thermal gradients in Reeves County are 14.421\(^\circ\text{C}/\text{km}\) and 32.51\(^\circ\text{C}/\text{km}\), the deeper gradient being 2.25 times that of the shallow data.

In addition to these t-d graphs, the data were taken and average temperatures were calculated over 1,000-foot intervals (Table 4). Calculations were done in feet and degrees F. Within each 1,000-foot interval, the minimum and maximum temperatures recorded are listed along with the mean, median, and mode for the temperature data. The same statistical data was also determined for the depths within each interval. Of greatest interest were the wells that had temperatures around 93.3\(^\circ\text{C}\) (200\(^\circ\text{F}\)) and above. Eight depth ranges are shaded in color and represent depth intervals from 4.5 km to 6.7 km, with mean temperature from 111.7\(^\circ\text{C}\) to 152.2\(^\circ\text{C}\) (233\(^\circ\text{F}\) to 306\(^\circ\text{F}\)). An average temperature of 233\(^\circ\text{F}\) is reach within the 4,572 to 4,877-m (15,000 to 16,000-foot) interval.
Table 4
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**Pecos County:** Pecos County is southeast of Reeves in the central to south-central part of the Delaware Basin (Figure 26), and covers some 10,360 square kilometers (4,000 square miles) in area. Pecos is that part

![Figure 26](image-url)
of the basin where the deepest wells have been drilled, and thus a larger number of files were generated for this county. A total of 14 databases are provided for this county, which includes files found in Appendix 2 and 3. The database file labeled “@Mikes_DOWGEOTHERMALPROJECT_PecosCounty.xls” represents well data entered into the file from the beginning of the project. The file labeled “@MOST UP TO DATE FOR PECOS COUNTY_08012006.xls” includes combined wells from multiple databases. The third file labeled “@Pecos temps for RJE.xls” represents graphs of t-d information for Pecos County. File number three is based upon well data found in the file labeled “@CEED & WTERI Pecos sort 9-24-06.xls”, and represents the most recent continuation of database combinations. This file also includes statistical information compiled for Pecos County. Four files are provided that generate subsets of data from Pecos County based upon field and/or block location. These include “@Gomez data and trend_07312006.xls”, “@Grey Ranch data and trend.xls”, “@Puckett data and trend.xls”, and “@Pecos Wells Blk 130.xls”.

A total of 4,293 t-d points are presently in the Pecos temperature database. This includes information combined from three separate databases. These wells were plotted in both normal-normal and log-normal distribution (Figure 27 A, B). In both plots a linear and a logarithmic trend line was determined for these t-d points. The straight line had $R^2 = 90.41\%$ while the logarithmic function had an $R^2 = 90.83\%$. For the log-normal function the equation derived was

$$y = 3399.9 \ln(x) - 11198$$

and with $y = z$ (depth) and with $x = T$ (temperature), solving for $T$ results in the equation

$$T = e^{0.00029413(z+11198)}.$$ 

By taking the first derivative of this equation gives the temperature gradient as

$$\frac{dT}{dz} = (2.9413 \times 10^{-4})e^{0.00029413(z+11198)} = -\frac{q}{k}.$$ 

Finally by substitution we have

$$\frac{dT}{dz} = (2.9413 \times 10^{-4})T = -\frac{q}{k}.$$ 

By contrast a pure linear equation for the thermal gradient in Pecos County takes the form of

$$\frac{dT}{dz} = 0.023081 = -\frac{q}{k},$$

which is the equivalent of a constant $\sim 23.1^\circ C/km$.

We also tested the possibility that the t-d data points could be subdivided into a shallow to intermediate depth range versus a deeper set of t-d points (Figure 28 A, B). To conduct this
test, paired linear equations were generated as shallow and deep subsets. The best two straight lines were defined by multiplying their coefficient of determinations to maximize the value of $R_s^2 R_d^2 = R_{max}^4$ for the shallow and deep lines respectively. This resulted in two linear equations shown in Figure 28 for the ‘shallow’ and ‘deep’ t-d points that intersected at a mutual temperature and depth of about 67°C and 3,100m. These two equations were then differentiated to determine shallow and deep linear thermal gradients of the form

$$\frac{dT_s}{dz} = 0.015634 = -\frac{q}{k},$$
and

\[ \frac{dT_D}{dz} = 0.027699 = \frac{q}{k}, \]

Figure 28. Plots of 4,293 t-d points in Pecos County. Light blue represents points that are considered shallow to intermediate based on statistical analysis, while dark blue points are the deeper t-d values. Each plot has two best-fit straight lines shown in black with a red curve representing a logarithmic function. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.
where the $T_S$ and $T_D$ represent temperature in the shallow and deep realm respectively. This suggests that in this model approach the shallow and deep linear thermal gradients in Pecos County are $15.343^\circ C/km$ and $27.699^\circ C/km$, the deeper gradient being 1.77 times that of the shallow data.

In addition to these t-d graphs, the data were taken and average temperatures were calculated over 1,000-foot intervals (Table 5). Calculations were done in feet and degrees F. Within each 1,000-foot interval, the minimum and maximum temperatures recorded are listed.

### Table 5: Pecos Statistics on Temperature and Depth

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Within each 1,000-foot interval, the minimum and maximum temperatures recorded are listed along with the mean, median, and mode for the temperature data. The same statistical data was also determined for the depths within each interval. Of greatest interest were the wells that had temperatures around $93.3^\circ C$ ($200^\circ F$) and above. Eight depth ranges are shaded in color and represent depth intervals from 4.5 km to 6.7 km, with mean temperature from 108$^\circ C$ to 164$^\circ C$ ($227^\circ F$ to 327$^\circ F$). An average temperature of 164$^\circ C$ ($227^\circ F$) is reached within the 4,572 to 4,877-m (15,000 to 16,000-foot) interval. Higher temperatures up into the 204$^\circ C$ ($400^\circ F$) range were also encountered in the deepest 8,839 to 9,144-m (29,000 to 30,000-foot) wells.

In addition to establishing the t-d relations for the county at large, we began to develop preliminary subsets of this data that might be used to define specific areas of interest. In this manner we could begin to determine how variable the temperature-depth relation might be from field to field or area to area and how we might begin predicting t-d values in areas of low well density.

File “@Gomez data and trend_07312006.xls” represents data from around the Gomez field, the field being located on Figure 26 by the large red producing field in the northwest-central part of the county. A graph of Gomez data (Figure 29) shows the overall trend of several hundred t-d points. By continuing with the assumption of a log-normal curve, we get a temperature gradient of
\[
\frac{dT}{dz} = (2.492 \times 10^{-4}) e^{0.0002492(z+13790)} = -\frac{q}{k}
\]

Figure 29. Graph of t-d values in the Gomez field in Pecos County. Data is plotted in meters and °C.

or with substitution

\[
\frac{dT}{dz} = (2.492 \times 10^{-4}) T = -\frac{q}{k}.
\]

The data for Gomez were then split into a number of blocks that comprise the producing area of the field. These blocks include Blk OW, Blk 115, Blk 119, Blk 114, and Blk 146 (Figures 30 A-E respectively). A determination of t-d log-normal curves for these blocks, with the exception of Blk 119 (insufficient depth range), results in four equations listed as

\[
\begin{align*}
43) \quad \text{Blk OW} & \quad \frac{dT}{dz} = (2.4652 \times 10^{-4}) T = -\frac{q}{k}; \\
44) \quad \text{Blk 115} & \quad \frac{dT}{dz} = (2.7069 \times 10^{-4}) T = -\frac{q}{k};
\end{align*}
\]
45) Blk 114

\[ \frac{dT}{dz} = (2.7427 \times 10^{-4}) T = -\frac{q}{k}; \]
Figure 30. Graph of t-d values in the Gomez field in Pecos County as broken into A) Blk OW, B) Blk 115, C) Blk 119, D) Blk 114, and E) Blk 146. Data in Blk 119 is not of sufficient depth to be useful for determining a t-d curve. Block OW is also interesting because displays the appearance of steps within the data plot at temperatures of 100°C and 150°C. Data is plotted in meters and °C.

and

\[ dT = (2.6016 \times 10^{-4})T = -\frac{q}{k}. \]

For comparison purposes, if we assume a temperature of 200°C, then the thermal gradient for all of Pecos County versus the Gomez field at this temperature is given as 58.826 and 49.839°C/km respectively. Similarly, a comparison of Gomez with the four blocks that had a t-d curve calculated indicate the following breakdown: Blk OW = 49.305°C/km; Blk 115 = 54.139°C/km; Blk 114 = 54.853°C/km; and Blk 146 = 52.032°C/km. Thus we see that there can be variations in the thermal gradient from area to area that must be accounted for when determining the subsurface temperature architecture.

Southeast of the Gomez field are two fields, Puckett and Grey Ranch, that lie on a north-south trend on an uplifted structural block near the Pecos-Terrell County line. Two files named “@Puckett data and trend.xls” and “@Grey Ranch data and trend.xls” cover these two fields and part of the immediate surrounding area. Graphs of these two files (Figure 31 A and B) show how the t-d values plot and the corresponding linear and log-normal curves that were used to define the data. Following past procedures, two log-normal thermal gradients were defined for Puckett and Grey Ranch respectively, and are given by
Figure 31. Graph of t-d values in the Puckett and Grey Ranch fields in Pecos County. A) Puckett. B) Grey Ranch.

44) (Puckett) \[ \frac{dT}{dz} = (3.7521 \times 10^{-4})T = -\frac{q}{k} \]

and
For a 200°C temperature, then the thermal gradient is given as 75.041°C/m and 52.055°C/m for Puckett and Grey Ranch respectively. As these values show, while Grey Ranch reflects a temperature gradient similar to the Gomez field, Puckett has a much higher temperature gradient. Reasons for this variation are presently uncertain but could be related to local faulting and/or changes in basement rock affecting heat flow in the field. It is these types of changes that will be important to map out in the basin by defining numerous local thermal gradients and their proximity to subsurface structure, stratigraphy, and rock mineralogy.

Finally, we began to statistically look at individual deep wells with multiple temperature recordings. Several wells in Block 130 southwest and proximal to Grey Ranch field were incorporated into a file called “@Pecos Wells Blk 130.xls”. The wells were plotted together to show their relationship to each other (Figure 32). A slight curve is observable to the data when plotted in a log-normal manner. Additionally, each of the wells was plotted individually, and the reader is directed to the named file to observe the graphs of each of these wells. Four different curve fits were experimented with that included exponential, polynomial, logarithmic, and linear. These variations were used strictly for the purpose of demonstrating that what might be mathematically accurate, with $R^2 \to 1$, does not necessarily imply geological reasonableness.

**Terrell County:** Terrell County lies near the southern boundary of the Delaware Basin, with most of the county in the northern part of the Val Verde Basin (Figure 33). Seven files are
provided for this county. The file labeled “@DOE_GEO_TERRELL_COUNTY.xls” has information on 335 wells in various stages of data entry, with the total number of t-d point pairs at 443. This database also includes several sets of graphs and statistical data. The file “@DOE expanded stats.xls” represents a statistical spreadsheet showing the mean temperature in 1,000-foot intervals as well as minimum, maximum, median, and mode temperatures within the various depth intervals. File “@Terrell Pressure Data Report.xls” represents a DST on a well in

the county. File “@Amoco #1 Univ EY.xls” represents digital points from a continuous temperature log that was taken in 1976. Finally, files “@BLK Y of TCRR Chart with Overall Trend.xls”, “@Terrell county overall trend.xls”, and @Terrell County Trend_01312006.doc” are images of various graphs generated from the t-d data pairs.

The 443 s-t data points were plotted in normal-normal and log-normal distributions (Figure 34 A, B), with both linear and logarithmic trend lines being calculated. The linear trend
scored an R$^2$ of 86.64% and the logarithmic function had R$^2$ of 85.49%, both values being essentially the same. The log-normal trend gives an equation of the form

$$y = 3132.7 \ln(x) - 10510,$$

and with substitutions of $y = z$ and $x = T$, and solving for $T$, we have
\[ T = e^{0.00031921(z+10510)} . \]

Taking the first derivative gives the temperature gradient as

\[ \frac{dT}{dz} = (3.1921 \times 10^{-4})e^{0.00031921(z+10510)} = -\frac{q}{k}. \]

And by substitution we have

\[ \frac{dT}{dz} = (3.1921 \times 10^{-4})T = -\frac{q}{k}. \]

By contrast a pure linear equation for the thermal gradient in Terrell County takes the form of

\[ \frac{dT}{dz} = 0.025368 = -\frac{q}{k}, \]

which is the equivalent of a constant 25.368°C/km.

We also tested the possibility of subdividing the data into a shallow and deep component based upon the determination of the maximum value of \( R^2 \), \( R^2_d = R^2_{\text{max}} \). This resulted in two linear equations (Figure 35) that intersected at a temperature-depth value of 56.7°C and 2236 m respectively. The shallow and deep linear gradients are given as

\[ \frac{dT_S}{dz} = 0.0175 = -\frac{q}{k}, \]

and

\[ \frac{dT_D}{dz} = 0.0265 = -\frac{q}{k}, \]

where the \( T_S \) and \( T_D \) represent temperature in the shallow and deep realm respectively. The shallow and deep thermal gradients for Terrell County as determined by this model are 17.5°C/km and 26.5°C/km. The deeper gradient represents a value 1.5 times the shallow gradient.
Figure 35. Plots of 443 t-d points in Terrell County. The light yellow triangles represent the points used for determining the shallow linear trend and the dark yellow triangles are the points used for the deep linear fit. The green 'plus' sign represents 15 data points not included within the overall curve fitting or with the shallow-deep linear fit due to temperatures being either higher or lower than most other data points. The short red horizontal lines are the remaining 428 points that were used for the log-normal curve calculations. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

All of the data used to generate the spreadsheet is in the feet and degrees Fahrenheit. As this data was input, one of the students (Mike Sorensen) would occasionally generate graphs of the data for future investigative purposes. These graphs were generated at various times during the data entry process and thus do not necessarily correspond to the graphs that were calculated using meters and degrees Celsius and discussed above. As these graphs have been included in the various files for Terrell County, a brief explanation of these graphs is appropriate.
Often when wells are drilled to their final total depth (TD) the well may have been drilled over an extended period of time either by one operator or by multiple operators. In such a case there may then be multiple t-d measurements taken within the well. The t-d values were placed in the database in various columns called ‘Runs’ to represent the number of times that a given well had a temperature measurement. These ‘Runs’ were then plotted graphically to see how the resulting graphs would look (Figure 36 A, B).

![Log normal plots of t-d values in Terrell County.](image)

**Figure 36.** Log normal plots of t-d values in Terrell County. The data was plotted and color-coded according to the ‘Run’ that each t-d reading represented. Points labeled ‘Cooling run 1&2’ and Cooling run 3&4’ were not included in the curve calculations. Graphs are in feet and °F. A) This image represents three separate log-normal functions defined for the three pairs of ‘Runs’ (1&2, 3&4, 5&6) defined in this graph. B) A single function defined for the majority of t-d points plotted.
In Figure 36 A, a color-coding technique was used to define the various runs. A log-normal function was calculated for each of the three ‘Run’ pairs. Points that are labeled cooling run were not included in these calculations. These points appeared to be anomalously low or high in temperature when compared to similar depths in other wells. Thus they were not included within the calculations of the log-normal distributions. Figure 36 B is an overly graph of Figure 36 A with a single distribution calculated for the majority of data points. This distribution was determined based on feet and degrees F rather than meters and degrees C. Thus, it cannot be directly compared with previous equations that were determined using meters and °C. A revising of these two graphs is necessary for a direct comparison.

![Terrell County Overall Trend](image)

Figure 37. Log normal plots of t-d values in Terrell County. In this graph the shallow to mid range is represented by ‘Run 1&2’ t-d points, the mid to deep range is defined by ‘Run 3&4’, and deep is given by ‘Run 5&6’. Graph in feet and °F.

The data were also plotted in a manner to accentuate ‘Run 1&2’, Run 3&4’, and Run 5&6’ only (Figure 37). In this graph the terms shallow, mid, and deep are defined only according to the ‘Run’ that each t-d data point fell within. This is not necessarily the best way to determine any shallow to deep cut of range, but it was a graphical means to show how the t-d points fell within the graph according to the ‘Run’ that each data point defined.

While a graph of t-d data for the entire county is valuable for defining regional t-d functions to describe the data, it is equally important to be able to determine the types of variations that might exist within a given area of a county, or within a given well. To experiment with this approach, the deepest wells that were in the database for August 2005 were taken from Block Y, Survey TCRR and had their t-d values plotted (Figure 38). Linear and log-normal functions were determined with the $R^2$ value for the linear function being 92.88% and the $R^2$...
value for the log-normal function being 97.17%. One well located in Blk Y, Sec. 38 (Standard of TX – Monsanto, Bassett Trust #2-1) had 5 separate t-d ‘Runs’ and was graphed independently from the other wells. The $R^2$ value for this well was 92.79% using a log-normal distribution.

Figure 38. Log normal plots of t-d values in Terrell County from Blk Y, Survey TCRR. Graph in feet and °F.

In the process of building the Terrell database, we have not yet expressly added information from drill stem tests (DSTs). This is because we anticipate the database generated from the log header information to act as a first pass to allow for honing in on areas of interest with high temperature at specific target depths. After defining target areas, then any DST information would be added into the database specific to those wells of interest.

One particular well, the Conoco ACU #49-1, ran several DSTs and gathered other information that include water salinity and a velocity survey. One of these DSTs was taken within the depth range of 4,808-4908 m (15,776-16,102 feet) out of the Devonian formation. The reported reservoir temperature was 120°C (248°F) (Figure 39). This particular well had three ‘Runs’ and ‘Run 2’ had a t-d value of 132°C at 5,389 m (270°F at 17,680 feet), the closest interval to the maximum temperature recorded in this particular DST. Shutin period 2 for this DST was slightly under 2 hours. Apparently this part of the formation has extremely low permeability but with a reservoir pressure of the tested interval greater than 6000 psi.
In transferring data from the well headers to the database, we encountered a well, Amoco #1 University “EY”, that had a temperature log taken in 1976 to a depth of 2,649 m (8,690 feet). While not an extremely deep well it provided sufficient information to establish an interesting temperature-depth relation that is definitely non-linear.

No digital records were available. A spreadsheet (@Amoco #1 Univ EY.xls) was set up and depths were listed at 10-foot intervals from surface to 2,649 m (8,690 feet). A straight edge was then used to estimate the temperature to within 0.2°F for each of the 10-foot intervals, with the t-d values placed within the spreadsheet. The t-d pairs were then graphed to determine the type of line that was generated, shown as a light blue curve of 870 points in Figure 40.

The plotted points defined a curve rather than a straight line. Thus we felt there was no need to test a linear fit but rather wanted to test various curve fits to the data. The first curve to be tested was the logarithmic function, which was given as

\[ y = 7900.2 \ln(x) - 32751. \]

With appropriate substitutions for \( y = z \) and \( x = T \), the temperature can be written as

\[ T = e^{0.00012658(z+32751)}, \]

and with differentiation we get

\[ \frac{dT}{dz} = (1.2658 \times 10^{-4})e^{0.00012658(z+32751)} = -\frac{q}{k}, \]
or with appropriate substitution

\[ \frac{dT}{dz} = (1.2658 \times 10^{-4})T = -\frac{q}{k}. \]

The coefficient of determination was very high at \( R^2 = 99.33\% \), a very good fit indeed.

However, we wanted to see if other solutions were also possible for this data. Thus we next tested a 6\(^{th}\) order polynomial of the form shown in Figure xx. The \( R^2 \) fit was equally or slightly better than the logarithmic equation at 99.83\%. A solution to this equation as a function of \( \frac{dT}{dz} \) is not as simple, so before attempting to solve the equation in a more explicit form, we allowed the curve to do a forward forecast as provided in the Excel spreadsheet. When this was allowed, the polynomial peaked and started a downward turn in a manner that was not realistic of the data. A forward modeling of the logarithmic curve still maintained a reasonable increase of temperature with depth, but the polynomial did not.

Upon examination of the curve defined by the data we noticed that the points appeared to define a vertical tangent to the data at the location \( T = 70.5^\circ F, z = 0 \) feet. In fact the overall look of the curve strongly resemble a hyperbola. Thus we set about to determine a hyperbolic function that might fit the t-d data from this well. The general form of the hyperbola is given as

\[ \frac{x^2}{a^2} - \frac{y^2}{b^2} = 1. \]
where $a$ is the distance to the vertex, in this case 70.5, and $b$ is the distance from the vertex out to the asymptote. By choosing $x = 70.5$ and $y = 0$, we can solve for $b$, which gives 3,550. This constrains the curve to start at the shallowest t-d value reported on the log. Manipulating this equation we get

$$T = \sqrt{(3.9439 \times 10^{-4})z^2 + 4970.3} = -\frac{q}{k}, \quad (58)$$

and by differentiation we get

$$\frac{dT}{dz} = (3.9439 \times 10^{-4})z\left(\frac{1}{\sqrt{(3.9439 \times 10^{-4})z^2 + 4970.3}}\right) = -\frac{q}{k}, \quad (59)$$

or with substitution

$$\frac{dT}{dz} = (3.9439 \times 10^{-4})z\left(\frac{1}{T}\right) = -\frac{q}{k}. \quad (60)$$

This equation is a bit more complex than the logarithmic function due to $dT/dz$ being a function of $z/T$. However the $R^2$ value for this equation was very good at 98.25%, nearly the same value as found for the log function. A forward projection of the hyperbolic function was also reasonable in the temperature-depth values that could be determined. The database has a columnar description of how the coefficient of determination was calculated.

In addition to the t-d graphs, the data were taken and average temperatures were calculated over 1,000-foot intervals (Table 6). Calculations were done in feet and degrees F. Within each 1,000-foot interval, the minimum and maximum temperatures recorded are listed along with the mean, median, and mode for the temperature data. The same statistical data was also determined for the depths within each interval. This statistical analysis had 336 t-d points to use at the time it was completed. This table is very raw with respect to the statistical analysis. Even with this limited data a mean temperature of 61°C (200°F) or above can be found at the 3,353-m (11,000-foot) depth interval.
Table 6
Terrell Statistics on Temperature and Depth

<table>
<thead>
<tr>
<th>Depth</th>
<th>Number of wells</th>
<th>Terrell - UT Lands</th>
<th>Terrell - UT Lands</th>
<th>Terrell - UT Lands</th>
<th>Terrell - UT Lands</th>
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Crockett County: Crockett is immediately east of Pecos and Terrell Counties (Figure 41) and was not strictly part of this study. However the southwestern part of Crockett has several deep Ellenburger fields that are geologically connected to Ellenburger production to the west in Terrell County. As there was data available from a previous CEED database, we decided to include Crockett within this database development. Thus only one database labeled “@CEED_Crockett_logs.xls” is provided and covers wells throughout the county and that are available at CEED.

A total of 1,266 t-d points are presently in the Crockett County database. These wells were plotted in both normal-normal and log-normal distribution (Figure 42 A, B). In both plots a linear and a logarithmic trend line was determined for these t-d points. The straight line had $R^2 = 75.84\%$ while the logarithmic function had an $R^2 = 76.8\%$. For the log-normal function the equation derived was

$$\frac{dT}{dz} = (5.0958 \times 10^{-4}) \cdot e^{0.00050958(z-5983.7)} = -\frac{q}{k}.$$
Finally by substitution we have

$$\frac{dT}{dz} = (5.0958 \times 10^{-4})T = -\frac{q}{k}.$$ 

By contrast a pure linear equation for the thermal gradient in Crockett County takes the form of

$$\frac{dT}{dz} = 0.03499 = -\frac{q}{k},$$

which is the equivalent of a constant $\sim 35^\circ$C/km.

We also tested the possibility that the t-d data points could be subdivided into a shallow to intermediate depth range versus a deeper set of t-d points (Figure 42 A, B). To conduct this test, paired linear equations were generated as shallow and deep subsets. The best two straight lines were defined by multiplying their coefficient of determinations to maximize the value of $R^2_sR^2_d = R^4_{\text{max}}$ for the shallow and deep lines respectively. This resulted in two linear equations shown in Figure 42 for the ‘shallow’ and ‘deep’ t-d points that intersected at a mutual temperature and depth of about 50.6$^\circ$C and 1,783m. These two equations were then differentiated to determine shallow and deep linear thermal gradients of the form
Figure 42. Plots of 1,266 t-d points in Crockett County. Blue represents straight line and red represents logarithmic function. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

\[ \frac{dT_s}{dz} = 0.018216 = -\frac{q}{k}, \]

and

\[ \frac{dT_d}{dz} = 0.041307 = -\frac{q}{k}, \]
Figure 43. Plots of 1,266 t-d points in Crockett County. Light blue-gray represents points that are considered shallow to intermediate based on statistical analysis, while dark blue-gray points are the deeper t-d values. Each plot has two best-fit straight lines shown in black with a red curve representing a logarithmic function. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

where the $T_S$ and $T_D$ represent temperature in the shallow and deep realm respectively. This suggests that in this model approach the shallow and deep linear thermal gradients in Crockett County are $18.216^\circ$C/km and $41.307^\circ$C/km, the deeper gradient being 2.26 times that of the shallow data.

In addition to these t-d graphs, the data were taken and average temperatures were calculated over 1,000-foot intervals (Table 7). Calculations were done in feet and degrees F. Within each 1,000-foot interval, the minimum and maximum temperatures recorded are listed
Table 7

<table>
<thead>
<tr>
<th>depth</th>
<th>Crockett</th>
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<td>15,000</td>
<td>11</td>
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<tr>
<td>16,000</td>
<td>1</td>
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along with the mean, median, and mode for the temperature data. The same statistical data was also determined for the depths within each interval. This statistical analysis only had 110 t-d points to use at the time it was completed, and had not yet been updated at the time of this report. Also various cell listings had yet to be corrected from previous work. Thus this table is very raw with respect to the statistical analysis. Even with this limited data a mean temperature of 93°C (200°F) or above can be found at the 2,743-m (9,000-foot) depth interval, a much higher mean temperature at that depth than what has been seen in the other counties.

**Culberson County:** Culberson County is in the northern part of the Delaware Basin in Texas. This county lies immediately west of Reeves County with its northern border next to Eddy County, New Mexico (Figure 44). Culberson was not strictly part of this study, but as several wells were already available from the existing CEED database, this database is included under the name “@CEED Culberson 2.xls”.

Only 60 wells were in this database, and while there are other wells that can be added, this county is sparsely drilled in comparison to the previous counties that are described as found within the Delaware and Val Verde Basins. A total of 60 t-d points are presently listed in this database. These wells were plotted in both normal-normal and log-normal distribution (Figure 45 A, B). In both plots a linear and a logarithmic trend line was determined for these t-d points. The straight line had $R^2 = 81\%$ while the logarithmic function had an $R^2 = 80.06\%$. For the log-normal function the equation derived was

$$ y = 2980.4 \ln(x) - 9641.1 $$

and with $y = z$ (depth) and with $x = T$ (temperature), solving for $T$ results in the equation

$$ T = e^{0.00033553(z + 9641.1)} $$

By taking the first derivative of this equation gives the temperature gradient as
Figure 44. Image from the 1993 Producing Zone of The Permian Basin showing the boundary of Culberson County. The area outlined in orange defines Culberson County. Yellow represents production from Permian formations, blue from Pennsylvanian, purple from Mississippian, green from Devonian and Silurian, and red from Ordovician. Map is courtesy of Midland Map Company.

\[
\frac{dT}{dz} = (3.3553 \times 10^{-4})e^{0.00033553(z+9641.1)} = -\frac{q}{k}.
\]

Finally by substitution we have
Figure 45. Plots of 60 t-d points in Culberson County. The one large t-d point appears to be anomalous and was not used when determining the trend equations. Blue represents straight line and red represents logarithmic function. 
A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

\[
\frac{dT}{dz} = (3.355 \times 10^{-4})T = \frac{q}{k}.
\]

By contrast a pure linear equation for the thermal gradient in Crockett County takes the form of

\[
\frac{dT}{dz} = 0.025049 = \frac{q}{k}.
\]
Figure 46. Plots of 60 t-d points in Culberson County. The one large t-d point appears to be anomalous and was not used when determining the trend equations. Light brown represents points that are considered shallow to intermediate based on statistical analysis, while dark brown points are the deeper t-d values. Each plot has two best fit straight lines shown in black with a red curve representing a logarithmic function. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

which is the equivalent of a constant \(\sim25^\circ\text{C/km}\).

We also tested the possibility that the t-d data points could be subdivided into a shallow to intermediate depth range versus a deeper set of t-d points (Figure 46 A, B). To conduct this test, paired linear equations were generated as shallow and deep subsets. The best two straight lines were defined by multiplying their coefficient of determinations to maximize the value of \(R^2_sR^2_d = R^4_{\text{max}}\) for the shallow and deep lines respectively. This resulted in two linear equations...
shown in Figure 46 for the ‘shallow’ and ‘deep’ t-d points that intersected at a mutual
temperature and depth of about 57°C and 2,150m. Again, due to the small number of points, the
accuracy of this intersection is questionable. However, differentiating these two equations to
determine shallow and deep linear thermal gradients gives

\[
\frac{dT_s}{dz} = 0.016687 = -\frac{q}{k},
\]

and

\[
\frac{dT_d}{dz} = 0.025284 = -\frac{q}{k},
\]

where the \(T_s\) and \(T_d\) represent temperature in the shallow and deep realm respectively. This
suggests that in this model approach the shallow and deep linear thermal gradients in Culberson
County are 16.687°C/km and 25.284°C/km, the deeper gradient being about 1.52 times that of
the shallow data.

In addition to these t-d graphs, the data were taken and average temperatures were
calculated over 1,000-foot intervals (Table 8). Calculations were done in feet and degrees F.
Within each 1,000-foot interval, the minimum and maximum temperatures recorded are listed
along with the mean, median, and mode for the temperature data. The same statistical data was
also determined for the depths within each interval. This statistical analysis only had 21 t-d
points to use at the time it was completed, and had not yet been updated at the time of this report.
Even with the sparseness of the data, temperatures of 93°C (200°F) were being reached in the
3,353 to 3,658 m (11,000 to 12,000 foot) depth intervals.

| Table 8               |

<table>
<thead>
<tr>
<th>Culberson Statistics on Temperature and Depth</th>
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<tbody>
<tr>
<td><strong>Basin-Wide Discussion:</strong> A total of eight counties had t-d data collected for this project. A cumulative listing of the t-d data is given in the file named “Delaware Val Verde Basin data.xls”. A total of 8,050 t-d points were then plotted and color-coded on a county by county basis to determine how each county compared to the other (Figure 47 A, B).</td>
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</table>
Figure 47. Plots of 8,050 t-d points in the eight counties included within the Delaware and Val Verde Basin study. Each set of t-d points are color-coded to the county from which it is derived. A) Normal-normal plot. B) Log-normal plot.

In this graph (Figure 47), Crockett County is found to have the highest temperature gradient, followed by Terrell County. Both of these counties are in the southern part of the study area. Terrell was expected to have a higher temperature gradient due to its proximity to Marathon orogenic activity and to surface faulting probably related to Laramide and Basin and Range deformation. The t-d distribution for Crockett was more of a surprise. The t-d points tend
to follow the same general plot for the shallowest 2,000 m, after which this data diverges rapidly from the rest of the data.

The amount of this divergence between the t-d points for Crockett and Terrell is seen in Figure 48 where the overall temperature gradients for each of the eight counties are plotted. The

Figure 47. Plots of the average logarithmic gradient defined for each of the counties in the study. Each curve is color-coded to the county from which it is derived. A) Normal-normal plot. B) Log-normal plot.
higher thermal gradient for Crockett is a distinct surprise. Val Verde County, located to the south of Crockett, was not included in the database development at this time. Val Verde is expected to have a high gradient due to surface expressions of interpreted Laramide and Basin and Range deformation, thus being closer to more recent tectonic activity. However this was not expected for Crockett, and a more thorough analysis is needed to determine why Crockett has its higher temperature gradient.

To the north, Loving County appears to be the coolest (Figure 47), though at a depth of about 6,000 m the slope of the t-d data appears to change radically when compared to other counties. When looking at the log-normal function for Loving, the county on average actually appears to be somewhat warmer than both Ward and Winkler. Ward and Winkler Counties nearly lie on top of each other and appear slightly warmer than Loving based upon the t-d distribution in Figure 47. Culberson County is a surprise because though it is west of Loving, this county shows a temperature gradient similar to that found in Terrell County (Figures 46 and 47). Finally, Reeves and Pecos Counties form a large central block of t-d data that lie nearly on top of each other. We have not separated wells by area within these counties to any great extent, though we anticipate that wells in the western part of these two counties, being closer to Tertiary volcanic activity in the Trans-Pecos, will have t-d affinities similar to the Trans-Pecos region.

The importance of determining t-d curve relations within an individual county or within geographic areas (fields) within a single county has much to do with generating usable maps and with projecting what the temperature should be at a target formation depth. At the time of turning in this report only a few maps had been generated. However these maps show the size of the region and the work still to be completed.

All 8,050 t-d points were also displayed in a cumulative manner for the basin as a whole (Figure 48). In this manner a more direct comparison could be accomplished between the basin as a region and each individual county. Both linear and logarithmic functions were defined,
Figure 48. Plots of the 8,050 t-d points within the study region as a whole. No separation of data by county was undertaken in these graphs. Rather regional linear and logarithmic functions were determined for the basins as a whole for comparison with each of the county thermal gradients. A) Normal-normal plot. B) Log-normal plot.

giving thermal gradients of

75) (Linear) \[ \frac{dT_D}{dz} = 0.023638 = -\frac{q}{k} \]

and

74) (Logarithmic) \[ \frac{dT_D}{dz} = (3.1241 \times 10^{-4})e^{-0.00031241(z+10461)} = (3.1241 \times 10^{-4})T = -\frac{q}{k} \]

For the linear function a regional thermal gradient of 23.638°C/km is defined, whereas for a T=150°C, the logarithmic function gives a thermal gradient of 46.862°C/km.

We also took the basin-wide t-d data and divided the data into a shallow and deep range based upon the temperature (Figure 49 A, B). Paired linear equations were generated as shallow and deep subsets. The best two straight lines were defined by multiplying their coefficient of determinations to maximize the value of $R^2_s R^2_d = R^2_{\text{max}}$ for the shallow and deep lines respectively. This resulted in two linear equations shown in Figure 49 for the ‘shallow’ and ‘deep’ t-d points that intersected at a mutual temperature and depth of about 63°C and 2775m. These two equations were then differentiated to determine shallow and deep linear thermal gradients of the form
Figure 49. Plots of the 8,050 t-d points within the study region as a whole. Points were plotted in a manner to determine the best-fit shallow and deep linear thermal gradients to the data. A) Normal-normal plot. B) Log-normal plot.

\[
\frac{dT_s}{dz} = 0.017025 = -\frac{q}{k}
\]
and

\[ \frac{dT_D}{dz} = 0.026669 = -\frac{q}{k}, \]

where the \( T_S \) and \( T_D \) represent temperature in the shallow and deep realm respectively. This suggests that in this model approach the shallow and deep linear thermal gradients in the entire basin study are 17.03°C/km and 26.67°C/km, the deeper gradient being 1.57 times that of the shallow data.

Well top data provided by Geological Data Services (GDS) was imported into the Petra software-mapping package. Four maps were generated to show the number and location of wells within the majority of the study area. These maps displayed wells and well spots (undrilled well locations) from 0 to 30,000 feet (Figure 50) (file “@All Well 0 to 30,000 Ft.jpg”), 0 to 4,999 feet (Figure 51) (file “@All Well 0 to 4,999 Ft.jpg”), 5,000 to 11,999 feet (Figure 52) (file “@All Well 5,000 to 11,999 Ft.jpg”), and 12,000 to 30,000 feet (Figure 53) (file “@All Well 12,000 to 30,000 Ft.jpg”). These data from GDS can be used to cross-reference with the wells in the database to ensure that all of the wells presently available to GDS are also included in the database for t-d measurements. This part of the project has yet to be accomplished but will be conducted in the future.

![Figure 50](image.png)  
Figure 50. Plot of 44,525 well locations and well spots within the counties of Culberson, Reeves, Loving, Winkler, Ward, Pecos, and Terrell within the Delaware and Val Verde Basins. Crockett County was not included within the GDS well data that was provided for use. Depth is from 0 to 30,000 feet.
Figure 51. Plot of 33,481 well locations and well spots within the counties of Culberson, Reeves, Loving, Winkler, Ward, Pecos, and Terrell within the Delaware and Val Verde Basins. Crockett County was not included within the GDS well data that was provided for use. Depth is from 0 to 4,999 feet.

Figure 52. Plot of 8,802 well locations and well spots within the counties of Culberson, Reeves, Loving, Winkler, Ward, Pecos, and Terrell within the Delaware and Val Verde Basins. Crockett County was not included within the GDS well data that was provided for use. Depth is from 5,000 to 11,999 feet.
The Petra software package was designed to conduct various contour plots exclusive of temperature data. For example, the top and bottom of the thick, highly organic rich, black Woodford Shale is easily recognized on electric logs due to its high gamma ray reading. Thus a structure contour map on the top of this shale is useful for giving a regional structure map of the basin complex (Figure 54) (file “@WDFD contour 200 ft w wells.jpg”). The areas in blue and purple show the deepest parts of the basin which trends NW-SE through the center of the basin. To the east lies the Central Basin Platform and to the west the Diablo Platform, much of the platform being overlain by recent Tertiary volcanic rocks. This contour map is only based upon well top information. Regional 2D seismic lines are available but have not been incorporated into the regional map.

These types of maps are of great importance for determining the regional temperature profiles. In more conventional geothermal extraction, vertical fault pathways for hot water flow are of great importance due to many geothermal fields displaying plumes of heat in localized areas as a result of upwelling water. Extracting heat from deep sedimentary rocks may at times find vertical fault zones of importance but will more likely need to deal with lateral flow patterns over greater distances within specific target formations. Thus the volumes of heat stored in the rock-water combination are on mush larger orders of magnitude. While mapping the temperature at a constant depth is a good first pass for acquiring a regional picture of temperature
distribution, **mapping temperature within a single target reservoir** will be of far greater importance for targeting a specific site for heat extraction. The t-d measurements recorded in the database are not specific to any given reservoir. Thus determining the county or more geographical localized temperature-depth curve will allow predicting what the average temperature might be within a target reservoir at a specific depth. With this information it will be possible to also develop temperature maps within a specific formation and compare the temperature distribution to the structural changes within the reservoir along with proximity to major fault trends within the region. An unpublished map from a regional tectonic study of the Delaware-Val Verde Basin complex (Figure 55) produced for the O&G industry by the West Texas Earth Resources Institute shows the complexity of the region. Thus being able to
integrate the seismic with the log tops for target formations such as Devonian, Fusselman, Ellenburger, and others will provide detailed exploration maps that are useful to industry for heat extraction. With maps constructed showing the temperature distribution within a specific formation, calculating the volumetric heat energy stored within the reservoir using Equation 1 will be possible. Constructing isopach maps will help to determine the volume over which the heat is distributed, thus helping to solve for the stored thermal energy.

To date only one very preliminary temperature map has been created. This map (Figure 56) (file “@Wells below 18,000Ft at 1000 Ft interval.jpg” and file “@Pecos BHT summary map 2.jpg”) used a small number of wells within Pecos County with a small subset of t-d data in an effort to explore the ways to actually map the temperature data using the Petra software. The contour interval is 5°F, with darkest blue ranging from 265°F to 270°F, and deepest red from 410°F to 415°F. These temperatures are not related to a constant depth, but rather to a color-coding used on the wells. The wells are color-coded for every 1,000 feet, starting with light green.
ranging from 18,000 to 18,999 feet to dark red at 29,000 to 30,000 feet. If the lower half of the colored circle representing a well is shown in yellow, then a temperature within the depth range shown by the color in the upper half of the circle was used for creating the contour. Thus this map is read by looking for wells that are split with the lower half circle being yellow, determining the well depth range from the color in the upper half circle, and looking at the color interval for the contour to determine the temperature at that well. This map is experimental only and must be used with caution until constant depth-temperature maps and temperature maps within a target formation are generated.

As previously discussed, the $\rho C_p$ value in Equation 1 is related to the specific heat of the aquifer $\rho_a C_a$ in Equation 2 ($\rho C_p = \rho_a C_a$). Porosity of the rock can be obtained regionally from a more targeted literature search and from studies conducted by O&G and service companies. The density of the brine was determined directly from proprietary water chemistry data provided by a company active in the Permian Basin. Over 18,000 water chemistries were used to construct the brine density versus TDS found in produced oil field waters (Figure 57). Thus for a given well
or a region, if the TDS of the water is known, an average calculation for the water density can be read from this graph. This is important because an increase in the water density should increase the specific heat of the fluid in the rock. On the other hand increasing temperature and pressure, as related to depth of produced fluid, should also affect the specific heat of the aquifer. Data compile by the CRC Handbook of Chemistry and Physics (87th Edition) on fresh water and sea water at various low temperatures and pressures does suggest changes in both density and heat capacity. However, a detailed look at this data and an investigation of produced oil field waters involving density and heat capacity has yet to be included in this project.

Plotting the t-d data from wells gives important information regarding how the temperature varies as a function of depth. The data plots demonstrate that the thermal gradient $dT/dz$ can readily be modeled as a non-linear function, at least according to least squares fit and the coefficient of determination. Considering that Fourier’s law of heat conduction was conducted within a controlled laboratory environment, samples of rock, metal, or other materials that are only a few inches across that fit a linear equation is not surprising. Fourier never had to deal with the real-world situation of many thousands of feet of heterogeneous rock that must be dealt with in the real geothermal environment, especially if the rock is not of the same type for the entire thickness. If a very small increment of distance were chosen along any of the log-normal curves shown for the above counties, then it would be easier to model a linear equation rather than the non-linear form for that small incremental distance. **I suggest that when dealing with these large rock thicknesses, of varying rock types, a non-linear equation to describe the temperature gradient is the norm.** In essence Fourier’s law is correct for the laboratory environment but must be altered into a non-linear form for larger thicknesses of material, such as rock found in its natural environment. It may also be that in the real world we must deal with a true three-dimensional solution rather than the simple one-dimensional approach. This is another reason why mapping temperature laterally within a formation is important because it will give some empirical data as to the variation of temperature in two other dimensions.

![Figure 57. Graphical display of unpublished, proprietary produced brine water in the Permian Basin. Water chemistry database was provided by an anonymous company active in the Permian Basin.](image-url)
On the other side of Fourier’s one-dimensional law (Equation 5) lies heat flux \( q \) and thermal conductivity \( k \). As discussed earlier, various investigators have shown that thermal conductivity can decrease as a function of increasing temperature (Equation 6). Investigators also demonstrated that conductivity would increase as pressure increases, though temperature might have the stronger influence. Since the \( dT/dz \) values determined for the counties studied tended to increase with depth, this would suggest that conductivity must decrease on the right side of Equation 5, assuming that heat flux remains constant. Equation 6 demonstrates that as \( T \) increases, conductivity decreases, which would tend to drive the thermal gradient up with depth, the very thing seen in the t-d data plots.

If we take Fourier’s law and rewrite it for heat flux, with the addition of Equation 6, we get

\[
q = \left( A + \frac{B}{350 + T} \right) \frac{dT}{dz} .
\]

Zoth and Hanel (1988) evaluated \( A \) and \( B \) for limestone as 0.13 and 1073 respectively in the temperature range of 0-500°C. However limestone is not the same worldwide, and thus the conductivity for a limestone will vary according to its porosity, fluid content (wet or dry), and other aspects of its mineralogy. Birch and Clark (1940a, b) also demonstrated that conductivity varied within a given limestone based upon measurements either perpendicular or parallel to bedding. They also demonstrated that dolostone generally has a higher conductivity than limestone. Thus knowing the percentage of dolomitization within a target formation is important for determining conductivity.

In order to obtain an idea of the impact of these effects, we took the work of Birch and Clark and estimated high and low temperature and conductivity values from their graph as displayed in Figure 11. We used their curves for limestone perpendicular and parallel to bedding, and their curve for dolostone. We could then set up two equations based upon Equation 6 and solve for values of \( A \) and \( B \). We then solved for heat flux using Equation 77 as a test for Terrell and Crockett Counties, using the best-fit log-normal curve that defines \( dT/dz \) for each county. At 150°C for Terrell County, we solved for limestone in a perpendicular and parallel flow condition as 41.7 and 54.4 mW/m², and for dolomite at 68.4 mW/m². Similarly, at 150°C for Crockett County, we calculated 167.7 and 218.8 mW/m² for limestone in perpendicular and parallel flow conditions, and a value of 275.5 mW/m² for dolostone. In Terrell and Crockett Counties, 150°C on average corresponds to depths of about 5,200 and 3,900 meters respectively. To better determine heat flux and heat recovery would require experimental work with the rocks of the target formation. However this does give an idea of heat flux values that might be considered on average for these counties. More work, including laboratory study, must be done to better refine this approach and to better predict the amount of recoverable heat for electrical power generation.

Trans-Pecos Region: Brief Analysis And Discussion

The Trans-Pecos region of West Texas includes the counties of western Culberson, Hudspeth, El Paso, Jeff Davis, Presidio, and Brewster. As such this region was not formally part of this study. However, the director of UTPB/CEED had a number of wells in the region and had built them into a small spreadsheet. Thus we felt it was appropriate to include this data for
the purpose of suggesting that this region is equally important as a target region for geothermal
electric power development following a somewhat more traditional geothermal approach.

The Trans-Pecos is represented by a series of Paleozoic, Mesozoic, and Cenozoic
sedimentary rocks overlain by Tertiary volcanic rocks of various ages (48 to 17 m.y.). These
volcanic rocks were deposited from several major volcanic centers in Texas and adjacent
Mexico. The region also displays surface outcrop evidence of Ouachita-Marathon, Laramide,
and Basin and Range tectonism with faults (strike-slip, thrust, and normal) and folds found
throughout the region. Locally surface data exists that suggests Quaternary age faulting in the
form of extension. This evidence has been found from the southern part of Big Bend National
Park northward through many of the intermontane basins of the Trans-Pecos (Collins and Raney,
1997). Occasionally recorded earthquake activity in the Trans-Pecos supports the premise that
this area is still active seismically, though in a more localized manner.

To our present knowledge, and with only a cursory examination of this region, no
detailed investigations or surface exploration has been conducted for geothermal resources. No
descriptions of surface sediment or mineralogical alterations due to hot fluid flow along
Quaternary faults have been documented to our knowledge. This might be due to few geologists
looking for these types of surface indicators rather than a lack of these features. To date only
investigations of local hot springs or water wells have been undertaken for geothermal
investigations. For example Hoffer (1979) and Henry (1979) identified hot springs or water
wells in various areas with elevated temperatures at or near the surface. Waring (1965) defined
thermal springs in West Texas as those that have waters equal to or above 30° C. Both Hoffer
and Henry followed this definition in their thermal studies of the region. Hoffer collected
groundwater samples throughout the Trans-Pecos region as part of a four-year study, which
included El Paso, Culberson, Hudspeth, Jeff Davis, Presidio, and Brewster Counties. Hoffer
concluded from silica geothermometry that seven areas in the Trans-Pecos existed with
subsurface waters above 125° C. These included areas in northeast El Paso, western and
southeastern Jeff Davis, western and northern Presidio, and southern Brewster Counties. Henry
(1979) identified areas in the Presidio and Hueco Bolsons, and parts of the Big Bend region with
hot springs whose heat comes from abnormally high (30° to 40° C/km) geothermal gradients.
Henry also proposed that thinner crust from Basin and Range extension in these areas enhanced
the heat flow. He argued that the Presidio and Hueco Bolsons represented the best potential for
future geothermal development in the region.

The file labeled “@Trans Pecos WELL BOTTOM HOLE TEMPS.xls” represents the
data that was compiled for graphing. Most of this data comes out of Presidio County, though
there are other scattered O&G wells throughout the Trans-Pecos that need to be added to this
small database. A total of 65 t-d points were plotted for Trans-Pecos analysis in both normal-
normal and log-normal distributions (Figure 58 A, B). In the first graph, two linear functions
were calculated in an attempt to fit the data to a shallow and deep temperature gradient. The low
number of data points and the broad scatter of the O&G data made determining best-fit straight
lines difficult. Coefficient of determination calculations were very low (Figure 58 A) and thus
Figure 58. Plots of 65 t-d points within the Presidio County area. Blue diamonds correspond to O&G well BHT data whereas the purple squares are shallow temperature data taken from a file produced by SMU and their Geothermal Laboratory. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

we felt that defining a shallow and deep gradient with this small amount of data was too uncertain. However, when the depth scale was changed to log-normal, the data displayed a more continuous pattern (Figure 58 B) that resembled data from the counties in the Delaware and Val Verde Basins. Both linear and log-normal curves were determined for the t-d points, with the log-normal curve having a slightly better $R^2$ value than the linear fit.

We also decided to make a comparison of the Trans-Pecos data with t-d data from the Delaware and Val Verde Basins. The Trans-Pecos data were overlaid on a graph that had been previously constructed using only the West Texas Earth Resources Data (WTERI), and which
had been made available to UTPB/CEED for inclusion within this project (Figure 59). The overlay of the Trans-Pecos t-d data appeared to reasonably follow the WTERI data, though it was somewhat warmer at depth than the four counties displayed. This data has not yet been overlain on the most recent graphs provided in this written project description.

The Trans-Pecos data appears to define an area where some wells from Pecos County show hotter temperatures at shallower depths, and thus fall within the region defined by the Trans-Pecos t-d points. The actual locations of these wells with respect to the Trans-Pecos data have not yet been determined, though this can be done through the existing databases. These wells could be located along the western margin of Pecos and thus have t-d values more closely resembling the t-d values for the Trans-Pecos. It was also a surprise that the Trans-Pecos data could be described as a log-normal function. When the nonlinear functions were first being defined in the Delaware Basin, we thought that the reason for the rather good fit to the data might reflect thick shale in the Basin acting as a thermal blanket, suppressing heat flow and thus raising the thermal gradient in the deeper limestone and dolostone reservoirs. However, the potential agreement of the Trans-Pecos data with a nonlinear function raises questions to this hypothesis. The rock strata within the Trans-Pecos are substantially different from the subsurface stratigraphy that is found in the Delaware and Val Verde Basins. Thus the idea of a ‘thermal blanket’ acting to alter the thermal gradient from a linear to nonlinear function is questionable. Presently, the earlier suggestion that Fourier’s law is linear only when dealing with small thickness and that Fourier’s law is actually a nonlinear function over large distances remains a possible hypothesis for further investigation.

Two additional files named “@DOE expanded stats 8-28-05.xls” and “@ Temperature Averages by depth 2.xls” are include for the reader to review. The first of these two files provides the statistical breakdown for all eight counties within the study as well as a sheet labeled “small stuff” that contains statistical data on wells in Brewster, El Paso, Hudspeth, Presidio, and Val Verde Counties. The second file includes information on wells in the eight focus counties along with additional information on Trans-Pecos counties.
Conclusions And Suggestions

In a previous geothermal proposal about sedimentary basins written in 1999, a milestone plan was developed for the project development. Although this plan was not formally required in this proposal, this previous milestone plan acted as a broad guide for the work conducted in this project. Although this present project is incomplete (originally designed as a 3-year project), I will use this milestone plan to indicate accomplishments to date.

Phase I – Develop Database
A database template was developed within which well log and production information could be added. Over 8,000 temperature-depth recordings were written into this database for eight counties within the Delaware and Val Verde Basins of West Texas. The temperature data is from log header information. Little to no cross-referencing to scout ticket and drill stem test information about well temperature has been conducted due to the massive amount of well data that became available. Cross-referencing was just not possible at the present time. Permeability and porosity data has yet to be gathered in detail, however this can be accomplished later as various areas become target for geothermal extraction. Some drilling salinity information was gathered from log headers and placed into the database. A large volume of formation fluid salinity data was acquired (some 18,000 data points) for the entire Permian Basin. This data is not listed by individual wells due to the proprietary nature of the data. This type of information would need to be gathered at future date and focused to particular target formations.

Evaluation – Graphs & Maps
With the development of the t-d database, numerous graphs have been generated and more can be developed. Temperature-depth graphs for each of the counties have been developed and discussed in this paper. Similar maps can be developed for target areas within each county based on field location, on survey subdivision, or on subsurface geological features. Comparisons of the plotted temperature data have been made at the county level; field size comparisons have been initiated locally. Some well temperature profiles have been looked at but a greater effort must be initiated in this direction. Fluid salinity versus temperature (heat content) has not specifically been addressed, but brines can be obtained for determining heat content at various temperatures in the laboratory.

Detailed temperature maps have yet to be developed, and the single map generated to date was mostly a test of software and data entry. Thus temperature maps have yet to be developed. A proprietary database was acquired under long-term loan for generating regional subsurface maps on the tops of target formations. Regional 2D seismic data has also been made available for use in this study. No surface maps of present day land use have been generated.

Target Reservoirs
Identifying the most permeable strata will be accomplished using the available oil and gas production data from deep formations, which indicates the relative permeability of target zones. Deep formations such as the Devonian, Fusselman, Montoya, Simpson (maybe), and Ellenburger are definitely target formations. The amount of water squeezed off within such deep formations is presently unknown, but should be much higher than the amount of water produced.
from existing wells. The size of these zones, aerial coverage and thickness, are still to be
determined in detail, but they should be substantially bigger than existing geothermal fields.

**Economic Analysis**

The cost for power plant development and geothermal field lifetime has not been
addressed in great detail. Copies of previous presentations and reports sent to the DOE have
begun to address this issue based upon analogy with the Brazoria power plant in South Texas.
This information was not discussed in this report because of this data having previously been
submitted to the DOE.

**Technology Transfer**

I have attended numerous meetings and given a large number of oral presentations
addressing geothermal energy production from sedimentary basins. This has included O&G
geological societies and petroleum engineering groups, as well as the GRC and GPW meetings.
I have participated with SMU in the Texas Geothermal Workshop and been in contact with the
Texas Renewable Energy Industry Association (TREIA) regarding geothermal. Several Texas
newspapers as well as online papers have picked up on the possibility of geothermal energy from
sedimentary basins. I have been interviewed on TV several times through a local show called ‘In
The Pipeline’ where I have spoken extensively about geothermal energy. I have spoke to several
civic groups through contacts at the USDA. I have had numerous contacts with renewable
energy companies that are expressing serious interest in this approach to geothermal
development in Texas. Finally, I have had contact with several independent and one major O&G
company that are interested in potentially developing geothermal from produced brine. Two of
these companies are actively seeking information on small turbine capabilities.

**Other Accomplishment/Suggestions**

1) From my involvement with the geothermal industry to date (ie. GRC), I have noted that most
discussion about natural hot water and heat emplacement (not EGS) revolves around
proximity to fault systems and fracture density within a target area. Geothermal from
sedimentary rock, via a conduction-dominated or geopressed approach, must also include
the natural surface to subsurface charging of a water-wet reservoir. Thus this project has
helped to define a different approach for geothermal extraction compared to the traditional
fault and fracture dominated approach. Proper well location in a sedimentary rock must
consider the hydrologic regime of that formation, a formation that is laterally very extensive.
Proximity to faults may not be as important as the hydrologic drive. Thus while O&G wells
extract from the crest of a structure, hot water may best be acquired from much lower on the
structure to take advantage of the hydrologic head. Hot shallow formations can readily point
to water flowing upward from a deeper hot reservoir to charge the shallow target zone. An
already deep sedimentary target formation cannot point to water moving upward from a
‘deeper’ zone due to basement complexes not necessarily containing water. Thus the
geothermal industry will need to ‘reeducate’ themselves and work in conjunction with the
O&G industry to bring about geothermal energy development in a sedimentary province.

2) Fourier’s law for one-dimensional heat flow relates the thermal gradient to heat flux divided
by conduction in a very linear manner. Past efforts by various authors show that conductivity
will change as a function of both temperature and pressure, especially for sedimentary rock
within the first 500°F, and can change depending on the conductivity being measured parallel
or perpendicular to the rock strata. Similarly, this project is demonstrating that over large thicknesses of material, the thermal gradient may not be linear but instead may follow a nonlinear function such as a logarithmic function, or even in some cases a hyperbolic function within the first 30,000 feet or so of sedimentary strata. Thus Fourier’s law may need certain revisions for very thick materials and for variations in temperature through that same material.

3) There is a need to experimentally determine rock thermal conductivity for target geothermal formations in the subsurface of the region. Such conductivity measurements do not presently exist among companies that were contacted during this first year of study. Numerous other parameters can be determined from well log data and other experimental investigations that will allow the determination of thermal energy stored in the subsurface.

4) The logarithmic curves of t-d for a region define the average thermal gradient for a large number of data points. Local variations from this average or variations from one area to the next should reflect changes in the subsurface geology and heat transfer characteristics that affect the local t-d relationship.

5) Temperature contour maps generated at a constant depth are important for a quick regional look at what is happening in the subsurface. However, mapping the temperature variations within a single target formation will be far more important for developing future heat extraction procedures. For industrial best use practice, many local determinations of the t-d relations will allow for calculating the expected temperature within a formation at a specific site when the data availability is sparse to nonexistent. This approach will help in developing ‘temperature-formation’ (t-f) maps when no temperature is reported in a specific well or area within a specific formation by determining local ‘phantom points’. This is analogous to converting a time map in reflection seismology to a depth map using a contoured velocity grid map.

6) Unless temperature data is acquired from a DST, log header temperature data should be considered the minimum temperature to be expected within a formation at the depth of the BHT recording. Attempting to compensate for a lack of thermal equilibrium by various calculations may be a waste of time due to uncertainties inherent in oil field drilling and temperature recording practices. It is far better to consider log header temperature data as a minimum temperature, a lower boundary condition, and work with the data from that standpoint.

7) A BHT analysis versus the age of wells in various areas may be useful to see how recorded temperature data may have varied over time. Comparing log header temperature with more modern continuous log temperature data would also be useful in determining quality control. Comparison of temperature data with local vitrinite reflectance information may also help in giving an historical perspective to temperature changes from the past to the present.

Appendix 1

Appendix 1 represents information describing what each of the spreadsheet columns represents. This was put together for student benefit, however it seemed appropriate to include this information as an Appendix within this document as well. Note that some changes may have occurred in the spreadsheet format since the time of writing this description primarily because this effort is still a work in progress and has yet to be finalized. However this description will still be a help file to anyone that looks at the Excel files in the attempt to
understand the work and what the columns signify. Files labeled “@duplication.xls”, “@DOE_County Data Template.xls”, and “@DOE index.xls” provide additional information and descriptions about the columns, cells, and colors used for highlighting purposes. Realize that there may have been variations on these columns, cells, and colors since the files were originally conceived.

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**KEY TO SPREADSHEET COLUMNS**

We decided to do the sheets as “stand alone” and combine them later so each of us will work a county – or part of a county. There are 10 boxes of Terrell County logs. There are about 60 boxes of Pecos County logs, the index program lists about 3500 wells. We will divide the county further for the purposes of this study and recombine when I get a newer computer.

The version of EXCEL I use at CEED uses alphabetical labels for the columns, the version I have at home uses numerical labels across the columns.

- **A/1** We will fill this column after we finish – that way, we know how many wells we have and can get them back in order if we sort on operator then another parameter. Dr. Erdlac used this procedure previously and found it useful.

- **B/2** County – this may be redundant.

- **C/3** API number – we won’t find all of them without going to other sources. 42 indicates Texas. The 3 number group indicates county – 371 is Pecos, 443 is Terrell, etc. The last 5 numbers are the “unique number” – they started at 30000 in about 1970. We will usually need to look up anything prior to that date. Lower numbers were assigned in alphabetical order by operator - sorta.

- **D/4** I’m being lazy on this – there may be an East Gomez – I just enter Gomez as that indicates the general area. A field in Winkler County has 23 producing zones – I just list it as Keystone because wells can be plugged back to a shallower designation and we may not have that information. Or, someone may be interested in a well that TD’s in Ellenburger but pass a well because it says “Keystone – San Andres”.

- **E/5** Operator – again, I’m being lazy – just Chevron, not Chevron USA or Jones instead of Jones Bros. Drilling. There are enough Coxes that initials need to be used and there are several Browns. Except for the wells in University Lands Survey, we will use the information we have in house. And Dr. Trentham tells me that we should get a collection from Faskin in July. Much of that will be duplication though hopefully, additional logs. With some luck, it will be in the same order I used – block and section!

- **F/6** Well Name – This is usually the person or organization that owns the mineral rights. If the well shows as the Erdlac 23-1, I enter it as Erdlac “23” #1 or for the Erdlac A-1, I added it as Erdlac “A” #1. The “23” will usually indicate section number, “A” usually indicates “lease A”. ExxonMobil owns the deep rights under my place – if a well is drilled in my west pasture, it would probably be a farmout designated ExxonMobil-Armour #1 (or Armour-ExxonMobil #1)
Texas land is unlike 35 other states. The initial Texas surveys were done when the area was a Spanish
territory, then part of Mexico, and eventually an independent country. We have Spanish varas, ("a" as father)
leagues, and labors (accent on the “bors”) as well as feet and miles like you expect. The Rail Roads began
surveying the area so T&P indicates a rail road. The founders of the Republic of Texas set aside properties and
assigned some to the various county schools (CSL surveys) and some were designated UL – the rentals/mineral rights,
whatever income from those surveys goes into the coffers to help support the Texas universities. Then there are
"long lot surveys" back to the days of the Spanish so everyone would have access to a river. Questions? – I've
given this lecture to several classes and groups of technicians so come ask.... It will be a pleasure to answer a
question for someone who actually cares about the answer!

G/7 Block – whoever surveyed it gets to name it – some used numbers, some used the alphabet, others used their name – those are usually newer surveys.

H/8 Some townships (mostly by the T&P RR) are numbered north or south from a base line – so, you'll need 1 S, 2 S or whatever if you run into them. I don't remember any north surveys in our area. T&P is the only survey that uses this system.

I/9 Section number.... (unless it's a 1 well block then it gets the block name and whoever surveyed it)

J/10 Survey - well, that's the T&P, UL (University Lands), Archer CSL (County School Lands), PSL (Public School Lands), etc (CCSD&RGNG is the longest one.) I have a list in my office if you are interested.

THE ABOVE INFORMATION WILL BE ON ALL SPREADSHEETS, immediately below is the information on the BASIC sheet. The second batch will be from the DST spreadsheet. The third form is the TEMPerature sheet, and the last batch of data will come from the sheet with “engineering information”. (I eventually added a sheet for “geology” though I think I'm the only one who filled it out.)

K/11 I've tried to keep the footages with “from north line” (or south) in K and L, “from east line” (or west) in M and N. Many of these surveys were done using magnetic north (like Midland County) so if you look at the map, things look cock-eyed, that's why. If there is a rotation, I rotate clockwise – and some are almost 45° to true north. You'll find some wells are reported already rotated. And some are irregular with “stair steps” and they are reported as "from most southerly north line" – that makes no sense unless you look at the map. Dr. Erdlac said for us to go ahead and enter the data rotated – the lat-long will take care of the exact location.
Latitude and longitude – we’ll have to look those up later on 95%+ of the wells. The ones we can’t find will probably be the wells drilled before electric/sonic, etc. logs were invented. They won’t have information we need, anyway.

NM Location – will need to draw that for you. I had a boss in town who likes the New Mexico style locations – in some ways, it is redundant, in others, it is quite useful.

OK – will go back to proper labeling from here.

Richard has “comments” columns scattered liberally through his sheets so I thought I’d follow that lead – we can note which locations are rotated – or if it’s “most easterly west line” etc. Again, I’ll find an example for you.

Logging date – last run -- When you look at a log header, you may see “run1”, “run 2” all the way to “run 8”. On “Basic” sheet, we will use the last date. On other sheets, we will be adding columns for all dates. A shallow well probably was logged with 1 run.

Completion Date – completion dates are usually a day or more after the logging date. We’ll have to get that elsewhere.

Elevations – Surface, ground, land - whatever you walk on....

Floor – the drilling rig floor

KB – kelly bushing – they put a plate under the neck of the pipe to support it while they add (or remove) sections of pipe rather than let pipe/casing down even with the drilling rig floor. The kelly is usually a foot above the rig floor and they slide the support between it and the expansion at the top of the pipe. (if given with decimal, include the .6 rather than rounding up as I have done in the inventory sheet)

Log Datum – sometimes logs are measured from KB, sometimes from GL

There are several Total Depth measurements. Tradition says use the Driller’s depth. The logging tool may stretch the cable that suspends it. The driller counted the joints of pipe that went into the hole.

Drilling Contractor – we may have to look for this information. Some give reliable information, others guess.

Logger’s Total Depth – the head logger counts how many feet of cable went into the hole with the logging equipment + the length of the equipment.

Logged Depth – this will be different from the total depth. Logging tools may be 20 feet long. Some send a tone from the bottom of the device; a recorder at the top calculates the speed of transmission through the rock. An electric log sends a pulse through the rock – this tells how much oil/gas and water is in the hole. Logging tools are often run together so the top of the top tool may be 40 feet from the bottom of the hole.

FM at TD – or formation at TD

Logged Top – they don’t necessarily log all the way to the top, especially on a second or later logging run.

On this sheet, just put in the number of logs we have available. There are a number of logging
companies and several types of logs – everyone has a different name for their product. “Sonic” is the generic name.

AF/32 There is a difference between a MUD log and a SAMPLE log – will provide an example. I also note dip logs and temperature logs in this column – there aren’t many. (Mud log is done at the time the well is drilled. A sample log is made from well cuttings from 10 foot intervals – and may be done 30 years after the well was drilled! I’ve done them.)

AG/33 Number of runs – look at the log header, if there are more than 4, you may have to look below the list or, depending on how the log is folded, on the next “page”. If there are multiple logs, check the dates – there may be a 5th run that doesn’t show up on the header with the other 4 runs. Also, you may need to check the logging date to be sure they didn’t bother to combine the runs on one log.

AH/34 Scout info – that’s scout cards (4 X 6 or bigger for old ones),
AI/35 Scout tickets – old ones come hand written on 5 x 8 notebook paper. Newer ones are typed.
AJ/36 If Gulf bought a well from Kewanee, cleaned out the well or did something else to it, that is a work over – OWWO (oil well work over). Chevron bought Gulf then drilled the well deeper – OWDD.
AK/37 Space to put in Kewanee/Gulf so we know who else may have logged this well. If there is something else that is of interest, put it in here. We may add another column for the same sort of information. Another problem – locations can be given in alternate forms, like from lease boundaries.... That’s usually a problem with older wells. I have maps of the areas we will work – and a scale to measure locations....

AL/38 IP – Initial Production – Barrels of Oil Per Day,
AM/39 Barrels of Water Per Day
AN/40 Thousand Cubic Feet of Gas per Day – remember your Roman numerals – M for 1000.

AO/41 We will have to look up the well status. It may have been plugged and abandoned at the time it was drilled. It may have produced for a while but gone dry. Or it may still be producing. It may have been plugged back to a more shallow zone – there are quite a number of options and we will need to look this up when we near the end of the project so we will have the latest information.

AP/42 Lease status – is it HBP – Held By Production, has the lease expired, or has someone recently leased a shallow / deep zone.... Again, there are numerous options and we will need to look this up later.

AQ/43 There are core and sample “libraries” so for this project, we need to note whether the well was cored – I’m not sure how to check for samples donated to a library.

AR/44 We’ll repeat A/1 just so it will be easier to follow lines across should we print this out.

The BASIC sheet will give us more log information.

The first 12 columns are a repeat of the general sheet. The duplication is to keep us from having to flip back and forth from sheet to sheet. This one has grown longer than my “spreadsheet from hell” that I did at Mobil.

M/13 There are several types of logs. It will probably be easier for us to use Schl for Schlumberger (pronounced Slumber-jay) or Hal for Halliburton, etc – rather than for us to try to sort out all of the types
of sonic logs, neutron/neutron-density logs, etc. There’s a difference between a mud log and a sample

Examples are on the paper with headings, etc. Sometimes we get lucky and find a dip meter log, a temperature log, or on the really new stuff, computer generated logs. We’ll call them “other” in this example, I’m showing 1 mud log and 2 sample logs

Number of runs – again, this is a repeat. Look at the log header, if there are more than 4, you may have to look below the list or, depending on how the log is folded, on the next “page”. If there are multiple logs, check the dates – there may be a 5th run that doesn’t show up on the header with the other 4 runs. Also, you may need to check the logging date to be sure they didn’t bother to combine the runs on one log.

Record the name of the original operator. When we go into the University Lands office, we may need to add “next operator” to this.

Repeats - the Oil Well Work Over or Oil Well Drilled Deeper.

Driller’s depth – (number of joints of pipe in the well x 30)

Whose rig and crew did they use? Some companies are more reliable than others – if there’s a discrepancy, this may decide whose information we use

There usually are multiple casing strings - we may need to add more columns here, too.
And a space for extra casing strings not reported with the logging runs – later.

These are repeats again. The logger often does not agree with the driller – cable stretch....

The logged depth may not be all the way to the bottom – or to the top.

Do we have the 4 x 6 new card (or the old 8 x 5 card) and how many?
Do we have the small 3 hole punched scout ticket – either hand written or typed – and how many? We have several boxes of scout tickets behind the computer room – bring gloves and long sleeves if you plan to get into those – they’ve not been opened in 2+ years and I have seen black widow spiders. I expect a few scorpions, too.

Do we have access to the well file information? Or DO WE NEED TO CONTACT SOMEONE TO GET IT?

This would be forms filed with the Rail Road Commission. They should also be in the well file – if we have it.

Date the well was completed – few days after the logging date.

Spud date – when industry was starting, the machines used to start the hole sputtered as they ran. Sputter was corrupted to “spudder” which was shortened to “spud”.

This collection is data specific to a logging run – the date, the top of the logged interval, the driller’s TD,

bit size and casing size.


(Ar/44, As/45, At/46, Au/47, Av/48 – run 3 – we may need to add more but by then, if it doesn’t match, it won’t matter!

Surface bit – the biggest one – we may not find this information

Surface casing – this is specified by the Railroad Commission and is supposed to be deep enough to protect whatever aquifer.
After they get below the depth they must protect, they can go to a smaller diameter bit. For shallow wells,

this will be the size bit they use to go to TD. In deeper wells, there will be more than one more bit used. It’s “intermediate. Likewise, the second “string of casing” is the intermediate casing. Some clays / shales swell when salt water comes in contact with them. An operator will set the intermediate (or smaller) casing to protect against that – if not, they may “loose the hole”

Fluid in hole – some wells are drilled using air to cool the drill bit. Others use fresh water (<3000 ppm total dissolved solids – “cow fresh”), most use salt water or “drilling mud”.

Fluid level – this information often is not available

Fluid density – barium and other things are added to the fluid to keep formation water/gas from getting into the sides of the well bore. There’s a place for fluid viscosity and pH on the log header but it isn’t very often found filled in. If they know they are loosing fluid into the formation, sometimes that loss is reported. And if they get a sample of the water, does it come from the tanker that brought in the fluid or did it come from the mud pit?

And again, we may need to copy and paste more in here but by then, it probably won’t matter.

Is there Hollingsworth or Paleontological data available for the well? That may be on the log or there may be an extra sheet of information in the envelope.

Add a column for information that doesn’t fit anywhere else.

The green lines were moved to another sheet. We also have columns on it for whatever information we can find on logs that indicate where someone else thought they encountered the “Ellenburger” or “Yates” formations.

These columns are for formation tops for the major formations followed by a space for whatever comments. I don’t know if we will have the fun of doing this or not. Some are easy, others are not.

The main thing is to be consistent. And start at the bottom of the log and work up – this is the way to build a cake (lasagna?) from the bottom. If there has been erosion, you’re more likely to catch it if you work bottom up than top down.

The only place this set differs is with the Woodford. It is a shaley layer, usually above “clean” limestone or dolomite – this call causes trouble occasionally but I suspect I’ll show it to you once and you’ll have little to no trouble finding it! I left a space for the top of the Woodford.

If we find Cambrian or Precambrian other than on the Central Basin Platform, I’ll be amazed.
CO/93 Anything listed as Kewanee, Gulf, Chevron or Getty is operated by ChevronTexaco. Any logs shown as Superior or Mobil is operated by ExxonMobil. The big 2 may not have gotten around to a workover – or they may have sold it again. Last operator

CP/94 We can add whoever else we can find who has had a shot at these wells.

CQ/95 Richard had a column to note whether there were samples, slides, or core available. I’ll make it 1 column instead of one for each formation and each type of information.

CR/96 We may be able to use seismic information on this. We can check at the Midland Energy Library to see if there are velocity surveys available for the well in question. That’s usually requested by county and they look for it. We copy it.

CS/97 Again, a spot for comments

CT/98 We’ll copy column A after it is filled in and copy it here.

Drill Stem Test SHEET - DST information 2, etc. will be a repeat of the columns in DST 1

J/10 division between copied information and new stuff....

K/11 We will almost certainly add to this set of columns – If a well isn’t completed “open hole”, they shoot holes

L/12 in the casing and production comes in through them. I’ve allowed for 2 sets of “perfs”... Of course we

M/13 may need to add columns.

N/14

O/15 break before the first of 24 columns of DST information

P/16 the top depth of the test

Q/17 the bottom depth - will usually be the same as TD

R/18 Chlorides – in parts per million

S/19 Duration of pre-flow – these are not always done

T/20 the pressure of the pre-flow

U/21 Initial Shut In Pressure – the length of time it is shut in; 3' means 3 hours, 30” means 30 minutes

V/22 the pressure, usually given in pounds

W/23 Final Shut In Pressure – the pressure at the end of whatever length of time

X/24 the pressure

Y/25 Flowing Pressure – this isn’t always given – gives an initial pressure

Z/26 and a final pressure

AA/27 Hydrostatic Pressure – this isn’t always given, either – initial pressure

AB/28 and final pressure

AC/29 Open – how long is the tool

AD/30 Gas To Surface – time for it to get there – often stated as GTS in 15” (gas to surface in 15 minutes)

AE/31 amount – 15 cfgh cubic feet of gas per hour or minute.... I

AF/32 Time – time for other fluids to get to the surface as 1’10” (1 hr, 10 min, or 70 min)

AG/33 Other recoveries – I’ve made a list for you – came from “the Spreadsheet from Hell” – 30+ columns that weren’t heavily populated.

AH/34 Amount – however many barrels of whatever – mud, (gas cut) water, (sulfur water) etc.

AI/35 Repeat other recoveries, just in case
AJ/36 And again – how much of whatever
AK/37 Comments

AL/38 Sample chamber (about 1 liter worth) – how long is it open
AM/39 How many cubic centimeters in the sample chamber
AN/40 pressure, usually in pounds
AO/41 And 3 columns for other recoveries – I’ll run off copy of abbreviations for you – they aren’t all here, but
AP/42 most are... Other recoveries – as 3 cubic centimeters of Gas & Water Cut Mud or 10 cubic centimeters.
AQ/43 of Salty Sulfur Water or 5 cubic centimeters of Drilling Mud.
AR/44 The usual “comments” for what doesn’t fit in any other column.
AO/41 break between DST’s

And the rest of this one is a repeat of the above 29 columns. And there may be 8 to 10 DST’s - we’ll copy and paste the above as many times as we need....

TEMPERATURES

J/10 Usual break between information
K/11 Driller’s depth on log header, location variable – sometimes (especially with new logs) it will be in a section below the header.
L/12 Logger’s depth on log header, either just below or just above driller’s depth
M/13 Logging date for run 1 (or 2....)
N/14 Temperature – this will be listed with the bottom hole temperature line - if we’re lucky. We may need to look at Rm @ BHT – Rm is a measurement used, especially with electric logs to figure out how conductive/resistive the fluid is and that says how much is water, how much is oil. If we’re really unlucky, we’ll have to go to the DST’s to get this information.
O/15 If you really like converting degrees F to degrees C, have fun. Otherwise, we’ll ask the program to calculate that after we finish.
P/16 Source of the information – the Bottom Hole Temperature, Rm @ BHT, or Drill Stem Test.
Q/17 The formation tested – we may need to look that up.
R/18 If we have a temperature, look up Rm, Rmf, etc. on a chart – just add the temperature. There is a place
S/19 for the information on most logs newer than about 1960.
T/20 if you have to write the entire thing out, leave a space on either side of the “@” or the computer will try to turn it into a web address.... (Rm @ BHT).
U/21 We will probably need more than a log header and a scout ticket to find out when they stopped running drilling mud through the system to cool it.
W/23 Sometimes we can find out how long the logger had his tool at the bottom of the hole.
X/24 Time since circulation – tells us if the hole has had a chance to get back to its proper temperature
Y/25 Comments - again
Z/26 break between repeat.... And we’ll probably end up with about 8 of these. Richard says he’s seen up to 10 runs.

AA/26 and repeat of column A again

ENGINEERING INFORMATION

A 4-Point test is also called a production test. It is usually run 4 times – and may be run on more than 1 formation....

J/10 division between usual common information

K/11 date test run

L/12 bit size

M/13 casing size

N/14 MCF – thousand cubic feet of gas (remember your Roman numerals?)

O/15 time duration of the test

P/16 wide open, or choked back, usually in 64ths.

Q/17 Flowing top pressure?

R/18 Bottom hole pressure

And this is repeated, usually 4 times per test. And if they tested more than 1 zone or formation, we’ll just copy as many times as needed....

S/19 break column

T/20 second test on formation

U/21

V/22

W/23

X/24

Y/25 break column

Z/26 third test on formation

AA/27

AB/28

AC/29

AD/30

AE/31 break column

AF/32 fourth test on formation

AG/33

AH/34

AI/35

AJ/36

AK/37 This will end the first formation test as they are usually done in groups of four. The next 23 columns are a repeat.... If we find a 3rd 4-Point test, we will have to do another copy and paste.
Appendix 2

One of the students, Mike Sorensen, began to investigate various methods of conducting detailed statistics in a workbook form that would give an idea how various analyses of these data might be undertaken. As Mike is a mathematics and geology major, I believed that this was as much a learning opportunity for him as it was a database development for the project. Thus enclosed below is a description of his work. Three files were also enclosed that are part of his efforts, and include “@County(Statsbook)_Template.xls”, “(897)PecosCounty(Statsbook)_07112006.xls”, and “(728)PecosCounty(Statsbook)_07032006.xls”.

Design:

The Statistics Workbook uses the Depth and Temp data from the county workbook of choice. The well temp and depth are arranged as below to provide an index back to the data as listed in the main workbook. The data is simply copied and pasted into a temporary book, in this case book 1, and indexed by the entry number from the main (original) workbook. The entry number is repeated for each run so that additional runs are indexed just as is the first. The data is then ordered in two columns, Depth and Temp, sorted by Temp, and copied and pasted into the Statistics Workbook.

Note: (the print screen insert below does not show all the runs for workbook from which it was copied. This is just an example)

Note: It is important to check the validity of the data before starting the Stats Workbook. If there are inconsistencies, as is accounted for in the compensated data for Pecos, then that data must be dealt with.
The entry number preserves the integrity of the original data. This example shows how one run ends and the next begins as the entry numbers start over.

After the data is sorted by Temp, it is copied and pasted into the Statistics Workbook in the “sort by temp” and “sort by depth” columns. At this point the data can be sorted by depth for the “sort by depth” column. (sorting by temp first groups the data with depth and temp info together and the rest can be discarded as it would be of no use in the calculations. The only data that is discarded is that which does not have depth and temp info.)
At this point the data is ready for analysis. The analysis is unique to each data set so the Stats Workbook be built for each data set.

The following is a description of each column and function as is in the workbook from left to right.

**Column 1 & 5** -- This is the index to match the data back to the original workbook. There will be some numbers that repeat (those wells with more than one run, data set), and some numbers will only be listed once (those wells with only one data set). In short, if there are data sets with the same index number then those points, data sets, are from the same well.

**Columns 2, 3, 6 & 7** -- These are self explanatory. They are the sort parameters for the data sets.

**Column 8** -- Column is a from column that helps to identify the various Z’s or depth zones.

**Column 9** – Column 9 is used for formula referencing. The pre $\sum$ numerator column, column 16, uses column 9 in that calculation.

**Column 10 & 11** – This is simply a place for the average depth and temp to be calculated. The avg depth and temp that is in the same color as the particular Z is where the average formula resides. The light blue portion with the same data is what is referenced for graphing.
Column 13 -- This is another column dedicated to an average calculation. In this case it is the linear average for the depth and temp. These values are also highlighted in light blue for formula referencing and generating graphs.

Column 15 – Here the change in the average temp from the previous Z is calculated.

Column 16, 17 18 & 19 -- These are the columns where the standard deviation is calculated. The calculation is broken up into parts to help in understanding the effect of a particular data set on the standard deviation. Column 16 is the pre $\sum$ numerator. The value of the numerator gives a quick reference to locate data sets, points, that are close too or far off the average temp for a given Z. Column 17 completes the calculation for the standard deviation and displays that value. Column 18 is for calculating the $S_{T}$ for more than one Z. Column 19 is the $S_{T}$ for the entire data set.

Column 21 through 33 – This is a quick reference for the data after it has been entered and the calculations have been set up. For the most part, the info in self explanatory but there is a short explanation about those columns to the right of those columns.

Note: Within columns 10 – 14 there are some other statistical values. The max and min for the temp and depth and the mean, median and mode for the temp. The max and min are used in setting up columns 22 & 23 which are used for the graph “D(t) avgd using linear avg.” The mean, median and mode are for reference.

Purpose:

The standard deviation gives a value that is used to get an idea of the amount of variance for a particular data group. In the case of the temp and depth data sets for this project, we get an idea of how many and which data sets, points, are off the average for a particular Z. This does not necessarily mean that those points are not valid but that there is some anomaly that has caused a point or several points to be off the average.

Since these points are county wide there needs to be some research into which points are geographically related. This should produce some understanding of why the points, which are off average, are off by discovering what heat or cooling source lies within the vicinity of those points.

There are some interesting changes in the change of the average temp form one Z to the next Z. For example, 11,000 – 12,000 ft shows a change of 8°F from the previous Z (10K – 11K ft). The 12K – 13K ft Z increases by 10°F, and the 13K – 14K increases by 32°F. Why? Perhaps the greater the $S_{T}$ the greater the area represented by the data. If the area sampled were smaller, then the $S_{T}$ might be smaller due to the fact that the data sets represent a local trend. If this is the case then a large change in the average temp over a large area might represent something like a larger heat source or more heat due to pressure.
These graphs are from (897)PecosCounty(Statsbook)07112006 897 is the total number of data sets. The county of interest, what the file is, and the date the book was started.

The information needed to generate these graphs and others to come may help to better understand the dynamics of geothermal energy and best to tap into that source of energy.
Appendix 3

This appendix is based upon certain errors that were noted between the drillers depths and the loggers depth as observed on the log header information. Reference is made to a file named “@PecosCounty(compensated book)_07052006.xls”.

July 5, 2006
Michael W. Sorensen

After generating a plot for the overall trend for the Pecos County data it was discovered that there were several temperatures that appeared to be abnormal for the depths associated with the points on the graph. The initial data input was, and will continue to be, input into the file “DOEGEOTHERMALPROJECT_Pecos County” but the file “DOEGEOTHERMALPROJECT_PecosCounty(compensated_mmddyyyy)” has changes to the suspicious driller depth entries. The curious depths were found to be considerably different then their loggers depth so the logger depths were placed in the driller depths entry by pasting the original input into the “input sheet” of the compensated file and the “compensated sheet” of that file has the actual changes via formula referencing.

A reason for the data that was entered in the original xcell workbook to be misleading could be that the loggers depth for those particular wells/runs reflects the depth at which the logger actually logged the temp and the driller just entered the total depth. On the questionable entries this appears obvious. For example; On well entry #54, run 3 was TD at 15,050ft where as the first run showed 15,050ft with a temp of 109F and loggers depth of 6,118ft.

The following is the 1) Overall trend from the compensated file, and 2) the trend as calculated by the average depth plotted by average temperature.
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<th>Depth</th>
<th>Temp</th>
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<td>2695.32</td>
<td>95.57</td>
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<tr>
<td>3250.60</td>
<td>104.51</td>
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<tr>
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<tr>
<td>5365.96</td>
<td>110.04</td>
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</table>

\[
y = 16148\ln(x) - 71513
\]

\[R^2 = 0.982\]
References


