GEOPOWERING TEXAS

A REPORT TO THE TEXAS STATE ENERGY CONSERVATION OFFICE ON DEVELOPING THE GEOTHERMAL ENERGY RESOURCE OF TEXAS

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EXECUTIVE SUMMARY

This report provides a compilation of data and information that addresses the development of a new energy resource industry in Texas…geothermal energy. The report includes information developed specifically for this report, along with information derived from two other reports sponsored by the federal government. The Department of Energy provided funding for the first year of a proposed 3-year resource assessment of geothermal energy within the deep Delaware and Val Verde Basins (DE-FG36-05-GO85023). Additionally, the Department of Commerce Economic Development Administration provided funds to investigate renewable energy strategies in West Texas, covering geothermal, solar, and wind energy (#08-06-04006).

With the development of wind and biofuel resources in various parts of the state, the idea of developing geothermal will come as a surprise to many due to various preconceived ideas. Most people, if they know anything about geothermal, will first think of volcanoes, geysers, and surface hot spring activities. While some parts of the Trans-Pecos region do have local hot springs, volcanoes and geysers are definitely lacking, leading to the conclusion that geothermal development is not possible in Texas, with maybe a few local exceptions. However this is not true and a thorough understanding of the various approaches to geothermal energy development will assist the reader in accepting that geothermal energy can indeed be more fully developed in Texas.

Geothermal energy can be utilized at low (<90°C or <194°F), medium (90°-150°C or 194°-302°F), and high (>150°C or >302°F) temperature ranges, and the various ways of implementing geothermal energy tend to follow with the temperature of the resource. The low temperature range is good for geothermal heat pumps and direct use industrial technologies. The geothermal heat pump is a heat exchange system involving a home or building environment and the upper 200 feet or so of the ground. Heat can be stored or extract from the ground to either cool or heat the air space in a building, at a much higher efficiency and at a cost savings of 40 to 60%. Direct use geothermal uses the hot water or the heat from subsurface hot water in industrial uses that require heat. Thus cement curing, fish farming, nurseries, and numerous other industries can make use of geothermal energy in their operations. The medium to high temperature levels for geothermal energy are primarily used for electrical power generation. The medium level generally uses a binary fluid system whereby heat is extracted from subsurface water through a heat exchanger to vaporize the working fluid that drives an electrical generator. The high temperature level uses either a flash power plant system or natural steam if found in the subsurface reservoir.

Earliest work at investigating Texas geothermal energy for electrical production goes back to various studies conducted in the 1970's. The DOE/AAPG conducted a North American investigation that used bottom hole temperature (BHT) data from the oil and gas industry. This data showed that various deep areas in Texas had temperatures at or above 300°F. One of the results of this work was a geothermal pilot plant built by the DOE in Brazoria County (Pleasant Bayou #2) that generated 3,445 MWh of electricity during its 121 days of operation. This plant, generating electricity from hot water and

dissolved natural gas from a zone in the Frio Sand, demonstrated that geopressured geothermal production was possible for electric power generation.

From work conducted in the 1970's, and more recent efforts by The University of the Permian Basin Center for Energy & Economic Diversification (UTPB/CEED) and the Southern Methodist University Geothermal Lab (SMU), at least five major areas exist in Texas that have the potential for geothermal electric power production. These include the Gulf Coast, East Texas, the Delaware and Val Verde Basins, the Anadarko Basin in the Panhandle, and the Trans-Pecos Region. The region consisting of the Maverick Basin along the South Texas–Mexico border may represent an independent sixth area for consideration. UTPB/CEED has developed databases of over 8,000 temperature-depth (t-d) points within the Delaware and Val Verde Basins. These data help to generate t-d profiles for predicting the temperature that is expected to be encountered in various subsurface target reservoirs. The idea behind Texas geothermal production is the reuse of wells drilled by the oil and gas industry that have either drilled sufficiently deep to encounter hot water, or that could be deepened into these hot zones. In Pecos County, for example, temperatures of nearly 300°F are found in wells of around 18,000 feet.

Finally, this report provides various recommendations for consideration to help in the development of geothermal energy production in Texas. These recommendations are within the categories of technical assistance, industrial/economic development, advocacy, and policy/legal development. Recommendation 1 suggests that the state develop a technical assistance program that would create a "Texas Geothermal Atlas" specifically targeted for geothermal electric and direct use activities. Recommendation 2 requests a reinvestigation of leasing definitions and clarifications on existing leases for geothermal production. Recommendation 3 would allow for a grandfather period by oil and gas companies actively producing on state/public lands to expand existing leases to include geothermal energy production in order to minimize separation of oil and gas and geothermal leases, and the ensuing difficulties with lack of integrity of a reservoir. Recommendation 4 would allow for financial forums to be developed for a company to find investors. Recommendation 5 suggests that 'nesting' of various energy resources be a goal for the production of a steady outflow of electrical power from a given geographical area. Recommendation 6 suggests that a retrofit process be established for state buildings to convert to geothermal heat pumps for heating and cooling a building environment. Recommendation 7 would expand and enlarge the existing incentives for the various renewable energies in the state to include geothermal energy. Recommendation 8 would require that a stronger consideration be given by the state to those renewable energies that have higher capacity factors, and that capacity factor become the measuring scale for renewable energy success in the state. Finally, recommendation 9 would clarify geothermal ownership, especially when shallow geothermal energy is used such as with geothermal heat pumps.

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GEOTHERMAL ENERGY: WHAT IS IT? – HOW TO USE IT?

According to the Geo-Heat Center at the Oregon Institute of Technology, geothermal energy is defined as heat (thermal) derived from the earth (geo). It represents the thermal energy contained in the rock and fluid, which can fill the fractures and pores within the rock, in the earth's crust. This thermal resource is classified as low temperature (<90°C or <194°F), moderate temperature (90°-150°C or 194°-302°F), and high temperature (>150°C or >302°F).

In like manner geothermal energy has three broad applications that are somewhat temperature dependent. Ground source or geothermal heat pumps (also called geoexchange systems) operate in the very low temperature range, and can work nearly anywhere in the United States (Figure 1). This resource has the lowest cost involved and can be developed anywhere in Texas. Small independent businesses that work with environmental heat and cooling, as well as shallow drilling contractors, can be active in the development of this energy resource.

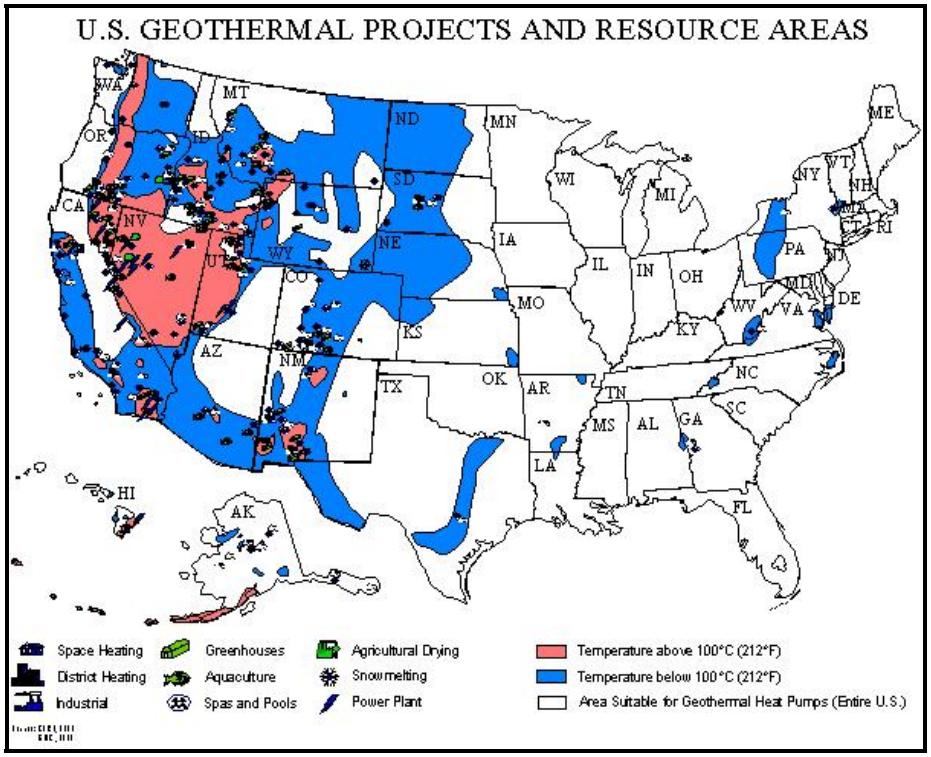


Figure 1. This image shows where in the U.S. various geothermal usages are possible. Geothermal heat pumps (GHP) or geoexchange systems can be developed anywhere in the country due to the nature of the resource and how it is used (white). Direct use projects need a source of hotter water and are thus a little more restrictive (blue). Geothermal electrical power generation has traditionally been more restricted to the western states (salmon) where high temperatures are closer to the surface of the Earth. A different approach for developing geothermal electricity in Texas will be discussed later. Image courtesy of the Geo-Heat Center.

Direct use applications work within the low to moderate temperature range. Usage of this resource still covers a large portion of the United States (Figure 1). Cost for development is higher than what is needed from ground source heat pumps. A company that needs hot water for

its operations can make use of this level of geothermal development. The company needs to be situated close to the source of the hot water, which might be from a local hot spring or from a well that has tapped into the proper temperature water needed for business operations.

Finally, electrical power generation uses moderate to high temperatures. Traditionally, this resource has been developed in the western states where high temperatures are found close to the Earth's surface (Figure 1). A higher investment cost is required due to generally greater depth necessary for acquiring the needed temperature. However there is also a higher economic reward for the sale of geothermally derived electrical power when compared to direct use or ground source heat pumps. An in-place delivery system is necessary to get electricity to market due to its low-storability. Deep, hot wells are required for development, which can restrict the area in which electrical power can be generated.

Geothermal Heat Pumps (GHP)

How They Work

Geothermal heat pumps, ground source heat pumps, or geoexchange technology are terms that mean the same thing. This technology is able to develop shallow thermal energy within the earth to heat or cool a house or building during the winter or summer respectively. Anyone who has gone underground into natural caverns has experienced the constant temperature that exists within the subsurface. This technology works on a similar principal to maintain a year-round near constant temperature within a surface building.

The individual homeowner to the operator of an office building can take advantage of a geoexchange system. Various studies (http://www.geoexchange.org) have shown that approximately 70% of the energy used in a geoexchange heating and cooling system is renewable from the ground. The remainder is electrical energy that is used to concentrate heat and transport it from one location to another. This can drastically reduce monthly heating and cooling bills along with reducing maintenance costs.

Geoexchange systems work on a different principle from standard furnace and air conditioning systems. A furnace must burn a fuel, like natural gas, propane, or fuel oil, to generate heat. A geothermal heat pump exchanges heat within the upper few hundred feet of the Earth through a closed fluid loop system. This is different from the conventional heat pump that uses outside air as their heat source or heat sink. The temperature of the ground or groundwater a few feet beneath the Earth' surface remains relatively constant year round, even when air temperatures may radically change. In most places around the world the temperature of the ground at a depth of about six feet remains rather stable between 45°F and 70°F. Thus less energy is used when compared to a conventional heat pump due to the more moderate temperatures year round.

In the winter, a geoexchange system captures heat from the shallow subsurface through a closed fluid loop system and carries this heat to the surface and into a building. Electrically driven compressors and heat exchangers then use a vapor cycle, similar to a refrigerator, to concentrate the heat and release it inside the building at a higher temperature. Duct fans then distribute the heat to various rooms.

During the summer, the process is reversed in order to cool the building. Excess heat is drawn from the building, expelled to the loop, and then absorbed by the Earth. This method works in the same manner as a refrigerator to keep the contents cool, by drawing heat from the interior, not by injecting cold air.

The loop of an installed geoexchange system remains out of sight beneath the Earth's surface while it works to heat and cool a building. The loop is usually made of a high-density polyethylene that does not retard the exchange of heat within the Earth. Some loop manufacturers offer up to 50-year warranties due to the toughness of the loop material. The fluid within the loop is water or an environmentally safe antifreeze solution that circulates through the pipes in a closed system. Another type of system called a Direct geoexchange (DX) system utilizes copper piping placed underground. A refrigerant within the loop transfers heat through the copper into the Earth.

For best results, professionals who follow procedures established by the International Ground Source Heat Pump Association (IGSHPA) should conduct installation. Installers should be certified by IGSHPA or be able to show equivalent training by manufacturers or other recognized authorities at a recognized training institution.

These systems do the work of two appliances, the furnace and an air conditioner. They can be located indoor, taking the place of the furnace, because there is no need to exchange heat with the outside air. They are generally very quiet, and they are compact (Figure 2). They can be installed in a basement or attic, and some are sufficiently small that they can fit within a closet space. An indoor location also means that the equipment is protected from mechanical breakdowns that might otherwise occur when exposed to harsh weather.

Geoexchange Loop Types

The length of a geoexchange loop depends upon various factors that include the type of loop configuration, the building's heating and air conditioning load, soil conditions, local climate, and landscaping. Larger homes with a large space-conditioning requirement generally need a larger loop than for a smaller home. Homes in a climate where there are large temperature extremes also generally need a larger loop. A heat loss/gain analysis should be conducted before the loop is installed.

Most loops for residential use are installed horizontally or vertically in the ground, or submerged in water such as a pond or lake. Each type of loop configuration has unique advantages and disadvantages to its use.

Horizontal Ground Closed Loop: This configuration (Figure 3A) is usually the most cost effective if adequate yard space is available and trenches are easy to dig. Trenches are dug 3 to 6 feet below ground, a series of parallel plastic pipes are laid, and then the trenches are backfilled making certain that rock and other sharp debris that might harm the pipe is removed. Fluid runs through the pipe in a closed loop. The horizontal loop is about 400 to 600 feet long per ton of heating and cooling capacity. Depending upon the size of the structure, a three-ton unit is typical for most homes. The pipe can be curled into a slinky shape in order to fit more of it into shorter trenches. This reduces the amount of land space needed but may require more pipe. This type of

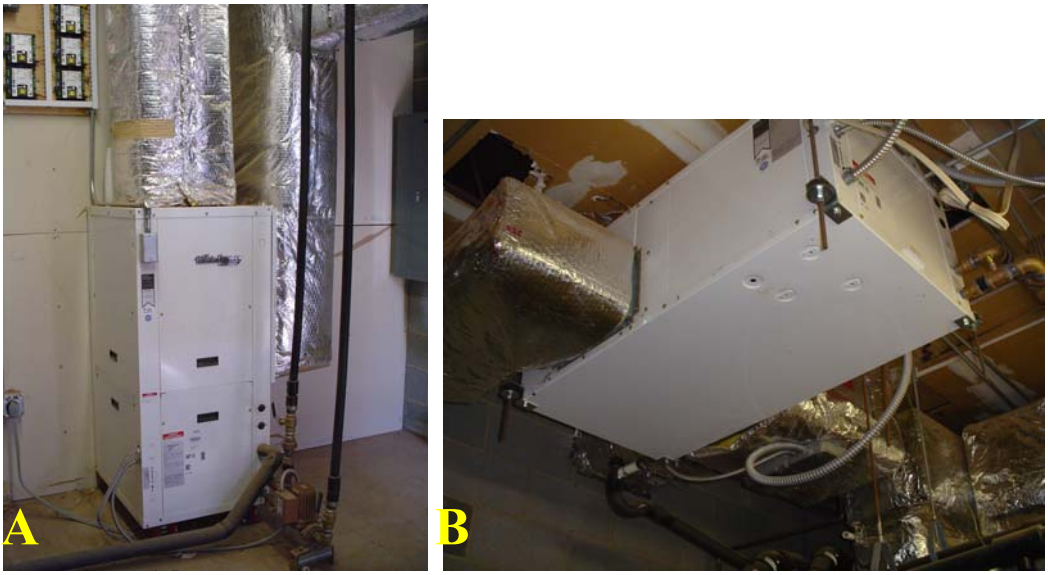


Figure 2. These pictures were taken at Lubbock Christian University in Lubbock, Texas. The University decided to convert their heating and cooling plant entirely to geothermal heat pump technology. At the time these pictures were taken (2005), four buildings had undergone conversion to geoexchange systems with a savings of at least 40% in heating and cooling bills. Plant personnel were pleased with the system due to low maintenance and the fact that they were getting caught up on other maintenance duties on campus. (A) Heat pump is installed in a vertical configuration similar to a home furnace. (B) Heat pump is attached to ceiling in a horizontal configuration. Images courtesy of Dr. Erdlac.

loop is easiest to install when a home is being constructed, however new types of digging equipment that allow horizontal boring allow for retrofitting existing homes with this type of configuration. These machines allow loops to be installed under existing buildings or driveways.

Vertical Ground Closed Loop: This loop type (Figure 3B) is great for homes where yard space is limited and insufficient for a horizontal system, when the Earth is rocky close to the surface, or for retrofitting where minimum disruption of the landscape is necessary. These holes may be 150 to 450 feet deep. Each hole contains a single loop of pipe with a U-bend at the bottom. The hole is backfilled or grouted after the pipe is installed. Each vertical loop is connected to a horizontal pipe underground that carries fluid in a closed system to and from the geoexchange system. Vertical loops are generally more expensive to install, but require less piping than the horizontal system because the temperature at this depth is alternatively cooler in summer and warmer in winter. According to one commercial installer located in West Texas, one vertical hole is required for each ton of heating and cooling.

Pond Closed Loop: A home that is near a body of surface water can take advantage of this type of design (Figure 3C), a design that can be more economical than the previous loop types. Fluid circulated through a closed loop polyethylene pipe system as with the ground loops. However the pipe runs to the water from the building and then connects to long submerged sections of pipe under water. The pipe can be coiled like a slinky to fit a larger amount into a given amount of space. This system is recommended only if the water level never drops below 6 to 8 feet at its

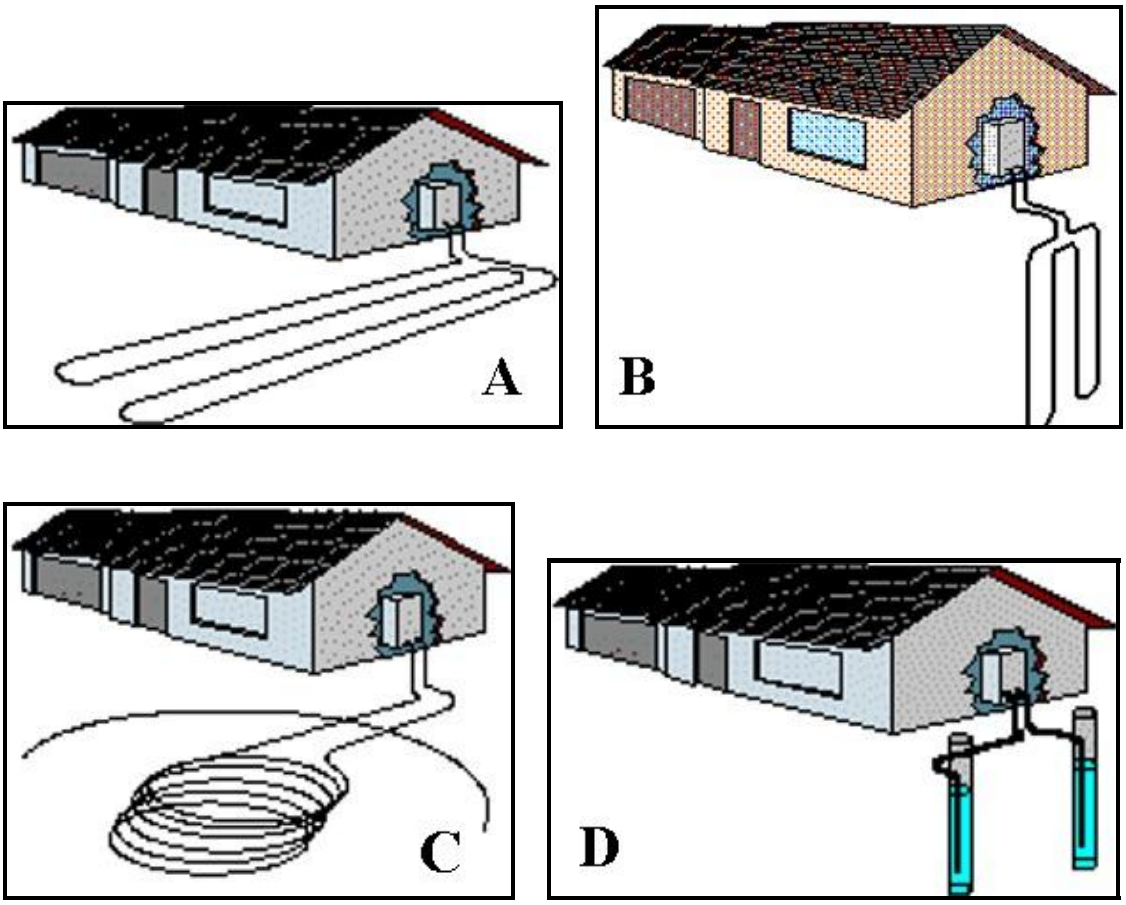


Figure 3. Images representing four geoexchange loop system types that can be used for heating and cooling buildings. (A) Horizontal Ground Closed Loop. (B) Vertical Ground Closed Loop. (C) Pond Closed Loop. (D) Standing Column Well System. These images are courtesy of the Geothermal Heat Pump Consortium, Inc.

lowest level to assure sufficient heat-transfer capability. These systems do not cause harm to the aquatic environment.

Open Loop System: This system is not used as often, but may be employed cost-effectively if ground water is plentiful. These systems are the simplest to install and have been used successfully for decades in areas where local codes permit. Ground water from the aquifer is pipes directly from the well to the building, where it transfers heat to the heat pump. The water is pumped back into the same aquifer via a second well located at a suitable distance from the first. Local environmental regulations and officials should be consulted if this system approach is being considered. There can be restrictions on the use of ground water that could prohibit this system, however only heat is being transferred; no pollutants would be discharged into the groundwater system.

Standing Column Well System: Many places in the United States, especially in the northeast, have established standing column wells or turbulent wells as a method for heat exchange (Figure 3D). These wells are usually 6 inches in diameter and may be as deep as 1,500 feet. Temperate water from the bottom of the well is withdrawn, circulated through the heat exchanger, and then

returned to the top of the water column in the same well. This well also often serves to provide potable water. However, this system requires that ground water is plentiful. If the water table were too deep, pumping would be too costly. Under normal conditions the water extracted for building use is replaced by constant-temperature ground water, which makes the system function like an open-loop system. If the well-water temperature gets too high or low, water can be "bled" from the system to allow ground water to restore the well-water temperature to the normal operating range. Local rules and regulations must be consulted to determine permitting conditions for discharging the bleed water, even though quantities are small and the water is never chemically treated.

Making Hot Water

A geoexchange system can also be used to provide all or part of a household's hot water. This is accomplished by using a desuperheater within the geoexchange unit. A desuperheater is a small, auxiliary heat exchanger that uses superheated gases from the heat pump's compressor to heat water. The hot water then circulates through a pipe to the water heater tank in the home. During the summer, the desuperheater uses excess heat that would otherwise be expelled to the geoexchange loop. If the geoexchange system is running frequently, then a homeowner can obtain all of their hot water through the process virtually free of additional cost. In winter, a conventional water heater can meet the needs of the homeowner if the desuperheater is not producing enough hot water. A conventional water heater might also be needed during the spring and fall if the geoexchange system is not in much use. With the high efficiency for water heating from this system, some manufacturers offer triple function systems that provide heating, cooling, and hot water in a single package.

Geoexchange Advantages And Examples

If a homeowner, business owner, or developer decides to consider a geoexchange system rather than the conventional combustion or electric heating and cooling system, then they need to know what type of savings they will receive on their initial investment. When comparing these systems, issues that include safety, installation, operating, and maintenance cost must be considered (Table 1). A simplified way to look at all of these issues is to combine installation, operating, and maintenance costs into a life-cycle cost that represents the cost of ownership over a period of years.

Compare	Safety	Installation Cost	Operating Cost	Maintenance Cost	Life-Cycle Cost
Combustion -based	A Concern	Moderate	Moderate	High	Moderate
Heat pump	Excellent	Moderate	Moderate	Moderate	Moderate
Geoexchange	Excellent	High	Low	Low	Low

Table 1. A comparison of safety and cost issues associated with combustion-based, heat pump, and geoexchange systems for heating and cooling. The heat pump referred to in this table is an exchange system with the atmosphere. Table is courtesy of the Geothermal Heat Pump Consortium, Inc.

If a homeowner is concerned about the safety issues that surround a combustion system, such as natural gas, then a geoexchange system is a very good alternative. Issues such as flue gas venting, gas leaks, fire, and carbon monoxide detectors can be eliminated as related to this type of heating and cooling system. Installation cost of a geoexchange system is usually higher than with other systems, however the operating and maintenance cost savings is far lower, giving a low life-cycle cost for the system. This higher installation cost is directly related to the underground connections related to heat exchange.

The efficiency of geoexchange systems has been found to be far higher than other systems. The EPA compared these various systems, accounting for losses in the fuel cycle including electricity generation at power plants (Table 2). They concluded that geoexchange systems are much more efficient than competing fuel technologies. On average, they are 48% or more efficient than the best gas furnaces on a source fuel basis, and over 75% more efficient than oil furnaces. Modern geoexchange systems will outperform the best gas technology, gas heat pumps, by an average of 36% when heating and 43% when cooling. How does this higher efficiency translate into cost savings?

On average, a geoexchange system can cost about $2,500 per ton of capacity, or roughly $7,500 for a 3-ton unit, a size typically found in a home. By contrast other systems will cost $4,000 with the inclusion of air conditioning. If included in the mortgage, the homeowner has a positive cash flow from the start. If the extra $3,500 will add $30 per month to each mortgage payment, the energy cost savings will easily exceed that added mortgage amount over the course of each year. In a retrofit, the higher efficiency usually means lower utility bills, allowing the investment to be recouped in 2 to 10 years. And with some of the added incentives for renewable production, this payout may even be faster.

Examples of the savings benefit can be demonstrated when comparing different types of space-conditioning systems (Table 3). General savings on electrical usage can be considerable for geoexchange systems compared to other system types. In real homes this savings can add up to several hundred to over $1,000 per year (Figure 4). This savings comes from using a geoexchange system for heating, cooling, and for generating hot water. This type of savings is possible both with emplacement in a new residence at the time of construction or in later retrofitting a home with a geoexchange system. It is important for a homeowner to realize that their home, which may have been built in a time when the geoexchange process was not available, can go through a retrofit process that will decrease the cost of their energy bill year-round.

Owners or operators of large office buildings can also take advantage of energy savings through geoexchange systems, even in downtown conditions (Figure 5). The renovation of a 1937 building with a nearly $30,000 annual energy savings is proof that many older existing building in major cities across the country can cut their energy cost by retrofitting of such a systems. The Galt building in Kentucky is important because this system was installed when the building was constructed in 1984. It has been the world's largest geoexchange system, meeting all heating and cooling needs with a 4,700 ton system. The 750,000 square-foot Galt House East hotel uses

a 1,700 geothermal heat pump system, at a cost of $1,500 per ton compared to a conventional system at $2,000 to $3,000 per ton. The system saves $25,000 per month in energy costs and

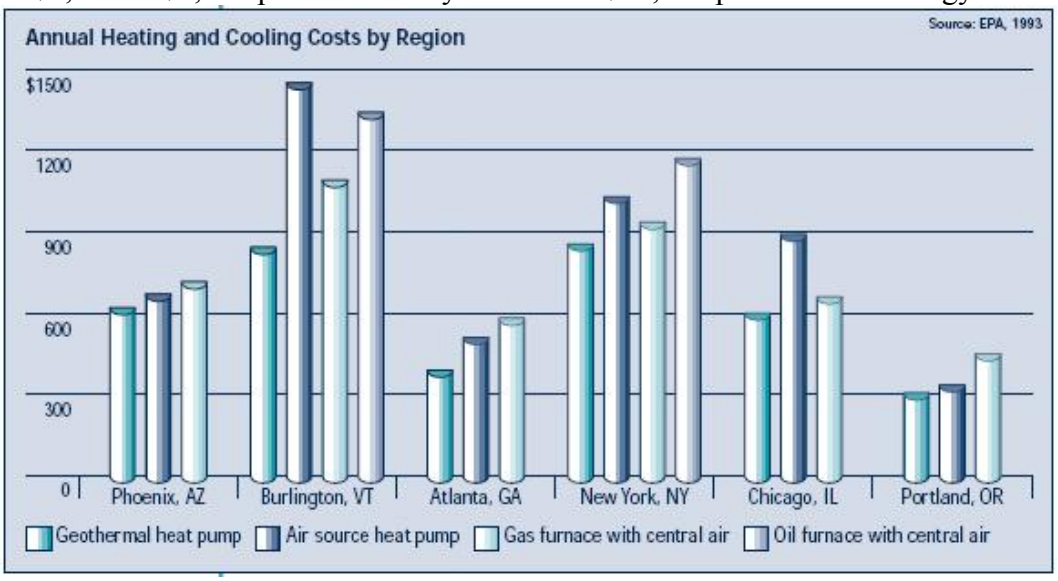


Table 2. From an EPA study (1993) entitled "Space Conditioning: The Next Frontier," EPA 430-R-93-004. This study was in six major cities across the country, with the purpose of comparing the performance and costs of various emerging high-efficiency space-conditioning equipment with equipment already in the market. In all locations, geothermal heat pumps were found to be the most efficient heating and cooling systems over other types of space-conditioning equipment including high-efficiency gas furnaces and air conditioners. Table courtesy of the Geothermal Heat Pump Consortium, Inc.

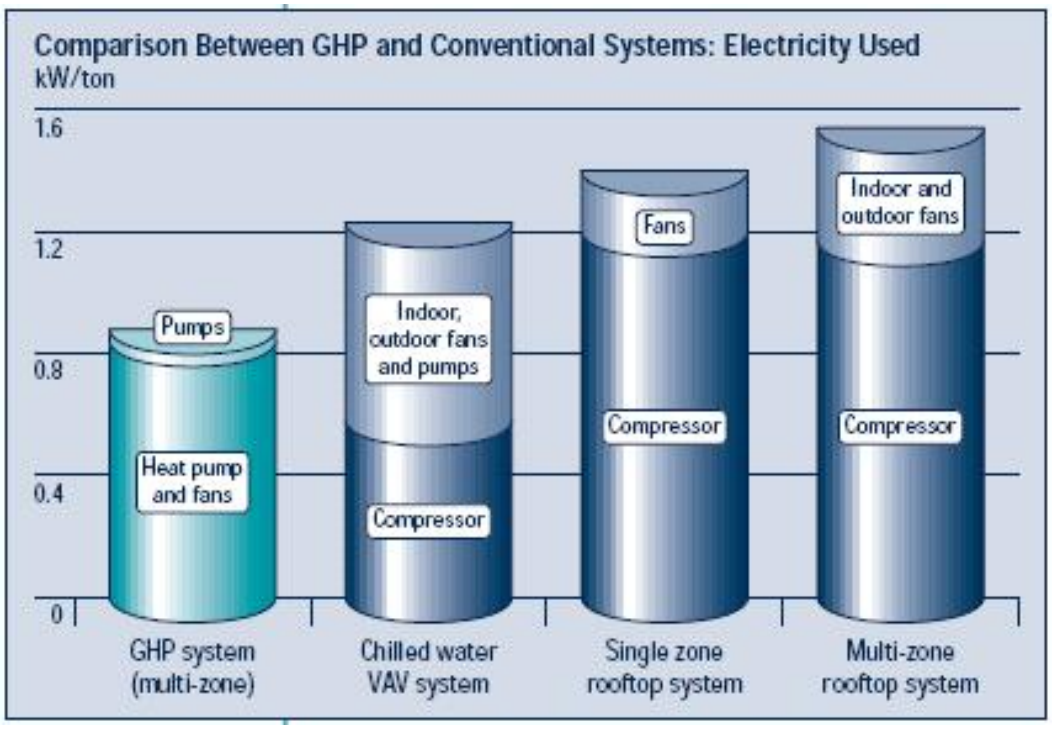


Table 3. Comparison of electrical usage between geothermal heat pump , chilled water VAV, single zone rooftop, and multi-zone rooftop systems. Table courtesy of the Geothermal Heat Pump Consortium, Inc.

A NEW CONSTRUCTION SOLUTION

OPERATING ESTIMATE / COST COMPARISON

RESIDENCE: ..... St. George, Utah
TOTAL AREA: ..... 3,067 sq. ft.

HVAC Systems	Annual Heating	Annual Cooling	Annual Hot Water	Total Cost
Propane furnace/electric AC	$839	$592	$337	$1,768
Gas furnace/electric AC	314	592	122	1,028
Air source heat pump	218	592	183	993
Geoexchange system	64	166	98	328

Rates based on electricity @ $.046/kwh, natural gas @ $.055/therm and propane @ $1.40/gallon.

A PERFECT FIT FOR RETROFIT

OPERATING ESTIMATE / COST COMPARISON

RESIDENCE: ..... Oklahoma City, OK
COMPLETED: 1996
TOTAL AREA: ..... 2,300 sq. ft.
OLD SYSTEM: ..... Gas fired heat, electric air conditioning
NEW SYSTEM: ..... Geoexchange

HVAC Systems	Annual Heating	Annual Cooling	Annual Hot Water	Total Cost
Propane furnace, electric AC	$1,443	$507	$476	$2,426
Gas furnace, electric AC	653	507	228	1,388
Air source heat pump	380	419	476	1,275
Geoexchange	189	258	228	675

Data provided by ClimateMaster, Oklahoma City, OK.

Figure 4. Two examples comparing a geoexchange system with other systems in a new residence and in a home that is retrofit for a geothermal heat pump system. Savings are easily in the 25% to 50% range annually. Images courtesy of the Geothermal Heat Pump Consortium, Inc.

THE RIGHT FIT FOR RENOVATION

THE ENTERPRISE CENTER

PHILADELPHIA, PA

Original Construction: 1937

Building Type: ..... 36,000-sq.-ft. television studio converted to offices

Previous Heating System: . Traditional boiler and chillers

Renovation: ..... Begun 1995, completed 1997

HVAC: ..... Closed loop geoexchange, 66 bore-holes, 290 ft. deep, 27 heat pumps

System Comparison: ..... Air-to-air heat pumps, and split A/C with electrical resistance heating

Estimated Annual Energy-Cost Savings: $29,279

BIG SAVINGS FOR A BIG COMPLEX

GALT HOUSE EAST HOTEL

LOUISVILLE, KY

Building Type: ..... 1.7-million-sq.-ft. office/hotel/ apartment complex

HVAC: ..... Geoexchange, with four 130-ft.-deep wells, 1200 heat pumps, 220,000-gallon system, 4500-ton capacity

System Comparison: ..... Centrifugal chillers, cooling towers, insulated pipes

Annual Savings: ..... $300,000 (Galt House vs. Galt House East)

Figure 5. These two examples represent a retrofit on an existing building versus the use of a geoexchange system since construction of the building. Images courtesy of the Geothermal Heat Pump Consortium, Inc.

frees up about 25,000 square feet for additional commercial space that would have otherwise been used for heating and cooling equipment. When the Waterfront Office Buildings were built in 1994, the additional 960,000 square feet of office space was heated and cooled by almost 3,000 tons of geothermal heat pumps. Cost savings were far more than anticipated, with a reduced savings in maintenance costs to just 7.5 to 10 cents per square foot per year.

Geothermal Direct Use Activity

Geothermal reservoirs that have temperatures within the low to moderate range can have heat extracted, usually using hot water, from the subsurface and used in various residential, industrial, and commercial processes. This resource is also generally widespread in the U.S. (Figure 1) and has been used to heat homes and offices, commercial greenhouses, fish farms, food processing facilities, gold mining operations, and a host of other applications (Figure 6). Spent fluids from geothermal electric plants can also be subsequently used for direct use applications in a "cascading" process. Direct use of geothermal energy for homes and commercial operations is much less expensive than using traditional fuels, with savings that can be 80% lower than fossil fuels.

Developing geothermal energy in a direct use manner typically includes three components:

1) A production facility, usually a well, to bring hot water to the surface.
2) A mechanical system consisting of piping, heat exchanger, and controls to deliver the heat to the space or process.
3) A disposal system in the form of an injection well or storage pond that receives the cooled geothermal fluid.

The primary uses of low-temperature geothermal resources are in district and space heating, greenhouses, and aquaculture facilities, though numerous other uses for geothermally heated water exist (Figure 6). Over 120 operations throughout the U.S. are using geothermal energy for district and space heating. District systems distribute hydrothermal water from one or more geothermal wells through a series of pipes to several houses and buildings, or to blocks of buildings. District heating can save consumers 30% to 50% of the cost of natural gas heating. By contrast space heating uses one well per structure. In both cases the geothermal production well and distribution piping replace the fossil-fuel-burning heat source of the traditional heating system.

In Texas, the Falls Community Hospital and Clinic of Marlin, Texas, formerly the Torbett-Hutchings-Smith Memorial Hospital, continues to use geothermal water for space heating. Use of these waters is also shared with the Marlin Chamber of Commerce. The original well was drilled to 3,900 feet and yielded 600 gpm from the Hosston Sands aquifer, at temperatures between 140° to 155°F (Valenza, 1995).

Direct use geothermal energy has been well received within the agribusiness industry, with the two primary uses being greenhouses and aquaculture (fish farming). Geothermal water (100°F water and above) has been used within greenhouses since the late 1970's, with at least 40 greenhouses in 10 western states (Geo-Heat Center). Many of these facilities cover several acres, raising vegetables, flowers, houseplants, and tree seedlings. Aquiculture pond and

racetrack heating (85°F water and above) is conducted in 12 western states, with at least 49 sites in use since the 1970's.

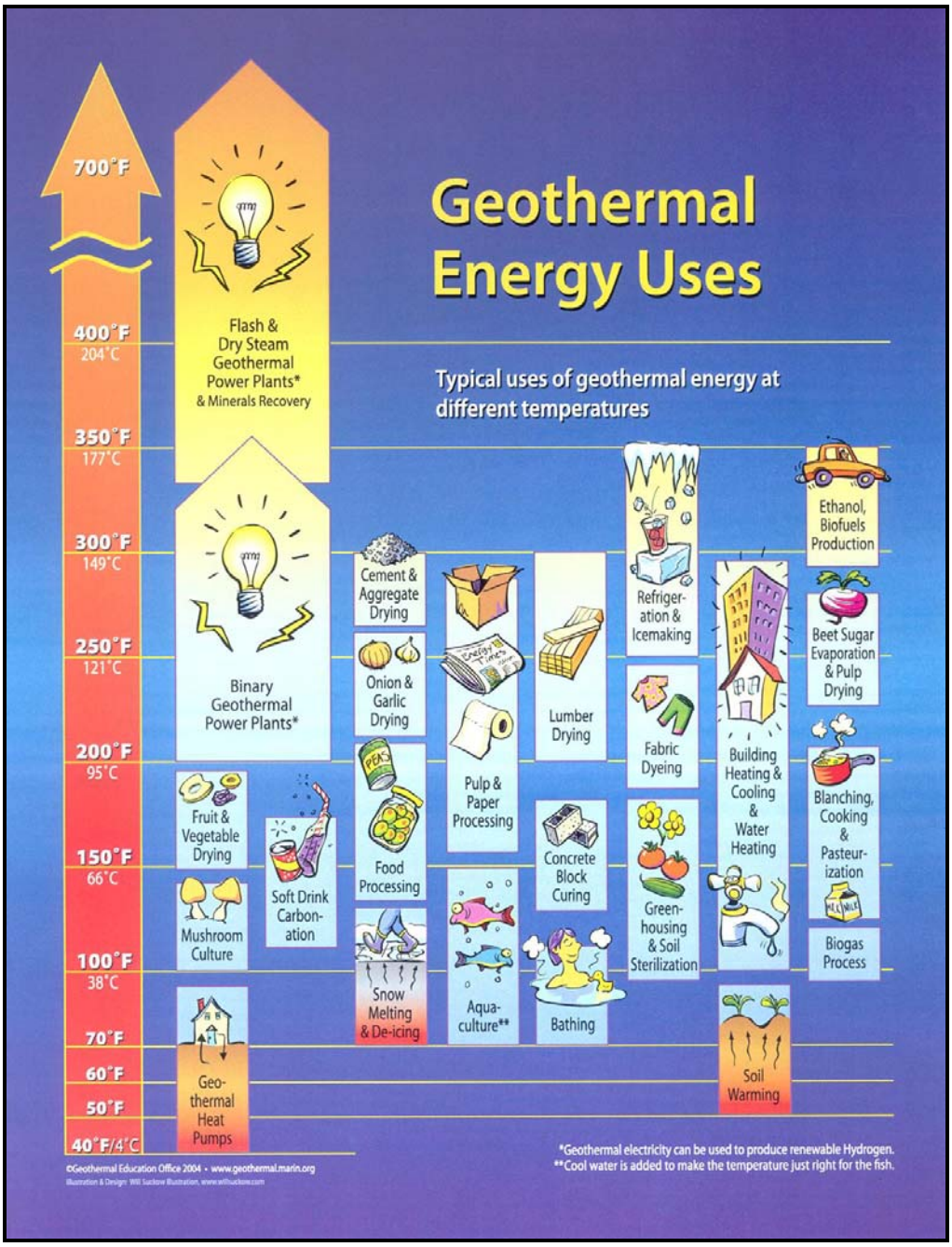


Figure 6. This diagram shows the typical uses of geothermal energy at the various temperatures that can be acquired from underground. Not all of these uses are possible in West Texas, however various businesses such as nurseries, cement processing, and aquiculture, to name a few, could make use of a geothermal energy resources in Texas. The availability of such a local resource could also result in the establishment of one of these businesses for local economic development. Image courtesy of the Geothermal Education Office.

Most greenhouse operators estimate that using geothermal resources instead of traditional energy resources saves around 80% of fuel costs. An additional savings of 5% to 8% has occurred from operating costs. Many of these sites are in relatively rural settings due to the source of the geothermal resource, offering advantages that include clean air, few disease problems, clean water, a stable workforce, and generally lower taxes.

The use of this low temperature geothermal resource in greenhouses employs simple and usually off-the-shelf equipment. If the geothermal fluid is corrosive or causes scaling, a plate heat exchanger is used to isolate the fluid from the greenhouse heating system. Most standard greenhouse heating systems that include unit heaters with and without a plastic distribution tube, finned pipes, bare tubes, fan coil units, and various combinations of this equipment, are adaptable to geothermal energy. For peaking needs, other energy resources, such as fossil fuel, can be incorporated with geothermal heat.

The closest location to West Texas where a nursery employs geothermal heat can be found at New Mexico State University in Las Cruces (Figure 7). Their geothermal greenhouse research facility has operated as a pilot scale incubator since 1986. It is located on campus and comprises 13,000 square feet, with a 2,400 square foot warehouse and office building. The wellhead on site provides a water flow with a constant 146°F water temperature. New Mexico has 49% of all the geothermally heated greenhouses in the U.S. Nurseries can employ 50 to 100 people full time, thus being a source for employment, especially in a rural setting.

Figure 7. Images of the New Mexico State University incubator green house facility. At the time of this visit, one of the buildings was growing cactus for market sale. Tubing that underlies the cactus can be seen in part of the image. Cactus picture courtesy of Dr. Erdlac.

Aquaculture applications of geothermal heat allow their siting in colder climates or closer to markets where conventional heating may not be as economical. In most instances, off-the-shelf

equipment is used in conjunction with geothermal waters. A plate heat exchanger can be used to isolate the pond fluid if the geothermal fluid chemistry is not suitable for direct use. Aquatic species such as Tilapia, catfish, Malaysia prawns, tropicals (cichlids), alligators, and eels have been successfully raised using geothermal heat. For example, in the Imperial Valley of California, 15 geothermal aquaculture operations produce eight million pounds of catfish, Tilapia, and hybrid striped bass annually.

New Mexico State University also operates an aquiculture research facility adjacent to the geothermal greenhouse facility (Figure 8). It is enclosed within an arched greenhouse structure of 3,000 square feet. Recently the facility has been devoted to production of two species of Tilapia, a fish native to Africa and the Mid-East that require warm culture temperatures.

The key to the development of direct use geothermal energy in Texas is access to hot water. While there are some hot springs that have been identified within the Trans-Pecos region, an undeveloped source of hot water is from oil and gas wells drilled within the state, and those few wells that were drilled within the Trans-Pecos region in the search for oil and gas. A second important need is to site the business near to the well from which the hot water will be taken, near being within one mile of the wellhead. In this manner heat loss through the insulated surface pipe will be minimal.

A significant amount of well data is available to determine subsurface temperatures and the proximity to hot water zones. For example, a quick look at some deep fields in the Delaware and Val Verde Basins of West Texas document the average field temperatures at their average depths (Figure 9). These fields are correlated by temperature with various industrial processes that require specific temperatures. Some of these industries, such as sugar refining, may not be feasible in West Texas, but the drying and curing of

Figure 8. These images are of the aquiculture facility that resides next to the greenhouse facility on the New Mexico State University campus. Inside tank picture courtesy of Dr. Erdlac.

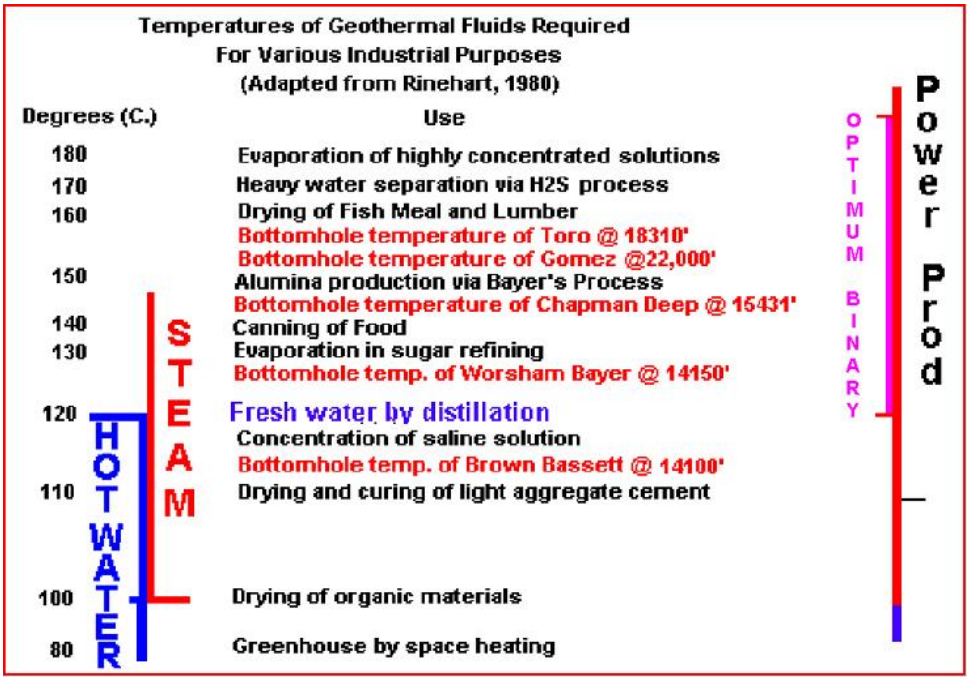


Figure 9. Figure shows average temperature and depth for selected fields in the Delaware and Val Verde Basins. These fields are shown in conjunction with various uses of hot water in industry.

light aggregate cement might be. For higher temperature needs of a specific industry, the deeper the wells must be in order to acquire the target temperature. In the Permian Basin, there are far more wells drilled to mid-level depths (~15,000 feet) than to greater depths. Thus the drying of organic materials or soft drink carbonation (Figure 6) could be conducted in West Texas with greater ease compared to other industries that might require higher temperatures. The owner of such a business would need to plan proximity to a hot water well as part of their business-siting requirement.

Geothermal Electrical Generation

Geothermal Resources

Electric power generation using geothermal energy has been very active worldwide over the last several decades. Areas of interest have focused on geological environments that contain active or dormant volcanoes, geyser fields, and hot springs, areas where heat from within the earth has reached sufficiently shallow depths to make the economics of heat recovery feasible. In the U.S., geothermal electric is used in California, Nevada, Utah, and Hawaii, and while other states also have the potential and are developing this resource, these four states have been among the first to generate electricity from geothermal heat.

The types of geothermal reservoirs fall into four, or possibly five, categories. These include: 1) hydrothermal; 2) geopressured; 3) hot dry rock; and 4) magma. Erdlac and Swift (2004) described a fifth category called 'deep permeable strata geothermal energy' (DPSGE) that is thought to be heated by the existing geothermal gradient within sedimentary basins.

Hydrothermal: Hydrothermal geothermal resources are composed of hot water and/or steam that is found in fractured or porous rock at shallow to moderate depths (100 m to 4.5 km) as a result of the intrusion of molten magma into the earth's crust, or from the deep circulation of water through fault or fracture systems. High temperature resources, from 180°C to over 350°C, and are usually heated from a source of hot molten rock. Resources within the 100°C to 180°C can be heated from either molten rock or deep-water circulation. Whether the hydrothermal resources come as steam or water is dependent upon the temperature and pressure involved. The best higher temperature resource is used for electricity production while the lower temperature resource is generally used in direct heating applications. This type of resource forms when there is a heat source, an aquifer containing accessible water, and a seal over the aquifer to keep the resource from leaking out. Drilling into the aquifer and extracting the hot water or steam taps into the geothermal energy resource.

Geopressured: A geopressured resource consists of hot brine saturated with methane and found in large, deep aquifers that are under higher pressure due to water trapped in the burial process. These resources are often found in sedimentary strata at depths of 3km to 6 km. Water temperature can range from 90°C to 200°C. Three forms of energy, thermal, hydraulic from the high pressure, and chemical from burning the dissolved methane, are potentially obtainable from this resource. The northern Gulf of Mexico is the largest region discovered that contains this type of resource. More will be said later about this region in conjunction with the Texas geothermal potential.

Hot Dry Rock: The hot dry rock (HDR) resource is a heated geological formation formed in the manner of hydrothermal resources, but containing no water due to the absence of aquifers or fractures required to transport water. This resource is huge in comparison to hydrothermal resources. Past difficulties with HDR technology has been the acquisition of heat, whereby cool zones are generated along induced fractures where water has been injected to acquire and transport the heat. However, continued investigations worldwide into HDR technology may yet result in this resource being very valuable in the future.

Magma: The deeper interior of the earth is in molten form. Molten rock is found at depths of 3-10 km and deeper, and is thus not easily accessible. Temperatures range from 700°C to 1,200°C or more, which while appealing for heat acquisition, the technology for such development is still in infancy.

DPSGE: Deep Permeable Strata Geothermal Energy is similar to hydrothermal in that hot water is trapped within porous and permeable rock within sedimentary basins, with temperatures in the 100°C to 200°C range. In most cases these formations have also produced oil and/or gas. Temperatures sufficiently high to melt rock would have cooked off these fossil fuels before their extraction. Thus the difference between the hydrothermal and DPSGE resource is that these rocks and formation waters have not been in proximity to molten rock in the subsurface for heat capture. Rather DPSGE heat is suspected to have resulted from the present or recent past geologic thermal gradients that provide sufficient heat over a period of time to be captured within the rock strata.

Heat Transfer In The Earth

Geothermal energy resources are renewable and sustainable so long as the rate of energy extraction is balanced by the recharge rate within a given geological system. The rate of heat replenishment is dependent upon the type of subsurface systems in which the heat is transported. There are four ways for heat to be transported in the subsurface: 1) convection; 2) advection; 3) conduction; and 4) radiation. All four mechanisms are active within the earth, though some are more important than others when talking about geothermal energy production.

Convection: Convection is the transfer of energy, such as heat, by currents within a fluid. Every time water is boiled on a stove the convective process is established for heat movement within the water. Convection arises when a temperature difference exists either within the fluid or between the fluid and its boundary, such as the air over the top of a pan of boiling water. In nature convection occurs deep within the earth in its mantle, as well as in the ocean and the atmosphere. Free convection occurs when the motion of a fluid is the result of unstable density gradients, such as hot air rising off the surface of a radiator. Forced convection occurs when fluid motion is imposed externally, such as when a person blows air across their food to cool it.

Advection: Advection is the transport of heat within a moving fluid from one location to another. Silt or pollutants within a river are transported due to the motion of the water in an advective manner. In the production of natural geothermal systems, energy recharge into the system is considered to occur through the advection process, and on a time scale similar to the scale of resource production. It is because of the advection process that geothermal energy is classified as renewable.

Conduction: Conduction is the transfer of heat across matter. This process is related to the temperature difference or gradient within the material and tends to be a slower process than either convection or advection. In environments of hot, dry rocks, and possibly in some of the hot water aquifers in sedimentary basins, energy recharge is only by thermal conduction. The slow rate of this process in these regions has been considered as a finite energy resource (Stefansson, 2000). However proper management of heat extraction versus heat input, and the specific geological environment, will play a significant role in the sustainability of such a resource.

Radiation: Finally, thermal radiation is electromagnetic radiation from the surface of an object that is related to the temperature of the object. For example, light emitted from an incandescent light bulb is thermal radiation. Thermal radiation occurs when heat from the movement of charged particles within atoms is converted to electromagnetic radiation. The impact of radiation on the generation of geothermal heat may depend on the geological environment as well. For example, organic-rich shale can fix or concentrate natural radioactive material such as uranium or potassium within the rock, thus generating what is called natural occurring radioactive material. However, the impact of the resulting thermal radiation is probably small by contrast to advection, for example. On the other hand, deep within the mantle of the earth, radioactive decay may add significantly to the heat that is present and driving global processes such as plate tectonics.

Acquisition

Geothermal electrical generation and power plants are described in MW (megawatt) deliverability. The typical size range for a geothermal power plant is from 10 to 250 MW. One MW (8,760,000 kWh) of electricity will meet the needs of approximately 1,000 households (~4,000 people) for one year. Meeting a 250 MW generating plant output from fossil fuels would require 1,288,994 bbls of oil, or 7,227,722 mcf of natural gas, or 280,769 tons of coal per year.

There are three primary approaches for acquisition of geothermal heat for electrical production, each being somewhat dependent upon the subsurface geological environment. These methods include: 1) dry steam power plant; 2) flash steam power plant; and 3) a binary cycle power plant. A brief look at each of these systems is appropriate for background information before discussing the Texas geothermal potential.

Dry Steam Power Plant: A dry steam power plant (Figure 10) can be used where natural steam is produced from an aquifer that has been superheated. In this type of well, pressurized steam at temperatures above 235°C is produced at high speed. The steam is directed at the turbine, which is turned to generate electricity. In some power plants the lower pressure steam is vented directly to the atmosphere, but more often the steam is condensed back into water that can be injected back into the subsurface, ideally into the same hot formation. This improves turbine efficiency and avoids environmental problems associated with release to the atmosphere. Waste heat is vented through cooling towers.

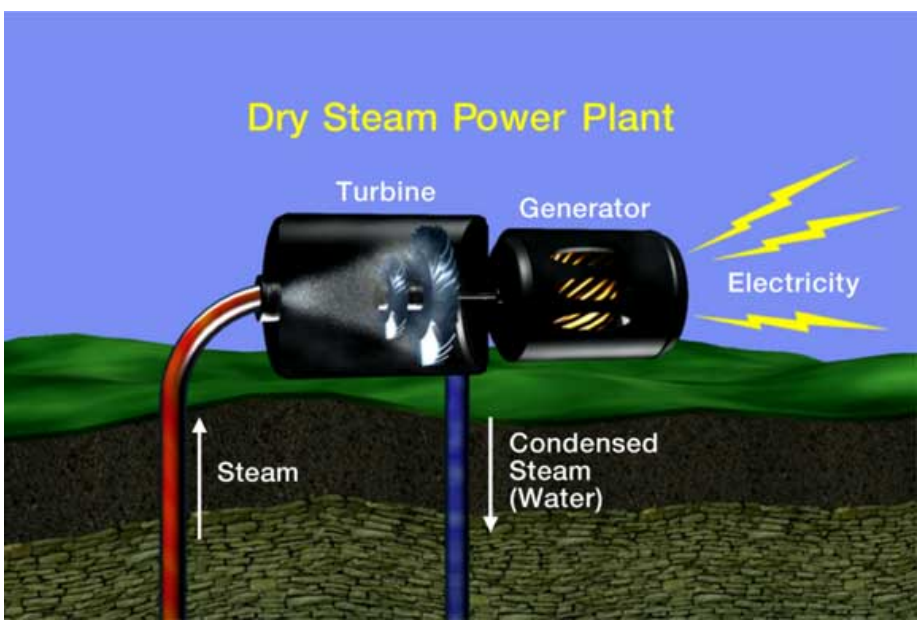


Figure 10. The dry steam power plant brings natural steam to the surface of the earth to drive a turbine and generate electricity. The condensed steam, now water, is injected back into the subsurface. Image courtesy of the Geothermal Education Office.

Energy conversion efficiencies are around 30% (Brown, 1996), with efficiency and economics being affected by the presence of non-condensable gases such as carbon dioxide and hydrogen sulfide. The presence of these gases tends to reduce the turbine efficiency, and the removal of these gases increases operational cost. However, even with these situations to deal with, the dry steam power plant is the simplest and most economical, and thus is widespread. The technology is well developed and commercially available, with units in the 35MW to 120MW range.

Flash Steam Power Plant: If the hydrothermal resource is composed of hot water above 182°C, then a flash steam system can be used (Figure 11). Produced hot water is sprayed into a tank that is at a lower pressure than the fluid, thus causing the water to rapidly vaporize (flash) to steam. The steam then drives the turbine in the same manner as the dry steam system. The well is maintained under high pressure to prevent the hot water from naturally flashing within the well bore. Much of the water does not flash, and this liquid is reinjected into the reservoir. The water can also be passed into a second tank, where a further pressure drop causes more steam development, this system being called a double flash system. A second turbine is then turned to produce electricity from this secondary flash chamber. A 20% to 25% increase in power output can be achieved with a double flash system, with a 5% increase in plant cost (Brown, 1996). Flash steam power plants generators are in the size range of 10MW to 55MW, with 20MW being a standard size being used in many countries.

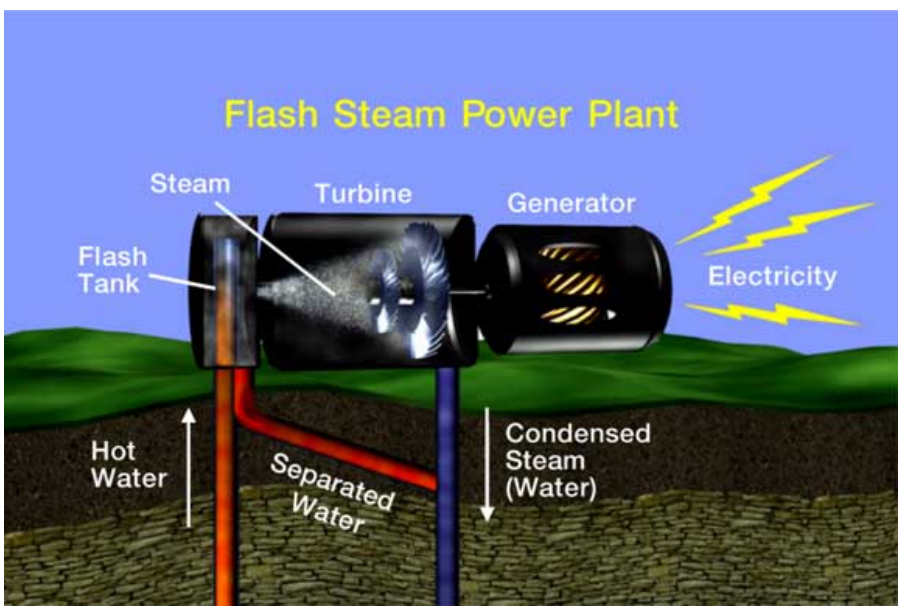


Figure 11. A flash steam power plant uses hot water that is 'flashed' into steam through a pressure drop within a flash tank. The steam then drives the turbine to produce electricity. The water is then reinjected or allowed to 'flash' a second time to produce additional electricity. Image courtesy of the Geothermal Education Office.

Binary Cycle Power Plant: The binary cycle power plant (Figure 12) is used where the geothermal resource is not hot enough to efficiently produce steam (107°C–182°C), or where too many chemical impurities are contained within the hot water to allow flashing. In this process, the geothermal fluid is brought to the surface and passed through a heat exchanger (Figure 13).

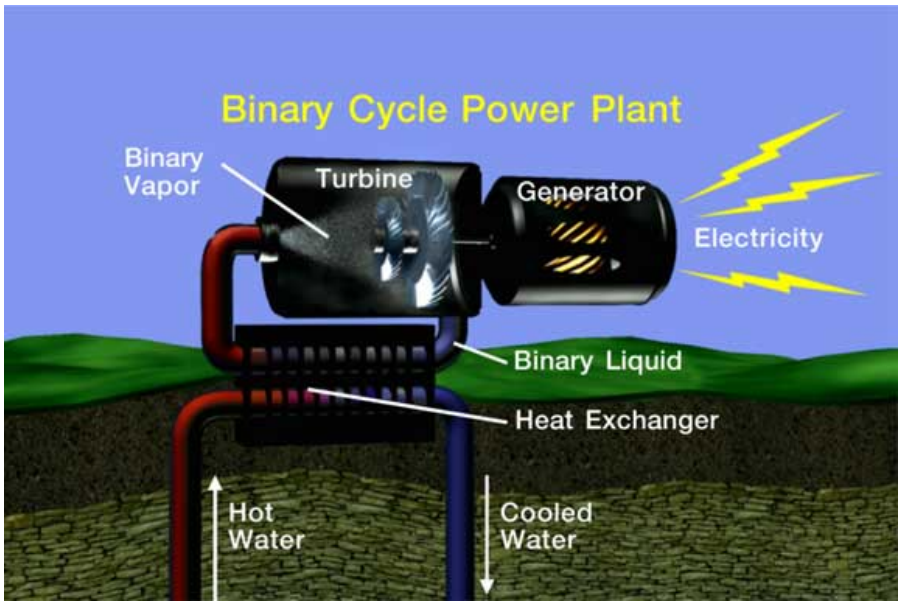


Figure 12. The binary cycle power plant extracts heat through a heat exchanger to vaporize a secondary working fluid that drives the turbine. The secondary fluid is reused again and again as it runs through vaporization and condensing phases. The geothermal fluid is injected back into the ground. Image courtesy of the Geothermal Education Office.

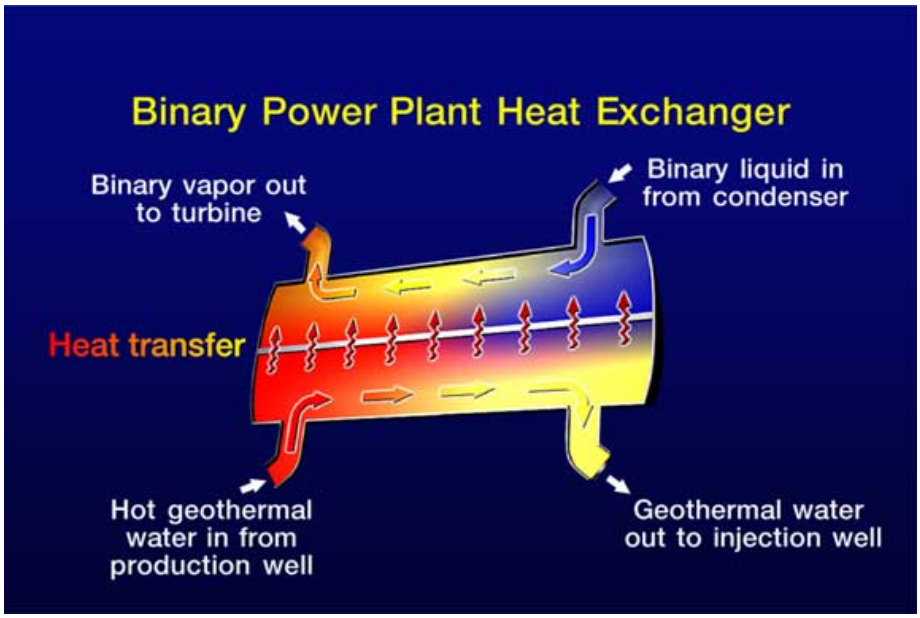


Figure 13. The binary plant heat exchanger allows heat to transfer between the geothermal fluid and the secondary working fluid that is vaporized to turn the turbine. Image courtesy of the Geothermal Education Office.

The secondary fluid in the heat exchange system is a fluid with a lower boiling point that water, such as isobutane, pentane, or ammonia. This secondary fluid is vaporized, and passed through

the turbine to generate electricity. The working fluid is condensed and recycled for another pass through the heat exchanger. All of the geothermal fluid is reinjected into the ground in a closed-loop system. The use of two separate fluids for power generation gives the name 'binary' to this type of power plant.

These systems can achieve higher efficiencies than a flash steam plant, and they allow for a lower temperature resource to be used. Corrosion problems can also be avoided. However, these plants are more expensive, and larger pumps are required that consume a portion of the power output of the plant. Unit sizes are usually in the 1MW to 3MW range and can be used in a modular arrangement.

TEXAS GEOTHERMAL ELECTRICAL POWER

Geoexchange systems and direct use of hot water are being utilized in varying amounts in different parts of the state. Geoexchange systems are the shallowest and least expensive means of employing geothermal energy for individual homes or businesses. And several facilities are using subsurface hot water for space heating purposes. But geothermal electric power production is not presently being used, and is an approach that has not been considered by most people. This has much to do with perception.

Geothermal electrical power conjures images of volcanoes, geysers, and hot springs, of which only hot springs are present in Texas, specifically in the Trans-Pecos region and some areas in South Texas near the Rio Grande. However while Texas does not have sufficiently hot shallow geothermal resources of the type mentioned above, it does have literally tens of thousands of oil and gas wells that have drilled sufficiently deep to reach temperatures of over 200, 300, and sometimes 400°F within well bores. The oil and gas industry has generally considered these high temperatures, and often the water found behind pipe in these formations as a major liability when in fact this hot water is an undeveloped energy asset that can develop out of the existing oil and gas industry. Similarly the existing 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. Although many of the same subsurface engineering and geoscience techniques are used in both industries, each industry has focused upon specific geological environments for entirely different energy goals. Thus the oil and gas and the geothermal industries are like brothers who rarely speak to each other, which in this case is a detriment to both.

The only state-wide geothermal survey that I know about was conducted and published in the mid-1970's by a joint effort of the USGS and the AAPG (Figure 14). This survey was part of a larger study of North America that discussed geothermal resources. This study is important because it made extensive use of many thousands of bottom hole temperature (BHT) recordings that were provided by numerous oil and gas companies. This map displayed temperatures above 290°F in the western part of the Permian Basin, a part of the Anadarko Basin that extended into the Texas Panhandle from Oklahoma, and the region covered by East Texas and the Gulf Coast.

Two more recent geothermal maps of the Texas geothermal potential have also been produced. Valenza (1995) provided a summary map of Texas geothermal resources that suggested the

locations for hydrothermal, geopressured, and hot dry rock resource potential. A variation on this map (Figure 15) was developed and sent to the EERE for their 2-page discussion of the Geothermal Technologies Program for Texas. Additionally, McKenna and others (2005) used data from Blackwell and others (1994) to generate temperature maps across the state at 4 and 6 km depths respectively (Figure 16). These maps suggest that a largely untapped energy resource lies underneath our feet that can be developed for electrical power generation. This paper also suggested that the DOE enhanced (or engineered) geothermal systems (EGS) program could be used to strong advantage within hydrocarbon fields where subsurface temperatures and available water are high, with successful results for geothermal electrical power production.

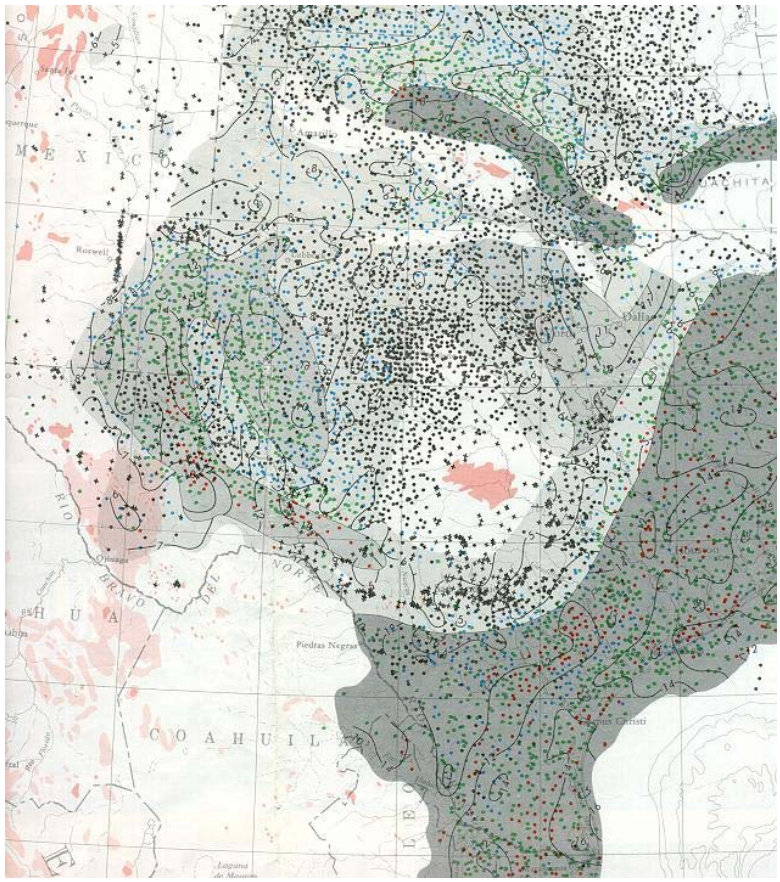


Figure 14. This scanned image of a portion of the original 1976 North American Subsurface Temperature Map as published by the AAPG/USGS displays the variations in temperatures recorded in the subsurface across Texas. Red dots represent temperatures ≥290°F, green dots for temperatures from 180° to 289°F, blue dots for temperature from 151° to 179°F, and black dots for temperatures ≤150°F. The dark gray area represents an area where the contoured isotherm is 302°F and the medium gray region represents an area where the contoured isotherm is 212°F.

From the standpoint of electrical power generation, there exist at least five major regions within the state that have a strong potential for geothermal electrical power production (Figure 15). These include East Texas, the Gulf Coast, the Delaware-Val Verde Basin region, the Trans-Pecos region, and the Anadarko Basin where it enters the Texas Panhandle. The Trans-Pecos

region is the only area that has geothermal dominated by a more conventional volcanic system; the other four regions are within sedimentary areas dominated by oil and gas production. A sixth area not shown on the map is called the Maverick Basin, and lies along the Texas-Mexico border southeast of the Delaware-Val Verde Basin (DVVB) complex. This basin could be an extension of the DVVB or of Gulf Coast structuring, but further data is needed to confirm or deny this suggestion. A brief discussion of each of these areas will be presented here.

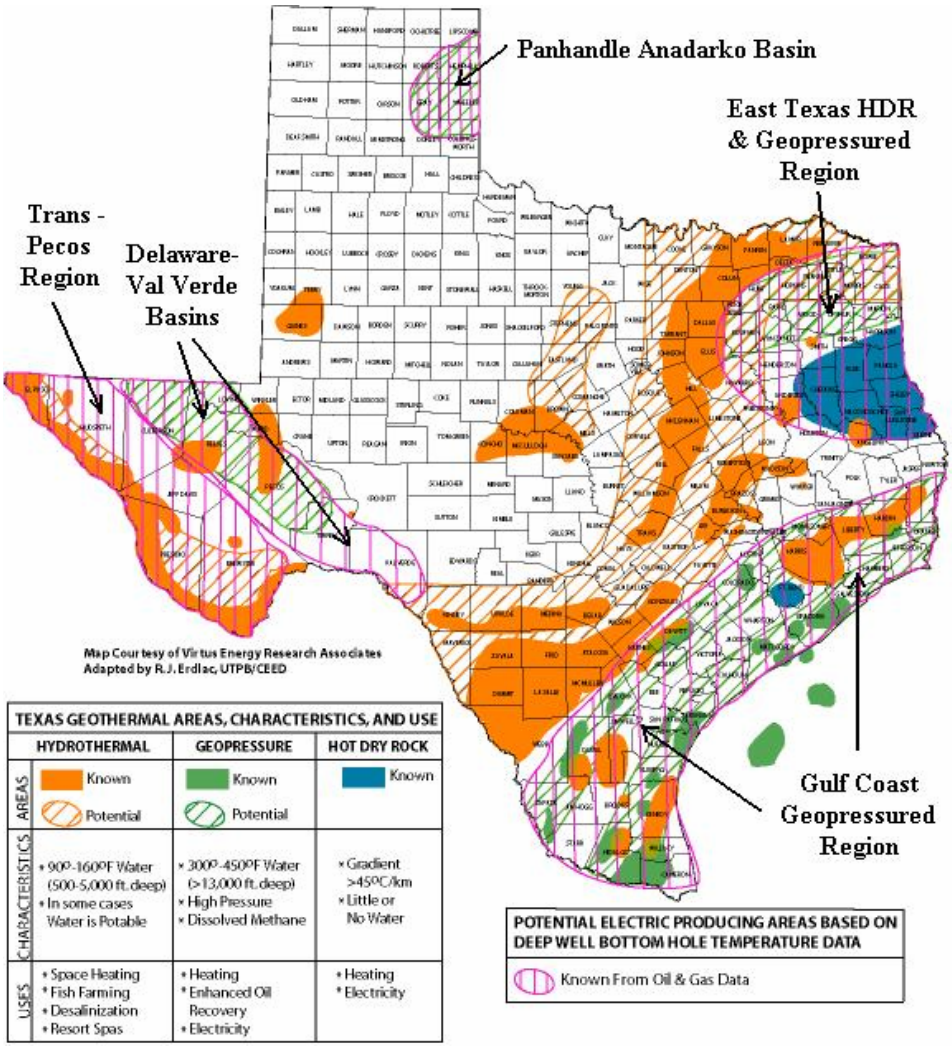


Figure 15. Virtus Energy Research Associates originally developed this map to show the approximate location and boundaries of geothermal areas in Texas. This map has been updated and altered as a result of work conducted by Erdlac for this report.

Gulf Coast Geopressured Region

Starting in mid-1970's and extending through the early 1990's, the DOE managed a 17-year, $200 million study of the northern Gulf Coast in Texas and Louisiana (Figure 17). This program conducted various types of research and well testing to investigate geothermal energy recovery

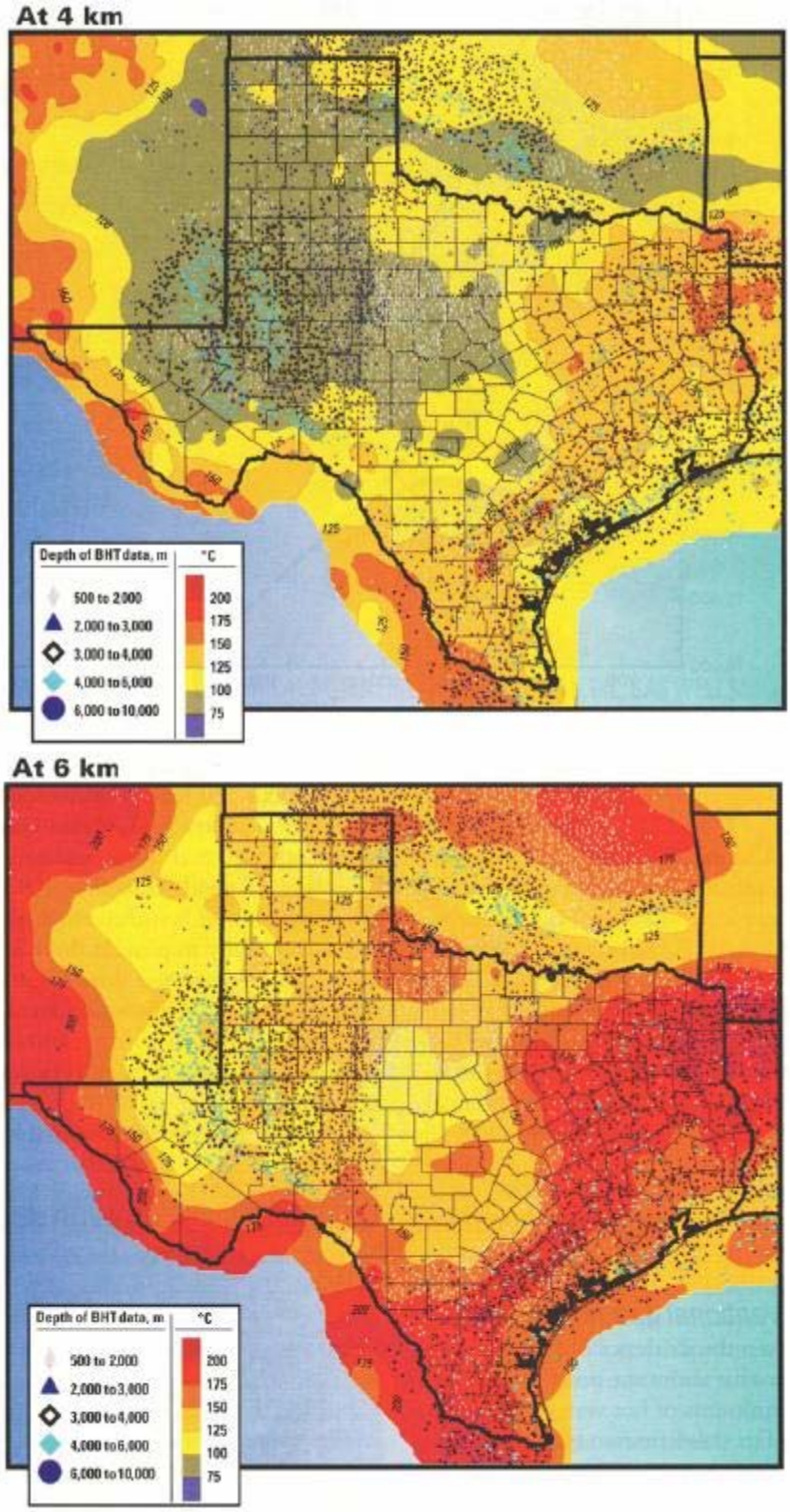


Figure 16. Subsurface regional temperature maps showing contours of varying temperature throughout the state at 4 and 6 km depths. From McKenna and others (2005).

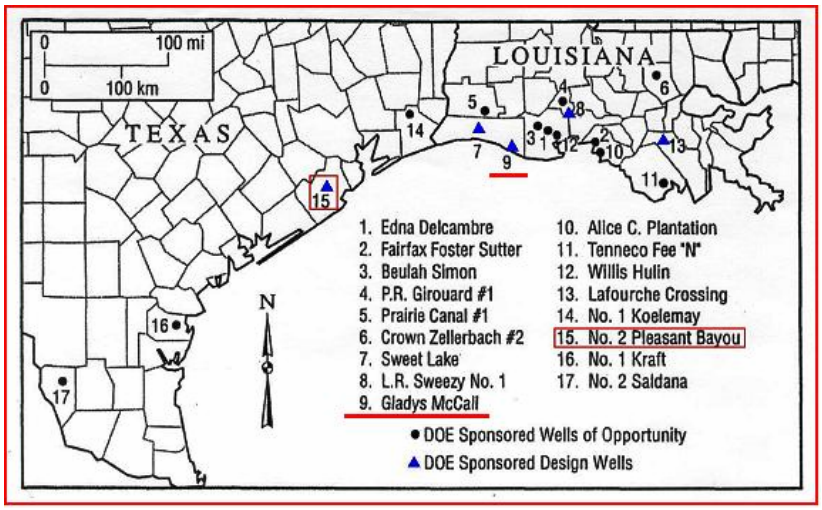


Figure 17. Area in the Gulf Coast that the DOE investigated for geopressured-geothermal resources, using 17 wells for testing and research purposes. Wells in blue triangle were drilled by the DOE while the black dots are wells donated to the project by industry.

in the region. 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.

In Texas, the Wilcox and Frio/Vicksburg strata were target reservoirs. Two testing programs were developed (Figure 17). "Wells of opportunity" represented wells provided by industry, and "design wells" were drilled by the DOE on potentially favorable geopressured sites based on existing geological/geophysical studies. While most of these wells were in Louisiana, the Pleasant Bayou #2 in Brazoria County, Texas became the first successful use of a deep well drilled in a sedimentary basin using a hybrid binary cycle system for electrical power generation.

The Pleasant Bayou #2 production well was drilled on the flank of the Chocolate Bayou salt dome (Figure 18), down dip from any oil and gas production. The structure map is on top of the T5 marker. This marker begins at a depth of –13,000 feet (-4,145 m) and extends to greater depths. Sandstones in the T5-T6 zone correlate with the *Anomalina birateralis* foraminifera zone of the Lower Frio. Wellhead brine production was estimated at a minimum of 20,000 bbls/day with 22 scf gas/bbl brine. The plant operated on only 10,000 bbls/day or 292 gal/min. Scale and corrosion inhibitors were effective over the operating range of brine temperatures. The bottom hole temperature of the well was 309°F (154°C) with a maximum produced brine temperature of 277°F (136.1^{o}C). Permeability in the producing zone was 159.8 md with an estimated reservoir area of 36,000 acres (56.26 sq mi).

Although most geothermal power plants have numerous wells tied into a single site for electrical production, most plants are rather small in aerial coverage, and the Brazoria power plant was no exception (Figure 19). The plant operated successfully for 121 days from the end of 1989 into early 1990. The minimum well rating was a minimum of 1.191 MW, with the binary cycle turbine producing 542 kW and the gas engine producing 650 kW. Parasitic load on the system was –209 kW, resulting in a net production of 982 kW

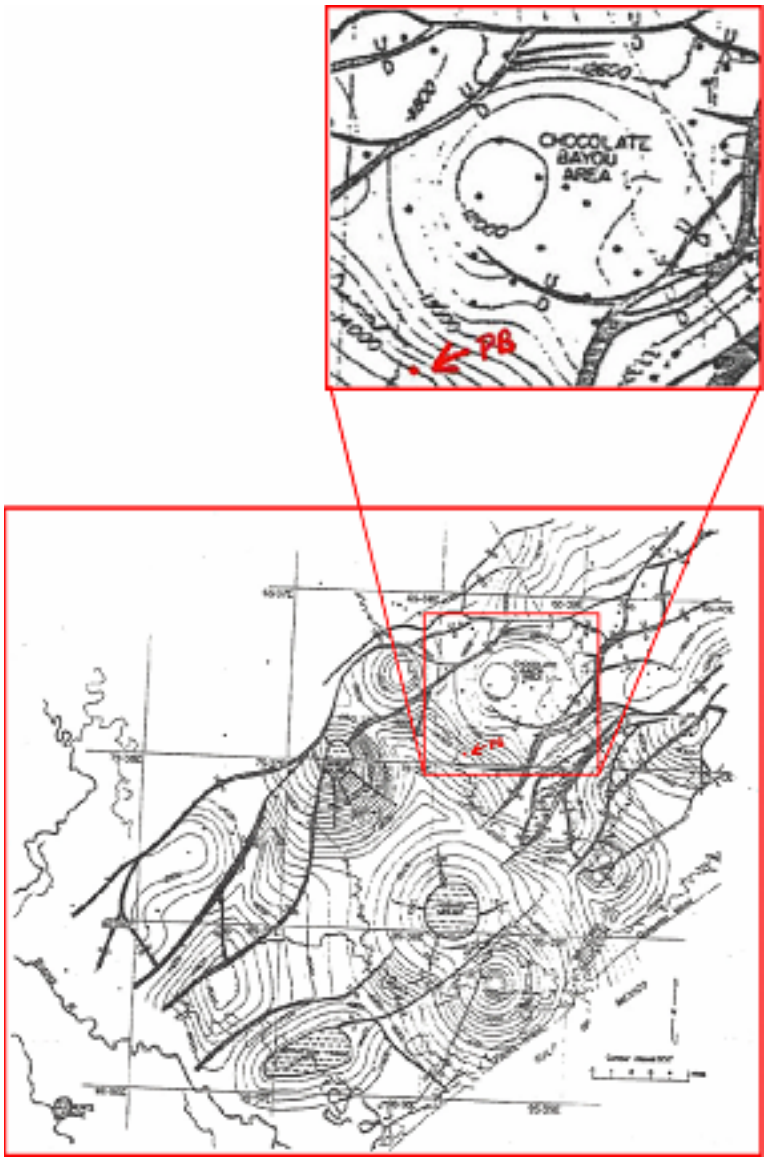


Figure 18. The site for the Pleasant Bayou #1 is on the southeast margin of the Chocolate Bayou dome along the Texas coast in Brazoria County, Texas.

for sale to a local electrical company. The capacity factor for the well was only 80.2% but that was due to a 3-day plant outage and a 4-week turbine outage. Plant availability was high at 97.5%. A total of 3,445 MWh were sold from the 121 days of operation.

The well was highly successful but was never able to be commercialized due to the low cost of alternative energy resources, specifically oil and gas. In 1989-1990 there did not then exist a Texas mandate for renewable energy production. Senate Bills 7 and 20 have changed that situation. Nor were most people concerned about additional electrical availability. This was before the California and northeast U.S. blackouts of this new 21st century.

Figure 19. The location of the geothermal power plant in Brazoria County, Texas. This picture shows the fire protection system and the relative size of the plant, small when compared to the processing plant in the distance.

Numerous references about this Gulf Coast study can be found by accessing the Office of Scientific and Technical Information over the Internet and search for geothermal investigations in Texas. Valenza (1995) indicated that information on the Texas geopressured resources were gathered at the now defunct Geopressured-Geothermal Information Systems (GGIS) under the auspices of the Center for Energy Studies at the University of Texas at Austin. This information included digitized well logs, well header information, salinity data, sand profiles and a bibliography. The Department of Petroleum Engineering has what is left of this database, but there was no further funding to maintain access to this data. In discussions with the Department, much of the data resides on real-to-real tape and no reader is presently available to translate the data to a newer electronic format. Thus at the present time, most of this information is inaccessible.

East Texas HDR And Geopressured Region

Part of the East Texas region lies within the geopressured-geothermal province of the Gulf Coast, and as such was discussed in the previous section. However, farther north lays an area that Valenza (1995) classified as hot dry rock country (Figure 15). This area has a geothermal

gradient on the order of 45 to 59°C/km, and represents a mid- to high-grade thermal gradient. Nunz (1993) gave the amount of HDR resource available for Texas as a whole, rather than breaking it up into various areas. He indicated that Texas has some 2,435,000 exajoules as a geothermal resource base. One exajoule is the equivalent of 176 million barrels crude oil equivalent, or 44.93 billion kWh, or 5.129 gigawatt-year. Nunz then indicated that the HDR accessible resource base for Texas is 1,033,000 exajoules, or the equivalent of 181.8 trillion bbls of oil equivalent. For electricity production, he suggested that 534,000 exajoules was possible, which is the equivalent of 2,737,000 Gwe-yr.

Even though these represent large numbers of electrical production, no concerted effort has been commercially mounted to tap into this resource. Similarly these numbers do not represent the sustainable amount of electrical power that might be provided. Further work in East Texas, along with the HDR approach, is necessary to better evaluate this energy potential.

Panhandle Anadarko Basin

Valenza (1995) showed this part of the state has being within a geopressured area (Figure15). Thus using the Gulf Coast as an analogy, this region would have a similar potential for electrical production from geothermal depending on the temperature of the resource. This area does display a contoured portion of the basin that has a contour isotherm that is 302°F or above. Several wells are shown with BHT recordings of 290°F or above. The work conducted during this study did not look at data from this basin as it enters Texas. Thus future work is necessary to investigate the basin in Texas in a more detailed manner.

Delaware And Val Verde Basins

The concept of 'deep permeable strata geothermal energy' (DPSGE) was first proposed by Swift and Erdlac (1999) through reconnaissance work in the Delaware and Val Verde Basins carried out at the West Texas Earth Resources Institute (WTERI) in Midland, Texas. Over 2,000 temperature-depth points were recorded in an Excel database in four target counties. Work continued sporadically until 2005 when three grants were obtained from the DOE (Congressional earmark), SECO, and the DOC/EDA to investigate geothermal energy in West Texas. These funds provided support for the first year of a proposed 3-year research study of the region. Work began in July of 2005 through the end of 2006 at the Center for Energy and Economic Diversification (CEED) of The University of Texas of the Permian Basin (UTPB) to expand upon this earlier reconnaissance investigation.

The purpose of this project was to investigate new regions for establishing geothermal energy production focused on electric power generation. Specifically, this project would work to identify optimum geologic and geographic sites for converting depleted deep gas wells and fields within a carbonate environment into geothermal energy extraction wells.

Three factors limit the expansion of geothermal expansion: distribution, field size, and cost. Historically, power production from geothermal energy has been relegated to shallow heat plumes near active volcanic or geyser activity, or in areas where volcanic rocks still retain heat from their formation. Thus geothermal development is spatially variable and site specific.

Additionally, existing geothermal fields are only a few 10's of square km in size, controlled by the extent of the heat plume. This plume tends to radiate heat both vertically upwards as well as laterally into the enclosing country rock. Heat withdrawal at too rapid a rate eventually results in a decrease in electrical power generation as the thermal energy is "mined". The depletion rate of subsurface heat directly controls the lifetime of geothermal energy production. Finally, the cost of developing deep (≥ 4 km) reservoirs of geothermal energy is perceived as being too costly to justify corporate investment. Thus further development opportunities for geothermal resources have been hindered.

To increase the effective regional implementation of geothermal resources, as an energy source for power production, requires meeting several targeted objectives. These include:

1. Expand (oil and gas as well as geothermal) industry awareness of an untapped source of geothermal energy within deep permeable strata of sedimentary basins;
2. Identify and target specific geographic areas within sedimentary basins where deeper heat sources can be developed;
3. Increase future geothermal field size from 10 km^2 to many 100's km^2 or greater; and
4. Increase the productive depth range for economic geothermal energy extraction below the current 4 km limit by converting deep depleted and abandoned gas wells and fields into geothermal energy extraction wells.

The West Texas project was initiated with the goal of working towards meeting these objectives.

At the time of writing this report, continuation of this project was on hold pending acquisition of additional financial support for the second and third years of the study. Thus the information provided here is a summary of the first year report sent to the DOE. Sixty four files were uploaded to the DOE, including a 113-page narrative of the study. These files were also submitted to SECO as another repository for the first year of data gathered and analyzed, and can be provided to the interested reader. The narrative report is the heart of these files, with the files being referenced within the narrative. I recommend that the interested reader go through this pdf report entitled "@1st year 2005 2006 rept edited.pdf".

Summary Of Delaware/Val Verde Basin Study

Literature Search: A literature search was initiated to help lay the theoretical groundwork for geothermal investigations within sedimentary basins. This search focused on three broad categories involving the thermal carrying capacity of rock, thermal conductivity, and thermal advection/convection within sedimentary rocks.

The thermal carrying capacity of a formation depends upon the density, the specific heat, the volume, and the temperature difference between the produced water and a reference temperature, usually the surface temperature of the reinjected water from a binary plant for example. The heat capacity is a product of the density and the specific heat of a substance, and in the case of rock, depends upon whether the rock is dry or wet, the type of fluid, and the porosity of the rock. Determining these parameters is a combination of laboratory investigations along with in-situ field measurements from logging equipment. However determining these parameters allows the determination of the thermal energy stored within a subsurface system. Initial data was obtained during the first year of the study to address this issue.

Thermal conductivity is a measure of the ability of heat to transfer through a solid or liquid material. In the simplest one-dimensional approach, conductivity is dependent upon the difference in temperature across a measured distance, or the difference in temperature divided by a distance $\left(\frac{T_1 - T_2}{z} = \frac{dT}{dz}\right)$ and the heat flux, or flow of heat per area per time. In the laboratory, measure of dT/dz is considered to be linear. This is because the temperature is measured at the two surfaces of a material across which heat flows at a constant rate. No temperature measurements can be made inside the material. In the analysis of the data collected for this project, we discovered that a lognormal description of dT/dz was possible and tended to have a better statistical fit with the temperature-depth points.

Past experimental work also shows that in sedimentary rock, especially limestone, the thermal conductivity is different if measured perpendicular to bedding or parallel to bedding, being as much as 35% higher parallel to beds than perpendicular. This difference in conductivity tends to decrease as the temperature increases. These experiments also suggest that a rock sample being subjected to higher temperatures will result in a decrease in thermal conductivity, but under higher pressures the conductivity will increase, these two physical parameters of temperature and pressure working against each other. Thus knowing the subsurface temperature and pressure of a formation becomes important for determining the heat conduction within a target formation.

Investigations of thermal advection/convection were minimal at the time of this writing. Further work will be necessary, especially in those circumstances where subsurface faults or fractures may act as a conduit for deeper moving water to bring heat to a shallower level, creating a local heat plumb in a subsurface target formation.

Basin Analysis: This project covered all or parts of eight counties, and included Winkler, Loving, Ward, Reeves, Culberson, Pecos, Terrell, and Crockett. UT Lands were included as part of this study within the three regions classified as 1, 2, and 3 (Figure 20). The project was defined as a 3-year investigation and 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 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.

The heart of the project was the database development, where well location and name could be recorded along with the temperature-depth (t-d) information. At this point, log header information provided the primary source of the t-d information that was put into the database. In addition to developing the prime database, two additional databases were made available for inclusion. These included the previous WTERI t-d database and a log database that had been built at CEED to document various logs that had been donated to the facility.

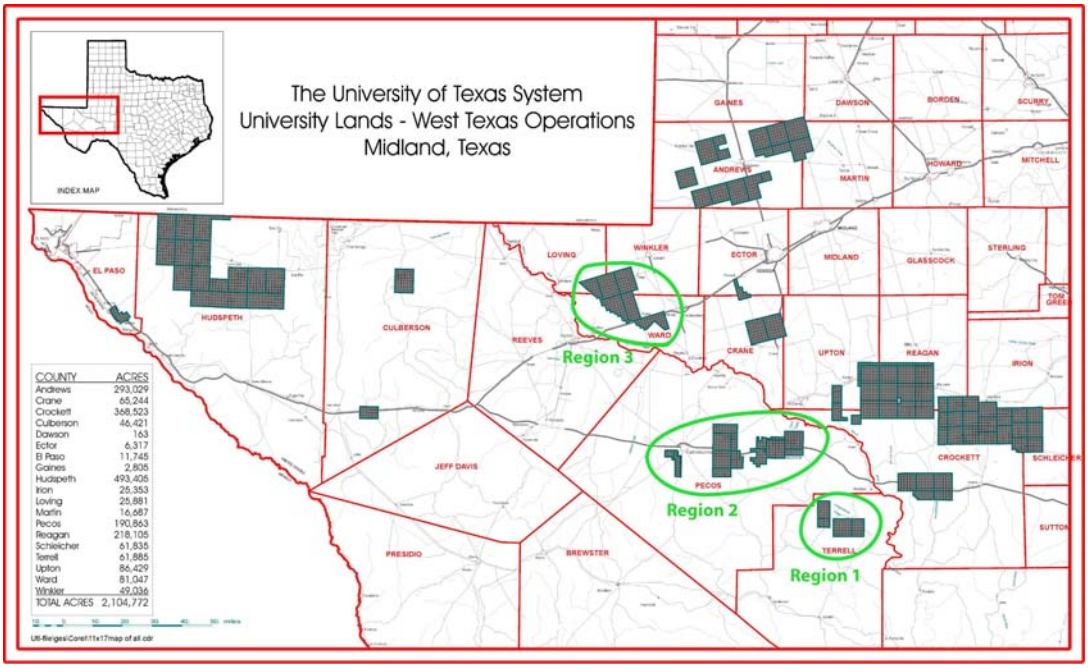
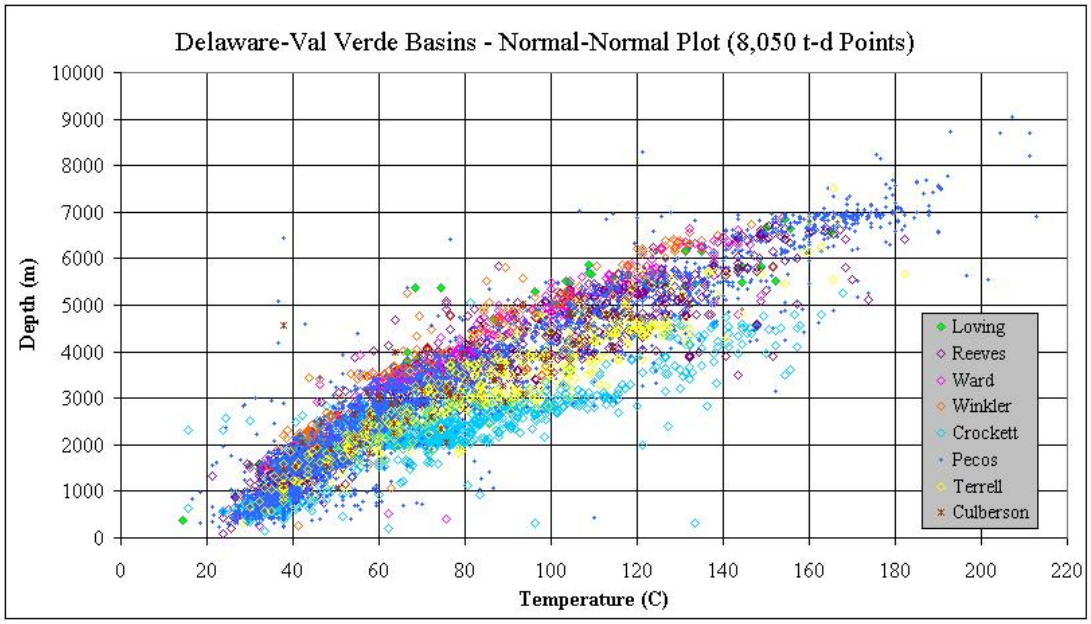


Figure 20. Map of West Texas showing the location of University of Texas Lands (UT Lands) and the three regions (1, 2, and 3) of these lands that lie within the Delaware Basin and northern part of the Val Verde Basin that were included in this study. All 2 million acres of land cover all surface and subsurface water and mineral rights.

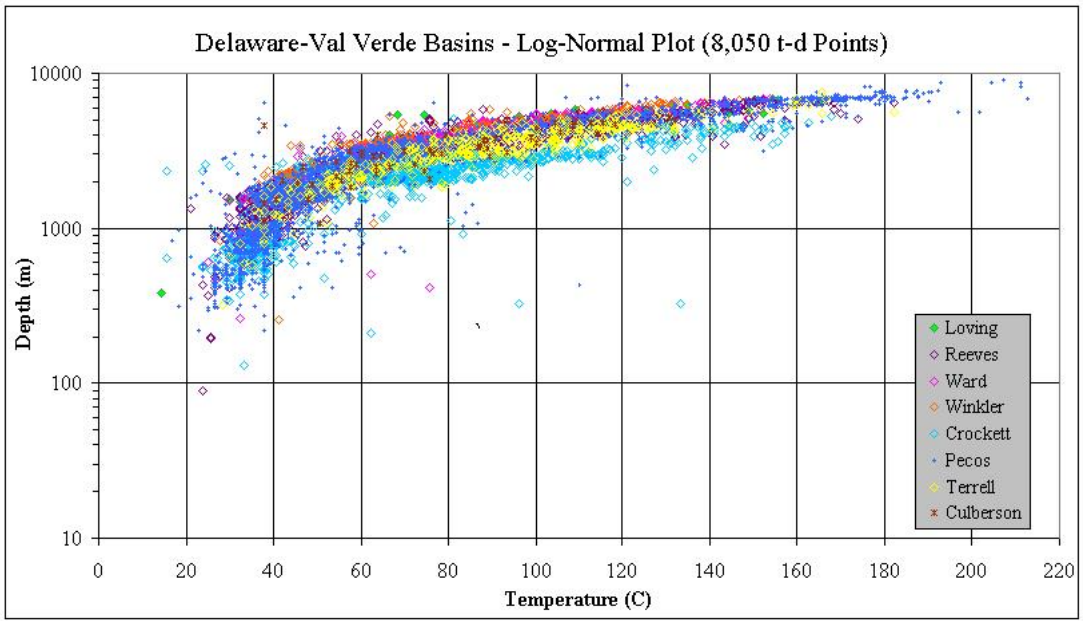
Over 8,000 t-d recordings were recorded into Excel spreadsheet format for retrieval and analysis. Many of these recordings were of a single bottom hole temperature (BHT) but there were also a number of wells that had multiple t-d recordings taken as the well was drilled. We worked first to obtain the t-d recordings from the deepest wells, and then began to include wells at mid-level and at shallower depths. In this manner we could begin to get an idea of the thermal gradient dT/dz within the various counties and the basins at large.

The data was plotted by county, as well as across the entire basin (Figure 21). The data was first plotted as a normal-normal distribution, which tended to show that the data did not plot as a straight-line function. We then plotted the data on a lognormal graph for comparison. When the best-fit linear and lognormal lines were compared, it was often found that the lognormal function was slight better in its fit to the data. This was an important find because it meant that calculating a subsurface temperature based upon a simple linear approach might result in too low a temperature for a specific depth. The reason(s) for this non-linear empirical result are presently uncertain and require further investigation. Terrell County 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. However we were surprised by the higher temperatures found in the southern parts of Crockett County. The t-d points tend to follow the same general plot as the rest of the data 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 22 where the overall temperature gradients for each of the eight counties are plotted. The higher



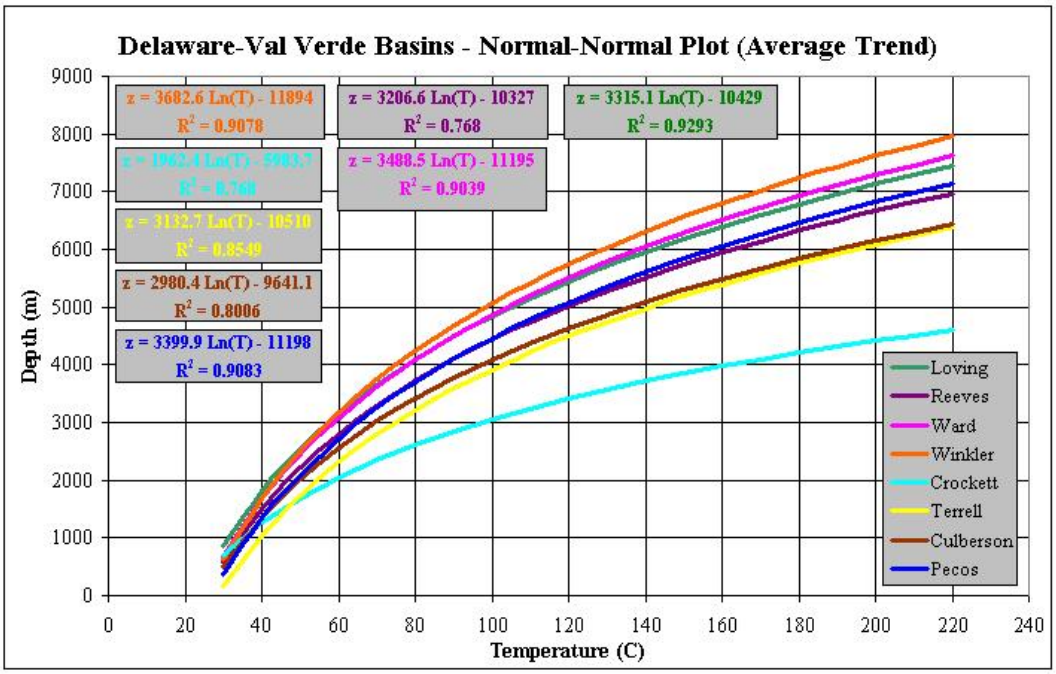
A



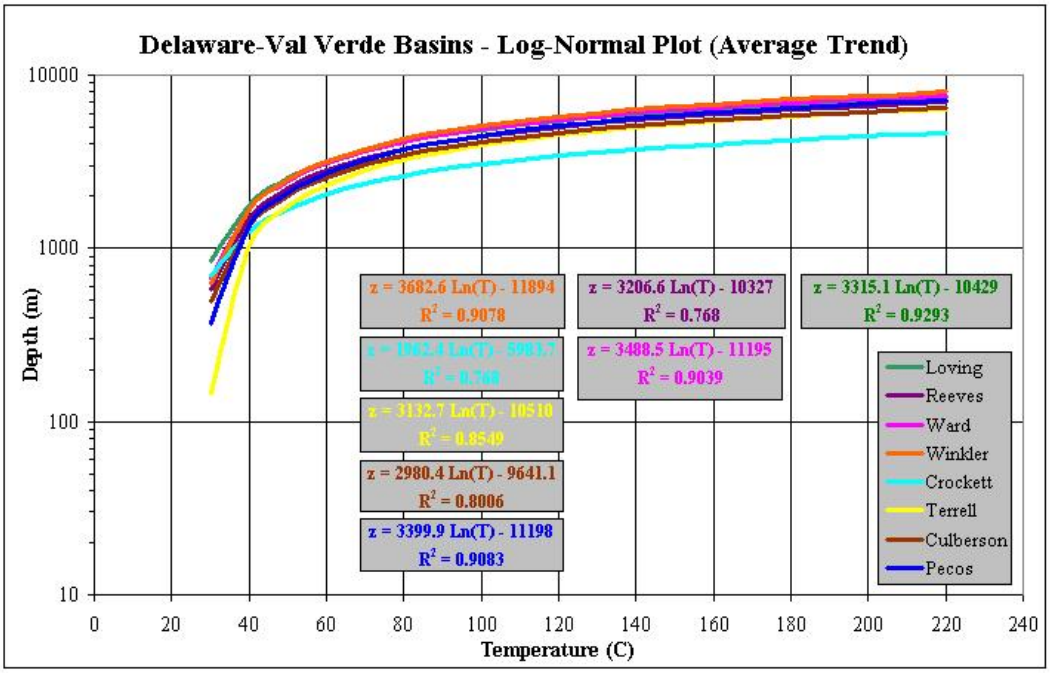
B

Figure 21. 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.

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.



A



B

Figure 22. 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.

The importance of defining these various thermal gradients will come into play when temperature maps are developed, not just at a constant depth as is normally the case, but within a specific target heat reservoir formation. Using these gradients at various locations it will be

possible to develop 'phantom points' that are within a specific target formation and map the temperature contour at that point within the target rock strata. This is important because the t-d recordings are not specific to any formation, and are thus found within a variety of rock types and formations. This will also help to define variations in thermal gradient laterally within the same formation that might result from localized advection or conduction of hot water from deeper formations through fault zones. A more detailed discussion can be found in the pdf file provided to SECO along with this report, the file entitled "@1st year 2005 2006 rept edited.doc".

Trans-Pecos Region

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.

A total of 65 t-d points within the Presidio County area had been placed within this database from various oil and gas wells drilled in the past. We were also able to download shallow t-d data from the SMU Geothermal Laboratory website that allowed the inclusion of shallower data, for a more complete t-d range of points. Upon graphing the data we found that a lognormal curve could also be used to describe the geometry of the t-d plot. A more detailed discussion can be found in the pdf file provided to SECO along with this report, the file entitled "@1st year 2005 2006 rept edited.doc".

This region should be further investigated as to its geothermal electrical power generation. It will require a combination of subsurface data along with surface geology mapping in areas that show more traditional signs of recent past surface to near-surface geothermal activity.

Maverick Basin

The Maverick Basin is a small basin, compared to some basin standards, that exists along the Texas-Mexico border between Maverick and Zapata Counties (Figure 23). 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 4). The wells were deemed of sufficient importance to be included within this report. These 12 wells were drilled to depths ranging from around 13,000 feet to a little over 17,000 feet.

Temperatures within these wells range from a low of 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 normal-normal and lognormal graphs in order to determine a best-fit trend line.

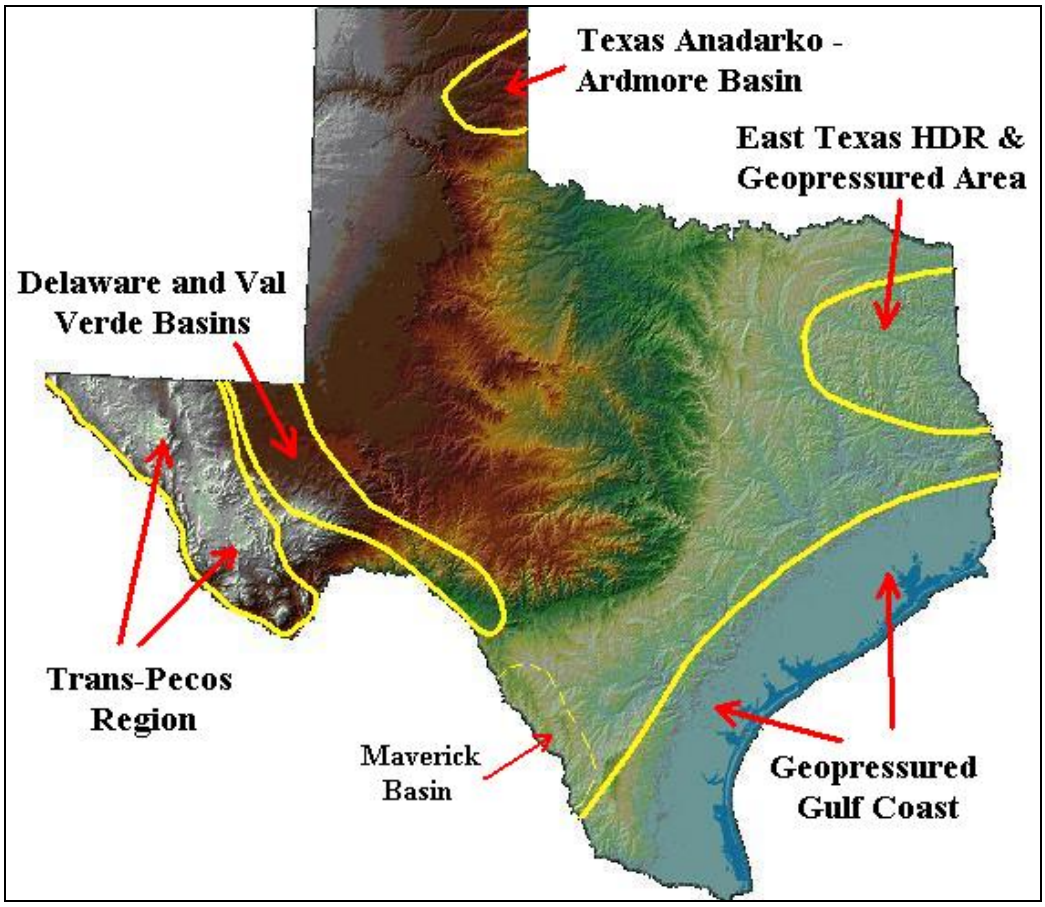


Figure 23. Target regions within Texas for geothermal energy in electrical power production. These regions are based upon the existence of oil and gas wells with temperatures that can get above 212°F.

Because so few wells were in the database, a straight-line function was chosen to describe this data, giving an average temperature gradient of 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 of the Maverick Basin is also unknown and should be studied further.

RECOMMENDATIONS FOR GEOPOWERING TEXAS

Development of geothermal energy in Texas will fall along three lines: geoexchange systems, direct use activities, and electric power generation. To some extent, each of these approaches to geothermal development can grow independently of the other two. For example geothermal heat pump installation does not care what the temperature is several thousand feet underground. By contrast direct use and electrical generation do care how deep a well may need to be before a usable temperature is reached. On the other hand advocacy and incentives to geothermal development will impact all three forms of geothermal energy.

Table 4 – Zapata County, Texas

Field	Well Name (including #)	Log Run 1			
		Logger's depth	Meters	Temp Data (F)	(C)
En Seguido (Wilcox)	Cavazos #1	14500	4419	322	161
En Seguido (Wilcox)	Cavazos #2	13114	3997	326	163
En Seguido (Wilcox)	Cavazos #3	13086	3988	328	164
En Seguido (Wilcox)	Cavazos #4	12700	3871	320	160
En Seguido (Wilcox)	Lopez #1	14050	4282	324	162
En Seguido (Wilcox)	Lopez #2	14050	4282	324	162
En Seguido (Wilcox)	Lopez #3	13590	4142	324	162
En Seguido (Wilcox)	Vela #1	13190	4020	326	163
Falcon Lake, E (Wilcox Conds)	Worley #1	16300	4968	410	210
Falcon Lake, E (Wilcox Conds)	Worley #2	15460	4712	362	183
Falcon Lake, E (Wilcox Conds)	Salinas 1	17110	5215	435	224
Uno Mas Tiempo (Sylvia Sand)	Siete Velas #1	13230	4032	340	171

Presently, numerous places around the state are using geoexchange systems, or having them installed, to take advantage of the cost savings in heating and cooling the inside of a building. Several different companies are centered in Texas and install geoexchange systems. Direct use application is less developed, and is used only locally at several places in Central Texas. Electrical power generation has yet to be commercially established, though the Brazoria County DOE demonstration facility showed that this approach to electrical generation is feasible.

The remainder of this document will focus on various recommendations for furthering Texas geothermal development. To best describe these recommendations, I have subdivided the discussion into four components: technical assistance, industrial/economic, advocacy, and policy/legal development. Where appropriate the discussion will pinpoint the type of geothermal (geoexchange, direct use, electrical) energy that is the focus of each component discussion.

The reader must recognize that unlike many other western states using and developing geothermal energy, federal lands in Texas are nearly non-existent. Land is owned by private citizens and by the state, through various public land surveys. Mineral development of these lands, specifically in the energy market, has been through industry injecting capital into target goals, specifically oil, gas, and coal (in East Texas), not by federal assistance. On the other hand Texas has taken up the challenge of providing incentive packages for companies to establish centers of development in the state for the economic benefits provided by an increase in jobs and the tax base. While educating the public to geothermal use is important, educating industry to the potential of geothermal development is even more significant. Thus many of the suggestions will have a focus on impacting industry, which will be the prime driver for geothermal development.

Technical Assistance

Geothermal energy can be used anywhere in the State of Texas. However the type of geothermal development is based upon the temperature of the resource necessary for its growth. The production of geothermal energy for electrical power or direct use activity is higher in cost than for geoexchange systems due to the need for deeper subsurface acquisition of the resource through either drilling new wells or acquiring existing wells and completing them for hot water production.

The research and development of geoexchange systems has improved over the years driven by the fact that these systems can generally be employed universally. Thus R&D activities specific to one area of the country or to the development of emplacement techniques can usually be used in other locations. This is not necessarily the case for direct use and electrical power development. Much of the existing geothermal electric power industry focuses on finding fault and fracture systems that extend into deeper and hotter rock strata with the idea that deep hot water aquifers flow upward to shallower levels that is then tapped for geothermal production. While this approach may prove successful in Texas for identifying areas for direct use application, power development from hot water will be from wells that have already drilled deep into hot wet rock for energy from natural gas.

Unfortunately information regarding deep temperatures, amounts of water available, thermal conduction, subsurface water movement, and other factors affecting geothermal production have not been readily available due to their lack of need by companies for extracting oil and gas. Thus at the present time, the biggest requirement by industry is information regarding the amount and availability of the geothermal resource so that companies can begin to include geothermal development into their energy portfolio of production along with oil and gas. Additionally, knowledge regarding turbine type and availability for the generation of electric power is also lacking in oil and gas companies. These are issues that can begin to be addressed by state agencies, with some federal assistance, which will further geothermal development.

The biggest technical issue facing geothermal development for electrical power generation and direct use activity in Texas is determining where and how deep the resource lies, and thus how companies can obtain the resource. Only two large geothermal databases are presently known to exist for Texas, the original 1976 regional data that has received extensive use by the SMU Geothermal Laboratory and the recently developed basin based database constructed at UTPB-CEED for the deep Delaware and Val Verde Basins. These two databases need to be greatly expanded in a manner that can foster this new industry. A third database, originally developed for the DOE Texas-Louisiana Gulf Coast study, presently resides in the Engineering School at The University of Texas at Austin. Unfortunately this database is in an old tape-based electronic format that is not presently able to be updated to a more modern format.

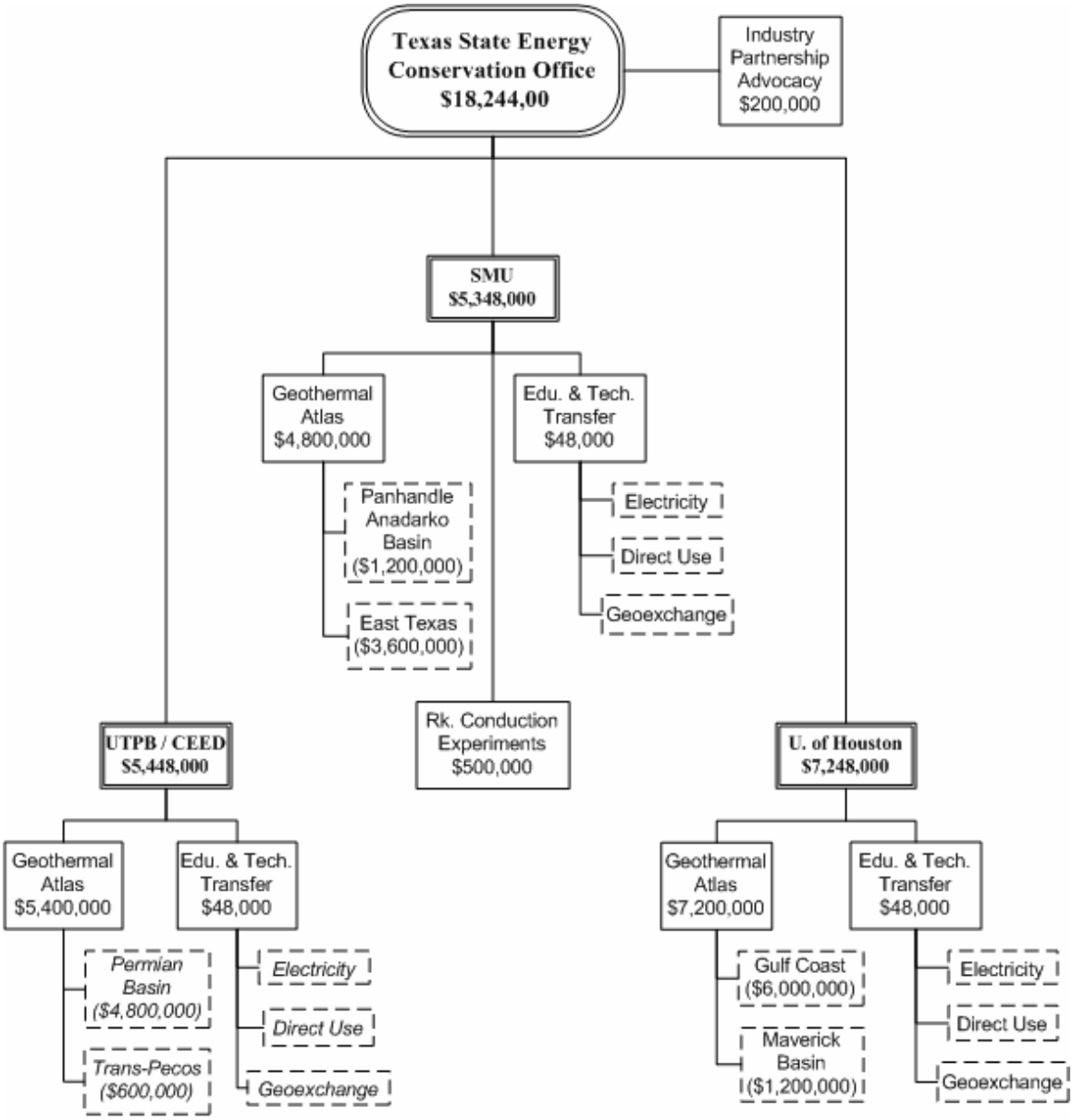
Recommendation 1 – State Funding

In structuring a technical assistance program, an emphasis would be placed on well information collection and analysis, map generation, rock property determinations of target formations, economic models for geothermal acquisition, and technology transfer. This data would form the

core of a "Texas Geothermal Atlas" that would be available for public and private dissemination. There would also be industry advocacy and educational outreach activities conducted.

This program would be totally state funded for a period of four years, and operated under the auspices of the State Energy Conservation Office (SECO) (Table 5). Funds listed in Table 5 are

Table 5



estimates only, and are based upon existing efforts conducted at UTPB-CEED during the 2005-2006 period of DOE-SECO support. A more detailed and joint discussion would be necessary to fine tune final budgets for this type of project.

All data collected and analyzed during this time would be placed in a public domain format as the "Texas Geothermal Atlas" to act as a jump-start for the Texas energy industry to begin developing geothermal energy. While SECO acts as the overseeing agency, most of the funding would be provided to three universities that have been recently conducting geothermal work in Texas or have an individual with past geothermal development experience on campus but whom is not presently involved. These three organizations are The University of Texas of the Permian Basin Center for Energy & Economic Diversification (UTPB-CEED), Southern Methodist University Geothermal Laboratory (SMUGL), and the University of Houston (U of H).

Each university, while maintaining a close working relation with each other, would focus their efforts on targeted geographical areas within the state. UTPB would focus on areas within the Permian and Val Verde Basins, and the Trans-Pecos region. This would involve expanding upon the existing Delaware Basin work conducted at UTPB-CEED as funded by the DOE and SECO during late 2005 and through 2006. An estimated $5.4 million would be targeted for the Permian Basin and Trans-Pecos Geothermal Atlases over the four-year period of state funding. An additional $48,000 would be provided as part of education and technology transfer to businesses and venture capital groups interested in developing geothermal energy within the West Texas regions.

SMU would receive $4.8 million for Geothermal Atlas development within the Texas Panhandle where the Anadarko Basin enters Texas, and for efforts conducted in the East Texas region. Education and technology transfer efforts would receive $48,000. In additional, SMU would receive $500,000 for conducting conductivity studies of the possible target geothermal formations throughout the state in the areas studied by UTPB, SMU, and U of H. In this manner a single group would be able to better coordinate these experimental efforts for the entire program rather than each organization conducting their own efforts for their respective study areas.

The University of Houston would receive $7.2 million for Geothermal Atlas development and $48,000 for education and technology transfer. The larger amount of funding for atlas development is necessary due to the larger area that is covered in the Texas Gulf Coast when compared with the other regions being covered by UTPB-CEED and SMU.

Finally, SECO itself would receive an additional $200,000 over the period of the study to assist in developing industry partnerships with the three universities to carry work beyond the four-year period of state funding. In this manner future university geothermal R&D funding would become supported by industry actively participating in developing geothermal energy applications within the state. The total estimated 4-year cost for such an effort is over $18 million (Table 2).

Industrial / Economic Development

Historically, Texas industrial and economic drives have had a strong focus with energy development. While the last couple of decades have seen major efforts at diversification into other industries, Texas has still been seen as an energy capital when compared to other states. This has especially been true with oil and gas production. More recently Texas has taken the lead over California with in-place 'nameplate' wind energy development.

In West Texas, economic dependence upon the oil and gas industry for high skill, high paying jobs has been the norm. Production, transport, and sale of oil and gas resources have outstripped other industries in the region. For example, between January and March of 1997 D&B Market Place reported that the petroleum industry amounted to a total of 1,795 businesses out of a total of 11,718 businesses within Midland and Ector Counties (Table 6). This represents only 15.3% of all the businesses in the region. However this number of petroleum businesses represents over 34.7% of all business sales, or $2,573,600,000 during this time period (Table 7). This amount of sales equates to an average of over $2,640,000 per business (Tables 6, 7). By contrast if all businesses, accept that the petroleum industry, are considered, the business average was only $487,201 per company. Thus the economic dependence upon the oil and gas energy industry has been enormous for high skill, high wage jobs.

The face of the oil and gas industry has changed drastically over the last several decades. Major O&G companies have pulled out of many domestic basins, looking for new areas to develop worldwide, or been bought out by other majors, most probably in the attempt to maximize producing assets in a world environment of dwindling availability of produced O&G resource. This has created somewhat of a vacuum that has been partially filled by smaller, more aggressive independent O&G companies. These companies have taken advantage of recent higher world energy prices to conduct more drilling in older fields and to drill smaller O&G plays that are now economically feasible to drill.

Table 6

Jan-Mar 1997 Business Statistics For Midland & Ector Counties		
Business Type	**Number Businesses**	**Number People Employed**
Bus. Excluding Petroleum ^	9,923	78,345
Bus. Excluding Petroleum & Agriculture ^	9,784	77,851
Petroleum ^	1,795	
Exploration & Prod Co. *	228	

^ From D&B Market Place
* SW Bell Yellow Pages

Table 7

Jan-Mar 1997 Business Statistics For Midland & Ector Counties	
Business Type	**Sales**
All Businesses ^	$7,408,100,000
Agriculture & Related ^	$91,600,000
Petroleum & Related ^	$2,573,600,000
Remaining Businesses ^	$4,742,900,000

^ From D&B Market Place

Over the last decade or so the wind energy industry has grown within Texas. Recent wind maps from the Energy Efficiency and Renewable Energy (EERE) website show Texas at 2,898 MW installed wind energy capacity, with California at a close second with 2,320 MW. Mr. Randy Sowell (personal communication), a West Texas wind energy professional, has informed me that for 1 MW wind towers, the number of average employees is 1 technician for every 10 MW of installed potential. Crews are generally composed of two individuals, with one taking care of electronics and computers, and the second being more involved with the mechanics and operation of the tower. For Texas this equates to around 300 people employed in the field. Beginning installation of 2 MW wind towers may alter this number to 1 technician to every 12 towers, but insufficient numbers of these larger towers are in place to determine the future employment rate. Thus while the development of wind energy is important for building a renewable energy portfolio, the employment level is far less than what has existed in the O&G industry.

This is a very different situation from geothermal energy development, where there exists a higher employment potential. Ormat Technologies, Inc., a Reno, Nevada based geothermal energy company operating facilities in California, Nevada, and worldwide, employs 12 to 14 people for a 20 MW plant and 40 to 50 people at a 50 MW plant. These people comprise administrative and supervisory personnel, plant operators, and maintenance personnel. It can be seen that the rate of employment at a geothermal facility can vary from a minimum of 6 to a maximum of 10 people for every 10 MW of produced electricity. If the 2,898 MW of wind energy were being produced by geothermal electric, the employment would range from 1,738 to 2,898 personnel. The employment potential in geothermal is larger than that presently found in the wind industry. This employment rate does not include the numerous geoscientists, (petroleum) engineers, drillers, and support staff presently found in the O&G industry, and who would play a vital part in developing and maintaining a Texas geothermal industry. The economic impact of geothermal development, both individually and in conjunction with the O&G industry, will be far greater than with the existing wind energy industry.

Recommendation 2 – Leasing Definition And Clarification

To help facilitate "the rapid and orderly development of geothermal energy and associated resources" (Geothermal Resources Act of 1975, §141.002(1)), and as "an integrated development

of components of the resources, including recovery of the energy of the geopressured water without waste, is required for best conservation of these natural recourses" (Geothermal Resources Act of 1975, §141.002(4)), and as there was a desire by the Texas Legislation for the "prevention of waste of natural resources, including geothermal energy and associated resources" (Geothermal Resources Act of 1975, §141.012(b)(2)), a clarification for the Texas energy industry is necessary regarding the potential of co-producing oil, gas, and geothermal energy resources simultaneously or in a planned multi-stage development process.

Many existing and producing wells for oil and/or gas quite often contain hot water in the range of 180 to 190°F and above. This water is simply part of the necessary fluid produced for the purpose of oil or gas extraction. The heat from the water is presently "wasted" by either the heat bleeding away while the water is stored in a tank for later injection and disposal, or by it being immediately injected back into the subsurface through a nearby well. In either instance the heat energy is lost. Can an existing lessee extract this heat and use it as an energy source as part of their existing lease, or must they have a geothermal lease separate from oil and gas?

Most existing O&G leases use phrases such as "oil, gas, and associated fluids" or "nonhydrocarbon substances produced in association" with the oil and gas. In this manner hot brine that could have heat extracted for electrical production or other direct use activities can be produced along with oil and/ or gas. However does this type of wording cover the purposeful extraction of heat energy from this water for renewable energy application? Obviously heat energy is nonhydrocarbon in nature and a lease that uses this phrasing might be argued to cover the targeted production of geothermal energy in conjunction with or after the extraction of oil and gas.

This is an important point that needs clarification. Presently heat energy is wasted in the same manner that natural gas was once flared by the industry. Today, there is a developing market for the use of this natural heat energy, one that was not present in the past. But to develop geothermal in Texas will require the expertise and knowledge of the O&G industry at large due to its cohabitation within sedimentary basins that were previously explored only for the oil and gas energy reserves. It will also take what I have called an energy triad development approach…oil, gas, and geothermal …which in the process will undoubtedly find bypassed oil and gas reserves or reserves that were sufficiently small in amount that only by such a triadic approach is it economically feasible for drilling to occur.

Recommendation 3 – Lease Expansion

Oil and gas is generally considered the byproduct of long ago buried organic material entrapped within sediments deposited within a basin. These organic materials, when buried sufficiently deep under the right pressure and temperature conditions, will then be converted into the oil and gas that we are extracting today. It is thus important to recognize that oil and gas is a byproduct of the geothermal conditions, the heat that existed within the basin.

The fact that oil and gas may indeed be severed from geothermal energy in a lease is of concern for another reason. It is conceivable that an unscrupulous individual could go into an area where deep gas is already being produced, along with associated hot water, lease the geothermal rights separate from oil and gas, and then sue the oil and gas operator because they are wasting the heat

that is contained within the hot water produced with the oil and gas. The reverse situation could also occur, where geothermal rights have been leased by one company and a second company leases the oil and gas rights at the same location, causing difficulties to the first company. Reservoir integrity is important for either oil or gas production, or for geothermal energy production.

Thus I would recommend that for state and county lands, as well as other public lands under state jurisdiction, existing oil and gas companies be allowed to freely grandfather into existing leases the right to develop geothermal energy along with the oil and gas that may already be in production. This development might occur in conjunction with oil and/or gas production, or it might be developed later on when dwindling O&G production allows for the opening of bypassed hot water zones for heat extraction. In this manner the "prevention of waste of natural resources, including geothermal energy and associated resources" would be facilitated in a more rapid manner.

Advocacy

Advocacy is the act of supporting, encouraging, backing, sponsoring, or promoting a particular business, concept, individual, or thing. Although geothermal energy is not new in Texas, development to its full potential will require education and general support to industry, public, and political representatives. Organizations such as the Texas State Energy Conservation Office (SECO) and the Texas Renewable Energy Industries Association (TREIA) have been active in providing important advocacy actions for the development of various renewable energy resources. For example SECO has helped in providing funding for renewable energy demonstration projects, and TREIA has worked to get various rules and regulations established for the support of renewable industry development. This same type of advocacy will also be necessary to launch geothermal electrical production within Texas.

Recommendation 4 – Financial Forums

In establishing any business, understanding the market and its demand, identifying the personnel capable of conducting the business, and securing the funding to bring the business into existence are all equally important. In many instances the market has been researched, the expertise is available, but the funds are lacking. I recommend that a series of renewable energy forums be established that can occur in different areas of the state on a yearly basis that would bring various sized investment organizations, venture capitalists, and angel investors together with startup companies that are looking to secure funding for their operations. This type of forum could be developed either for each individual renewable energy resource, or the forums could be held concurrently for any and all renewable energy companies seeking funding. I favor the second approach. That way the investor would be able to talk with people across all of the renewable energies at a single location, rather than establishing individual forums for each of the various renewable energy resources groups.

Recommendation 5 – Nesting

Each type of energy resource in use today has various strengths and weaknesses. For example wind and solar energy are more readily available than geothermal. Wind and solar energy are felt each day by people somewhere in the world due to this resource being a surface

phenomenon. By contrast geothermal energy is under the ground and is not readily available to everyone due to the need for drilling into the subsurface for its acquisition. On the other hand, sun light and wind are not always available at the same geographical location throughout the day. The sun does not shine at night and the wind may not be blowing. However the earth stores tremendous quantities of heat naturally in the subsurface that can be tapped any time of the day or night for electrical power generation.

I recommend that the concept of 'nesting' resources in a given area be advocated in order to provide a steady stream of energy availability. This entails a more integrated approach to electrical production, combining more than one energy resource in a developer's plans for electrical generation from a specified site. Thus the developer would be defining an area of land and a corresponding project out of which a minimum guaranteed amount of electricity would be produced, from multiple renewable energy resources developed within that area. The technology and resource used would be planed around the amount of guaranteed electricity that would be produced from that area. Although presently untested, this nesting approach within a defined geographic region might actually be cheaper in overall capital outlay when measured against capacity factor from a sole source resource development.

Policy / Legal Development

Numerous barriers or constraints have been sited as blocking or slowing further development of geothermal energy. In considering this problem, I have come to believe that there are few barriers but many constraints on geothermal development (Erdlac, 2006). The term barrier can imply an obstacle or a boundary through which further passage is impossible. But, a constraint suggests a state of being checked, a situation that may be temporary. Thus an "obstacle" that cannot be surmounted but which can be detoured may more truly be described as a constraint on the situation.

These constraints can be local in nature or more global, implying a fundamental impasse that can be difficult to surmount. In fact there may be situations that are perceived as constraints or barriers that are simply our own constructs, forms of thought or action that when altered or viewed from a different perspective disappear as a boundary all together.

Constraints do exist to furthering geothermal development, many of which are often unique to the area being investigated. However, there are constraints common to all geothermal electric power development. These constraints fall into three broad categories: natural or geological/geographical; technical; and human (Table 8). The list of constraints shown here is not complete. Still this approach does define a framework to evaluate the ability to overcome a specific constraint. Understanding the impact and interactions of these categories is of prime importance for developing the strategy necessary for the successful implementation of a major expansion of geothermal energy.

Some of these listed constraints are not always unique to the broad categories of natural, technical, and human. In fact many of these constraints may have multiple influences from each of these three categories. One way to visually see this is to define what I call a ternary constraint diagram using the three variables of nature, technology, and humans (Figure 24) (Erdlac, 2005).

Each apex represents 100% influence of that variable on any given constraint. Percentages of influence of each variable on a constraint are represented by the position of the field that that constraint occupies. A constraint that is influenced primarily by one variable will cluster around that variable. If two variables are involved, the field will lie on or near the line connecting those two variables. A constraint that is affected by all three variables will be found to occupy a field somewhere within the triangle.

Determining the location of these constraint fields is highly subjective and should be considered within a qualitative rather than a quantitative approach generally used in developing ternary diagrams. Landforms, geography, geology, heat resource availability, and reservoir characteristics were viewed as being within the univariable realm of nature. Constraints such as economics, politics, perception, information/technology transfer, ownership, and research fall within the primary influence of humans. I interpreted the fields of water as transfer/storage agent and heat acquisition methodologies as lying

Table 8

CONSTRAINTS TO GEOTHERMAL DEVELOPMENT			
Natural (Geological/Geographical)			
Surface	**Subsurface**	**Technical**	**Human**
Landforms/Geography/ Geology	Heat Resource Available	Drilling (techniques-horizontal, radial patterns)	Economics (cost vs. profit) (drilling costs)
	Reservoir Characteristics	Heat Acquisition Methodologies	Perception
	Water as Transfer/Storage Agent	Environmental Concerns (toxic & nontoxic minerals)	Transmission
		Data acquisition	Information/Technology Transfer
			Politics (gov., people [advocacy groups])
			Ownership
			Resource Management
			Research

within the bivariable realm of nature and technology. The remaining constraints, data acquisition, drilling, resource management, environmental concerns, and transmission, are influenced by all three variables that delineate the ternary diagram. Further work is necessary, not only to place other constraints not represented here within this analysis framework, but to also quantify and refine the impact of each of the variables on each constraint field.

The importance of this analysis comes in determine how geothermal energy is held back from development due to human imposed constraints. This is where policy and legal action can greatly assist in opening the doors for furthering geothermal development. This is where local,

state, and federal legislative action can be of the greatest assistance in furthering geothermal energy development. Constraints that are human made are also constraints that can be 'unmade'.

Recommendation 6 – Retrofit State Buildings

In a military action soldiers that are simply told to advance on the enemy are less likely to succeed unless one of the advancing soldiers is considered by others to be a leader. In the same way the desire to advance the greater use of geothermal energy in Texas must be done by leading, by showing an example of what can be accomplished.

The use of geoexchange systems saves the business or home owner cost on their heating and cooling bills. Part of this savings results from reducing the amount of electricity needed to operate the heating and cooling geoexchange system when compared to other systems. These systems, while more easily built into new construction, can be used to retrofit existing buildings, thus reducing heating and cooling bills and reducing the overall maintenance needs of the building. Thus I recommend that the State of Texas embark on a leadership role in geothermal energy planning by requiring that all state buildings and state supported facilities conduct a retrofit program to install geoexchange systems for building heating and cooling.

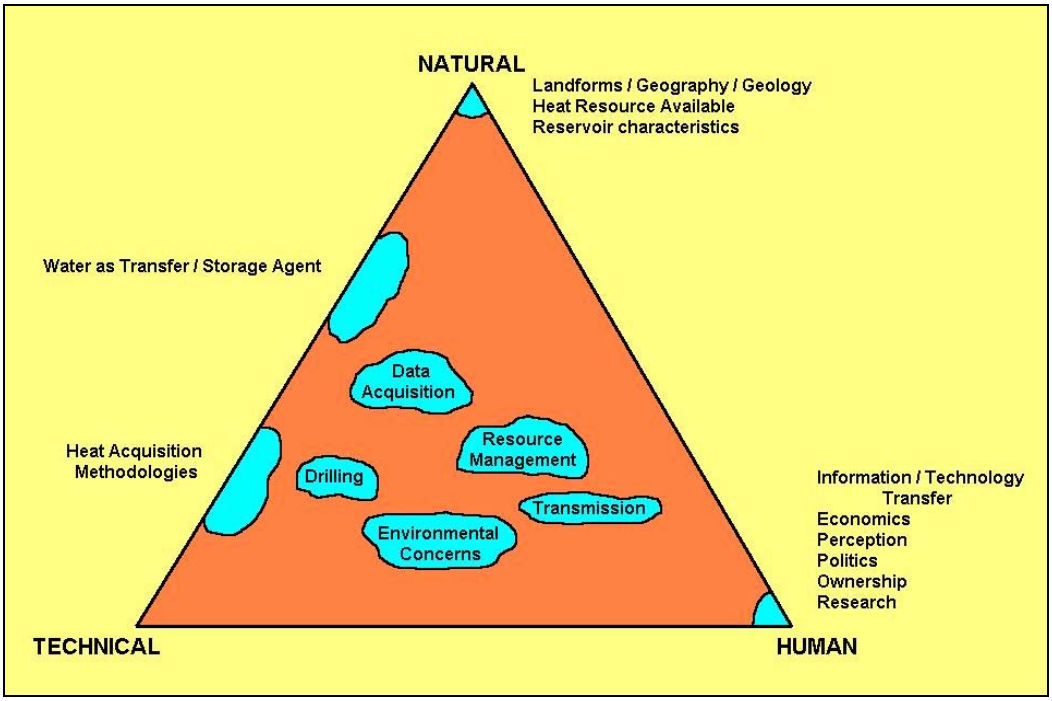


Figure 24. This ternary constraint diagram is defined by three variables: natural, technical, and human. Using these variables, a series of constraint fields were delineated to qualitatively describe the influence that each of these three variables might have on a given constraint

Such a program would be allowed to develop over a multiyear period similar to how Congress has mandated that U.S. military bases install renewable energy projects on site to reduce amount of off base electrical demand. Within a very few years of geoexchange system installation, the

State would begin to see a savings in heating and cooling costs on a building by building basis. Considering that the State does have a fiscal responsibility to its citizens, this program would demonstrate that Texas is stepping out as a leader in working to cut its own costs through the use of geothermal renewable energy. An example of a successful implementation of a large retrofit is found at Lubbock Christian University (LCU). The LCU has retrofit four buildings to date and is in the process of installing a geoexchange system to heat and cool the entire campus. They have already seen a 40 to 50% drop in heating and cooling costs. Their maintenance personnel have been able to get caught up with all of their work and actually conduct preventative maintenance throughout the University, which probably also lowers their overall long-term maintenance cost for the campus.

Recommendation 7 – Incentives

Texas has embarked on various financial incentive programs involving businesses and home owners to make greater use of renewable energy. For example businesses that either use or manufacture or install solar energy can receive franchise tax deductions and/or exemptions. There exists a property tax exemption involving solar, wind, biomass, and anaerobic digestion for business installation or construction of such systems. However these incentives presently exclude geothermal from participation. As the recent Renewable Portfolio Standard does include geothermal within the mix for electrical power generation, all existing incentives need to be expanded to include geothermal energy use and installation. Federal incentives do include geothermal energy production within various credit programs, and thus Texas should follow in the same manner in order to allow its own home-grown geothermal industry to develop. It is the responsibility of the State Legislature to ensure that a fair and even playing field is established for a broad development of its renewable energy potential, including geothermal energy.

Recommendation 8 – Capacity Factor

The availability of a continuous, uninterrupted source of energy, especially electrical, is absolutely necessary to maintain a technologically active civilization. It is important to recognize that renewable energy resources were not of sufficient quantity to launch the highly industrialized civilization that we have enjoyed for the last 150 years. Coal, oil, and natural gas were of extreme importance because of their higher energy density when compared to various renewable energy resources. These fossil resources are readily storable and have been called upon on demand to fulfill our energy needs in a rapid fashion and at any location where that energy is needed. This on demand capability might also be compared with the term capacity factor. Capacity factor should not be confused with availability factor.

Availability factor measures the number of hours that a power plant is available to produce power divided by the total hours in a set time period, which is usually a year in length. By contrast the capacity factor measures the amount of real time during which a facility is used. An analogy to describe this difference would be to think of a car. If the car is not in use, but is free of defects and is available for use, we would speak of the car's availability factor. If the car is actually being driven, we speak of the car's capacity factor. Geothermal has not only an availability factor of about 95%, but geothermal plants have capacity factors ranging from 89 to 97%, depending on the type of geothermal system in place.

For the successful transition from fossil fuels to renewable energy the capacity factor of the resource must be taken more seriously if a continuous energy supply in the form of electricity is to be maintained. In reviewing the wording of Texas SB 20, terms such as "generating capacity" and "cumulative installed renewable capacity" are used when discussing the requirement of 5,880 MW by January 1, 2015. These terms are not the same as capacity factor as described above but rather reflect availability factor. If Texas is serious about developing renewable energy for electrical production, then I recommend that the Texas Legislature begin to define the renewable energy electrical portfolio in terms of capacity factor rather than installed generating capacity (or capacity factor). It is the capacity factor that puts electrons on the wires for homes and businesses at anytime, day or night, not the potential that might be generated under the most favorable conditions. In this manner we can better determine the long term electrical needs of the state and plan for a targeted transition from fossil to renewable energy over time.

Recommendation 9 – Shallow Geothermal Use

Past legislation in Texas has defined geothermal as a mineral and energy resource, being managed by the Texas Railroad Commission (i.e. Oberbeck, A.W., 1977). It also appears from Oberbeck's discussion that geothermal is owned in general by the mineral owner. This is fine when dealing with the deeper production of geothermal energy for direct use or for electrical power generation. However geoexchange systems work in the upper 200 to 300 feet of the Earth's surface, which is usually considered to be part of the property owner's domain. Geoexchange systems use this portion of the Earth for storing heat from a building during the hot summer months and then extract this heat during the colder winter months. While no legal problems have developed to date, I would recommend that the Legislature revisit the definition of geothermal energy and the methods of its use to clearly define ownership of this resource based upon the depth from which it is extracted and how it will be used.

CONCLUSIONS

The development of geothermal energy in Texas will impact the growing needs of an energy dependent society. It will also be a powerful vehicle for maintaining and creating energy jobs across the state, from urban to rural settings. This energy resource has multiple ways of application that include ground source heat pumps, direct use applications of hot water in industry, and the generation of electric power. The State of Texas needs to become more actively involved in assisting to establish this energy resource as a new industry in the state. Industry will become the prime developer of this energy resource. But industry is often extremely conservative and economically cautious of starting new ventures when the future development of a product is unknown. Companies that have established themselves as experts in a particular industry are slow to change direction into a new venture when they have a lack of knowledge and experience in the newly proposed activity. Thus Texas must take a leadership role because of the long-term benefit to its citizens and provide the necessary incentives to entice industry into embracing a new direction of energy development. Most of the recommendations listed above can be initiated by the State with the goal towards leading the existing Texas energy industry into a new energy venture, the development of geothermal energy.

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APPENDIX 1

This appendix includes a copy of the first year written report on deep geothermal energy development in the Delaware and Val Verde Basins of Texas. Funding from the both the Department of Energy (DE-FG36-05-GO85023) and the State Energy Conservation Office (CM540) were instrumental in developing this information. The appendix is only part of the overall set of data files that have been electronically provided to both the DOE and SECO. The interested reader is welcome to request access to the rest of these files as they were supported by public funds.

A Resource Assessment Of Geothermal Energy Resources For Converting Deep Gas Wells In Carbonate Strata Into Geothermal Extraction Wells: A Permian Basin Evaluation

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

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Report written by: Dr. Richard J. Erdlac, Jr.

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

extraction. 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 in 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 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 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, 2003). 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 ≥290°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 <0.4^{o}F/100 ft at 5,000 feet, and for Texas the maximum correction was <0.2^{o}F/100 ft at 17,000 feet. Corrections for wells >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.

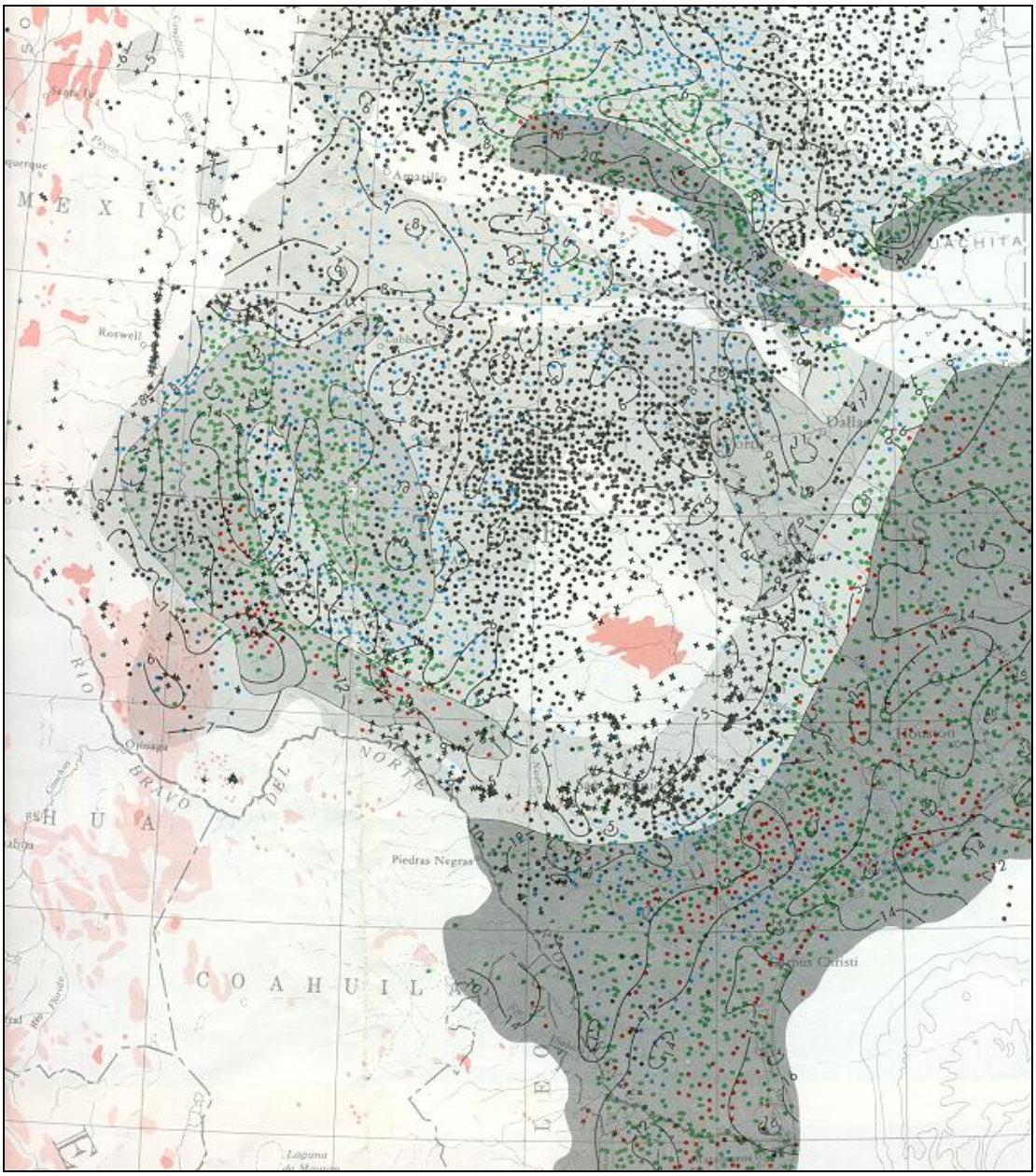


Figure 1. This scanned image of a portion of the original 1976 North American Subsurface Temperature Map displays the variations in temperatures recorded in the subsurface across Texas. Red dots represent temperatures ≥290°F, green dots for temperatures from 180° to 289°F, blue dots for temperature from 151° to 179°F, and black dots for temperatures ≤150°F. The dark gray area represents an area where the contoured isotherm is 302°F and the medium gray region represents an area where the contoured isotherm is 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 as defining 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 geopressured resources had been gathered at the now closed Geopressured-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. Besides 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 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 geopressured 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 this map 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 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 geopressured-geothermal electrical power generation is possible.

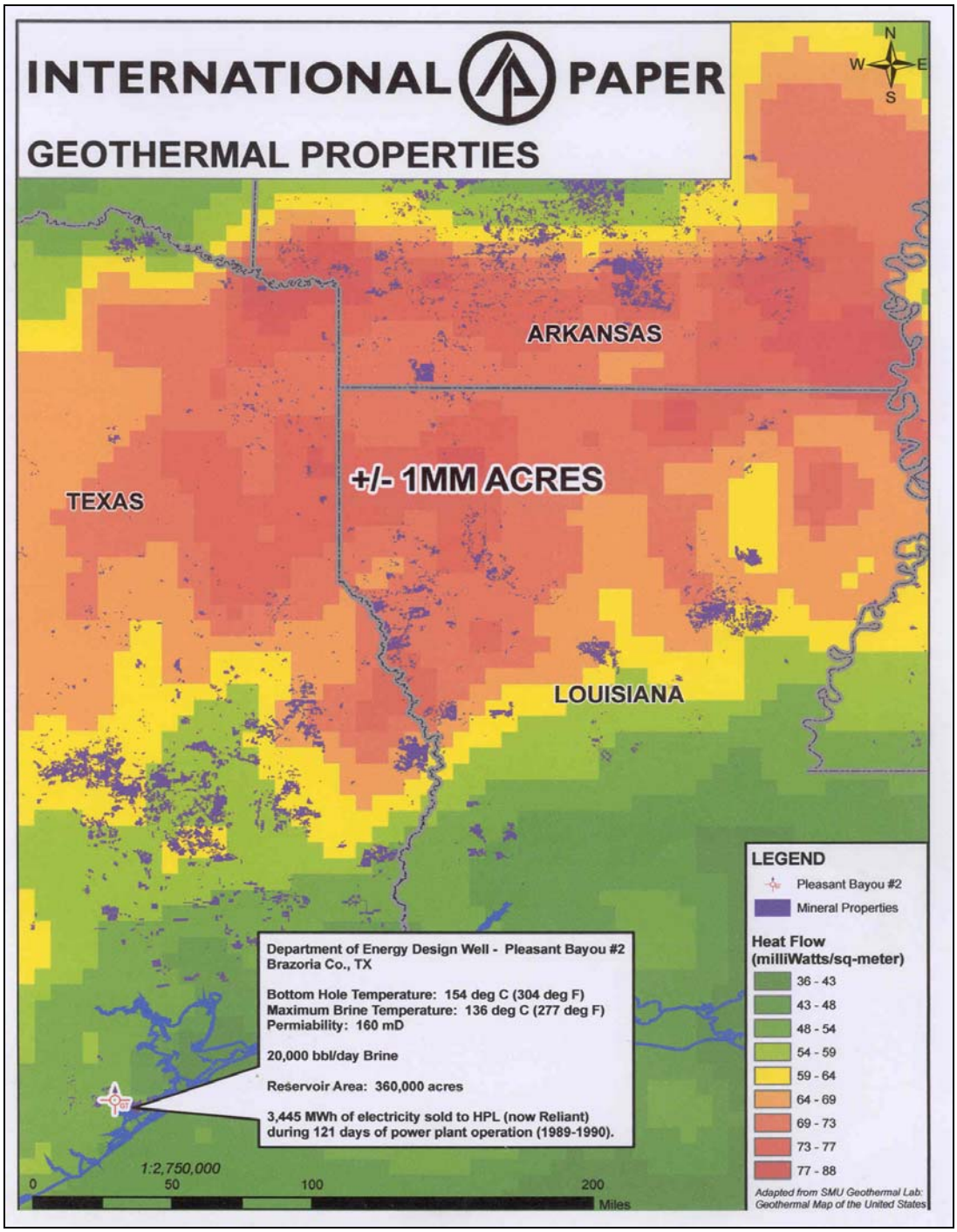


Figure 2. This scanned image shows geothermal mineral acreage reportably held by International Paper in the Texas and Louisiana Gulf Coast.

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 13,000 feet to a little over 17,000 feet.

Temperatures within these wells range from a low of 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^{o}C/m or 55.1^{o}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 covers 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 seems 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.

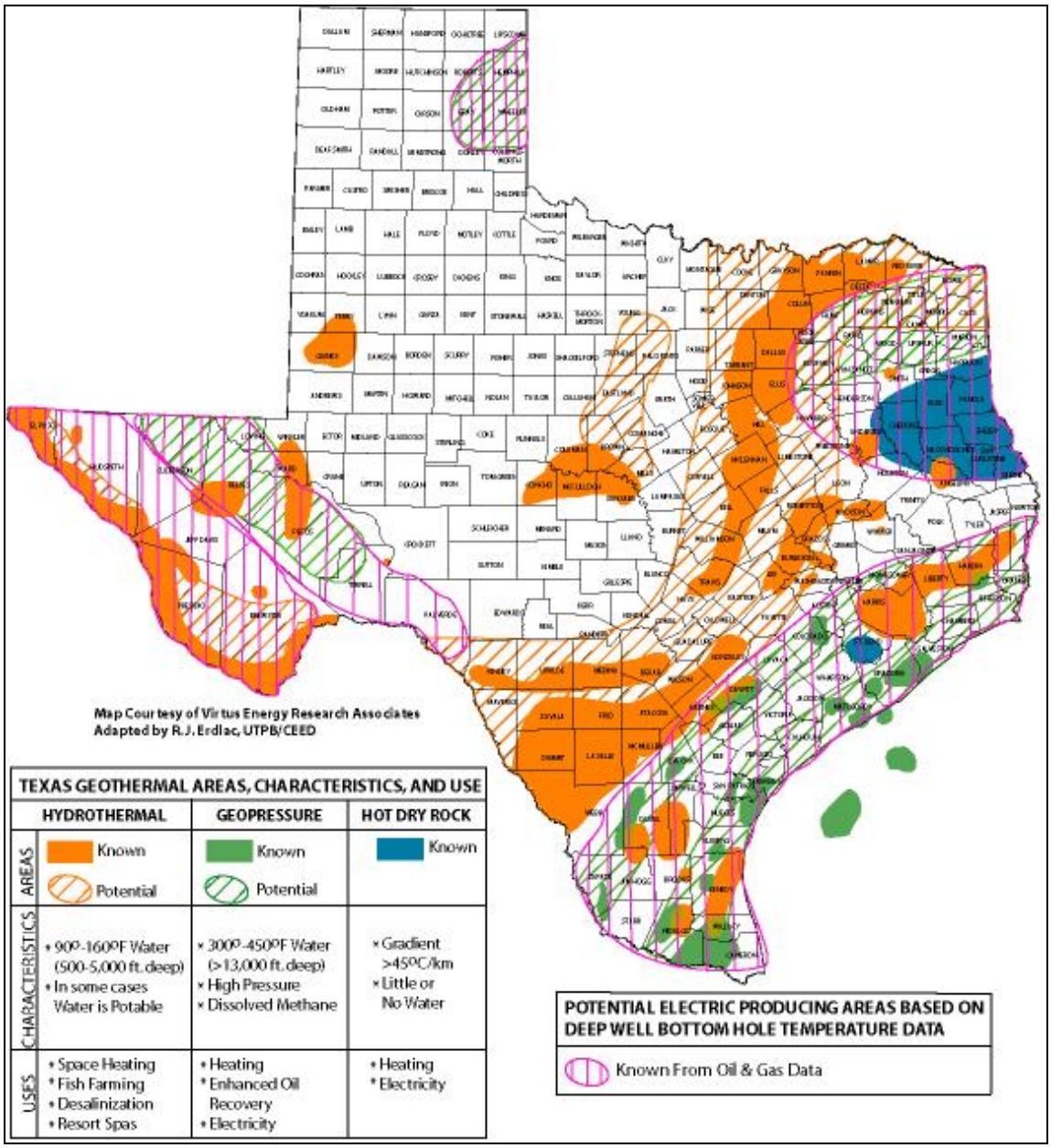


Figure 3. Summary map of Texas Geothermal Resources that was produced by Virtus Energy Research Associates. The location and boundaries of the geothermal areas is approximate. Adapted by Erdlac, 2006.

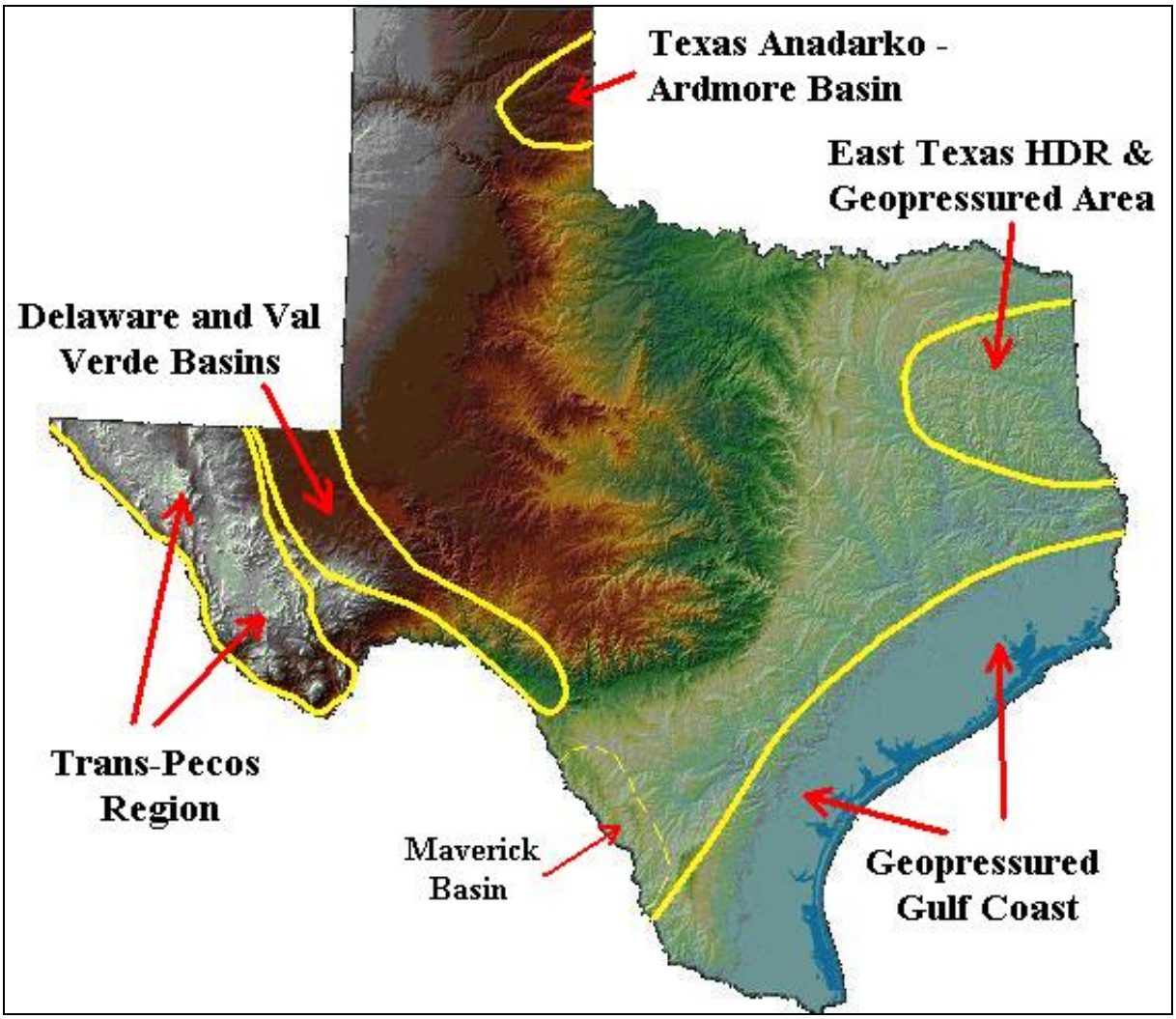


Figure 4. Target regions within Texas for geothermal energy in electrical power production. These regions are based upon the existence of oil and gas wells with temperatures that can get above 212°F.

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

Field	Well Name (including #)	Log Run 1			
		Logger's depth	Meters	Temp Data (F)	(C)
En Seguido (Wilcox)	Cavazos #1	14500	4419	322	161
En Seguido (Wilcox)	Cavazos #2	13114	3997	326	163
En Seguido (Wilcox)	Cavazos #3	13086	3988	328	164
En Seguido (Wilcox)	Cavazos #4	12700	3871	320	160
En Seguido (Wilcox)	Lopez #1	14050	4282	324	162
En Seguido (Wilcox)	Lopez #2	14050	4282	324	162
En Seguido (Wilcox)	Lopez #3	13590	4142	324	162
En Seguido (Wilcox)	Vela #1	13190	4020	326	163
Falcon Lake, E (Wilcox Conds)	Worley #1	16300	4968	410	210
Falcon Lake, E (Wilcox Conds)	Worley #2	15460	4712	362	183
Falcon Lake, E (Wilcox Conds)	Salinas 1	17110	5215	435	224
Uno Mas Tiempo (Sylvia Sand)	Siete Velas #1	13230	4032	340	171

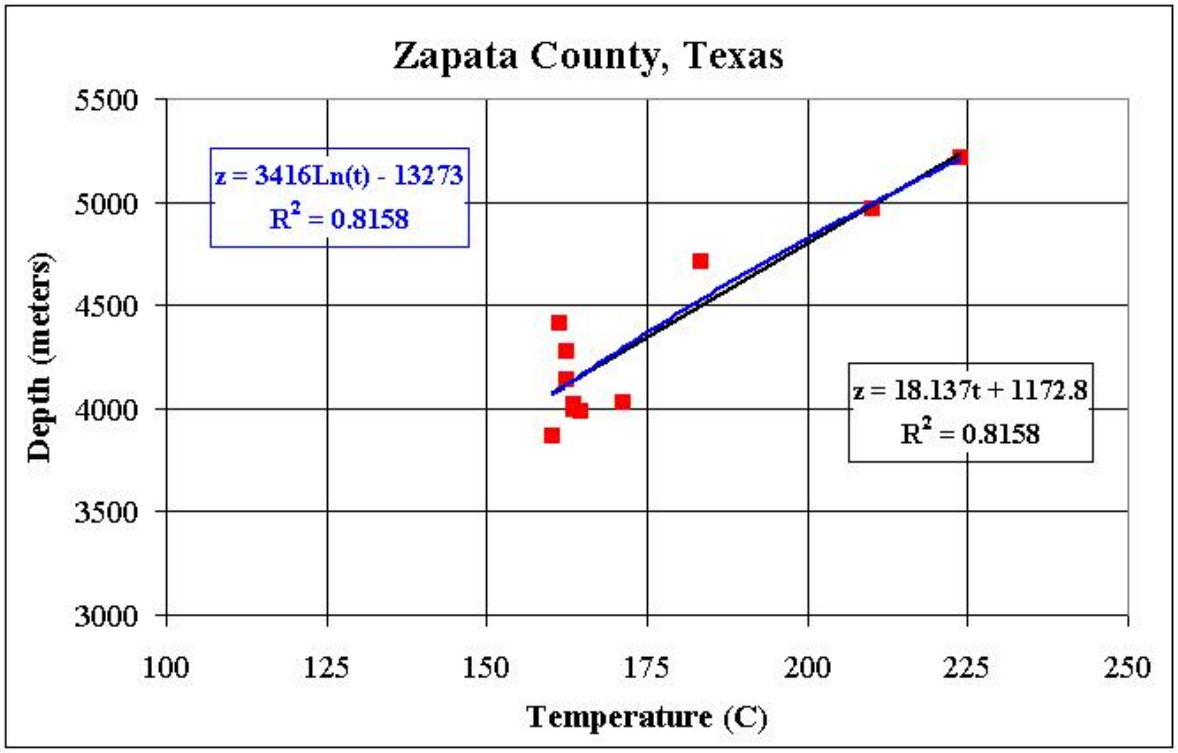


Figure 5. A graph depth-temperature (t-d) values from 12 wells located within Zapata County and the Maverick Basin of Texas.

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.

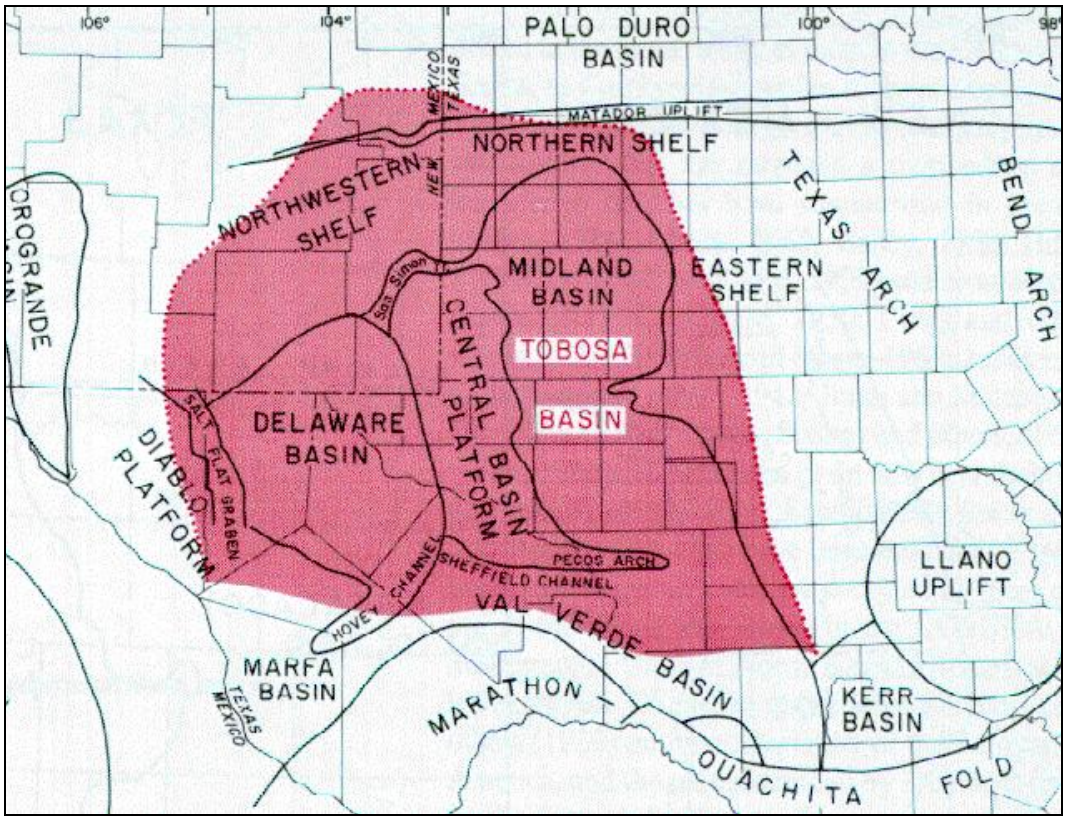


Figure 6. Geologic divisions of the Permian Basin and bordering region. The older Tobosa Basin is shown in red. Adapted from Frenzel and others (1988).

With this discovery, two elements had come together to provide a tectonic model for the Permian Basin. First, it was suggested 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 has existed relatively in tact 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 and rate of heat extraction from these sedimentary rocks.

SYSTEM	SERIES	DELAWARE BASIN	CENTRAL BASIN PLATFORM	EASTERN SHELF	SLOSS SEQUENCES
QUATERNARY	Holocene	Holocene Sand	Holocene Sand	Alluvium	Tejas
TERTIARY	Pliocene	Ogallala	Ogallala	Gravels	
CRETACEOUS	Gulfian Comanchean	Limestone Sand	Limestone	Limestone	Zuni
JURASSIC	Absent				
TRIASSIC		Dockum	Dockum	Dockum	Absaroka
PERMIAN	Ochoa	Dewey Lake	Dewey Lake	Dewey Lake	
		Rustler	Rustler	Rustler	
		Salado	Salado	Salado	
		Castile			
	Guadalupe	Bell Canyon (Delaware Mt.)	Artesia Gr.: Tansill	Artesia Group	
			Yates		
		Cherry Canyon	Seven Rivers		
			Queen		
		Brushy Canyon	Grayburg		
		Victorio Peak	San Andres	San Andres	
			Glorieta Ss.	San Angelo	
	Leonard	Bone Spring Limestone	Yeso: Clear Fork	Clear Fork	
			Wichita-Abo	Wichita	
	Wolfcamp	Wolfcamp	Wolfcamp	Wolfcamp	
PENNSYLVANIAN	Virgil	Cisco		Cisco	
	Missouri	Canyon		Canyon	
	Des Moines	Strawn	Strawn	Strawn	
	Atoka	Atoka	Atoka	Bend	
	Morrow	Morrow	Morrow		
MISSISSIPPIAN	Chester	Barnett			Kaskaskia
	Meramec	Mississippian Limestone	Osage-Meramec	Mississippian Limestone	
	Osage		Kinderhook		
	Kinderhook				
DEVONIAN	Upper Middle	Woodford	Woodford		
		Thirty one	Thirty one		Tippecanoe
SILURIAN	Middle	Wristen	Wristen		
		Fusselman	Fusselman		
ORDOVICIAN	Upper Middle	Montoya	Montoya		
		Simpson	Simpson		
	Lower	Ellenburger	Ellenburger	Ellenburger	Sauk
CAMBRIAN	Upper	Cambrian	Cambrian Ss.	Cambrian Ss.	
PRE CAMBRIAN		Pre Cambrian	Pre Cambrian	Pre Cambrian	

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).

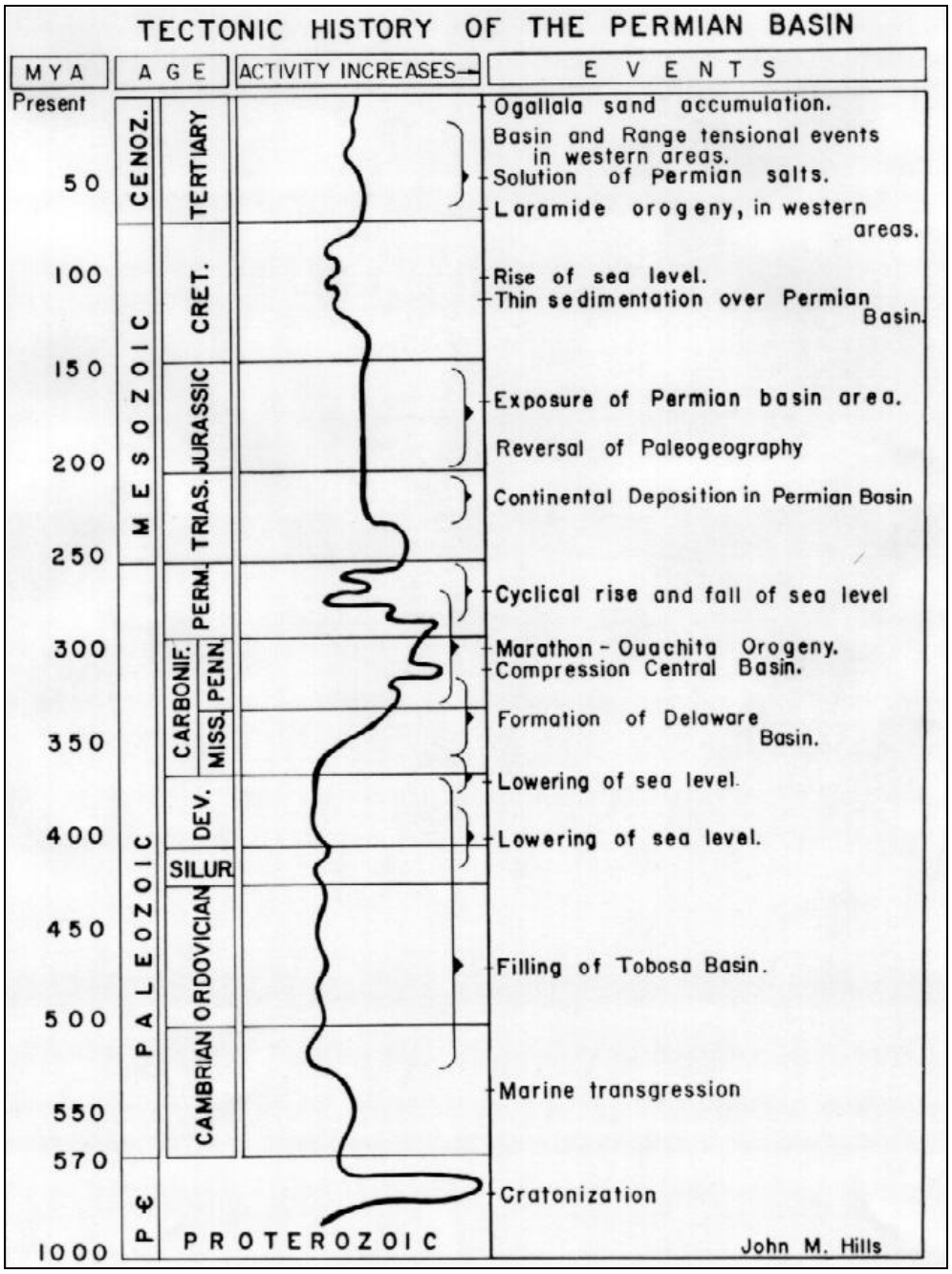


Figure 8. This tectonic history of the Permian Basin follows the overall concept established by Galley (1958). Adapted from Frenzel et. al. (1988).

TECTONIC EVENTS SUSPECTED IN THE PERMIAN BASIN

PERIOD	TIME (MA)	TECTONIC DEFORMATION	STRUCTURAL STYLES
	2	Basin and Range	Volcanism, Extension, Strike-Slip
	23		
Tertiary		?	?
	48		
	67	Laramide	Compression, Strike-Slip
	90		
Cretaceous			
	140		
Jurassic		?	?
	200		
	220		
Triassic		Mid-Triassic	Strike-Slip? (Compression ?)
	230		
	250	?	?
	260		
		Cherry Canyon Event	Volcanism
Permian	265		
		?	?
	272 to 288 (M. Leon to L. Wolf)		
	290		
		Marathon/Ouachita	Compression, Strike-Slip
Pennsylvanian			
	305 to 313 ? (Missourian to Atoka)		
	330		
Mississippian		?	?
	365	Pre-Woodford	Compression ?
Devonian			
	405	?	?
Silurian			
	425		
Ordovician		Precordilleran Equivalent	Compression, Extension, Strike-Slip
	500		
Cambrian		?	?
	570		
Precambrian		Grenville Orogeny	Compression

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 Erdlac (1988), or from tectonic studies conducted by other researchers. Ages used are from Hills and Kottlowski (1983).

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

1) $$E_T = \rho c_p V (T_{prod} - T_{ref}) \ .$$

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, ρc_p is the heat capacity of the rock, V is the volume, T_{prod} is the temperature of the produced water, and T_{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). There 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 will possess. 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

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

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 ϕ 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 ρ_w for equation 2. A

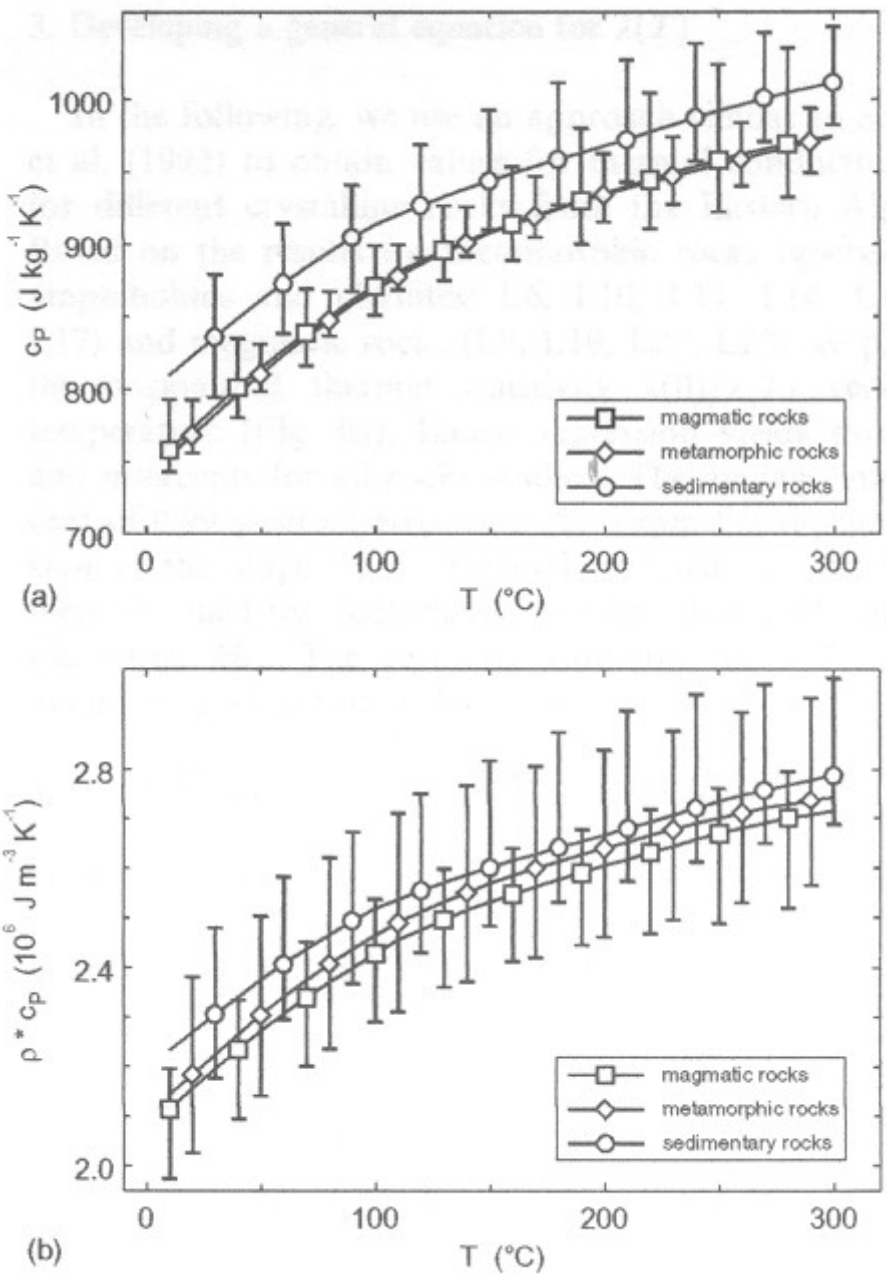


Figure 10. Mean values and the ranges of variation of the a) specific heat capacity at constant pressure, and b) the thermal capacity as a function of temperature for magmatic, metamorphic, and sedimentary rocks. The sample rate of the measuring device is $\Delta T = 0.05$ K. For best visualization the 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

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

where ϕ_D is the density derived porosity, ρ_{ma} is the matrix density, ρ_b is the formation bulk density read from the log, and ρ_{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

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

where k_w is the thermal conductivity of water, ρ_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

5) $$\frac{dT}{dz} = -\frac{q}{k}$$

where 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

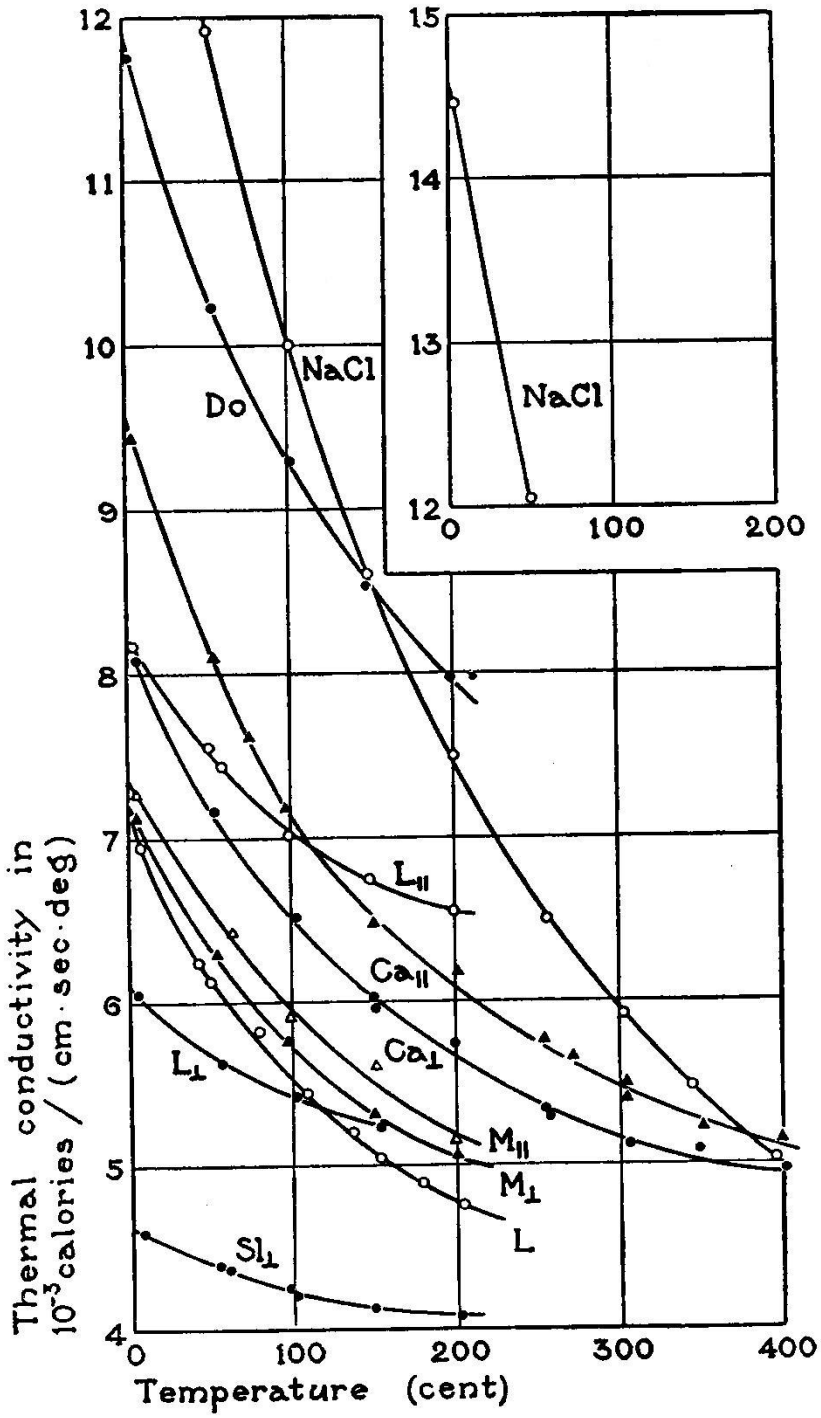


Figure 11. Thermal conductivities of calcite, marble, limestone, dolomite, halite, and slate as presented by Birch and Clark (1940a, b). $Sl_{\perp}$ = Slate, Penn., perpendicular to bed plane. $L_{\perp}$ = Limestone, Penn., perpendicular to bed plane, $L_{\parallel}$= Limestone, Penn., parallel to bed plane. L = limestone, Solenhofen. $M_{\perp}$ = Marble, Vermont, perpendicular to bed plane. $M_{\parallel}$ = Marble, Vermont, parallel to bed plane. $Ca_{\perp}$ = Calcite, single crystal, perpendicular to optic-axis. $Ca_{\parallel}$ = 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 the 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) $$k(T) = A + \frac{B}{350 + T}$$

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) $$z = \frac{\sigma_{zz}}{\rho g}$$

and choosing an average ρ = 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

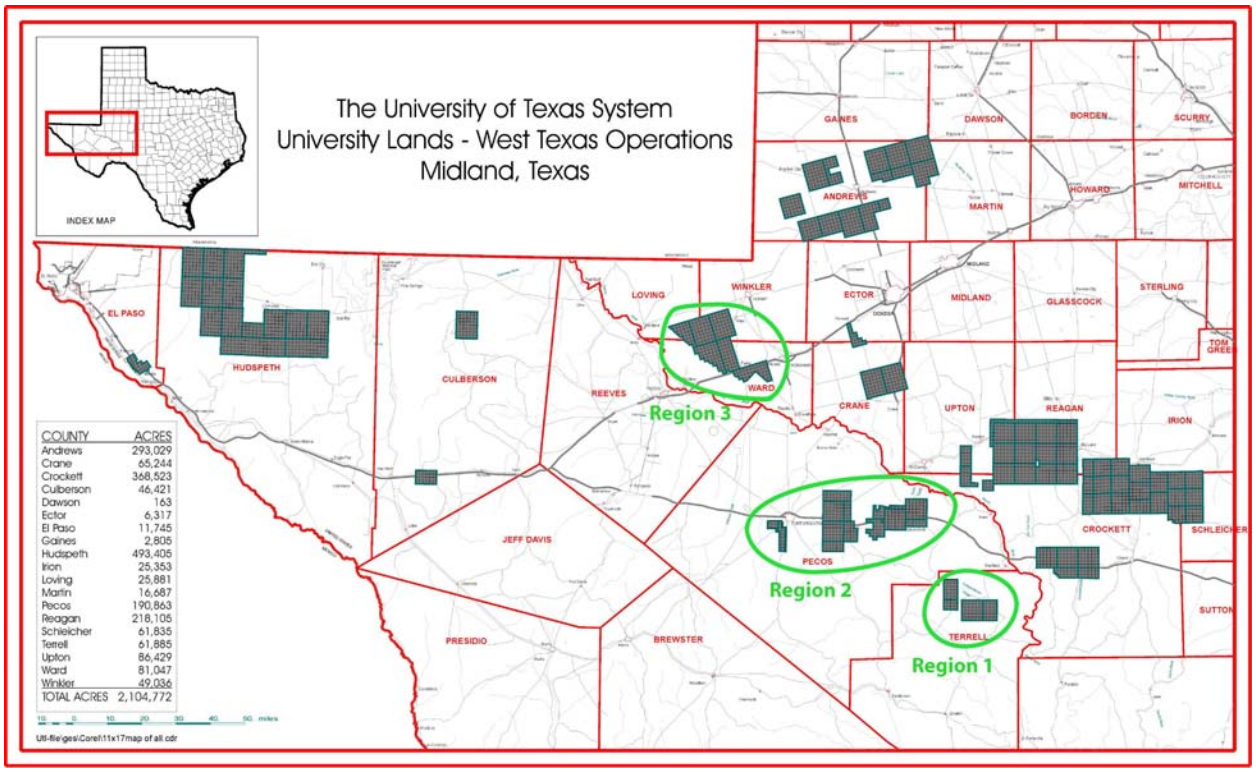


Figure 12. Map of West Texas showing the location of University of Texas Lands (UT Lands) and the three regions (1, 2, and 3) of these lands that lie within the Delaware Basin and northern part of the Val Verde Basin. These 2 million acres cover all surface and subsurface water and mineral rights.

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

8) $$y = 3315.1Ln(x) - 10429$$

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

9) $$T = e^{0.00030165(z+10429)}.$$

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

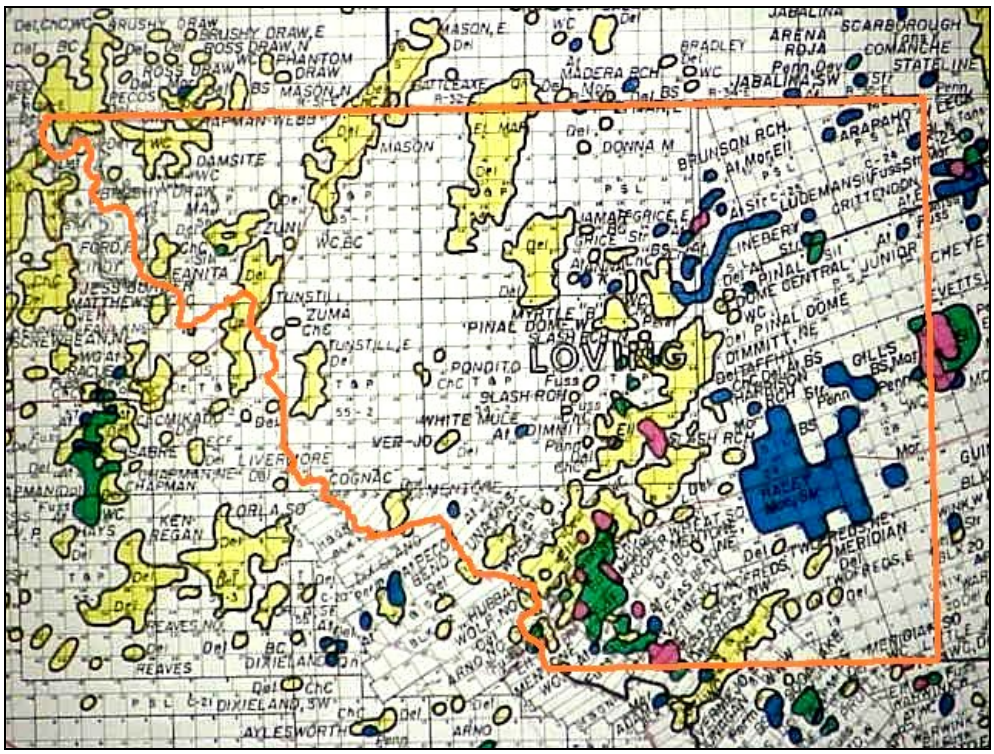


Figure 13. Image from the 1993 Producing Zone of The Permian Basin showing the boundary of Loving County. The area outlined in orange defines Loving County. Yellow represents production from Permian formations, blue from Pennsylvanian, purple from Mississippian, green from Devonian and Silurian, and red from Ordovician. Map is courtesy of Midland Map Company.

10) $$\frac{dT}{dz} = (3.0165x10^{-4})e^{0.00030165(z+10429)} = -\frac{q}{k}.$$

Finally by substitution we have

11) $$\frac{dT}{dz} = (3.0165x10^{-4})T = -\frac{q}{k}.$$

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

12) $$\frac{dT}{dz} = 0.022482 = -\frac{q}{k},$$

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

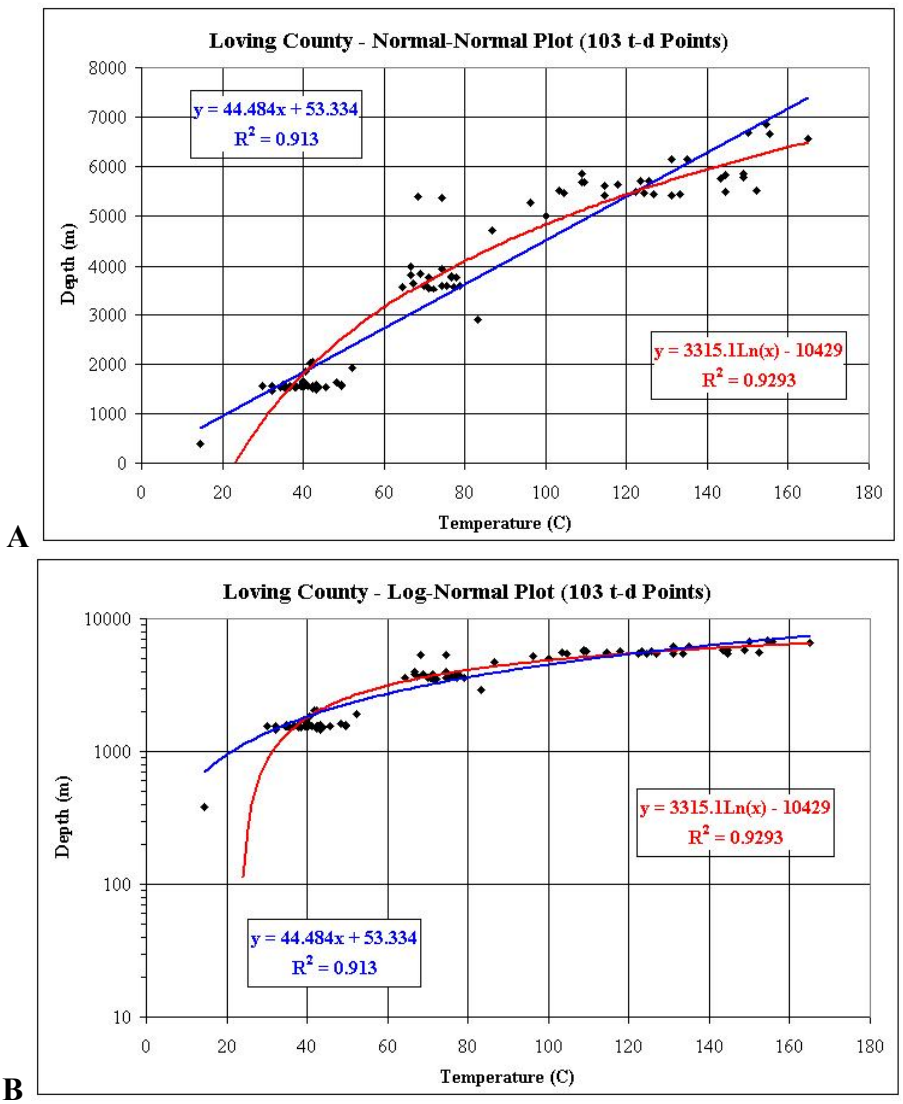


Figure 14. Plots of 103 t-d points in Loving County. Blue represents straight line and red represents logarithmic function. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

$R^2_s R^2_d = R^4_{max}$ 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

13) $$\frac{dT_S}{dz} = 0.0146 = -\frac{q}{k},$$

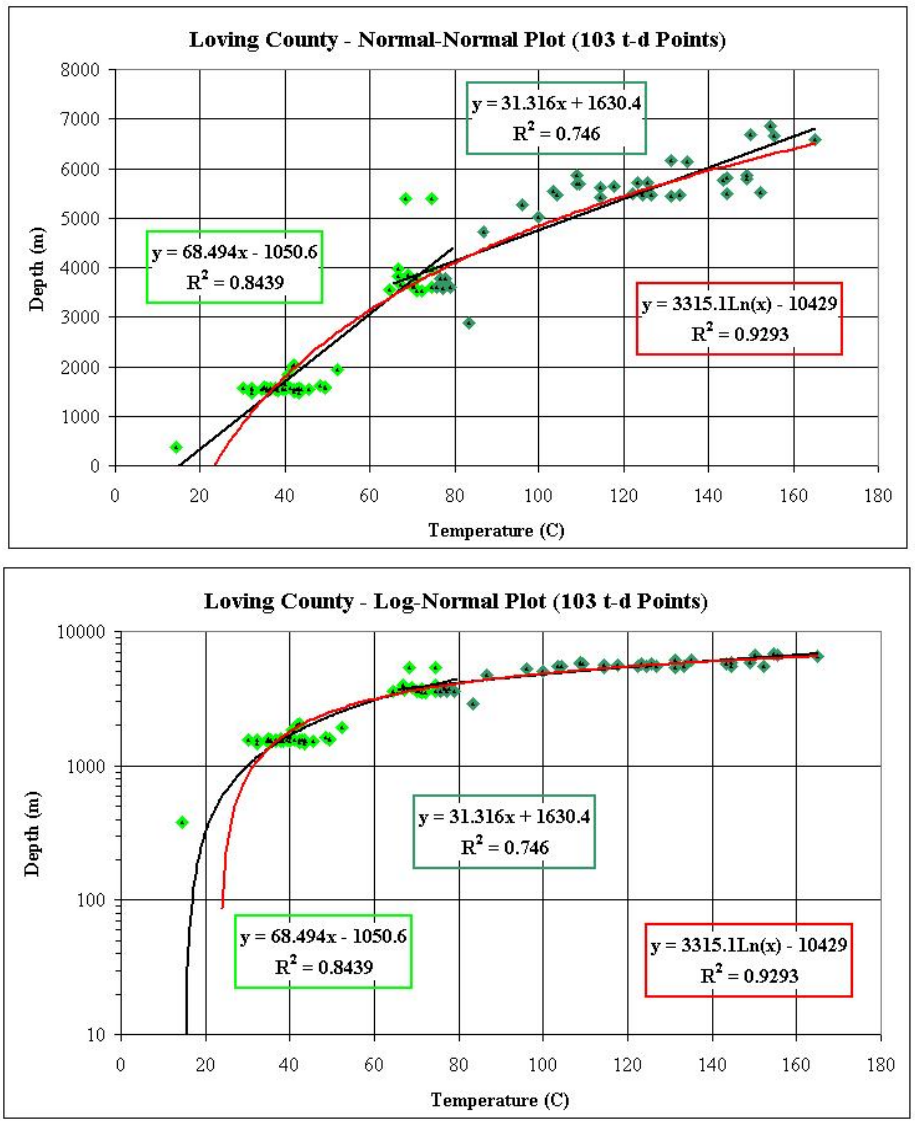


Figure 15. Plots of 103 t-d points in Loving County. Light green represents points that are considered shallow to intermediate based on statistical analysis, while dark green points are the deeper t-d values. Each plot has two best fit straight lines shown in black with a red curve representing a logarithmic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

and

14) $$\frac{dT_D}{dz} = 0.031933 = -\frac{q}{k} \ ,$$

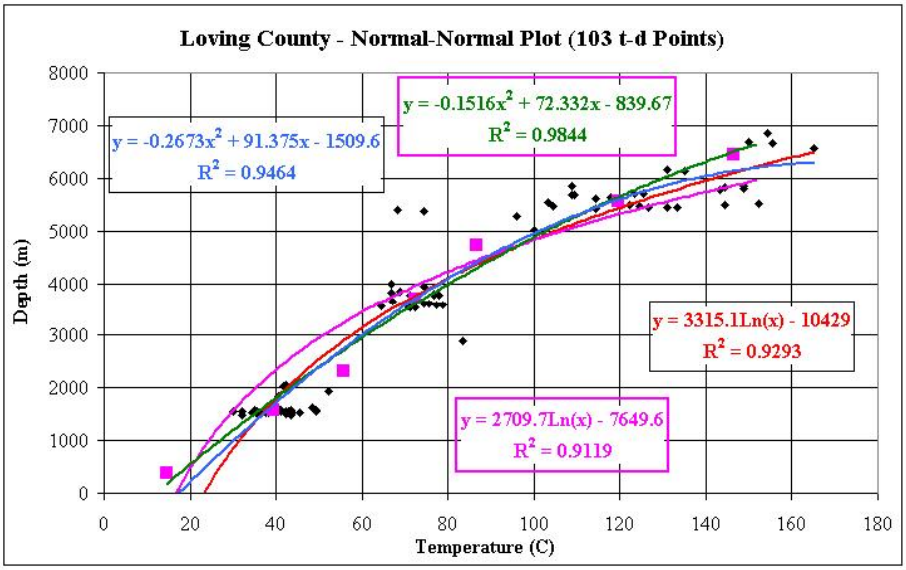
where the T_S and T_D represent temperature in the shallow and deep realm respectively. This suggests that in this model approach the shallow and deep linear thermal gradients in Loving County are 14.6°C/km and 31.9°C/km, the deeper gradient being twice that of the shallow data.

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.

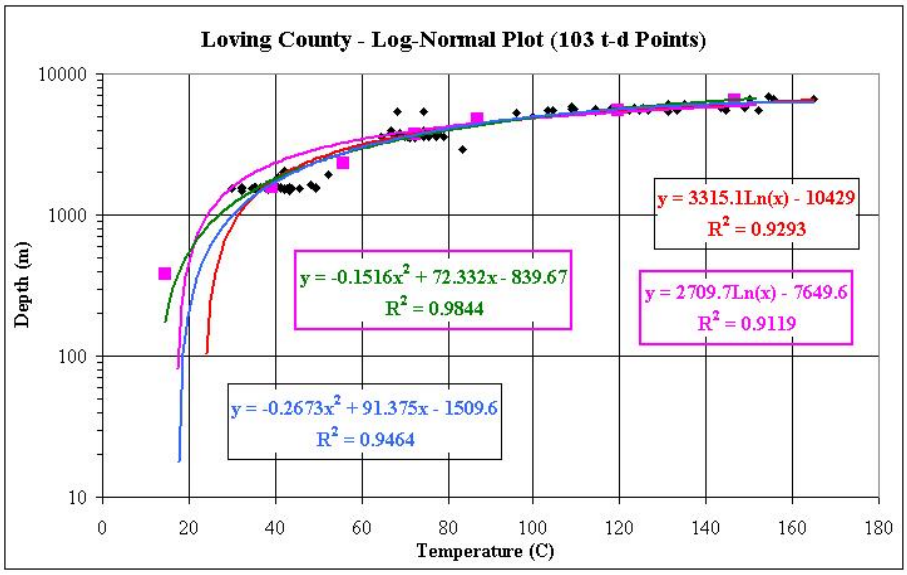
We also decided to determine what would be a representative curve for the average t-d pairs with a defined depth interval. Based upon Table 1, we chose the same 1,000-meter intervals so that we could make a direct comparison to the log-normal distributions defined in Figures 14 and 15. A total of seven 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

Depth @ 1000 ft	# t-d Points	Mean Interval T (F)
1000	0	0
2000	1	58
3000	0	0
4000	0	0
5000	5	101
6000	41	67
7000	4	112
8000	0	0
9000	0	0
10000	1	182
11000	0	0
12000	10	162
13000	7	164
14000	1	152
15000	0	0
16000	1	188
17000	1	212
18000	11	235
19000	9	252
20000	4	280
21000	3	273
22000	3	314
23000	1	310



A



B

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 2nd order polynomial applied to all 103 t-d data points, and the green represents the 2nd 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 2nd order polynomials had higher R^2 values than the log-normal curves, with the 2nd order polynomial for all 103 point being over 98%.

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

15) $$y = 3666.2Ln(x) - 11841$$

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

16) $$T = e^{0.00027276(z+11841)}.$$

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

17) $$\frac{dT}{dz} = (2.27276x10^{-4})e^{0.00027276(z+11841)} = -\frac{q}{k}.$$

Finally by substitution we have

18) $$\frac{dT}{dz} = (2.27276x10^{-4})T = -\frac{q}{k}.$$

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

19) $$\frac{dT}{dz} = 0.019653 = -\frac{q}{k},$$

which is the equivalent of a constant 19.653°C/km.

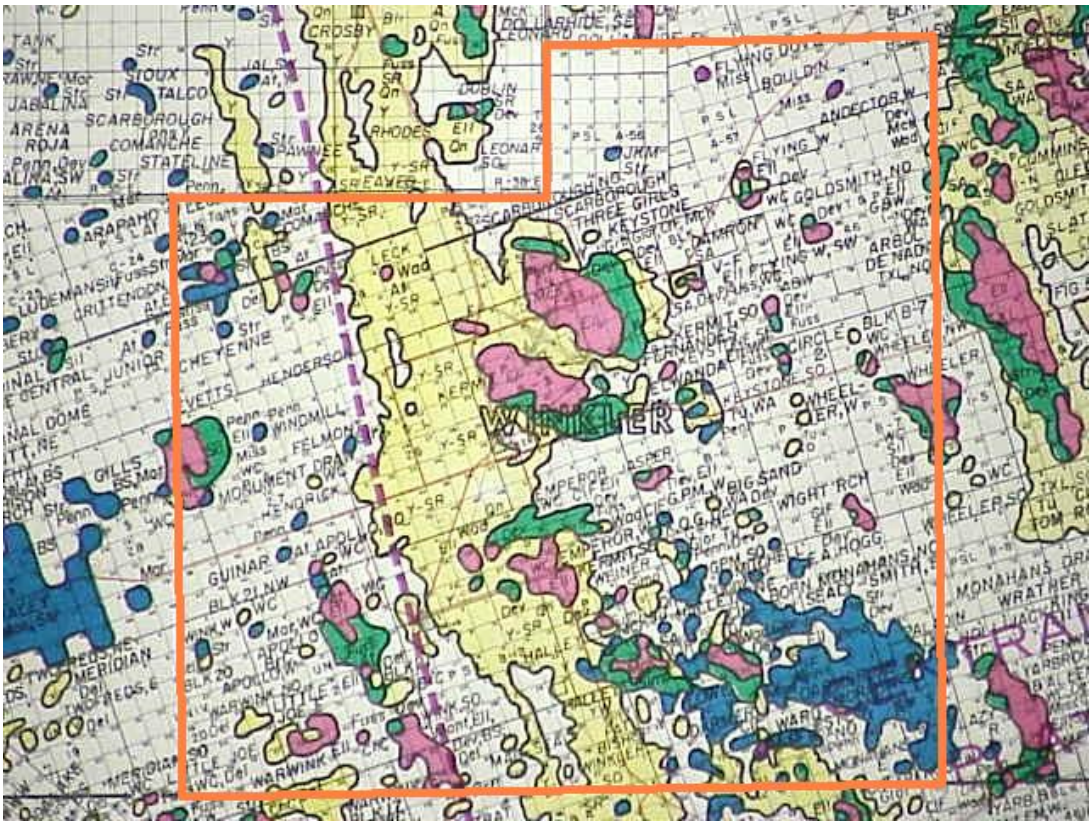
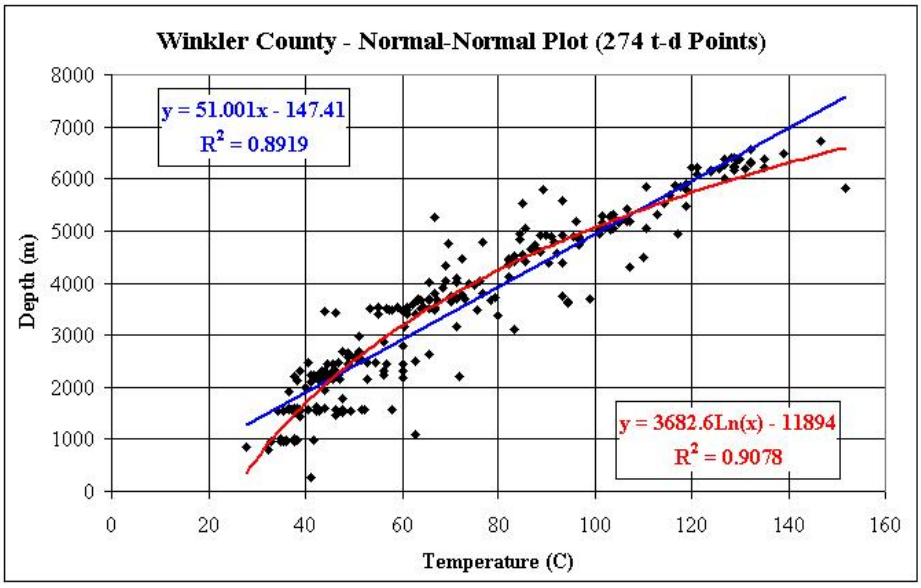
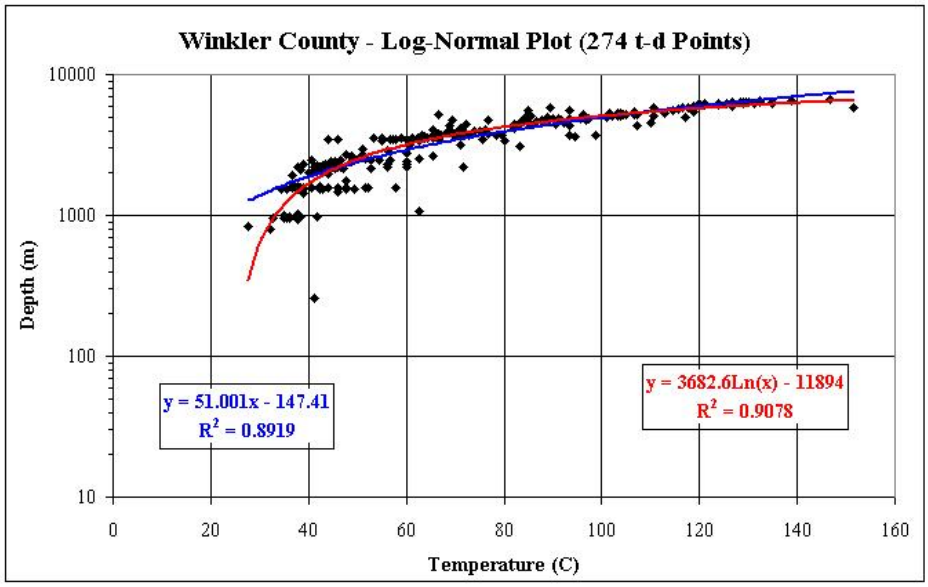


Figure 17. Image from the 1993 Producing Zone of The Permian Basin showing the boundary of Winkler County. The area outlined in orange defines Winkler County. Yellow represents production from Permian formations, blue from Pennsylvanian, purple from Mississippian, green from Devonian and Silurian, and red from Ordovician. Map is courtesy of Midland Map Company.



A



B

Figure 18. Plots of 275 t-d points in Winkler 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.

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 $R^2_s R^2_d = R^4_{max}$ 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 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 191°F to 296°F. An average temperature of 216°F is reach within the 17,000 to 18,000-foot interval.

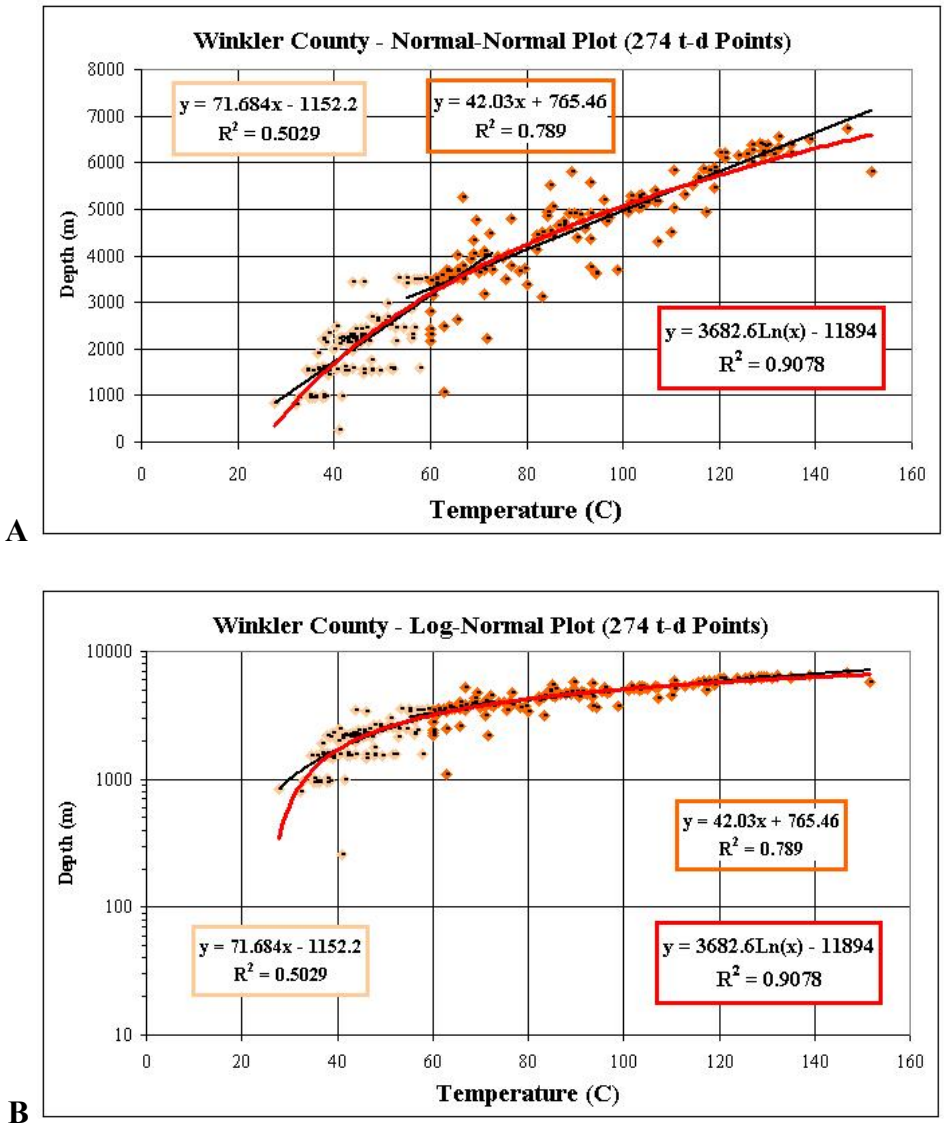


Figure 19. Plots of 103 t-d points in Winkler County. Light orange represents points that are considered shallow to intermediate based on statistical analysis, while dark orange points are the deeper t-d values. Each plot has two best-fit straight lines shown in black with a red curve representing a logarithmic function. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

Table 2
Winkler Statistics on Temperature and Depth

Winkler														
depth ft	# of t-d pts	mean temp	standard deviation	standard error	min temp	max temp	mean temp	median temp	mode temp	min depth	max depth	mean depth	median depth	mode depth
2000	2	86	5.656854	5.6569	82	90	86.5	86.5		2639	2750	2694.5	2694.5	
3000	14	101.1	13.166720	3.6518	91	145	101.14	97	96	3162	3550	3198.86	3163	
4000	4	109	8.755950	5.0553	101	118	109	108.5	100	4750	4998	4265.5	4857	
5000	37	105.5	10.487100	1.7479	94	136	105.5	100	100	5000	5810	5145.73	5132	5050, 5200
6000	6	105.2	5.269409	2.3566	98	111	105.17	105	111	6271	111	6586.83	6475	6400
7000	38	115.6	12.735436	2.0937	100	161	115.6	109	109	7000	7993	7318.97	7394	7200
8000	18	123.7	10.932951	2.6516	105	150	123.7	121.5		8000	8802	8326.4	8226	8000
9000	3	132.3	8.020806	5.6716	124	140	132.3	133		9150	9732	94.33	6418	
10000	3	161	20.548285	4.0299	141	182	161	160		10216	10400	10326	10364	
11000	27	152.25	20.945595	4.1078	111	202	152.3	142	142	11041	11930	11485	11476	11600
12000	19	162	17.540429	4.1343	146	210	162	158	150	12000	12850	12214	12150	12000
13000	8	163.4	9.101609	3.4401	150	180	163.4	162.5	160	1300	13555	13245	13220	
14000	13	189.9	21.021662	6.0684	156	225	189.9	182	180	14100	14895	14515	14500	
15000	16	191.3	113.355242	3.4992	157	207	191.3	190		15041	15903	15482	15521	
16000	18	208.9	15.892613	3.8545	184	243	209.9	214	214	16014	16972	15532	16354	
17000	11	216	23.748684	7.1605	152	246	216	219	219	17000	17921	17353	17340	
18000	4	215.75	27.548684	8.7117	185	240	215.8	219	224	18100	18653	183063	18236	
19000	8	245.88	31.008927	11.7203	193	305	245.9	245	246	19000	19700	19215	19150	19150
20000	20	261.55	8.236472	1.8896	248	275	261.6	264	264	20003	20987	205200	20420	
21000	3	271.67	9.609024	6.7946	263	282	271.7	270		21014	21528	21261	21301	
22000	1	296			296	296				22101	122101			

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

22) $$y = 3666.2Ln(x) - 11841$$

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

23) $$T = e^{0.00028666(z+11195)}.$$

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

24) $$\frac{dT}{dz} = (2.8666x10^{-4})e^{0.00028666(z+11195)} = -\frac{q}{k}.$$

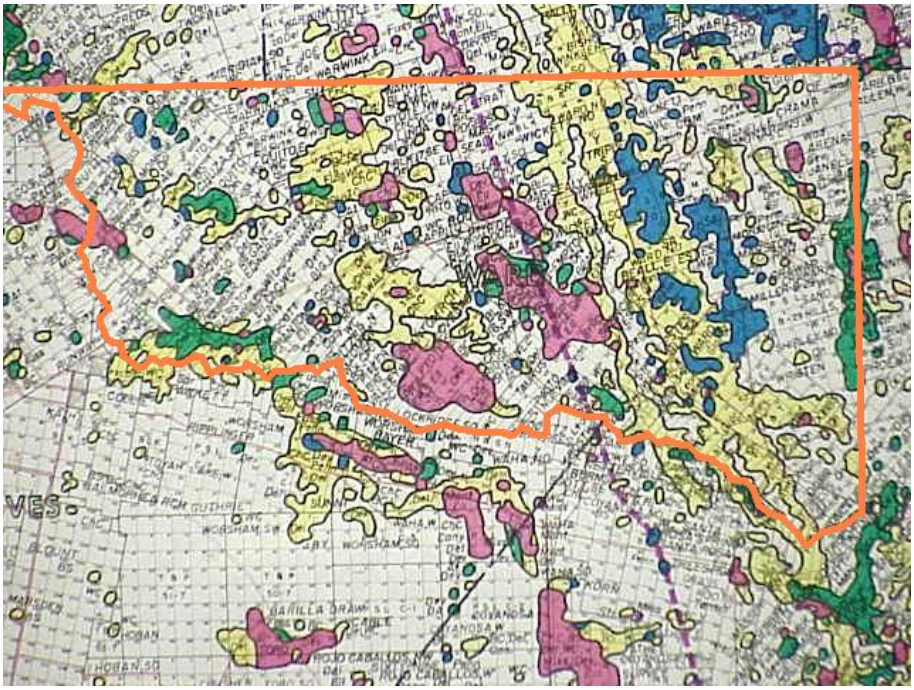


Figure 20. Image from the 1993 Producing Zone of The Permian Basin showing the boundary of Ward County. The area outlined in orange defines Ward County. Yellow represents production from Permian formations, blue from Pennsylvanian, purple from Mississippian, green from Devonian and Silurian, and red from Ordovician. Map is courtesy of Midland Map Company.

Finally by substitution we have

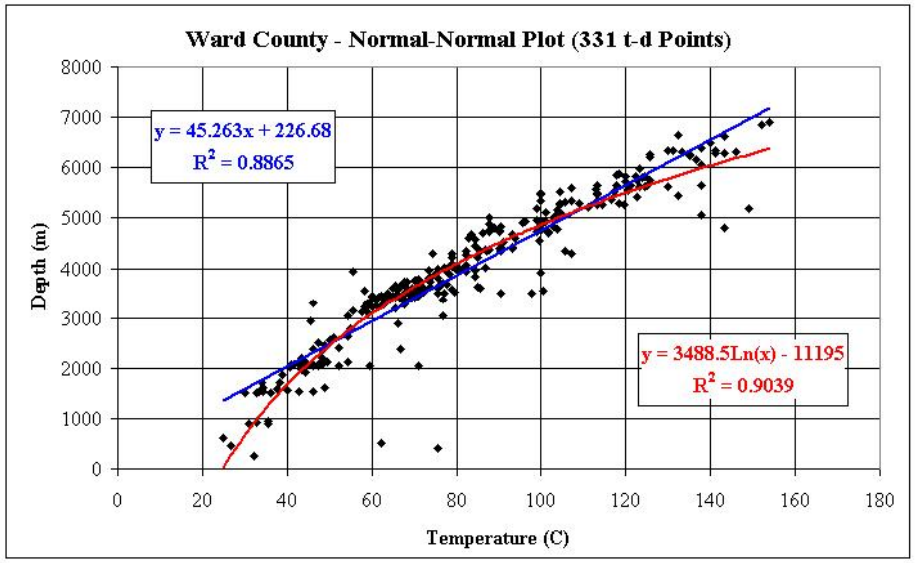
25) $$\frac{dT}{dz} = (2.8666x10^{-4})T = -\frac{q}{k}.$$

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

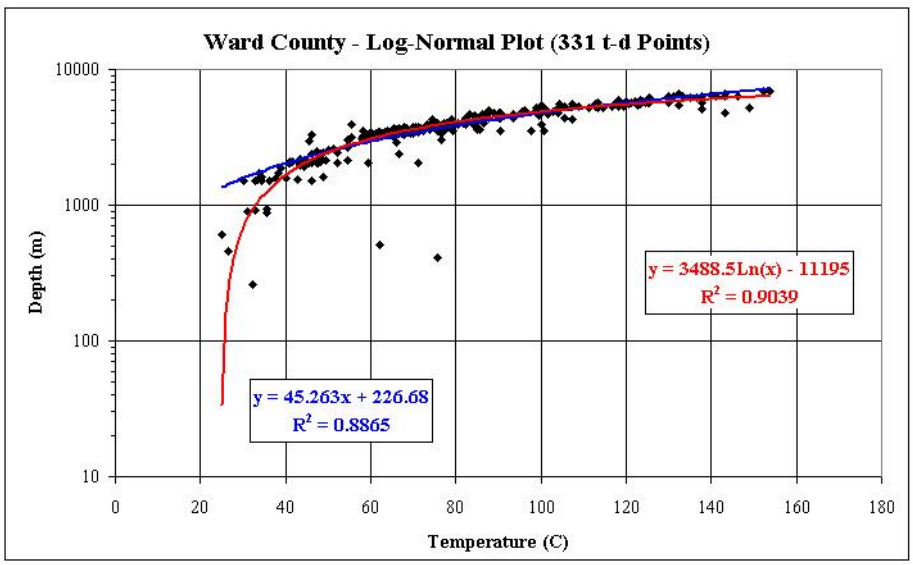
26) $$\frac{dT}{dz} = 0.022093 = -\frac{q}{k},$$

which is the equivalent of a constant ~22.1^{o}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 $R^2_s R^2_d = R^4_{max}$ 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^{o}C and 3,246m. These two equations were then differentiated to determine shallow and deep linear thermal gradients of the form



A



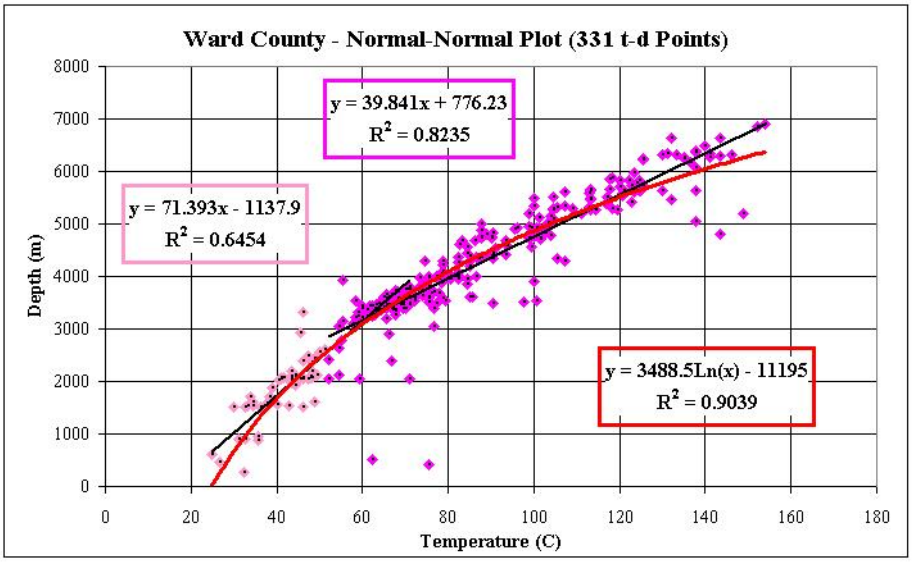
B

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.

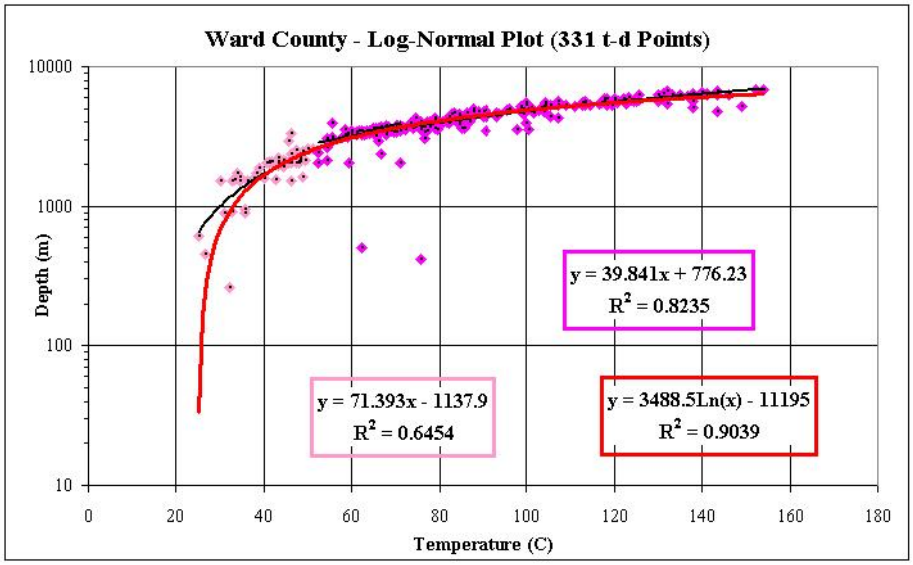
27) $$\frac{dT_S}{dz} = 0.014007 = -\frac{q}{k},$$

and

28) $$\frac{dT_D}{dz} = 0.0251 = -\frac{q}{k},$$



A



B

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°C/km and 25.1°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

Table 3
Ward Statistics on Temperature and Depth

Ward														
depth ft	# of t-d pts	mean temp	standard deviation	standard error	min temp	max temp	mean temp	median temp	mode temp	min depth	max depth	mean depth	median depth	mode depth
2000	3	87	9.539392	6.454	77	96	87	88		2000	2995	2632.67	2900	
3000	3	94.33	2.886751	2.0412	91	96	94.33	96	96	3000	3500	3066.67	3100	3100
4000	4	96.00	12.658989	7.3087	86	115.00	96.00	91	91	4931	4990	4953.5	4948	
5000	9	100.78	9.202958	3.2537	92	120.00	100.78	100	94	5008	5634	5254.33	5171	
6000	37	114.62	9.970377	1.6617	102	160.00	114.62	112	110	6131	6940	6717.03	6766	680
7000	8	124.00	12.873006	4.8655	110	126.00	124.00	120	119	7000	7924	7444	7487.5	7000
8000	5	122.60	4.878524	2.4393	117	130.00	122.60	122		8041	8630	8626	8414	
9000	4	141.50	24.283053	16.939	114	170.00	141.50	141		9144	9977	9249	9560	
10000	14	138.50	9.345916	2.5921	115	154.00	138.50	138	138	1000	10857	10540.15	10625	10600, 10650
11000	68	145.89	14.594151	14	137	231.00	145.89	151.5	150	11000	11990	11425.79	11353	11800
12000	27	167.63	16.24369	3.1857	132	212.00	167.63	165	165	12000	1955	12454.85	12325	12210
13000	21	175.76	5.985697	1.3384	164	188.00	175.86	174	174	13000	13991	13271.38	13150	
14000	18	193.33	14.962699	3.629	166	225	193.3	192	180	14061	14950	14386.5	14338.5	
15000	19	214.74	23.775264	5.5986	181	290	204	197.5		15000	15940	15515	15521	
16000	18	201.89	20.054705	4.864	190	280.00	201.89	214	190	16004	16925	16393.5	16370	
17000	21	234.33	21.45072	4.7965	210	300	234.33	232	218	17050	17971	17,430.33	17359	
18000	20	245.35	15.84555	3.6352	212	280	245.4	248.5	236	18000	18835	18415.1	18472.5	18500
19000	8	254.25	11.34838	4.2779	244	280.00	254.25	253		19000	19892	19292.25	19177.5	20831
20000	14	275.86	11.12072	3.0843	258	295.00	275.92	275	275	20250	20925	20624.14	20635	20831
21000	4	281.00	8.406347	4.8534	270	290.00	281.00	282		21000	21800	21482.5	21505	
22000	2	307.50	2.12132	2.121	306	309.00	307.50	307.5		22500	22610	22555	22505	

also determined for the depths within each interval. Of greatest interest were the wells that had temperatures around 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 215°F to 307°F. An average temperature of 215°F is reach within the 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 was 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

28) $$y = 3206.6Ln(x) - 10327$$

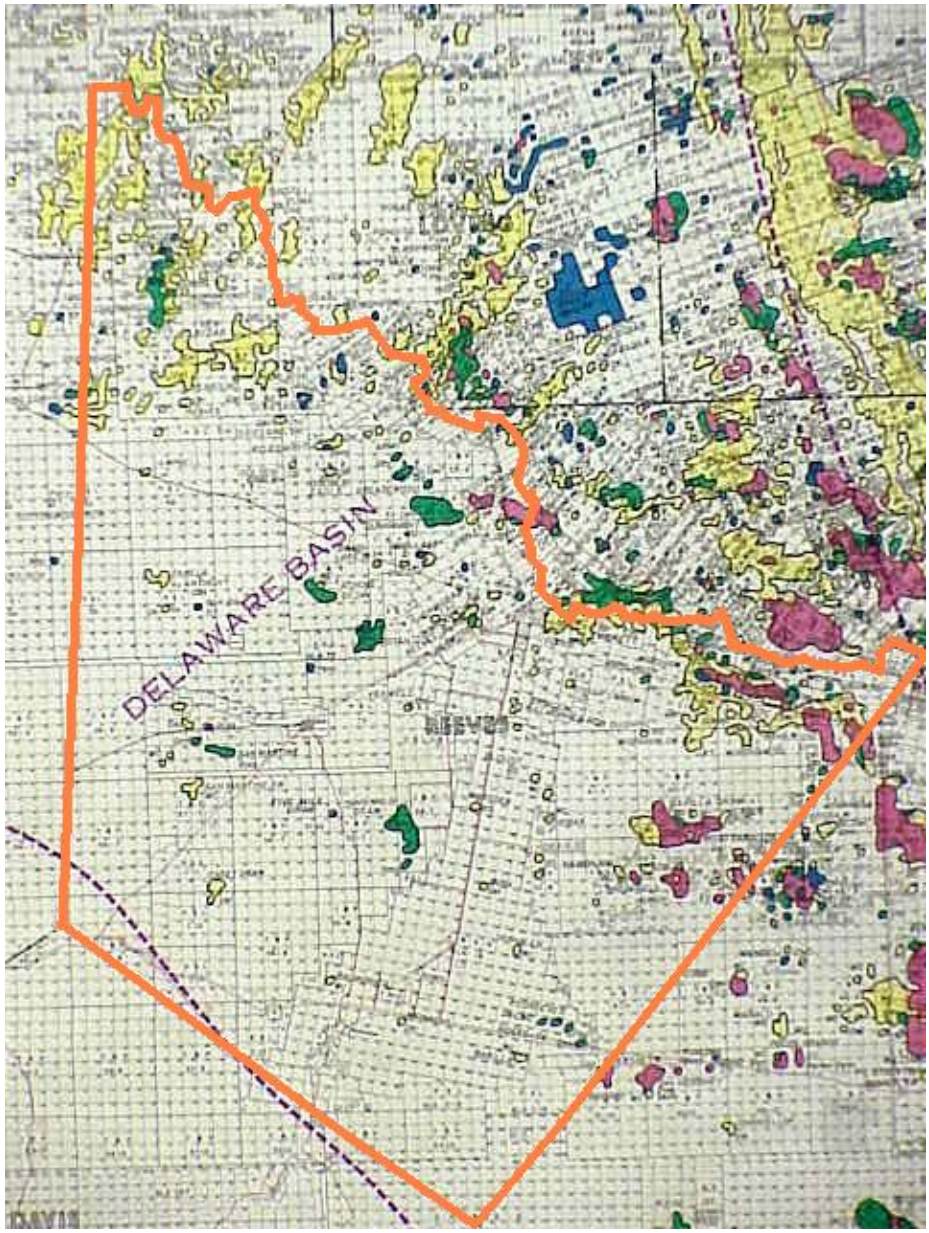
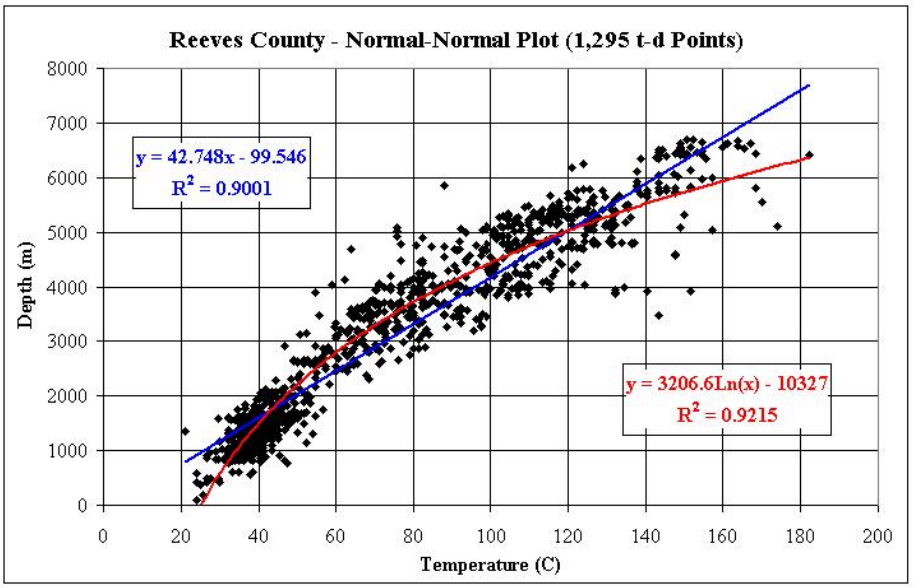


Figure 23. Image from the 1993 Producing Zone of The Permian Basin showing the boundary of Reeves County. The area outlined in orange defines Reeves County. Yellow represents production from Permian formations, blue from Pennsylvanian, purple from Mississippian, green from Devonian and Silurian, and red from Ordovician. Map is courtesy of Midland Map Company.

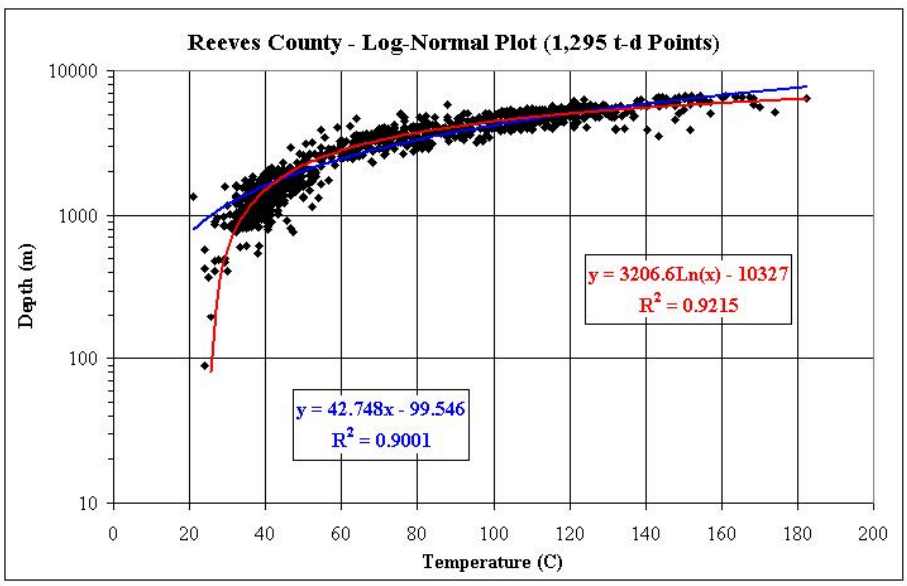
and with y = z (depth) and with x = T (temperature), solving for T results in the equation

29) $$T = e^{0.00031186(z+10327)}.$$

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



A

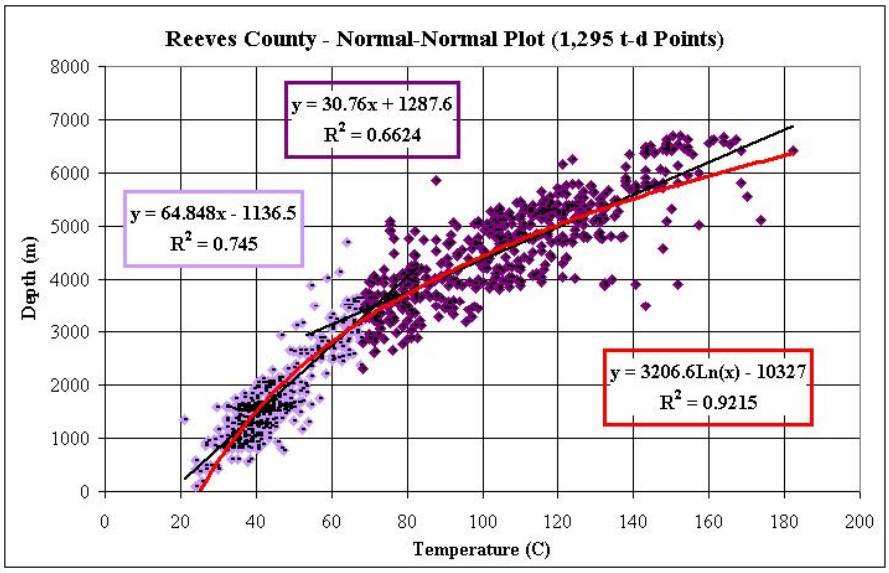


B

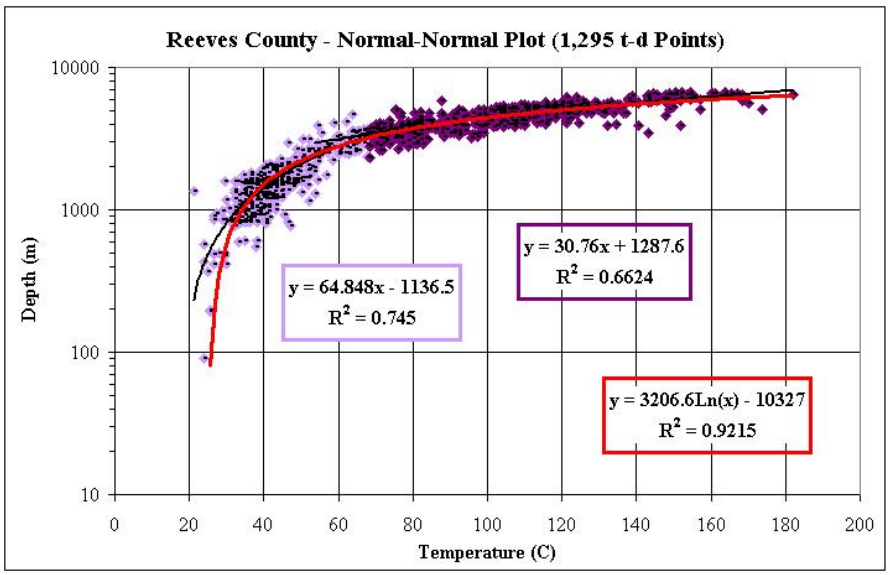
Figure 24. Plots of 1,295 t-d points in Reeves County. Blue represents straight line and red represents logarithmic function. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

30) $$\frac{dT}{dz} = (3.1186x10^{-4})e^{0.00031186(z+10327)} = -\frac{q}{k}.$$

Finally by substitution we have



A



B

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.

31) $$\frac{dT}{dz} = (3.1186x10^{-4})T = -\frac{q}{k}.$$

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

32) $$\frac{dT}{dz} = 0.023393 = -\frac{q}{k},$$

which is the equivalent of a constant ~23.4°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 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 $R^2_s R^2_d = R^4_{max}$ 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°C and 3,536m. These two equations were then differentiated to determine shallow and deep linear thermal gradients of the form

33) $$\frac{dT_S}{dz} = 0.015421 = -\frac{q}{k},$$

and

34) $$\frac{dT_D}{dz} = 0.03251 = -\frac{q}{k},$$

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°C/km and 32.51°C/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 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 233°F to 306°F. An average temperature of 233°F is reach within the 15,000 to 16,000-foot interval.

Table 4
Reeves Statistics on Temperature and Depth

Reeves														
depth ft	# of t-d pts	mean temp	standard deviation	standard error	min temp	max temp	mean temp	median temp	mode temp	min depth	max depth	mean depth	median depth	mode depth
2000	51	at the office												
3000	90	98.38	6.751742	0.7157	81	126	98.38	98.00	95.00	3000	3963	3418.10	3425.00	
4000	134	103.63	7.828684	0.6788	70	129	103.63	103.00	100.00	4003	4999	4506.72	44325.00	
5000	190	106.47	9.217912	0.6705	85	134	106.47	105.00	110.00	5000	5986	5274.45	5230.50	5400.00
6000	59	112.76	7.297470	0.0658	98	128	112.76	110.00	108.00	6000	6998	6474.66	6500.00	6500.00
7000	14	127.71	13.234155	3.6705	112	155	127.71	123.00		7019	7995	7477.64	7524.00	7500.00
8000	35	138.00	12.383575	2.1238	120	169	138.00	140.00	145.00	8004	8953	8534.60	8614.00	8696.00
9000	36	154.69	15.084182	1.0142	116	181	154.69	156.50		9055	9979	9484.39	9442.00	9395.00
10000	58	159.41	18.688616	2.4754	123	207	159.41	160.00	140.00	10030	10998	10483.84	10502.00	10288, 10700
11000	72	174.99	27.221312	3.2306	132	290	174.99	150.00	150.00	11001	11996	11527.81	11498.50	
12000	75	201.51	41.453449	4.8189	130	305	201.51	210.00	270.00	12002	12994	12565.11	12765.50	12745.00
13000	80	202.25	28.128323	3.1647	138	274	202.25	200.00	178, 218	13000	13987	13381.63	13305.00	13004.00
14000	39	215.05	22.741046	3.6891	170	252	215.05	214.00	214.00	14030	14964	14500.05	14470.00	14500.00
15000	85	233.75	30.023366	3.2758	147	298	233.75	234.50	260.00	15013	15981	15619.61	236.00	
16000	64	235.83	33.576520	4.2302	168	345	235.83	232.50	168, 210	16030	16992	16582.56	16603.50	16520.00
17000	88	246.72	15.983432	1.7136	216	302	246.72	244.50	240.00	17000	17994	17439.60	17402.50	
18000	35	269.94	20.835409	3.5732	240	338	269.94	265.00	285.00	1800006	18983	18592.03	18633.00	
19000	26	301.38	24.703368	4.9407	190	335	301.38	292.00	290.00	19005	19906	19012.19	19123.50	19050.00
20000	12	285.83	17.897858	5.3964	250	312	285.83	289.50	289, 290, 291	20078	20970	20669.42	20850.00	20850.00
21000	34	309.97	15.883068	2.7239	290	360	309.97	304.00	300.00	21039	21977	21389.68	21405.00	
22000	2	306	0.000000	0.0000	306	306	306	306.00	306.00	22000	22000	22000.00	22000.00	22000.00

Pecos County: Pecos County is southeast of Reeves in the central to south-central part of the Delaware Basin (Figure 26), and covers some 4,000 square miles in area. Pecos is that part

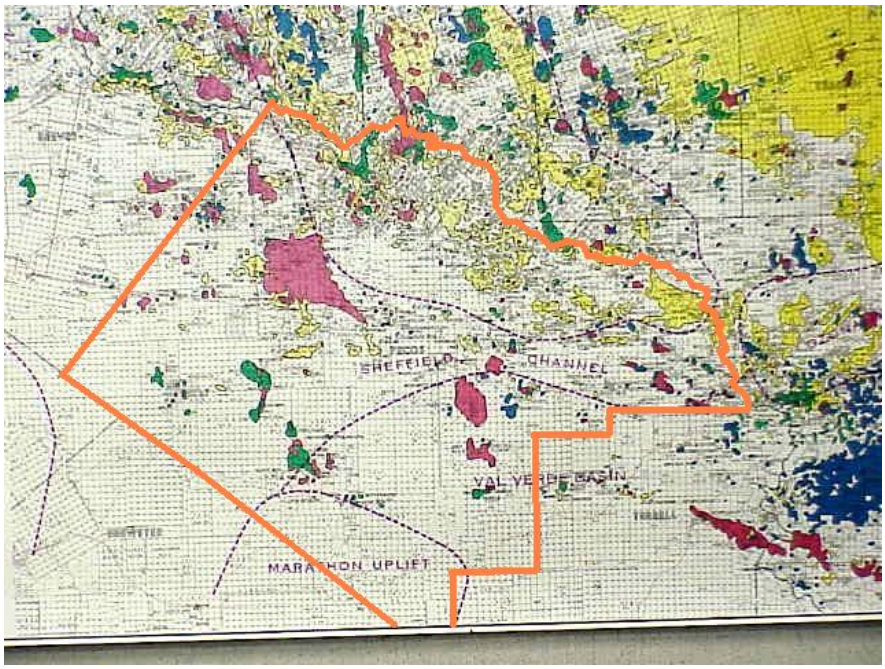


Figure 26. Image from the 1993 Producing Zone of The Permian Basin showing the boundary of Pecos County. The area outlined in orange defines Pecos County. Yellow represents production from Permian formations, blue from Pennsylvanian, purple from Mississippian, green from Devonian and Silurian, and red from Ordovician. Map is courtesy of Midland Map Company.

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

35) $$y = 3399.9Ln(x) - 11198$$

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

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

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

37) $$\frac{dT}{dz} = (2.9413x10^{-4})e^{0.00029413(z+11198)} = -\frac{q}{k}.$$

Finally by substitution we have

38) $$\frac{dT}{dz} = (2.9413x10^{-4})T = -\frac{q}{k}.$$

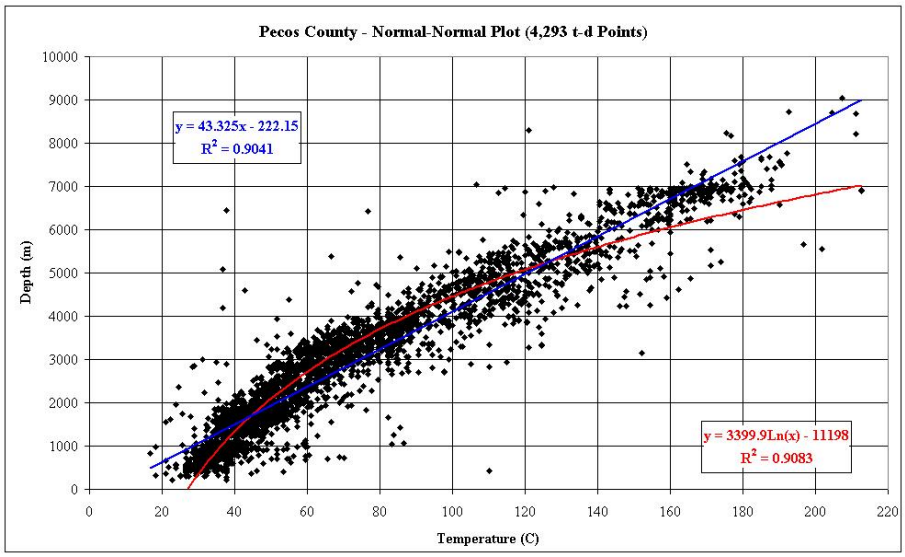
By contrast a pure linear equation for the thermal gradient in Pecos County takes the form of

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

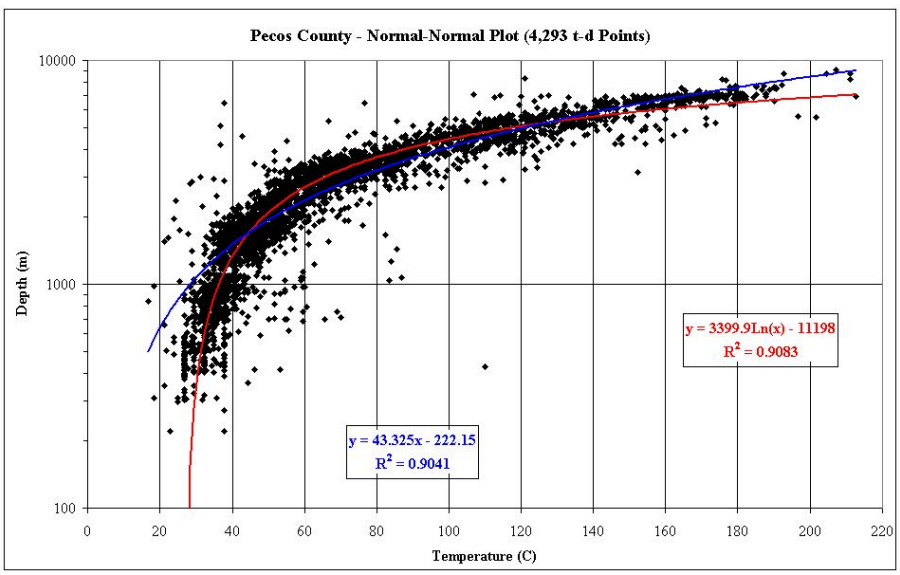
which is the equivalent of a constant ~23.1°C/km.

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 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 $R^2_s R^2_d = R^4_{max}$ 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



A



B

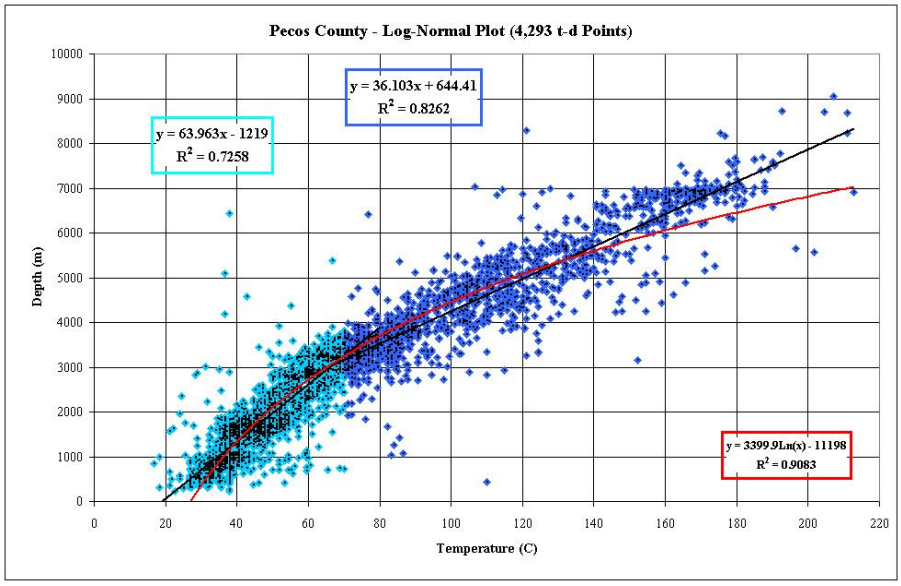
Figure 27. Plots of 4,293 t-d points in Pecos County. Blue represents straight line and red represents logarithmic function. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

to determine shallow and deep linear thermal gradients of the form

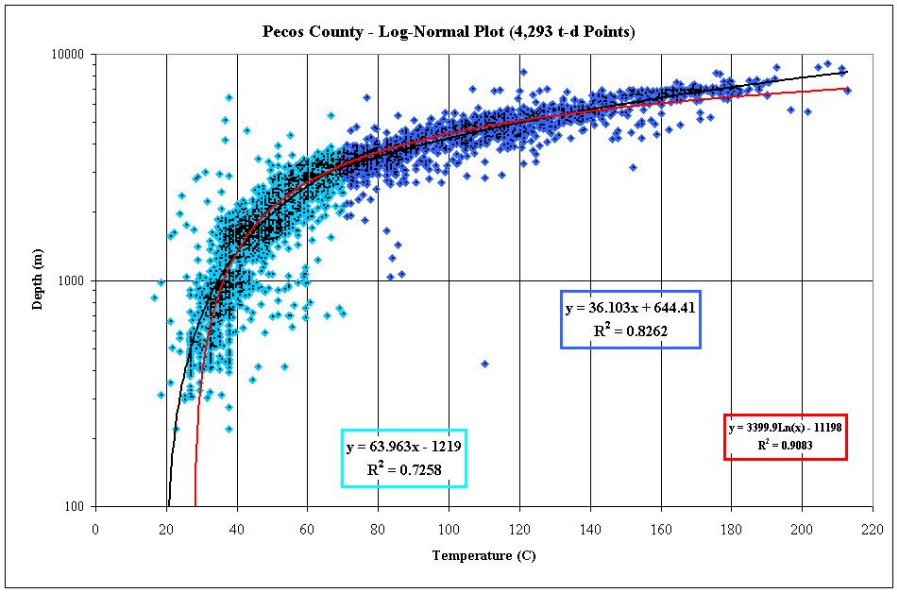
40) $$\frac{dT_S}{dz} = 0.015634 = -\frac{q}{k},$$

and

41) $$\frac{dT_D}{dz} = 0.027699 = -\frac{q}{k} \ ,$$



A



B

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 15.634°C/km and 27.699°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

depth	Pecos # of points	mean temp	standard deviation	standard error	min temp	max temp	mean temp	median temp	mode temp	min depth	max depth	mean depth	median depth	mode depth (3 or more)
1000	212	89.60	8.444097	0.0581	65	128	89.60	87	80	1001	1990	1589.67	1632.5	1761, 1780
2000	317	95.90	11.211971	0.6317	62	158	95.90	94	90	2001	2999	2566.57	2590	2800
3000	271	102.43	12.375655	0.7532	65	188	102.43	100	100	3000	3997	3316.84	3217.5	3400
4000	230	108.28	11.612114	0.7674	84	186	108.28	107	110	4000	4998	2592.24	4651	4800
5000	568	113.21	10.322861	0.4331	70	180	113.21	112	110	5000	5995	5480.16	5474	5500
6000	237	119.93	13.125822	0.5844	75	169	119.93	119	120	6000	6985	6391.41	6361	6500
7000	172	130.71	13.633778	1.0426	76	172	130.71	130	139	7000	7987	7485.01	7498.5	7600
8000	168	139.67	16.314461	1.2625	96	208	139.67	136	140	8000	8998	6460.71	2426	8000
9000	287	146.84	19.358883	1.1447	140	239	146.84	144	83	9000	9996	9479.56	9492	9600
10000	352	160.54	20.543936	1.0950	120	306	160.54	159	160	10000	10999	10520.92	10593	10600
11000	246	169.10	17.635963	1.1267	115	256	169.10	169	175	11000	11998	11488.99	11360.5	11000
12000	180	185.72	22.533911	1.6843	125	258	185.72	184	190	12000	12998	12461.75	12454.5	12000
13000	136	210.18	29.745559	2.5601	98	310	210.18	205.5	180, 190	13000	13991	13474.70	13412	00, 13200, 13700
14000	123	224.76	28.876884	2.6144	131	318	224.76	223	200	14000	14998	14507.11	14517.5	14050, 14700
15000	136	227.54	27.156312	2.3372	109	324	227.54	225	220, 230	15000	15998	15460.90	16466.5	15000
16000	106	244.57	33.029570	3.2234	98 / 194	340	244.57	239	240	16000	16989	16473.69	16494.5	16500
17000	100	249.72	27.158156	3.0406	152	345	249.72	247	235, 270	17000	17998	17655.29	17485.5	17050, 17568
18000	78	271.46	27.158156	3.0950	215	395	271.46	268.5	270	18000	18940	18405.60	18409.5	
19000	32	284.47	16.911505	3.0374	250	320	284.47	282.5	296	19016	19993	19399.19	19289	
20000	52	302.85	22.987110	3.2188	247	354	302.85	308.5	276, 320	20000	20942	20467.92	20437.5	
21000	74	314.14	22.959497	2.6872	255	374	314.14	319	326	21000	21978	21302.58	21614	21850
22000	161	327.18	23.342932	1.8454	235	415	327.18	332	340	22000	22990	22431.76	22644	22750
23000	22	343.05	28.845198	6.2945	224 / 326	370	343.05	347	336 / 340	23000	23956	23319.27	26260	
24000	13	357.69	17.259706	4.9824	328	375	357.69	356	375 / 375	24052	24900	24528.85	24632	
25000	5	366.40	8.294577	4.1473	355	378	366.40	365	365	25025	25475	25199.60	25182	
26000	2	381.00	43.840620	43.8406	350	412	381.00	381		26776	26960	26868.00	26868	
27000	1	348.00					348.00					27000.00		
28000	3	397.00	16.703293	11.8110	379	412	397.00	400		28510	28600	28556.00	25885	
29000	1	405.00					405.00					29670.00		

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 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 227°F to 327°F. An average temperature of 227°F is reached within the 15,000 to 16,000-foot interval. Higher temperatures up into the 400°F range were also encountered in the deepest 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

42) $$\frac{dT}{dz} = (2.492x10^{-4})e^{0.0002492(z+13790)} = -\frac{q}{k}$$

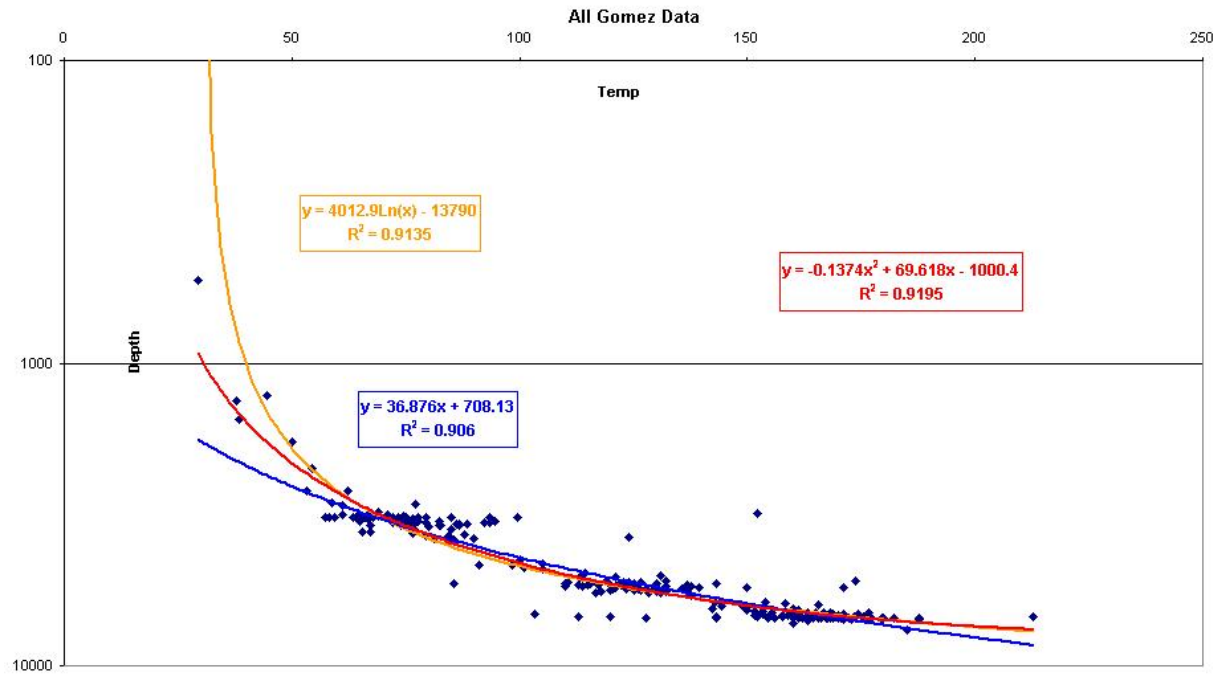


Figure 29. Graph of t-d values in the Gomez field in Pecos County. Data is plotted in meters and ^{o}C.

or with substitution

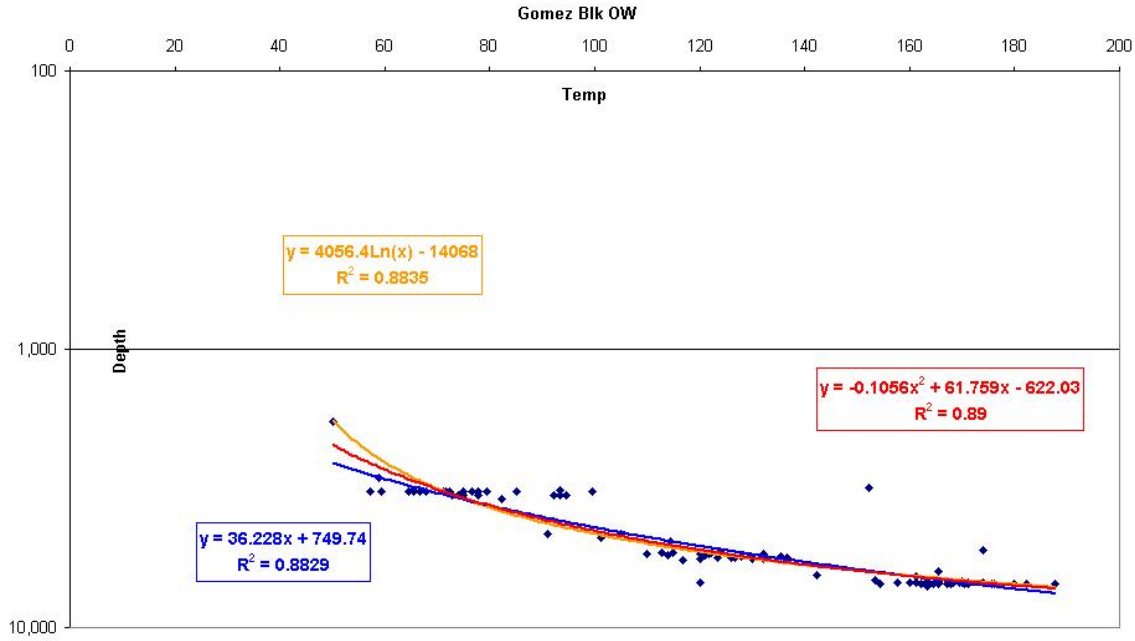
42) $$\frac{dT}{dz} = (2.492x10^{-4})T = -\frac{q}{k}.$$

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

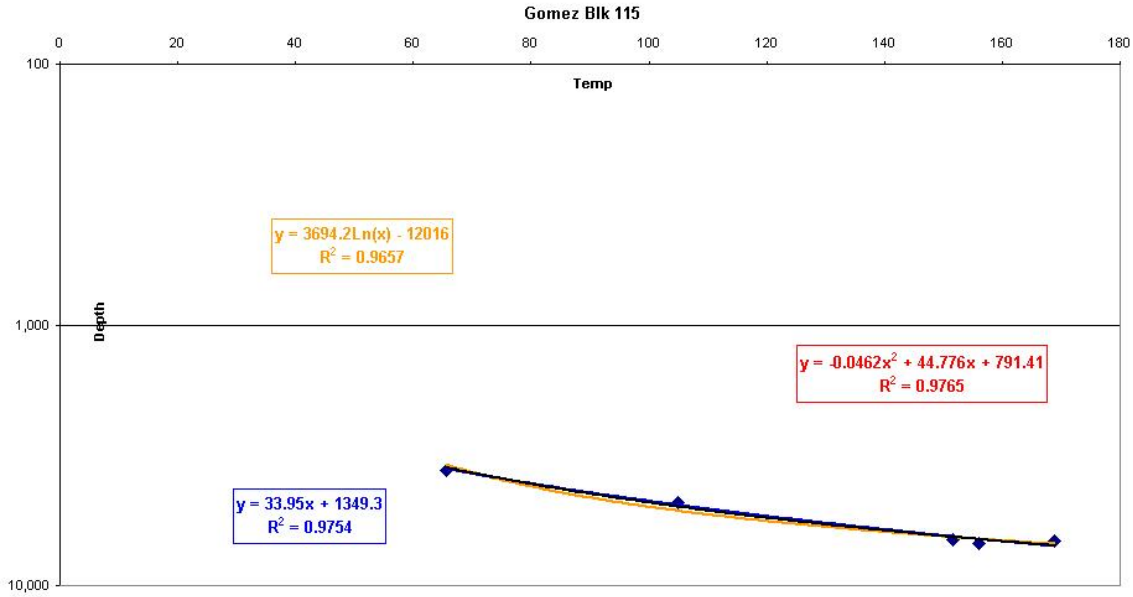
43) Blk OW $$\frac{dT}{dz} = (2.4652x10^{-4})T = -\frac{q}{k};$$

44) Blk 115 $$\frac{dT}{dz} = (2.7069x10^{-4})T = -\frac{q}{k};$$

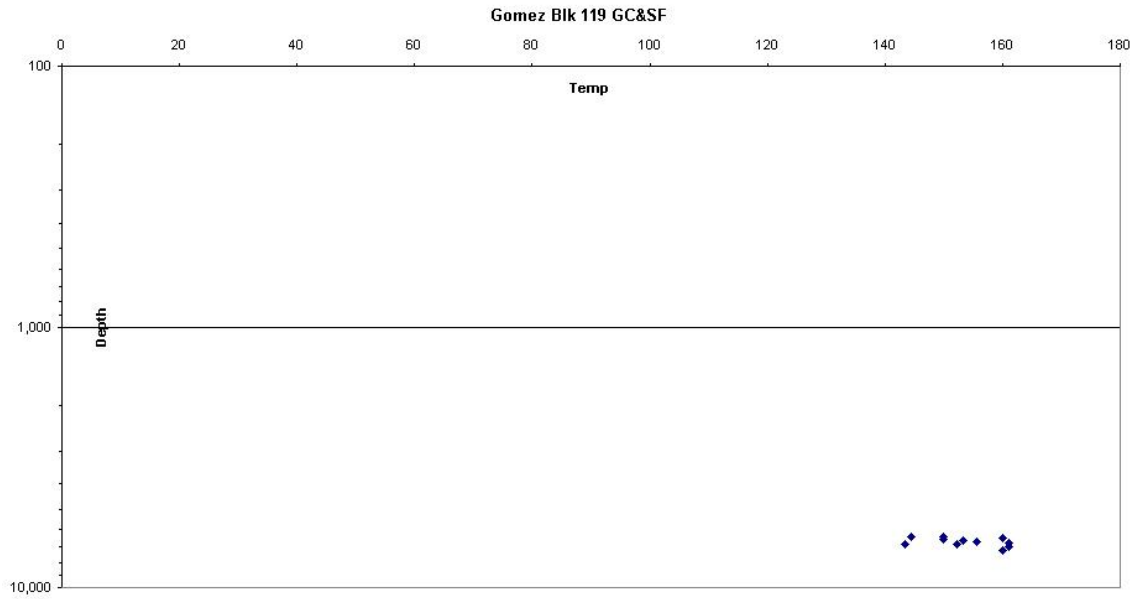
45) Blk 114 $$\frac{dT}{dz} = (2.7427x10^{-4})T = -\frac{q}{k};$$



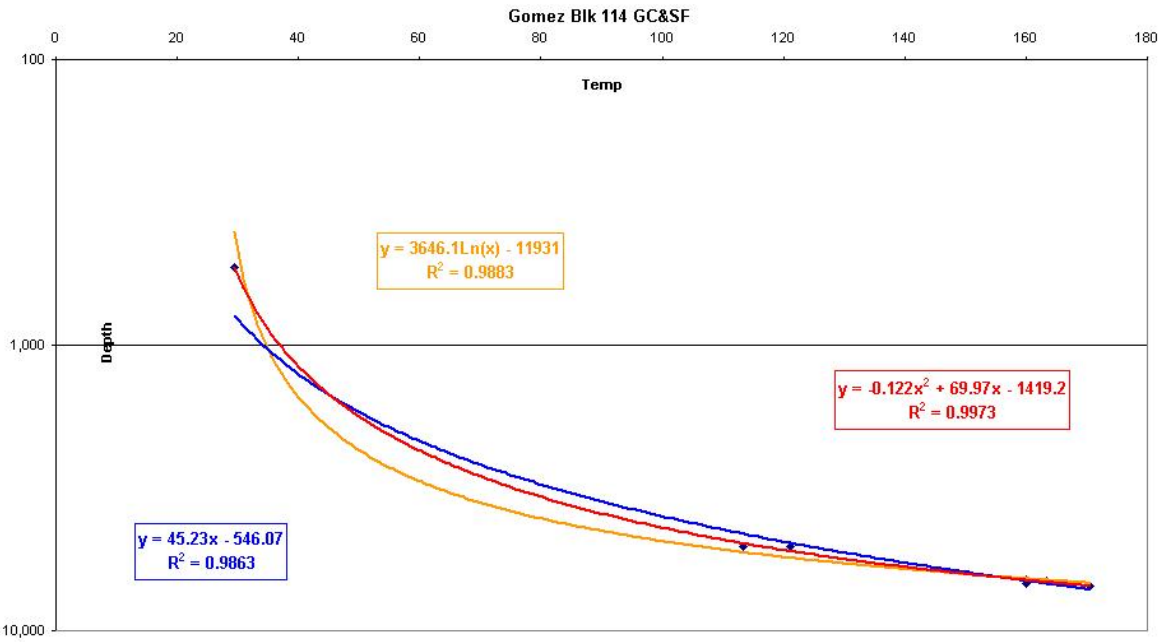
A



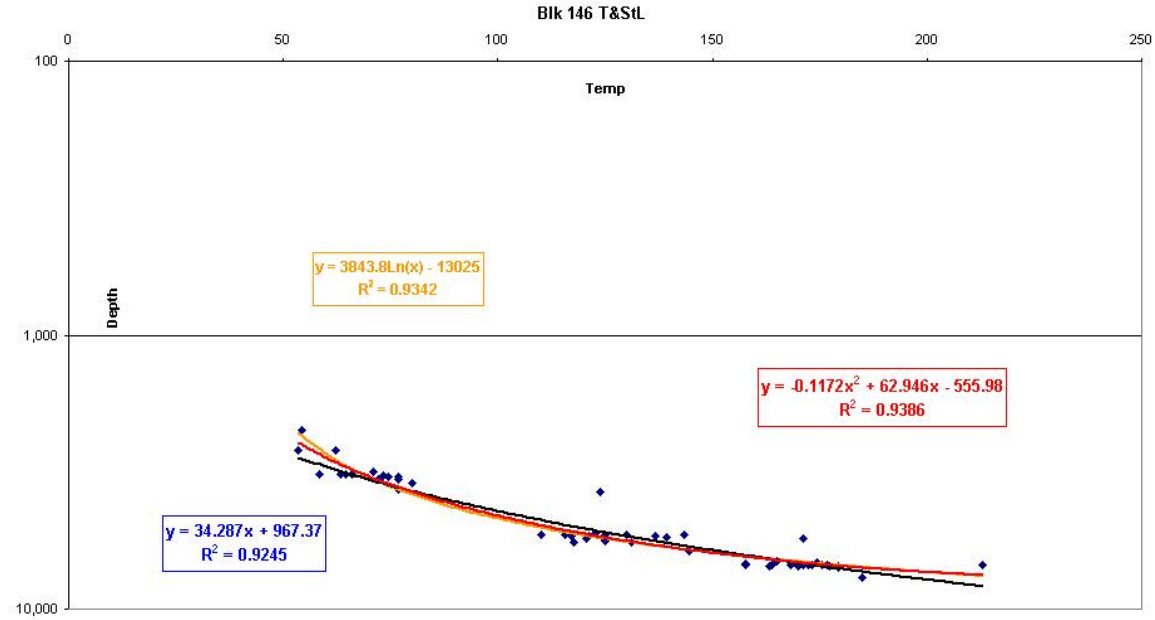
B


Gomez Blk 119 GC&SF
0
20
40
60
80
100
120
140
160
180
100
Temp
Depth
1,000
10,000

C


Gomez Blk 114 GC&SF
0
20
40
60
80
100
120
140
160
180
100
Temp
Depth
1,000
10,000
y = 3646.1Ln(x) - 11931
R2 = 0.9883
y = -0.122x2 + 69.97x - 1419.2
R2 = 0.9973
y = 45.23x - 546.07
R2 = 0.9863

D



E

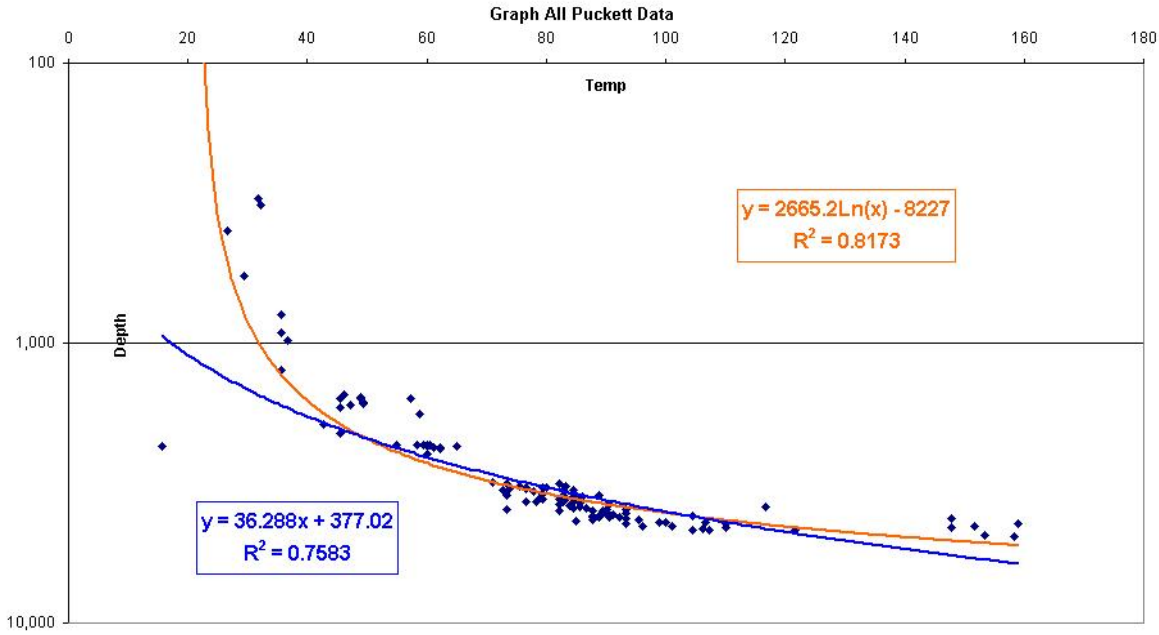
Figure 30. Graph of t-d values in the Gomez field in Pecos County as broken into A) Blk OW, B) Blk 115, C) Blk 119, D) Blk 114, and E) Blk 146. Data in Blk 119 is not of sufficient depth to be useful for determining a t-d curve. Block OW is also interesting because displays the appearance of steps within the data plot at temperatures of 100°C and 150°C. Data is plotted in meters and °C.

and

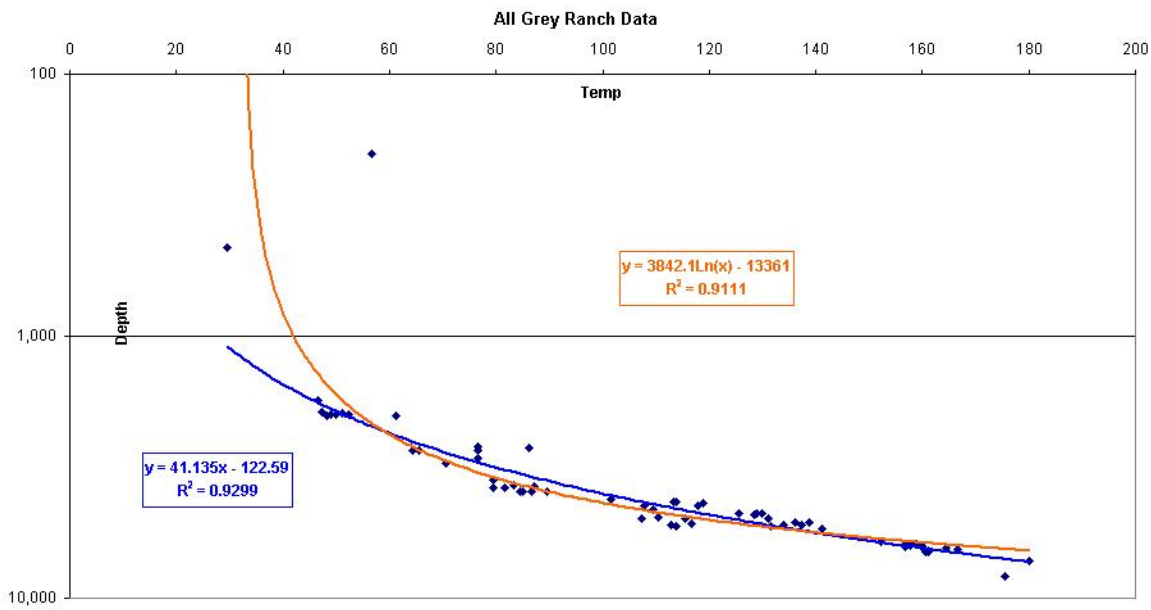
43) Blk 146 $$\frac{dT}{dz} = (2.6016x10^{-4})T = -\frac{q}{k}.$$

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



A



B

Figure 31. Graph of t-d values in the Puckett and Grey Ranch fields in Pecos County. A) Puckett. B) Grey Ranch.

44) (Puckett) $$\frac{dT}{dz} = (3.7521x10^{-4})T = -\frac{q}{k}$$

and

45) (Grey Ranch) $$\frac{dT}{dz} = (2.6027x10^{-4})T = -\frac{q}{k}.$$

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 $R^2 \rightarrow 1$, does not necessarily imply geological reasonableness.

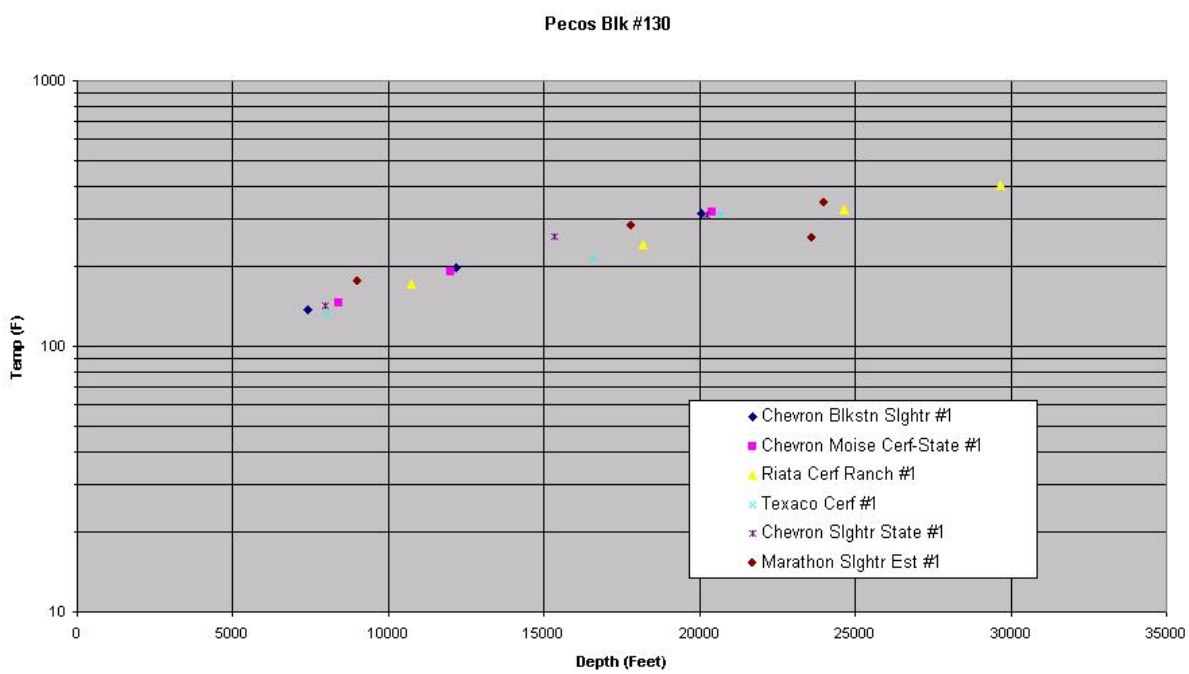


Figure 32. Graph of t-d values in several wells in proximity to the Grey Ranch field that have multiple temperature recordings. In this log-normal plot there is a slight curvature that can be identified that may be representative of the wells as a group. The graph is plotted in feet and °F.

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 "@DOEGEOTHERMALPROJECT_TerrellCounty 5.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

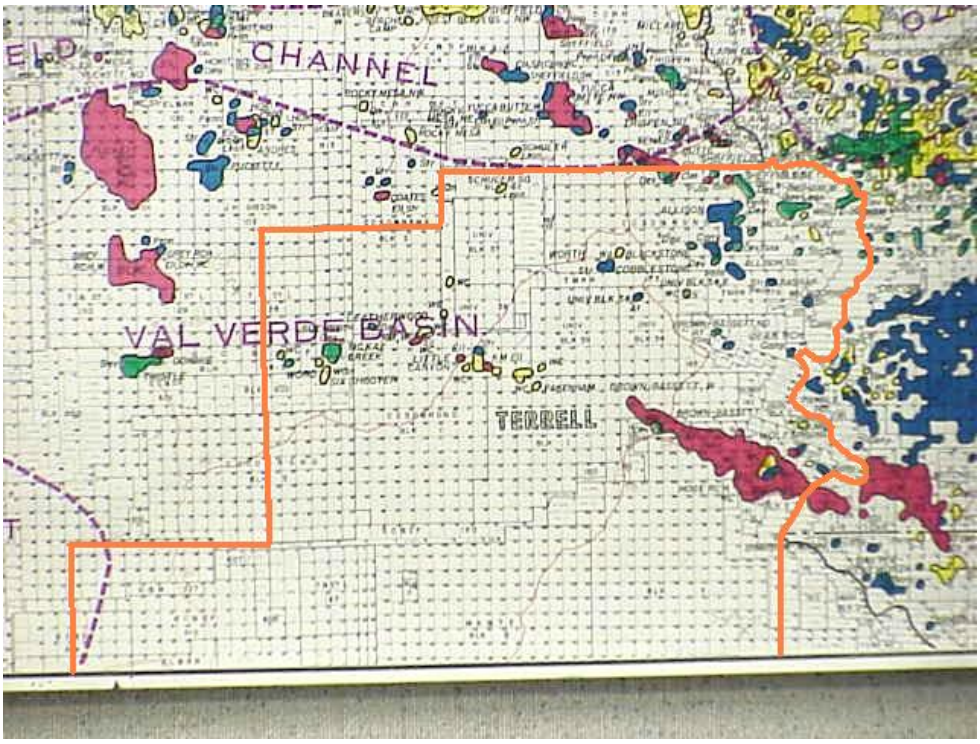
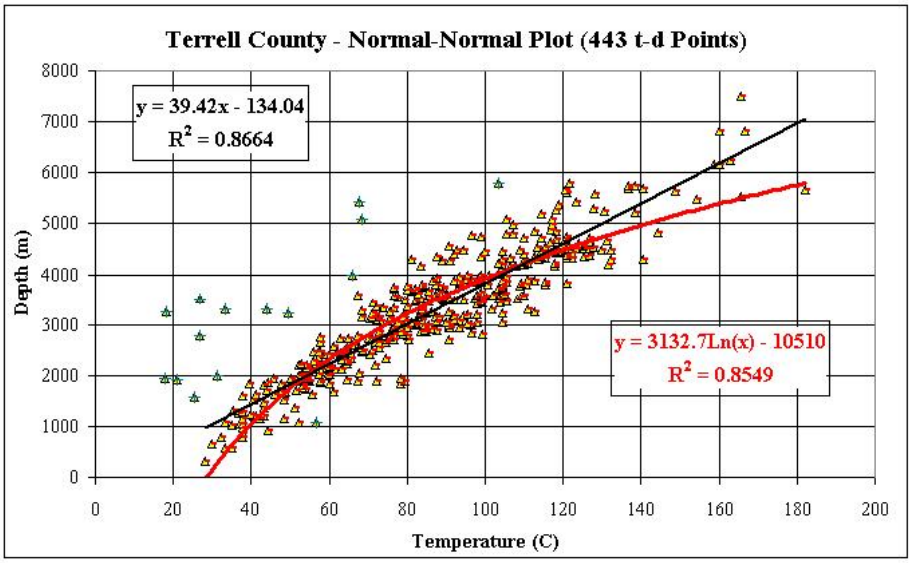


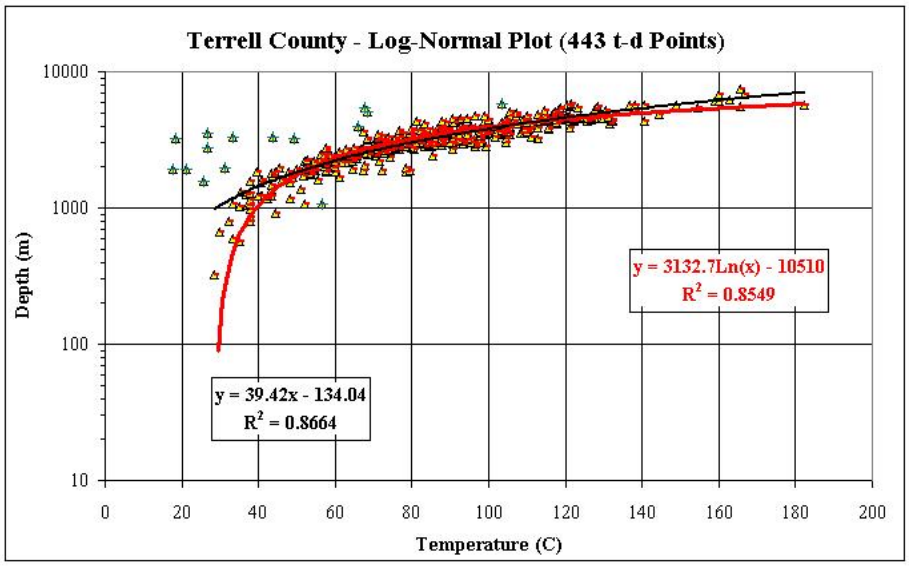
Figure 33. Image from the 1993 Producing Zone of The Permian Basin showing the location of Terrell County. The area outlined in orange defines the county. Only the northern 2/3 of the county is shown in this particular image. Yellow represents production from Permian formations, blue from Pennsylvanian, purple from Mississippian, green from Devonian and Silurian, and red from Ordovician. Map is courtesy of Midland Map Company.

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



A



B

Figure 34. Plots of 443 t-d points in Terrell County. The yellow triangles represent all of the points in the spreadsheet. The green 'plus' sign represents 15 data points not included within the overall curve fitting 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 linear and log-normal curve calculations. A) Plot constructed as a normal-normal distribution. B) Plot constructed as a log-normal distribution.

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

46) $$y = 3132.7Ln(x) - 10510 \ ,$$

and with substitutions of y = z and x = T, and solving for T, we have

47) $$T = e^{0.00031921(z+10510)}.$$

Taking the first derivative gives the temperature gradient as

48) $$\frac{dT}{dz} = (3.1921x10^{-4})e^{0.00031921(z+10510)} = -\frac{q}{k}.$$

And by substitution we have

49) $$\frac{dT}{dz} = (3.1921x10^{-4})T = -\frac{q}{k}.$$

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

50) $$\frac{dT}{dz} = 0.025368 = -\frac{q}{k},$$

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

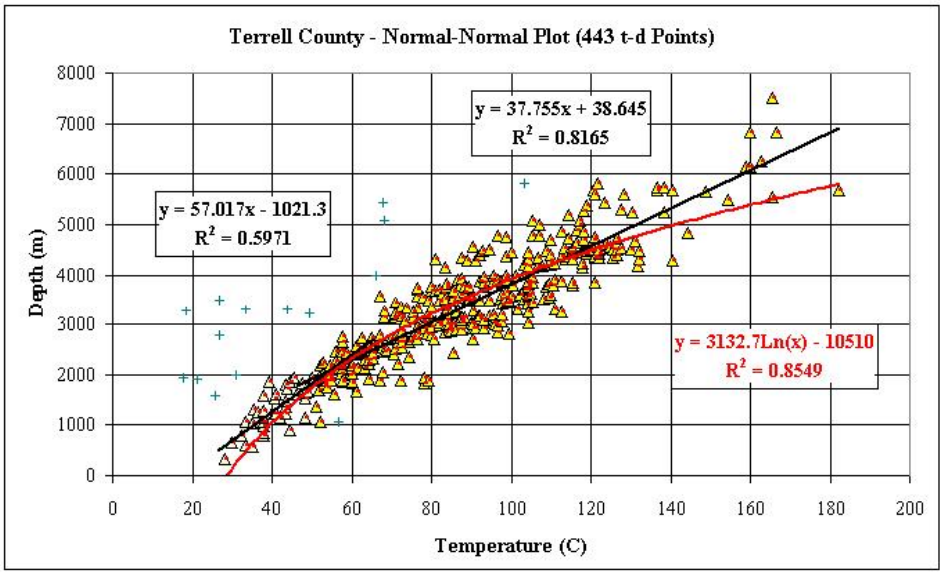
We also tested the possibility of subdividing the data into a shallow and deep component based upon the determination of the maximum value of $R^2_s R^2_d = R^4_{max}$. This resulted in two linear equations (Figure 35) that intersected at a temperature-depth value of 56.7°C and 2236 m respectively. The shallow and deep linear gradients are given as

51 $$\frac{dT_S}{dz} = 0.0175 = -\frac{q}{k},$$

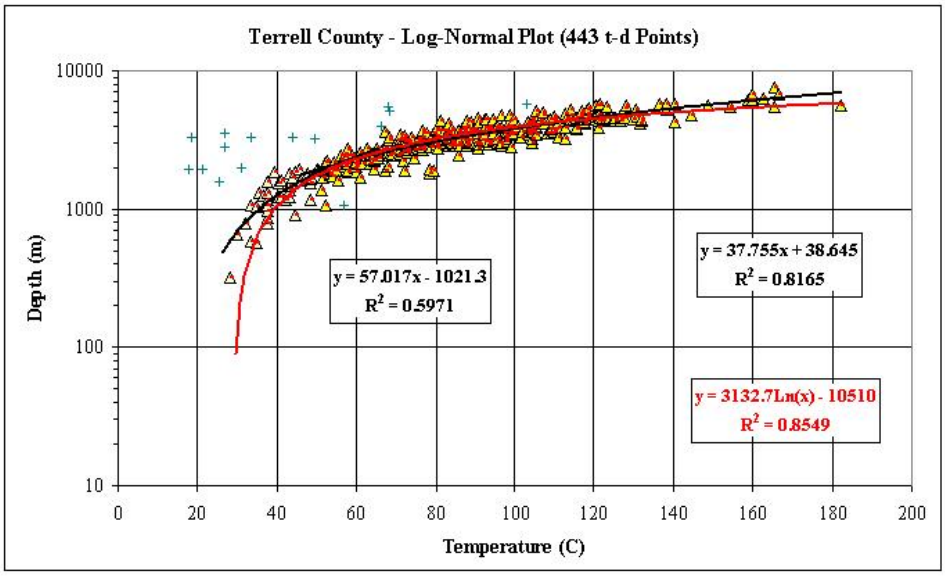
and

52 $$\frac{dT_D}{dz} = 0.0265 = -\frac{q}{k},$$

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.



A



B

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).

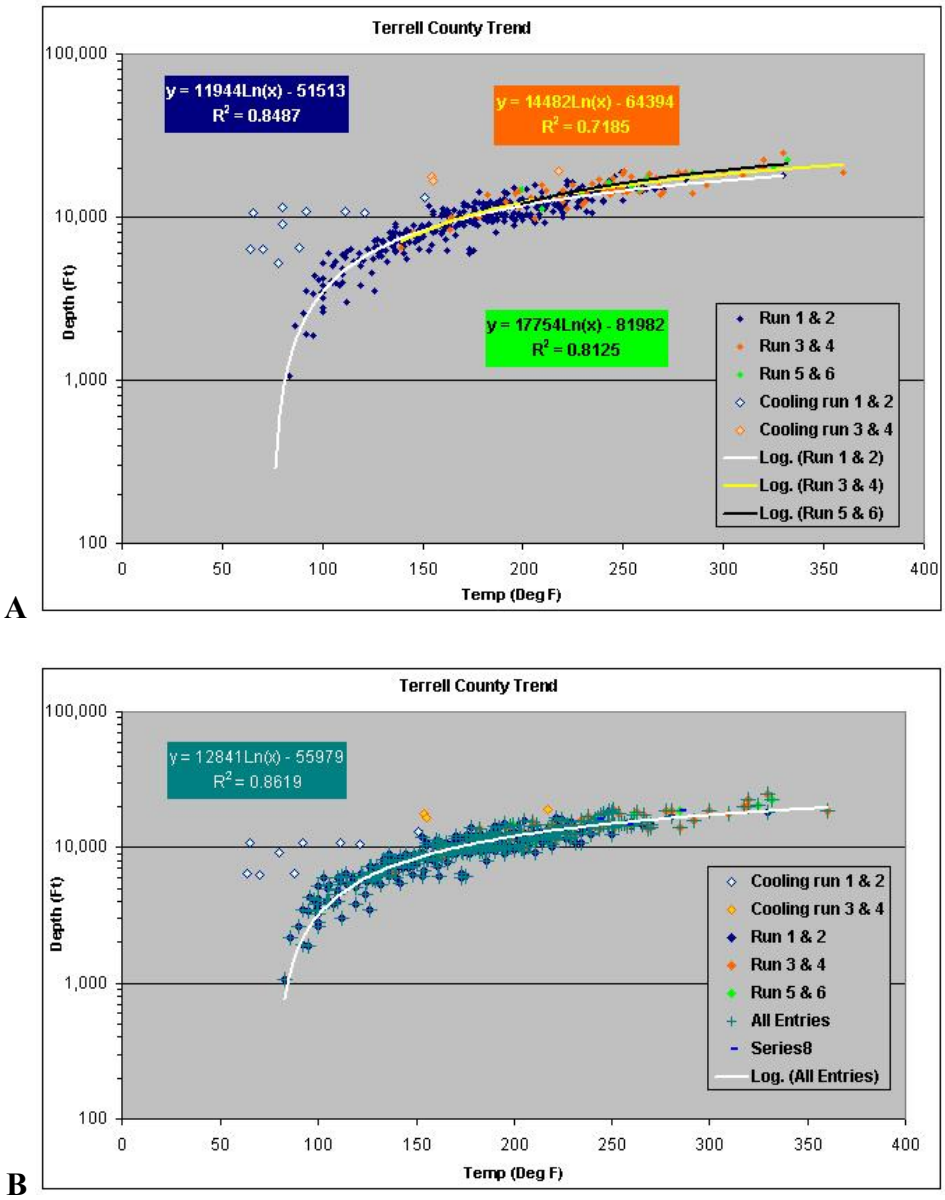


Figure 36. Log normal plots of t-d values in Terrell County. The data was plotted and color-coded according to the 'Run' that each t-d reading represented. Points labeled 'Cooling run 1&2' and Cooling run 3&4' were not included in the curve calculations. Graphs are in feet and ^{o}F. A) This image represents 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 decrees C. Thus, it cannot be directly compared with previous equations that were determined using meters and ^{o}C. A revising of these two graphs is necessary for a direct comparison.

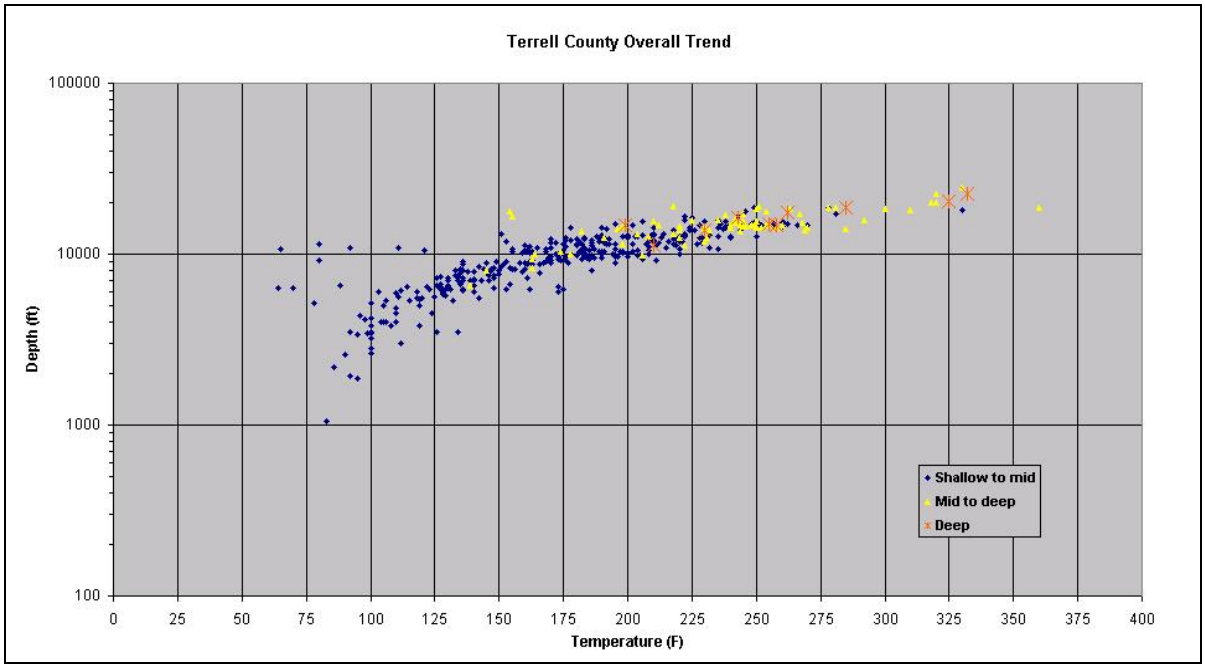


Figure 37. Log normal plots of t-d values in Terrell County. In this graph the shallow to mid range is represented by 'Run 1&2' t-d points, the mid to deep range is defined by 'Run 3&4', and deep is given by 'Run 5&6'. Graph in feet and ^{o}F.

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.

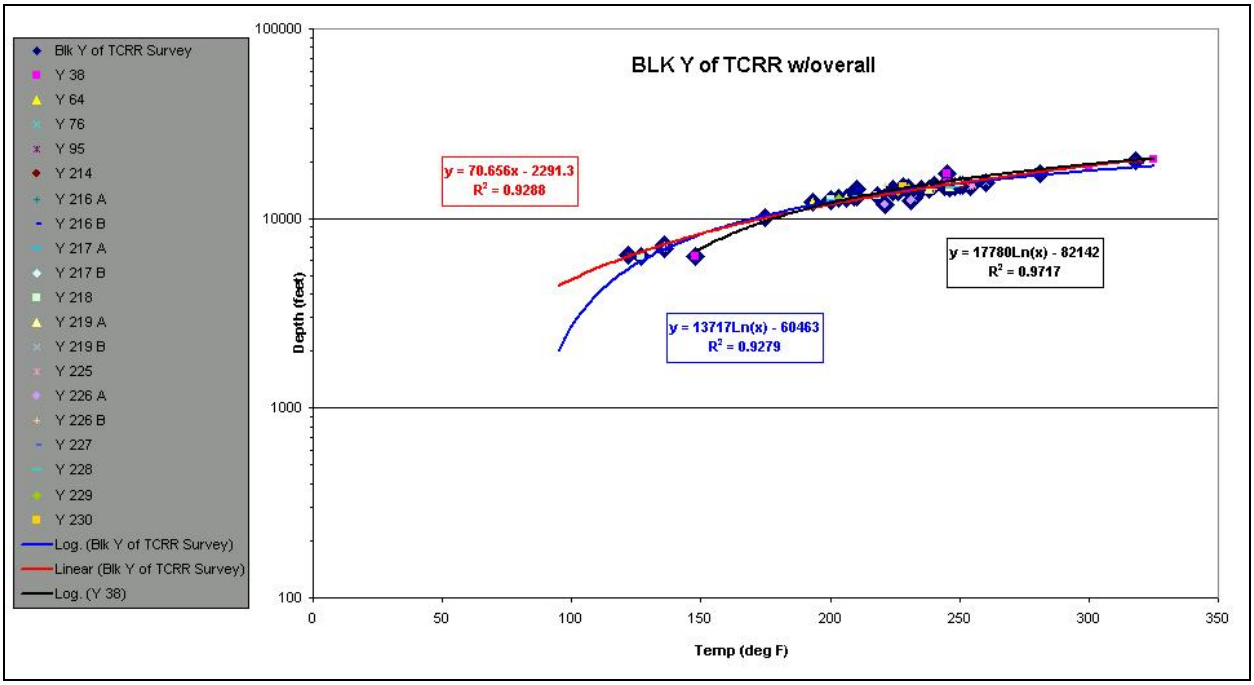


Figure 38. Log normal plots of t-d values in Terrell County from Blk Y, Survey TCRR. Graph in feet and ^{o}F.

In the process of building the Terrell database, we did not yet expressly add 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 15,776-16,102 feet out of the Devonian formation. The reported reservoir temperature was 248°F, or 120°C (Figure 39). This particular well had three 'Runs' and 'Run 2' had a t-d value of 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.

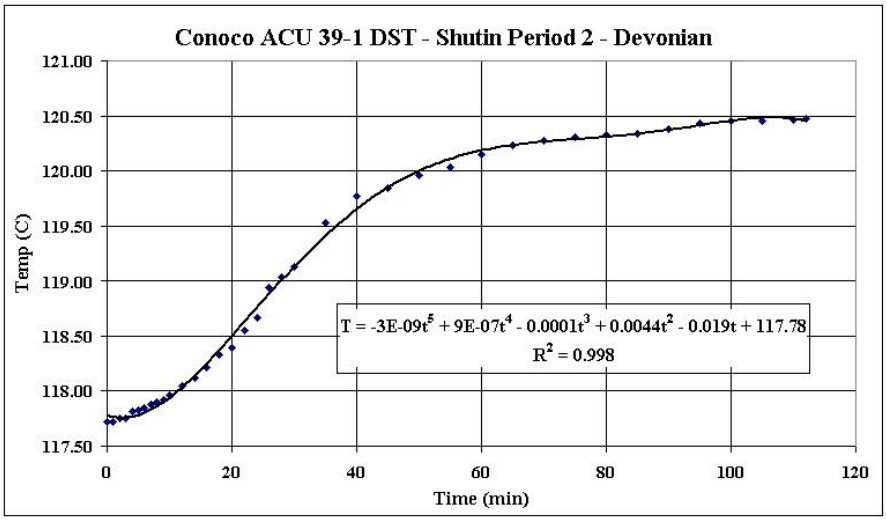


Figure 39. Temperature versus time from a DST in a well in Terrell County. Formation is the Devonian.

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 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 8,690 feet. A straight edge was then used to estimate the temperature to within 0.2^{o}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

53) $$y = 7900.2Ln(x) - 32751 \ .$$

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

54) $$T = e^{0.00012658(z+32751)} ,$$

and with differentiation we get

55) $$\frac{dT}{dz} = (1.2658x10^{-4})e^{0.00012658(z+32751)} = -\frac{q}{k} ,$$

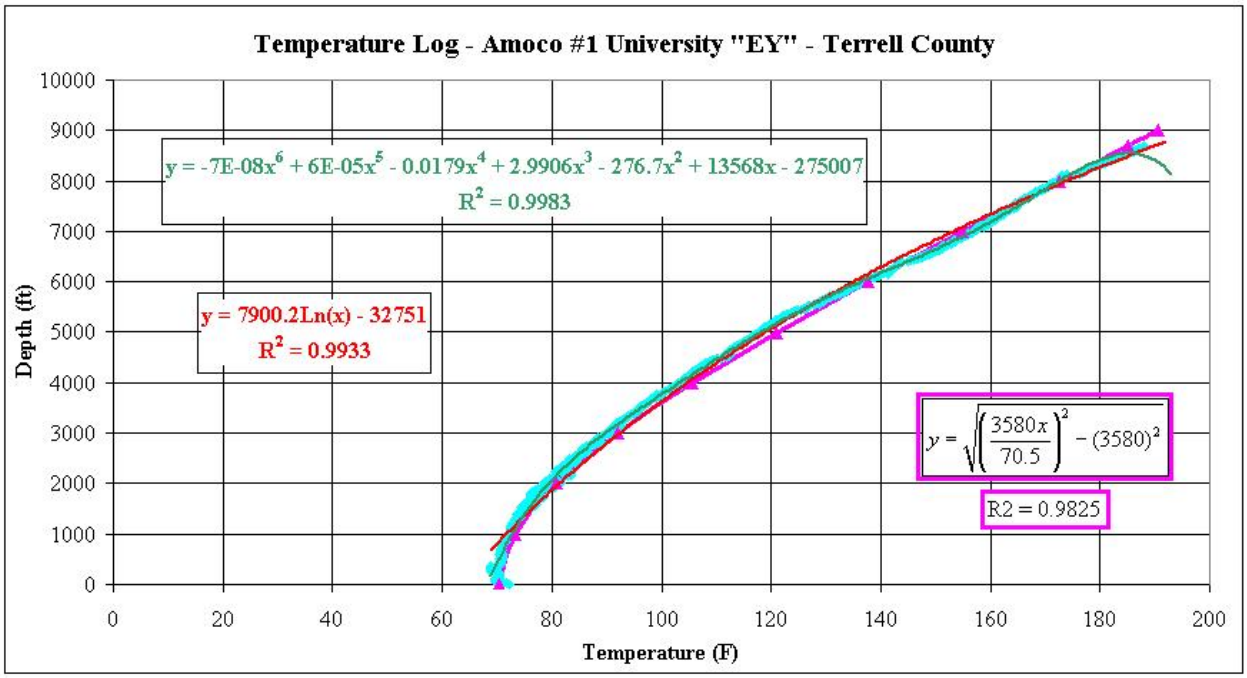


Figure 40. Temperature versus depth for a temperature log run in a well in Terrell County. The light blue dots represent 870 t-d pairs as graphed from the spreadsheet. The red represents a logarithmic function, green a 6th order polynomial, and purple a hyperbolic function for curve solutions. Graph plotted in feet and °F.

or with appropriate substitution

56) $$\frac{dT}{dz} = (1.2658x10^{-4})T = -\frac{q}{k}.$$

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 6th 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 of this equation as a function of 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°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

57) $$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$$

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

58) $$T = \sqrt{(3.9439x10^{-4})z^2 + 4970.3} = -\frac{q}{k},$$

and by differentiation we get

59) $$\frac{dT}{dz} = (3.9439x10^{-4})z\left(\frac{1}{\sqrt{(3.9439x10^{-4})z^2 + 4970.3}}\right) = -\frac{q}{k},$$

or with substitution

60) $$\frac{dT}{dz} = (3.9439x10^{-4})z\left(\frac{1}{T}\right) = -\frac{q}{k}.$$

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.

Ina 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 200°F or above can be found at the 11,000-foot depth interval.

Table 6
Terrell Statistics on Temperature and Depth

	Terrell				Terrell - UT Lands			
	# of wells	mean	standard	Student's	# of wells	mean		
depth	with temps	temp	deviation	T test	with temps	temp		
2000	4	106.5	12.500000	0.654	3	92	7.211103	5.0990
3000	3	117.67	9.073772	6.4161	10	109	13.564660	4.5216
4000	4	108.25	11.086779	6.4010	11	105.45	7.992041	2.5273
5000	4	134	26.470109	15.2825	16	117.19	15.1271	3.9058
6000	17	135.12	15.157021	3.7893	36	130.58	22.856540	3.8635
7000	19	146.21	15.167872	3.5751	25	141.16	10.358893	2.1145
8000	7	155	8.326664	3.3993	27	154.44	13.989923	2.7436
9000	22	190.64	15.170603	3.3105	34	179.91	23.798864	4.1429
10000	36	181.67	26.925293	4.5512	39	177.74	31.984962	5.1886
11000	26	207.35	17.663391	3.5327	39	196.21	27.159548	4.4059
12000	35	209.8	28.57889	4.9012	49	232.88	20.593986	2.9753
13000	22	228.09	26.111317	5.698	18	220	24.925772	6.0454
14000	83	230.47	20.977073	2.3165	52	238.33	22.908789	3.2079
15000	18	247.83	18.796902	4.5589	18	241.83	23.894991	5.7954
16000	9	255.33	35.724641	12.6306	5	221	37.967091	16.9865
17000	8	269.5	20.982986	7.8968	8	252.38	45.074343	5.1367
18000	10	294.5	40.869032	13.623	10	287.4	34.859081	11.6177
19000	1	251			1	251.00		
20000	3	329.67	9.073772	6.4161	2	322.5	3.535534	3.5355
20500								
21000	2	299	43.840620	43.8406	0			
21500								
22000	2	350	49.497470	49.4975	1	332.00		
22500								
23000	0				0			
23500								
24000	1	330.00			1	330		

Terrell	min temp	max temp	mean temp	median temp	mode temp	min depth	max depth	mean depth	median depth	mode depth
2000	90	125	102.5	107.5	100	2415	2982	2663.00	2606.00	2606
3000	95	126	105.22	100	100	3195	3803	3535.00	3476.00	
4000	98	124	106.5	105	98	4000	4513	4177.58	4065.50	4000
5000	100	173	124.31	118	118	5014	5983	5439.54	5297.00	5983
6000	107	173	131.9	130	130	6013	6993	6356.87	6332.00	6200
7000	126	196	144.24	140	140	7000	1950	7383.80	7308.50	7000
8000	135	181	156.35	157	145	8003	8940	8560.29	8684.00	8700
9000	158	223	187.17	184		9150	9980	9536.10	9530.00	
10000	111	238	181.83	182	175, 183	10000	10988	10201.76	10435.00	10,550
11000	153	230	204.75	210	208, 220	11007	11939	11545.69	1153.50	11235, 11528
12000	170	291	215.19	208		12000	12956	12543.35	1259.45	12700
13000	182	279	225.6	226		13000	13962	13564.47	13654.00	13654
14000	190	295	230.47	250	260	14016	14970	14523.05	14575.00	14800
15000	210	292	247.83	248.5	260	15079	15910	15715.66	15469.00	13575
16000	225	342	255.33	242	242	16033	16722	16299.44	16164.00	
17000	238	310	269.5	269		17044	17968	17392.50	17305.00	
18000	249	360	294.5	283		18011	18810	18467.50	18502.50	
19000	251	251				19041	19041			
20000	318	336	329.67	325		20079	20500	20253.67	20182.00	
21000	268	330	299	299		21,234	21,607	21420.50	21420.50	
22000	320	390	350	355		22400	22862	22631.00	22631.00	
23000										
24000	330	330				24,637	24,637			
25000										
26000										
27000										
28000										

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

61) $$y = 1962.4Ln(x) - 5983.7$$

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

62) $$T = e^{0.00050958(z+5983.7)}.$$

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

63) $$\frac{dT}{dz} = (5.0958x10^{-4})e^{0.00050958(z+5983.7)} = -\frac{q}{k}.$$

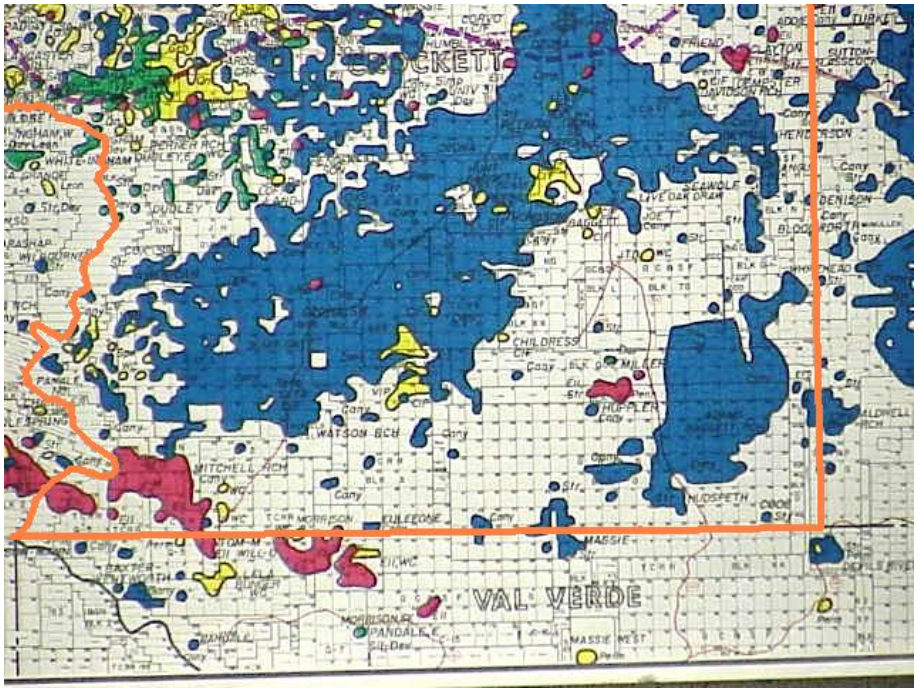


Figure 41. Image from the 1993 Producing Zone of The Permian Basin showing the boundary of Crockett County. The area outlined in orange defines Crockett County. Yellow represents production from Permian formations, blue from Pennsylvanian, purple from Mississippian, green from Devonian and Silurian, and red from Ordovician. Map is courtesy of Midland Map Company.

Finally by substitution we have

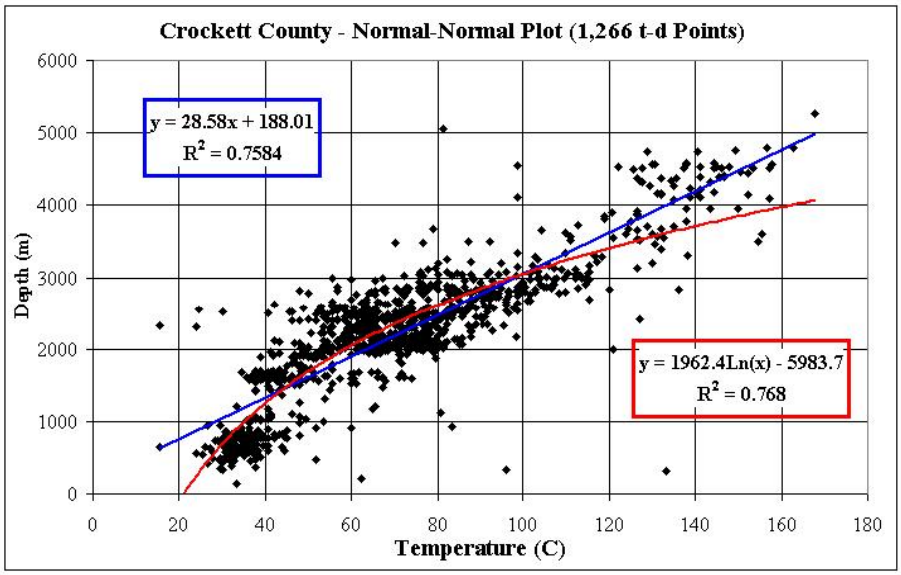
64) $$\frac{dT}{dz} = (5.0958x10^{-4})T = -\frac{q}{k}.$$

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

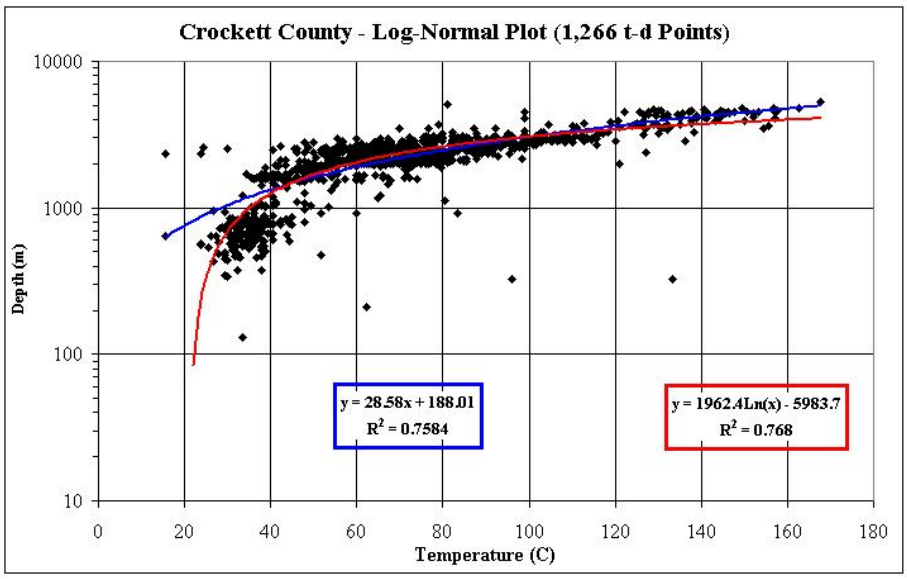
65) $$\frac{dT}{dz} = 0.03499 = -\frac{q}{k},$$

which is the equivalent of a constant ~35°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 $R^2_s R^2_d = R^4_{max}$ 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^{o}C and 1,783m. These two equations were then differentiated to determine shallow and deep linear thermal gradients of the form



A



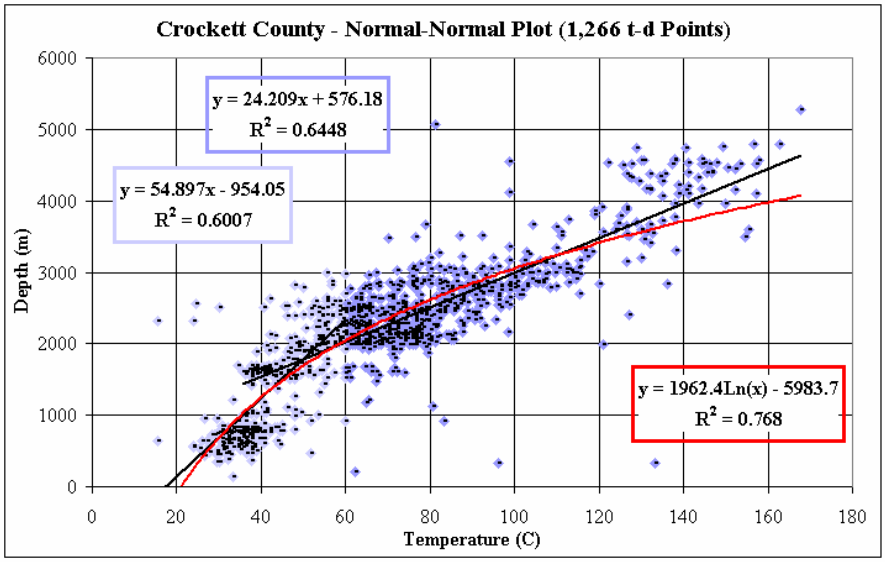
B

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.

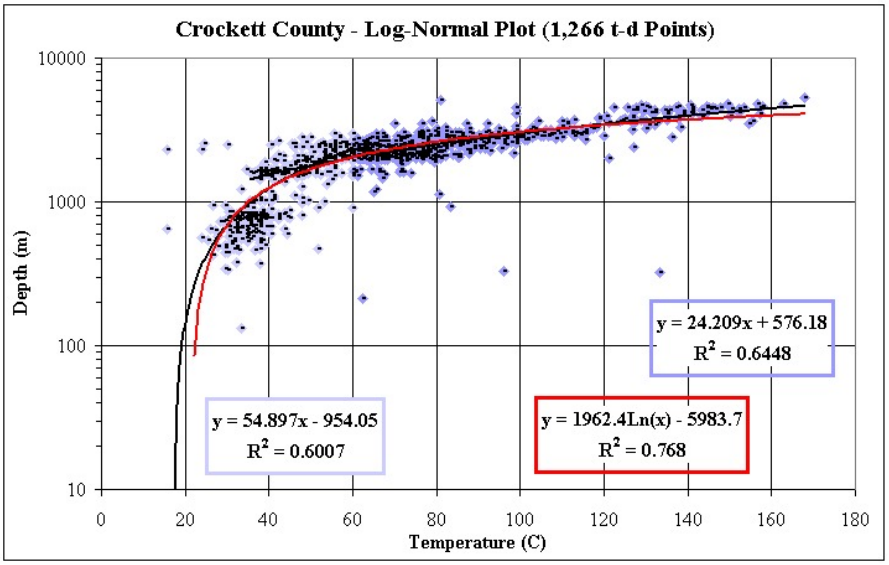
66) $$\frac{dT_S}{dz} = 0.018216 = -\frac{q}{k} ,$$

and

67) $$\frac{dT_D}{dz} = 0.041307 = -\frac{q}{k} ,$$



A



B

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°C/km and 41.307°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
Crockett Statistics on Temperature and Depth

depth	Crockett # of points	mean temp	standard deviation	standard error	min temp	max temp	mean temp	median temp	mode temp	min depth	max depth	mean depth	median depth	mode depth
2,000	3	3	92.33	5.507571	87	98	92.33	92		2200	2798	2496	2490	
3,000	2	2	163.5	19.091883	150	177	163.50	163.5	checking	3697	69788	3837.5	3837.5	
4,000	5	5	116.2	13.330416	100	131	116.20	111		4320	2800	4643.4	4700	4700
5,000	5	5	138.2	4.5497255	132	143	138.20	140		5000	5500	5231	5200	
6,000	12	12	164.67	14.04054008	135	185	164.67	163.5	160	6048	6946	6495.5	6500	
7,000	12	12	171.5	30.583715	139	261	171.50	170	170	7000	7900	7172.08	7070.5	7000
8,000	3	3	160.67	21.93931	156	198	160.67	188		8868	8950	8916.67	8938	
9,000	3	3	196	33.867388	171	236	211.50	187		9121	9904	9573.67	9696	
10,000	2	2	223.5	9.192388	217	230	223.50	223		10793	10960	10876.5	10876.5	
11,000	0	0												
12,000	11	11	257.55	32.973819	174	305	236.08	260	246, 260	12025	12974	12464.09	12400	
13,000	12	12	278.42	25.854341	210	315	278.42	282	270, 282	13358	13861	13605.92	13615	13600
14,000	28	28	279.61	22.407009	210	315	279.61	282.5		14020	14979	14568.86	14619	14429, 14880
15,000	11	11	293.91	20.762729	264	325	293.91	292.00	280	15000	15705	15333.91	15325	15000
16,000														
17,000	1	334.00			334	334.00								

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 200°F or above can be found at the 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

68) $$y = 2980.4Ln(x) - 9641.1$$

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

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

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

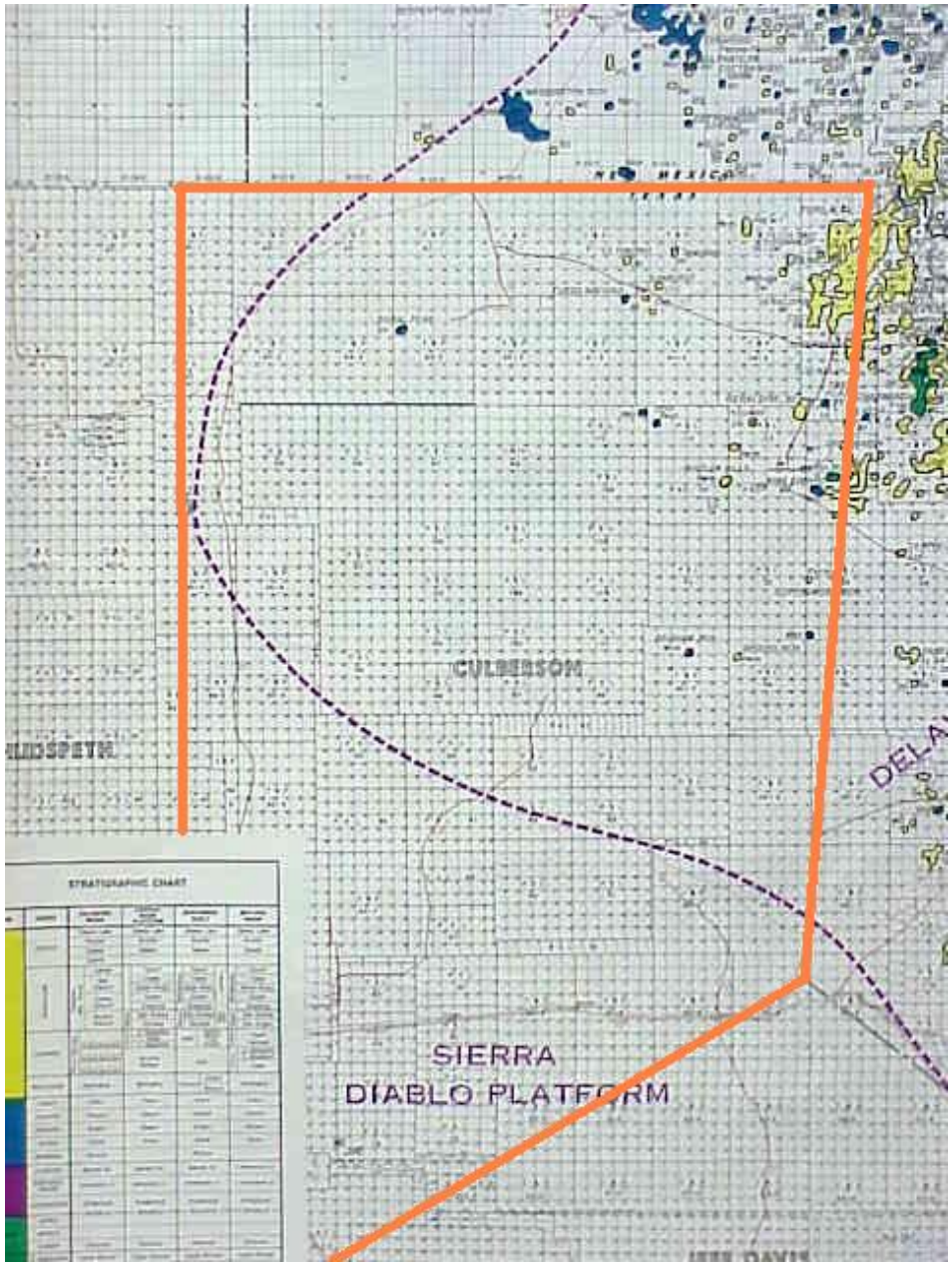
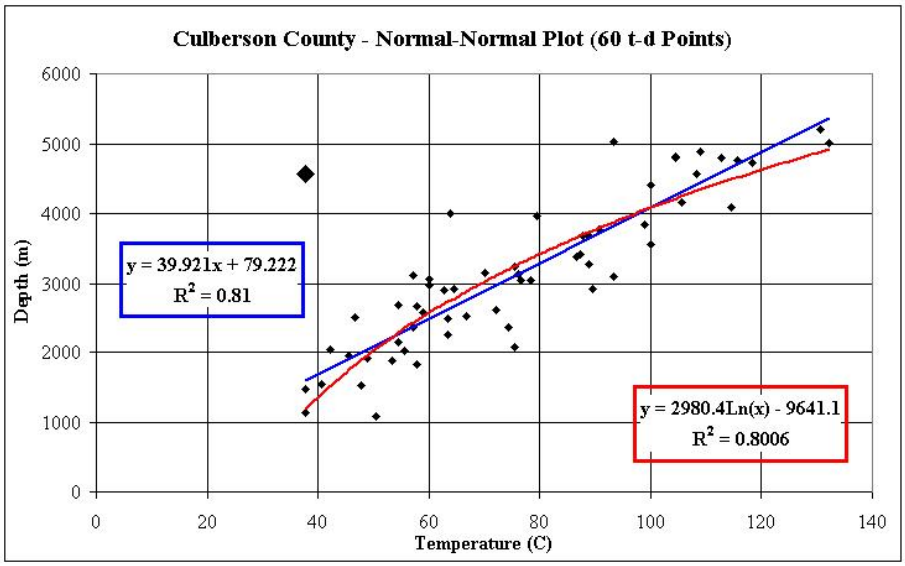


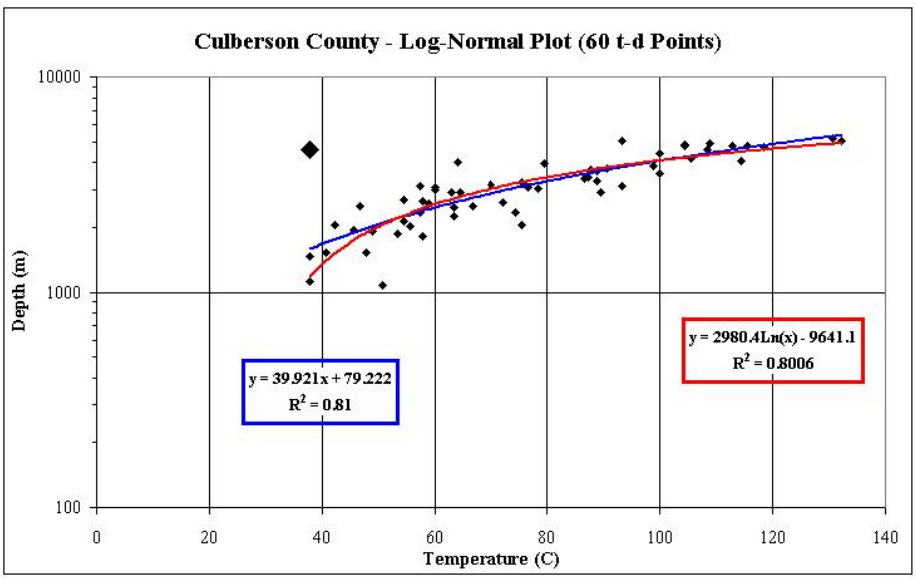
Figure 44. Image from the 1993 Producing Zone of The Permian Basin showing the boundary of Culberson County. The area outlined in orange defines Culberson County. Yellow represents production from Permian formations, blue from Pennsylvanian, purple from Mississippian, green from Devonian and Silurian,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

70) $$\frac{dT}{dz} = (3.3553x10^{-4})e^{0.00033553(z+9641.1)} = -\frac{q}{k}.$$

Finally by substitution we have



A



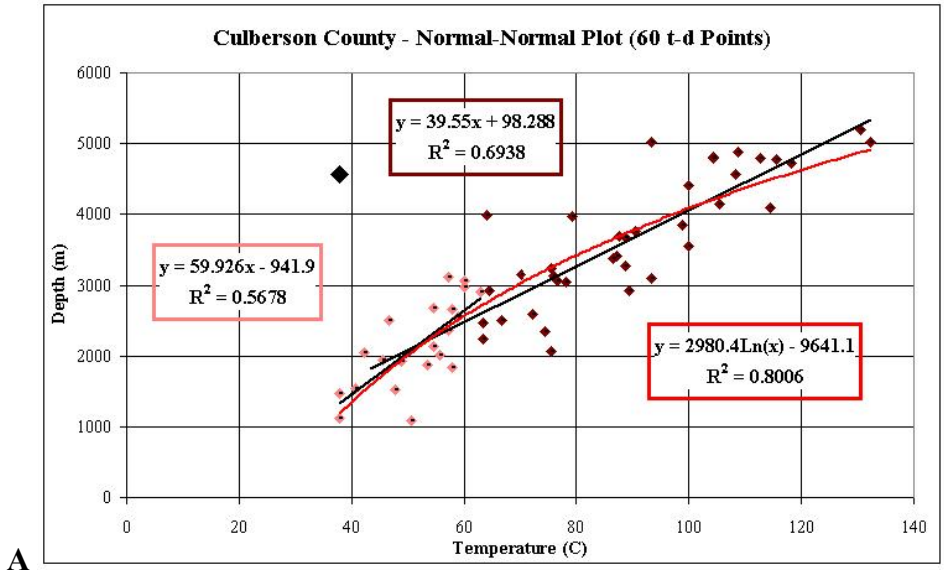
B

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.

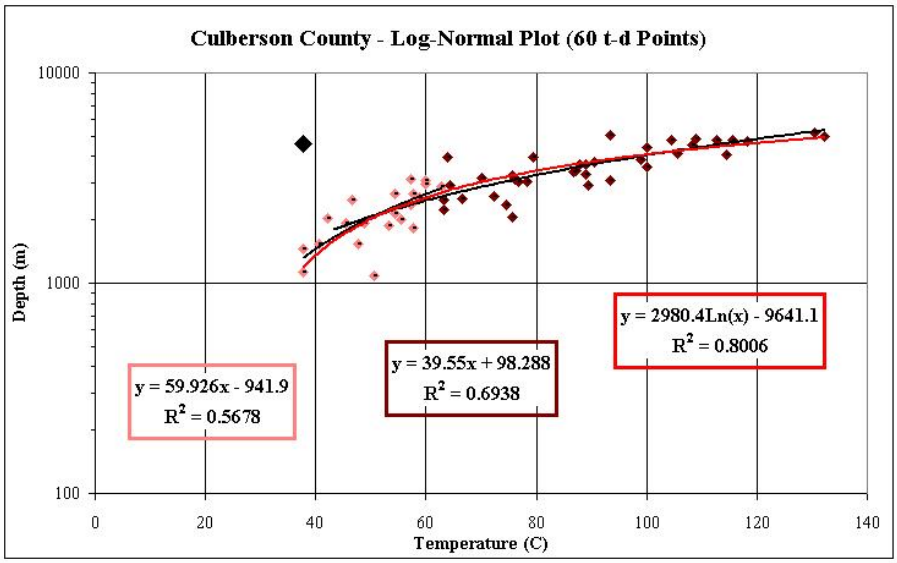
71) $$\frac{dT}{dz} = (3.3553x10^{-4})T = -\frac{q}{k}.$$

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

72) $$\frac{dT}{dz} = 0.025049 = -\frac{q}{k},$$



A



B

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 ~25°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 $R^2_s R^2_d = R^4_{max}$ 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

73) $$\frac{dT_S}{dz} = 0.016687 = -\frac{q}{k},$$

and

74) $$\frac{dT_D}{dz} = 0.025284 = -\frac{q}{k},$$

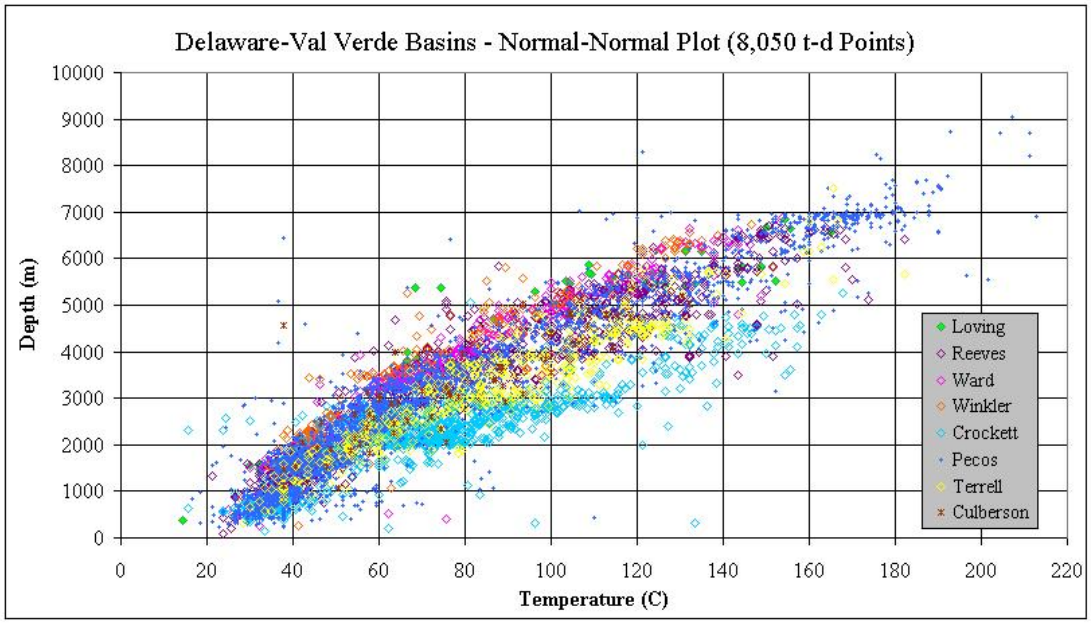
where the T_S and T_D represent temperature in the shallow and deep realm respectively. This suggests that in this model approach the shallow and deep linear thermal gradients in Culberson County are 16.687°C/km and 25.284°C/km, the deeper gradient being about 1.52 times that of the shallow data.

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 200°F were being reached in the 11,000 to 12,000 foot depth intervals.

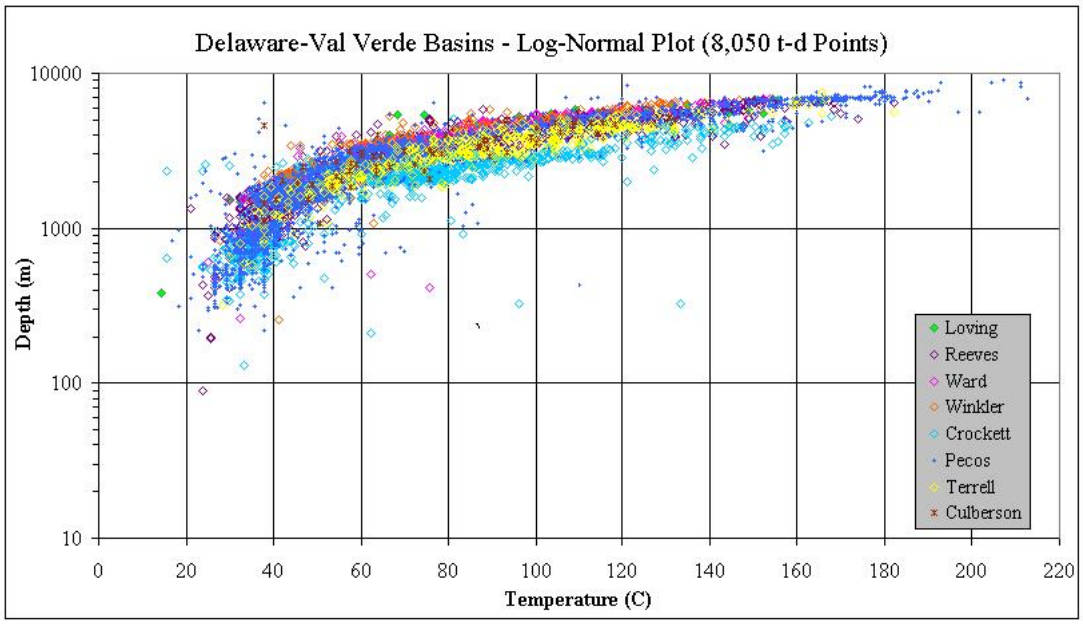
Table 8
Culberson Statistics on Temperature and Depth

depth	Culberson # of points	mean temp	standard deviation	standard error	min temp	max temp	mean temp	median temp	mode temp	min depth	max depth	mean depth	median depth	mode depth
2,000	0													
3,000	1	100			100	100				3700				
4,000	0													
5,000	0													
6,000	3	116.67	10.263200	7.5720	108	128	116.67	114		6147	6695	6401.33	6362	
7,000	4	144.25	15.966110	9.2180	130	166	144.25	156		7025	7745	7460.75	7536.5	
8,000	3	150	13.114877	13.1149	136	162	150	152		8220	8700	8479	8516	
9,000	3	159.33	29.263174	29.2632	140	193	159.33	145		9500	9765	7578	9578	
10,000	3	186	22.300972	22.3010	158	200	186	192		10163	10743	10505.33	10320	
11,000	1	212			212	212				11650	11650			
12,000	2	202.5	9.229157	9.2292	12350	12630	202.5	202.5		12350	12630	12490	12490	
13,000	1	238			238	238				13426	13426			

Basin-Wide Discussion: 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).



A



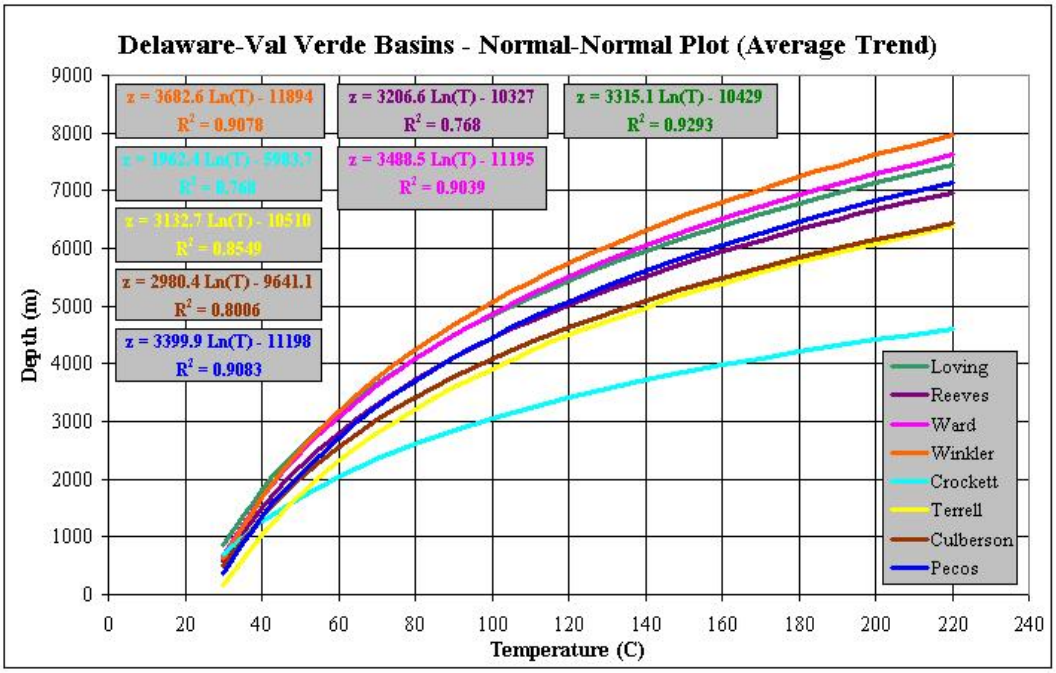
B

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.

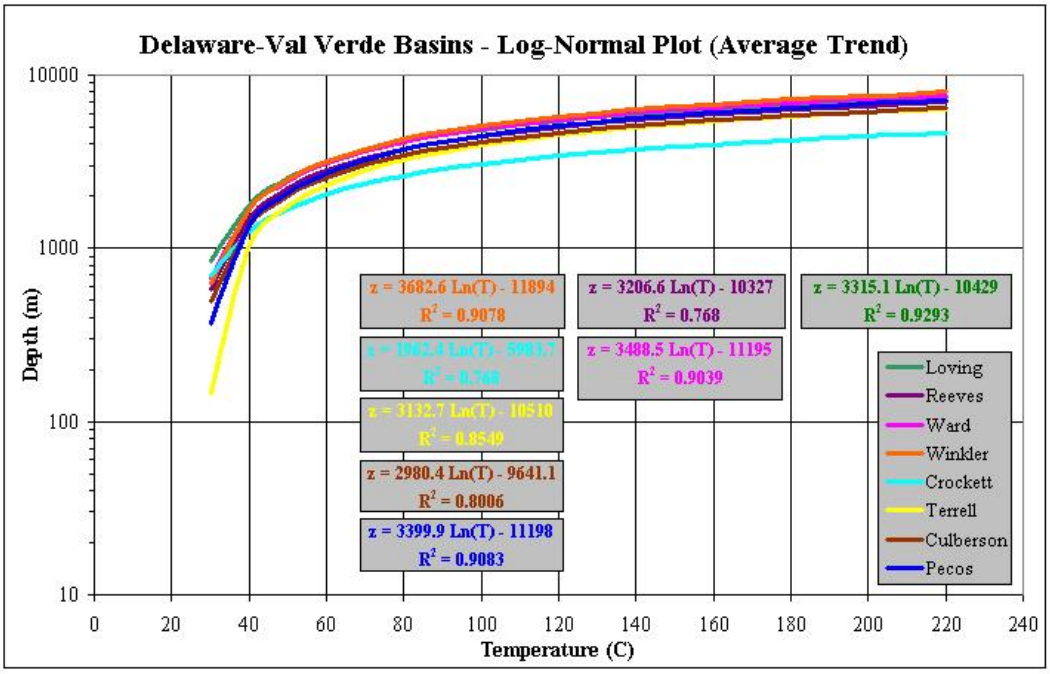
In this graph (Figure 47), Crockett County is found to have the highest temperature gradient, followed by Terrell County. Both of these counties are in the southern part of the study area. Terrell was expected to have a higher temperature gradient due to its proximity to Marathon orogenic activity and 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



A



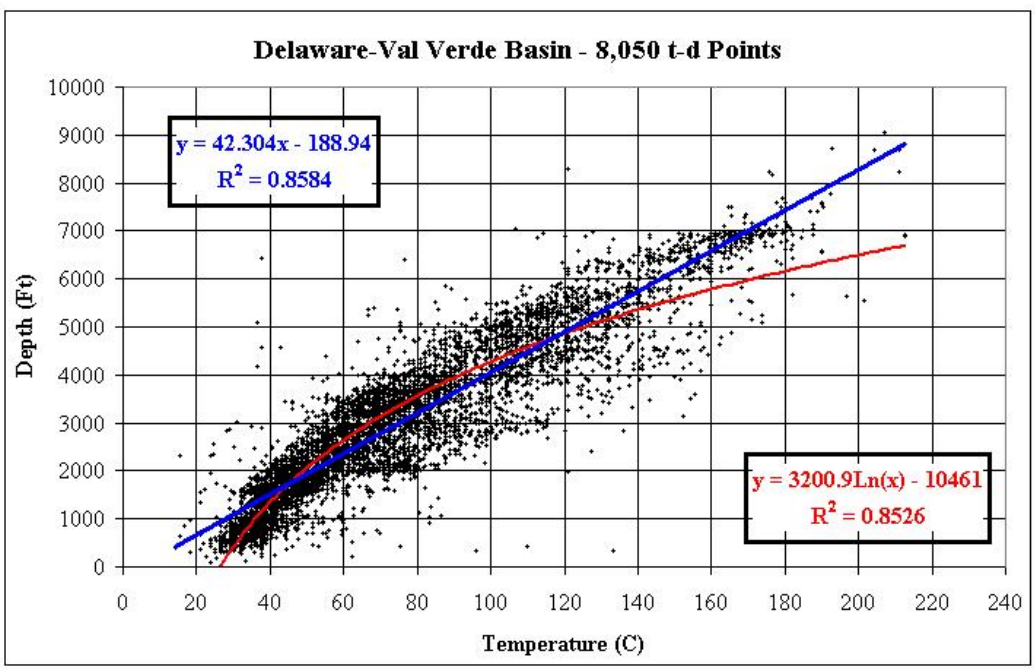
B

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,



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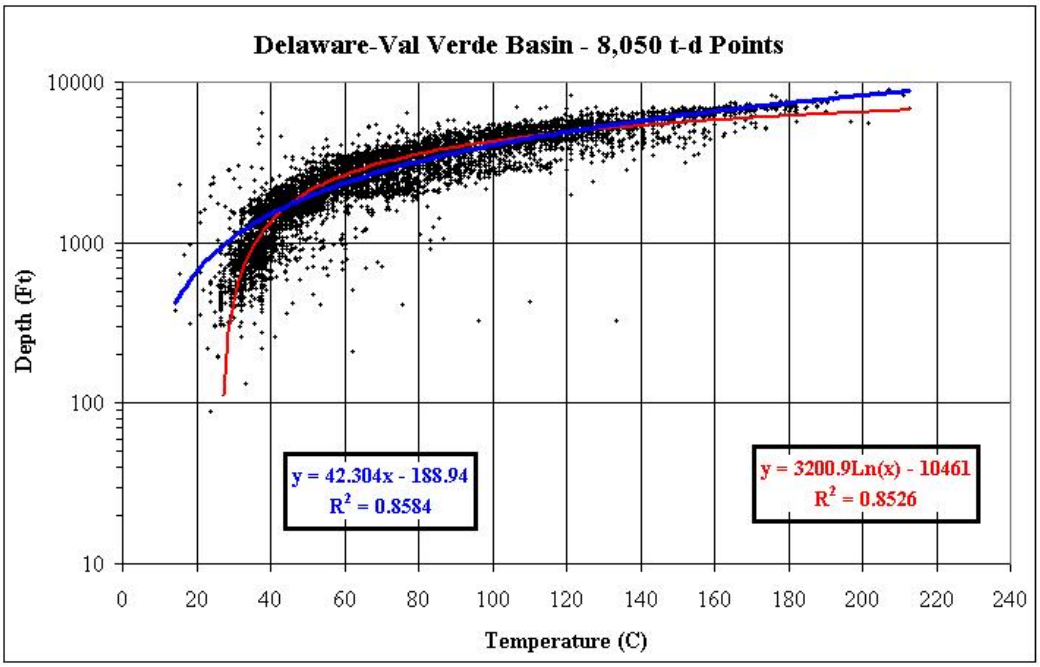


B

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

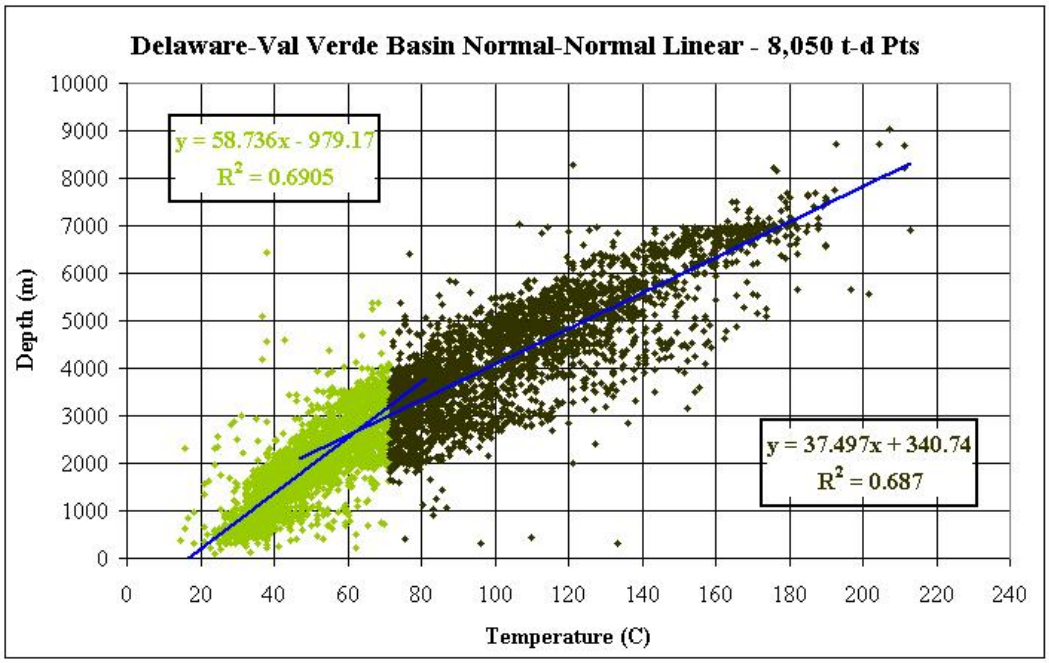
75) (Linear) $$\frac{dT_D}{dz} = 0.023638 = -\frac{q}{k}$$

and

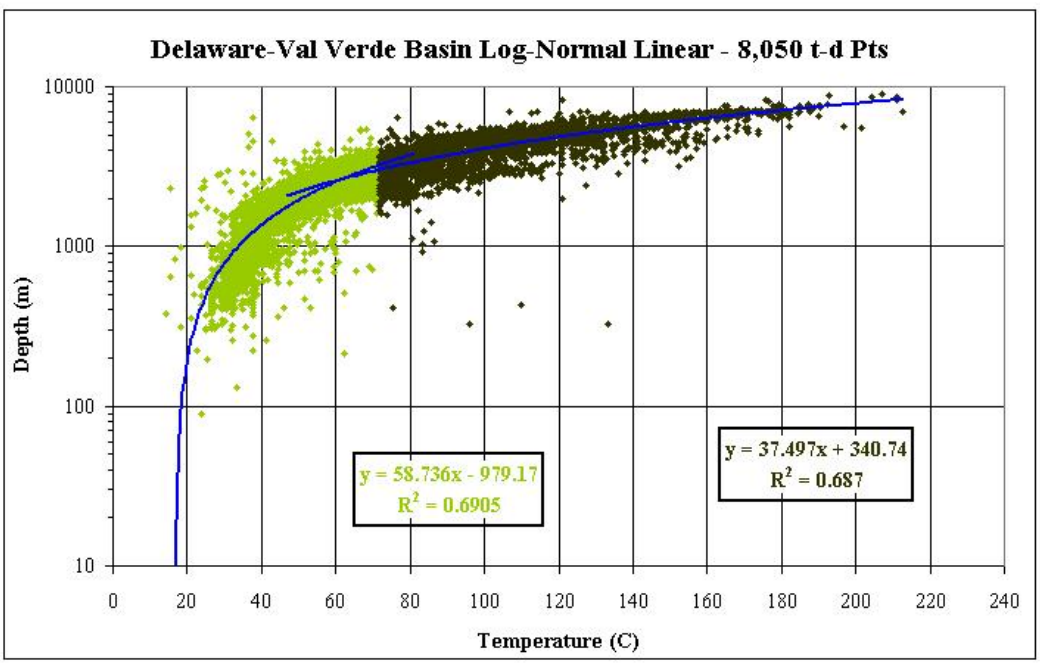
74) (Logarithmic) $$\frac{dT_D}{dz} = (3.1241x10^{-4})e^{0.00031241(z+10461)} = (3.1241x10^{-4})T = -\frac{q}{k}\ .$$

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 $R^2_s R^2_d = R^4_{max}$ 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



A



B

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.

75) $$\frac{dT_S}{dz} = 0.017025 = -\frac{q}{k} \ ,$$

and

76) $$\frac{dT_D}{dz} = 0.026669 = -\frac{q}{k} \ ,$$

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.

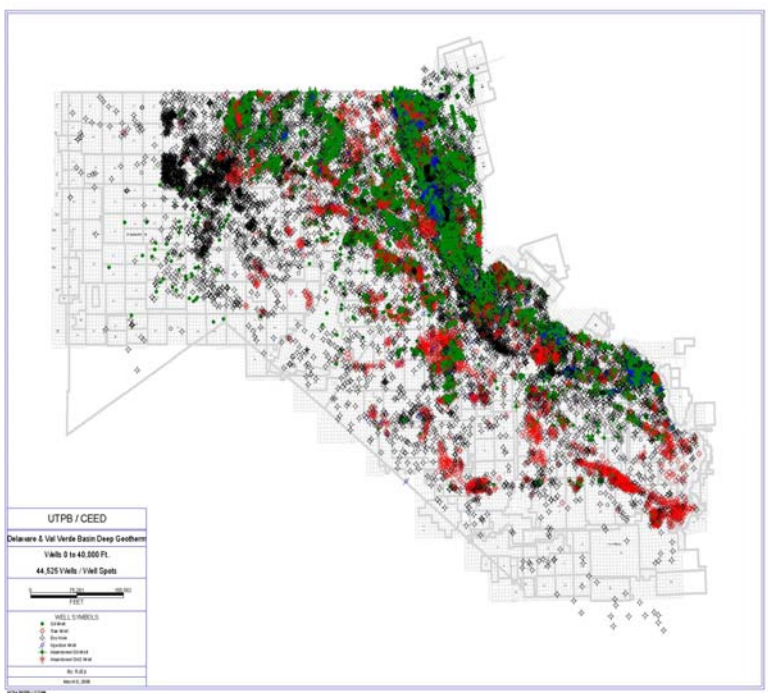


Figure 50. Plot of 44,525 well locations and well spots within the counties of Culberson, Reeves, Loving, Winkler, Ward, Pecos, and Terrell within the Delaware and Val Verde Basins. Crockett County was not included within the GDS well data that was provided for use. Depth is from 0 to 30,000 feet.

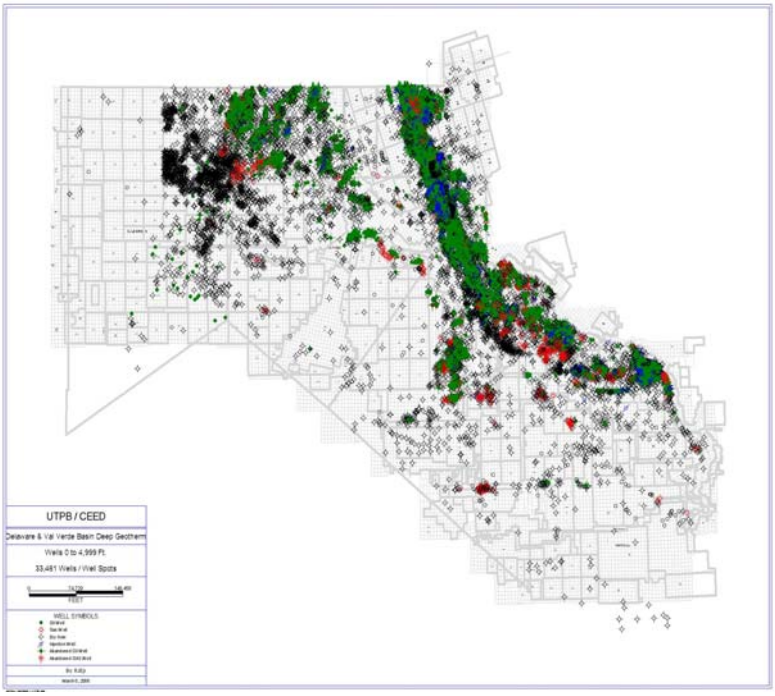


Figure 51. Plot of 33,481 well locations and well spots within the counties of Culberson, Reeves, Loving, Winkler, Ward, Pecos, and Terrell within the Delaware and Val Verde Basins. Crockett County was not included within the GDS well data that was provided for use. Depth is from 0 to 4,999 feet.

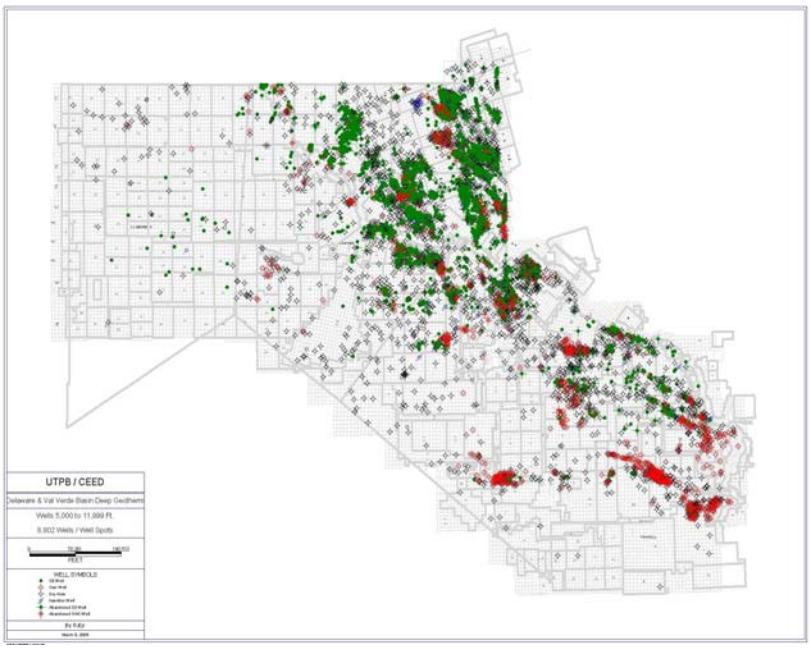


Figure 52. Plot of 8,802 well locations and well spots within the counties of Culberson, Reeves, Loving, Winkler, Ward, Pecos, and Terrell within the Delaware and Val Verde Basins. Crockett County was not included within the GDS well data that was provided for use. Depth is from 5,000 to 11,999 feet.

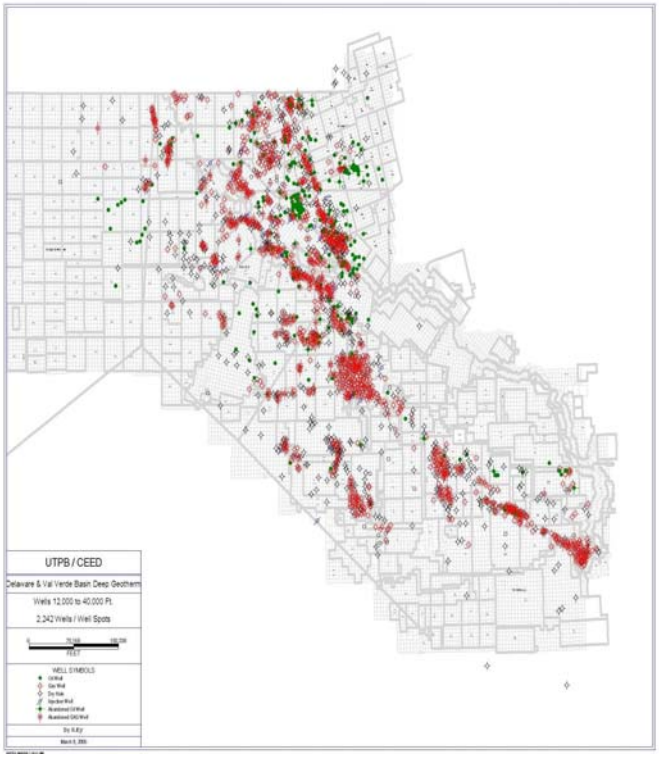


Figure 53. Plot of 2,242 well locations and well spots within the counties of Culberson, Reeves, Loving, Winkler, Ward, Pecos, and Terrell within the Delaware and Val Verde Basins. Crockett County was not included within the GDS well data that was provided for use. Depth is from 12,000 to 30,000 feet.

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

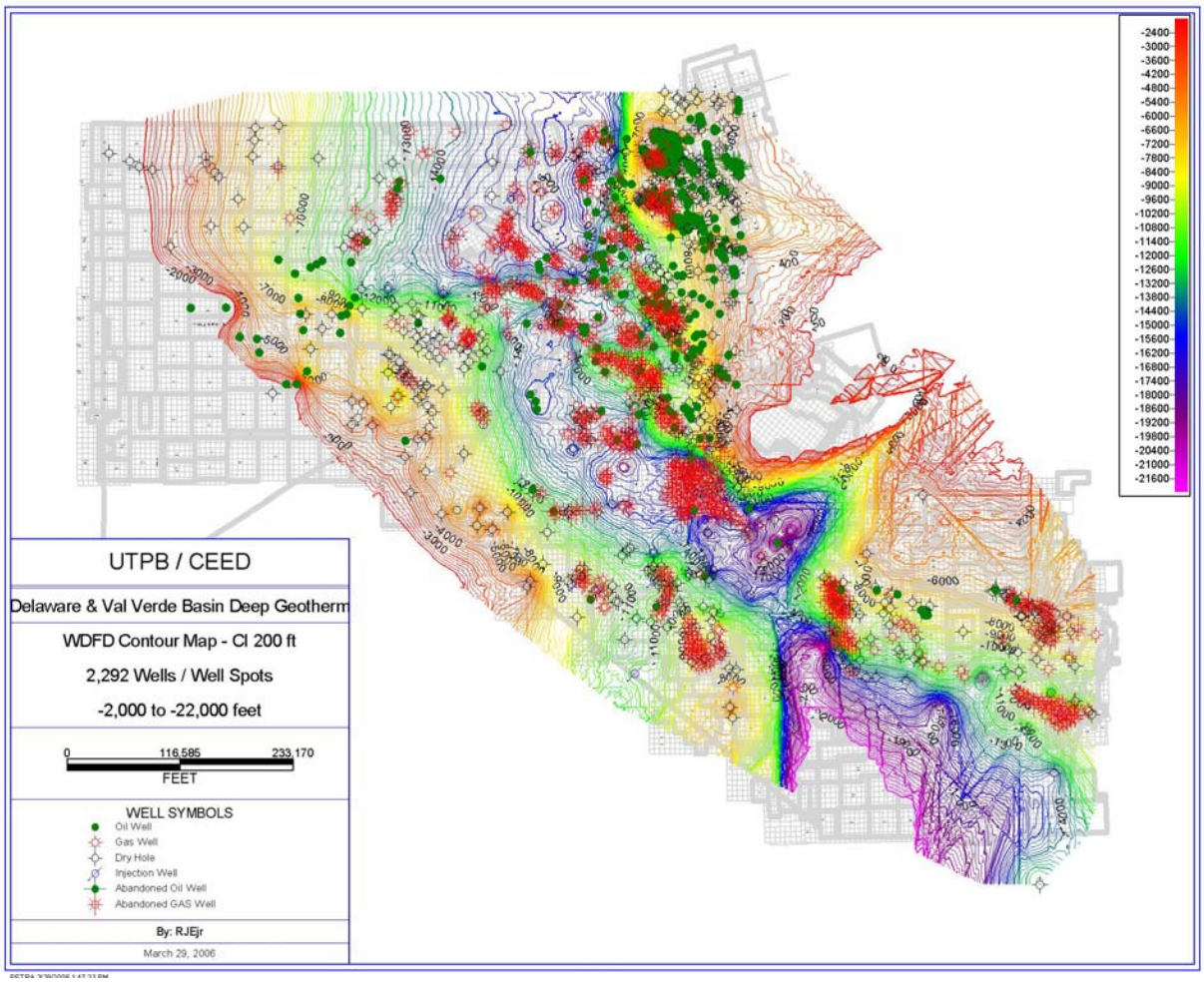


Figure 54. Structure contour map on the top of the Woodford created by Petra with a 200-foot contour interval.

distribution, **<u>mapping temperature within a single target reservoir</u>** 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

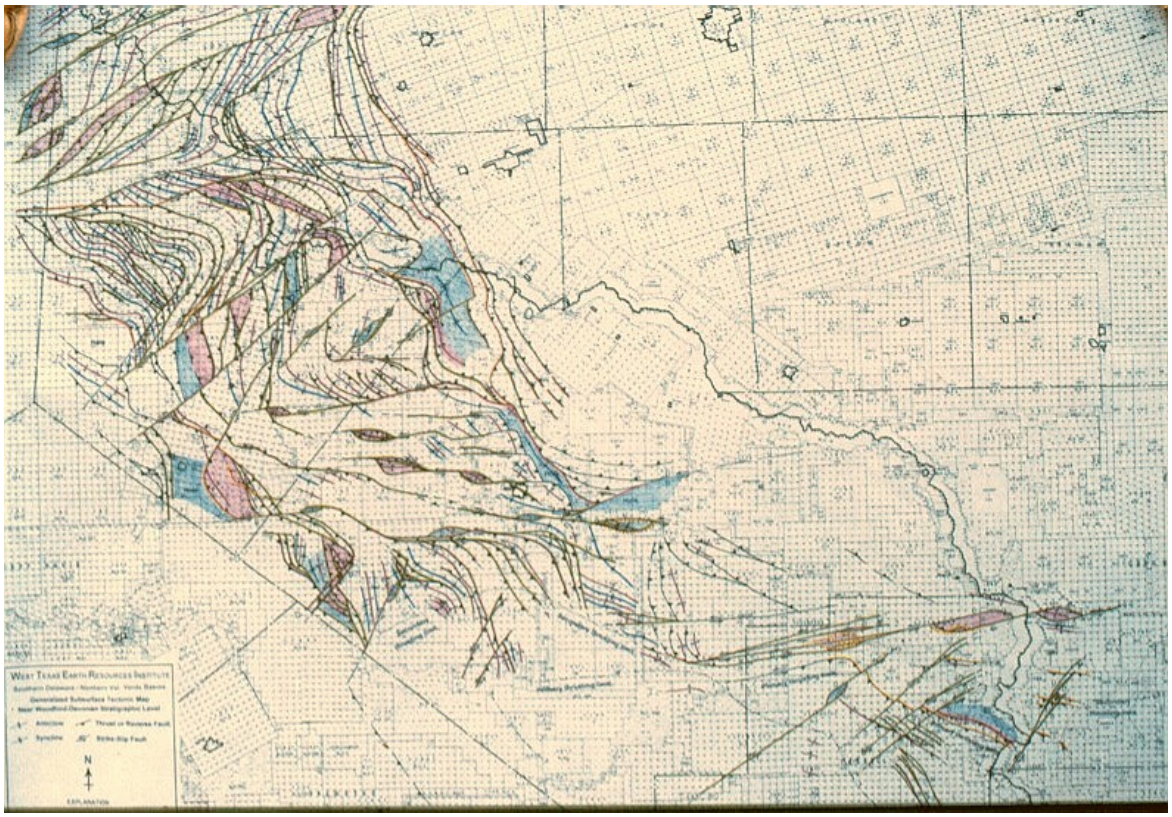


Figure 55. Unpublished tectonic map of the deep Delaware and Val Verde Basins as defined by regional 2D seismic data and well top information provided by Geological Data Services. The areas in blue show down-warped or down-dropped areas while the red areas show uplifted areas.

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° to 270°F, and deepest red from 410° 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

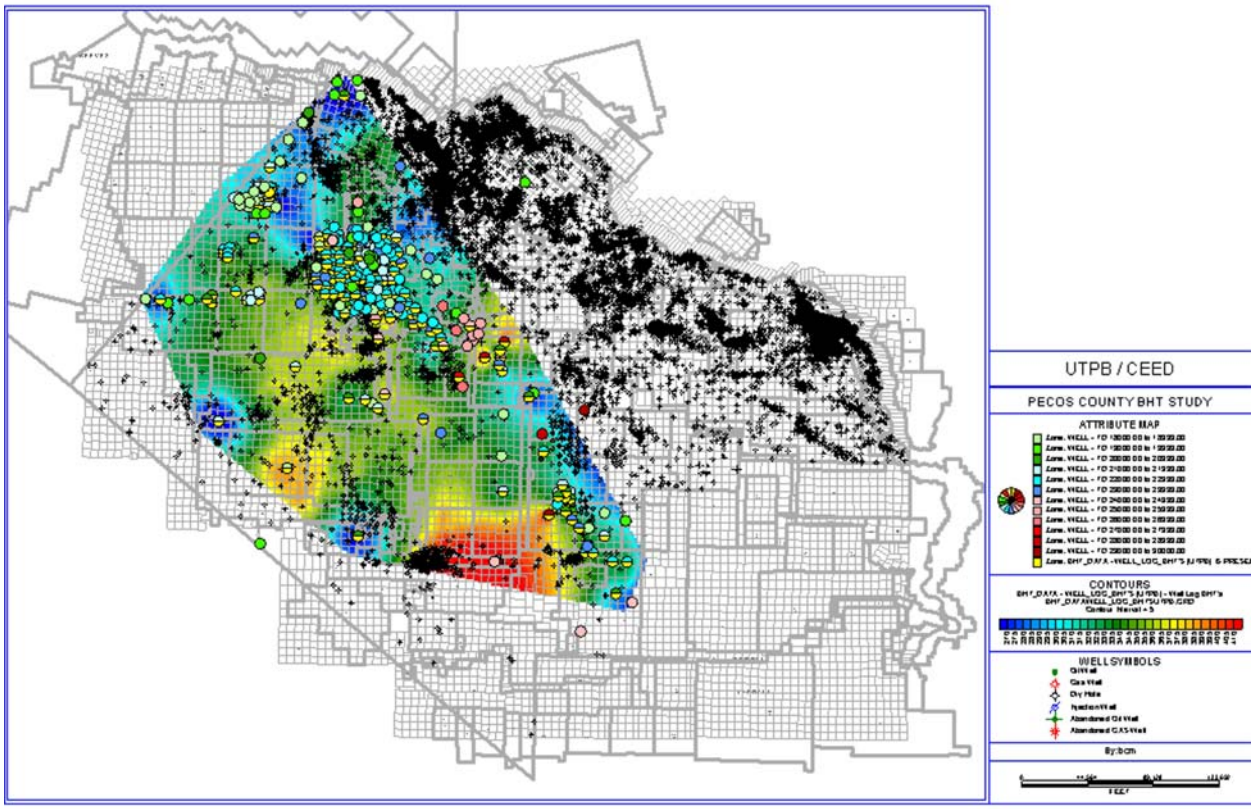


Figure 56. Map of temperatures and associated wells for depths of 18,000 feet and greater.

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 ρc_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 is a given well or

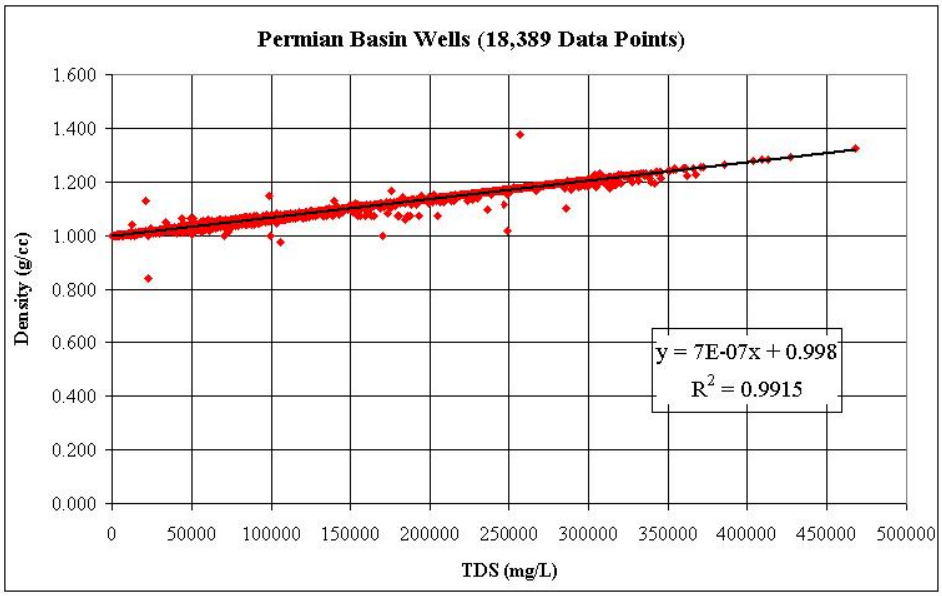


Figure 57. Graphical display of unpublished, proprietary produced brine water in the Permian Basin. Water chemistry database was provided by an anonymous company active in the Permian Basin.

in 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.

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

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

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/m^2, and for dolomite at 68.4 mW/m^2. Similarly, at 150°C for Crockett County, we calculated 167.7 and 218.8 mW/m^2 for limestone in perpendicular and parallel flow conditions, and a value of 275.5 mW/m^2 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 xx 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

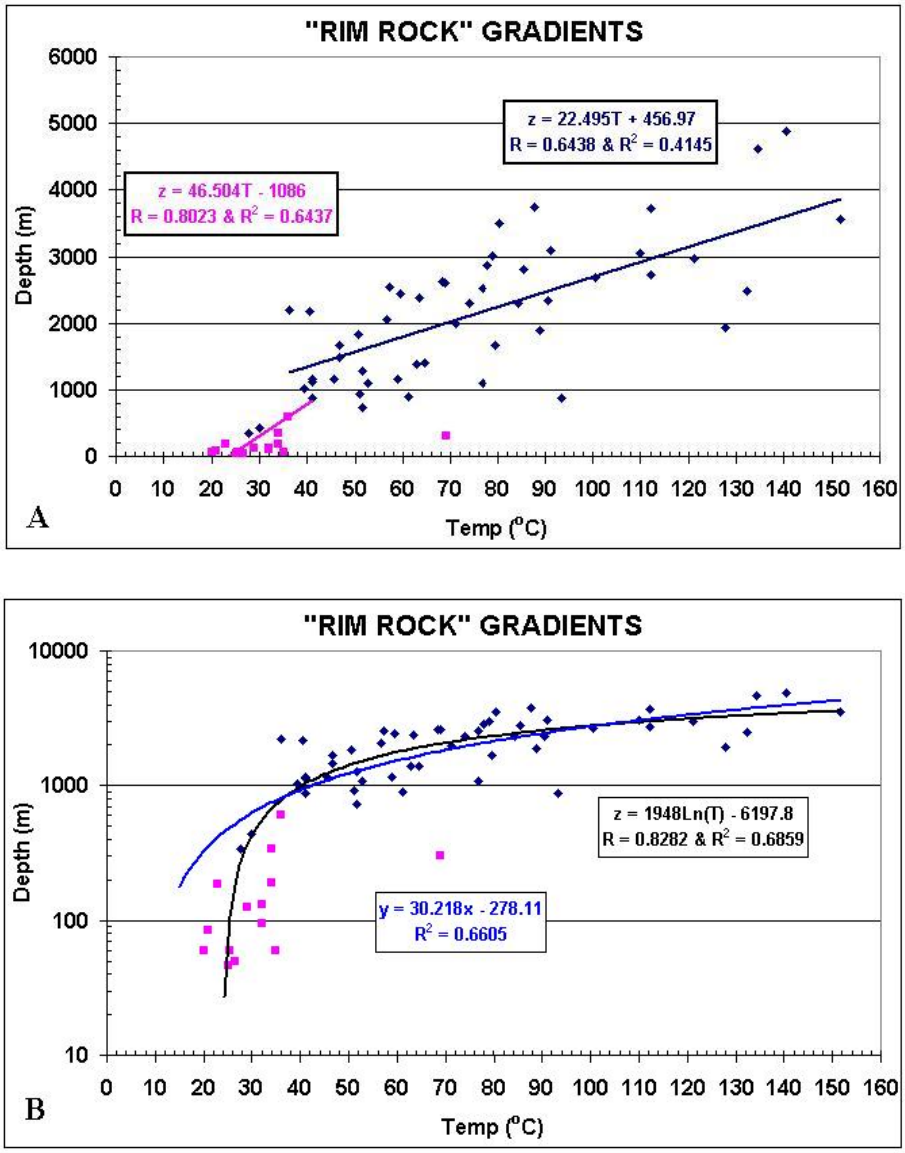


Figure 58. Plots of 65 t-d points within the Presidio County area. Blue diamonds correspond to O&G well BHT data whereas the purple squares are shallow temperature data taken from a file produced by SMU and their Geothermal Laboratory. A) Plot constructed as a normal-normal distribution. B) Plot constructed 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

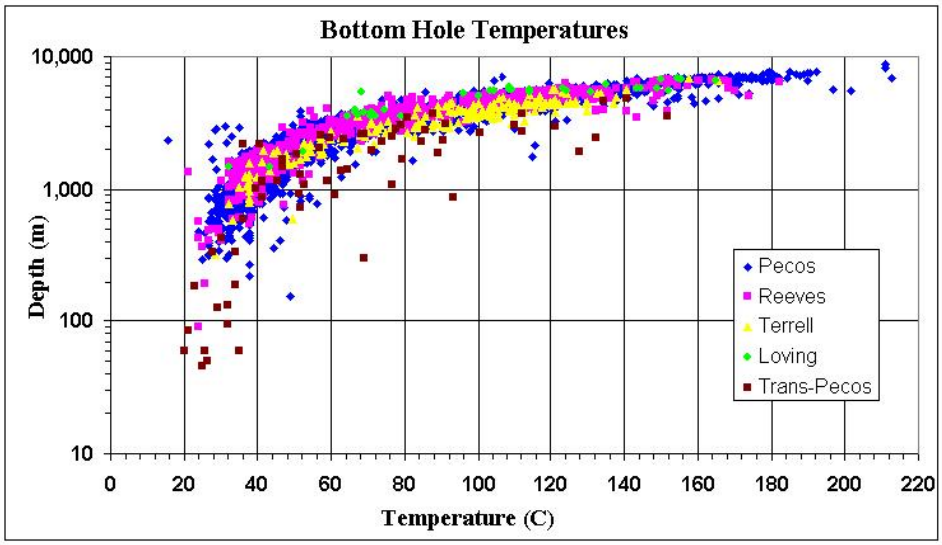


Figure 59. Plot of Trans-Pecos t-d points on top of 3,625 t-d points originally recorded by West Texas Earth Resources and subsequently donated to UTPB/CEED. The brown dots represent the Trans-Pecos data points.

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 best permeable strata will be accomplished based upon the available oil and gas produced 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 interview 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 geopressured 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 mush 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 up from a 'deeper' zone due to basement complexes not necessarily be water-wet. 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.

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 on the General sheet – I put this back in so we can locate the logs entered for the CEED catalog

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 INVORMATION 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 "**f**rom **n**orth **l**ine" (or south) in K and L, "from east line" (or west) in M
L/12 and N. Many of these surveys were done using magnetic north (like Midland County) so if you look at
M/13 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
N/14 "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.

O/15 Latitude and longitude – we'll have to look those up later on 95%+ of the wells. The ones we can't find

P/16 will probably be the wells drilled before electric/sonic, etc. logs were invented. They won't have information we need, anyway.

Q/17 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.

R/18 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.

S/19 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.

T/20 Completion Date – completion dates are usually a day or more after the logging date. We'll have to get that elsewhere

U/21 Elevations – Surface, ground, land - whatever you walk on....

V/22 Floor – the drilling rig floor

W/23 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)

X/24 Log Datum – sometimes logs are measured from KB, sometimes from GL

Y/25 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.

Z/26 Drilling Contractor – we may have to look for this information. Some give reliable information, others guess.

AA/27 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.

AB/28 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.

AC/29 FM at TD – or formation at TD

AD/30 Logged Top – they don't necessarily log all the way to the top, especially on a second or later logging run.

AE/31 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 – **B**arrels of **O**il **P**er **D**ay,
AM/39 **B**arrels of **W**ater **P**er **D**ay
AN/40 **T**housand **C**ubic **F**eet of **G**as per **D**ay – 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 – **H**eld **B**y **P**roduction, 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
N/14 (pronounced Slumber-jay) or Hal for Halliburton, etc – rather than for us to try to sort out all of the types

O/15 of sonic logs, neutron/neutron-density logs, etc. There's a difference between a mud log and a sample
P/16 – examples are on the paper with headres, etc. Sometimes we get lucky and find a dip meter log, a
Q/17 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

R/18 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.

S/19 Record the name of the original operator. When we go into the University Lands office, we may need to add "next operator" to this.

T/20 Repeats - the **O**il **W**ell **W**ork **O**ver or **O**il **W**ell **D**rilled **D**eeper.
U/21 Driller's depth – (number of joints of pipe in the well x 30)
V/22 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

W/23 There usually are multiple casing strings - we may need to add more columns here, too.
X/24 And a space for extra casing strings not reported with the logging runs – later.

Y/25 These are repeats again. The logger often does not agree with the driller – cable stretch....
Z/26 The logged depth may not be all the way to the bottom – or to the top.
AA/27

AB/28 Do we have the 4 x 6 new card (or the old 8 x 5 card) and how many?
AC/29 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.

AD/30 Do we have access to the well file information? Or <u>DO WE NEED TO CONTACT SOMEONE TO GET IT?</u>

AE/31 This would be forms filed with the Rail Road Commission. They should also be in the well file – if we have it.

AF/32 Date the well was completed – few days after the logging date.

AG/33 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".

AH/34 This collection is data specific to a logging run – the date, the top of the logged interval, the driller's TD,
AI/35 bit size and casing size.
AJ/36
AK/37 (AM/39, AN/40, AO/41, AP/42, AQ/43 – run 2)
AL/38 (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!

AW/49 Surface bit – the biggest one – we may not find this information
AX/50 Surface casing – this is specified by the Railroad Commission and is supposed to be deep enough to protect whatever aquifer.

AY/51 After they get below the depth they must protect, they can go to a smaller diameter bit. For shallow wells,
AZ/52 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"

BA/53 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".

BB/54 Fluid level – this information often is not available

BC/55 Fluid density – barium and other things are added to the fluid to keep formation water/gas from
BD/56 getting into the sides of the well bore. There's a place for fluid viscosity and pH on the log header but it
BE/57 isn't very often found filled in. If they know they are loosing fluid into the formation, sometimes that loss is
BF/58 reported. And if they get a sample of the water, does it come from the tanker that brought in the fluid or
BG/59 did it come form the mud pit?
(BH/60, BI/61, BJ/ 62, BK/63, BL/64, BM/65, BN/66 for run 2), (BO/67, BP/68, BQ/69, BR/70, BS/71, BT/72, BU/73 for run 3) And again, we may need to copy and paste more in here but by then, it probably won't matter.

BV/74 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.

BW/75 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.
BX/76 These columns are for formation tops for the major formations followed by a space for whatever .
BY/77 comments. I don't know if we will have the fun of doing this or not. Some are easy, others are not.
BZ/78 The main thing is to be consistent. **And start at the bottom of the log and work up** – this is the way to
CA/79 build a cake (lasagna?) from the bottom. If there has been erosion, you're more likely to catch it
CB/80 if you work bottom up than top down.
CC/81
CD/82 The only place this set differs is with the Woodford. It is a shaley layer, usually above "clean" limestone
CE/83 or dolomite – this call causes trouble occasionally but I suspect I'll show it to you once and you'll have
CF/84 little to no trouble finding it! I left a space for the top of the Woodford.
CG/85
CH/86 If we find Cambrian or Precambrian other than on the Central Basin Platform, I'll be amazed.
CI/87
CJ/88
CK/89
CL/90
CM/91

CN/92

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 if 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 **S**tem **T**est 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 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 cfgph **c**ubic feet of **g**as **p**er **h**our 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
U/21 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).

V/22 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.

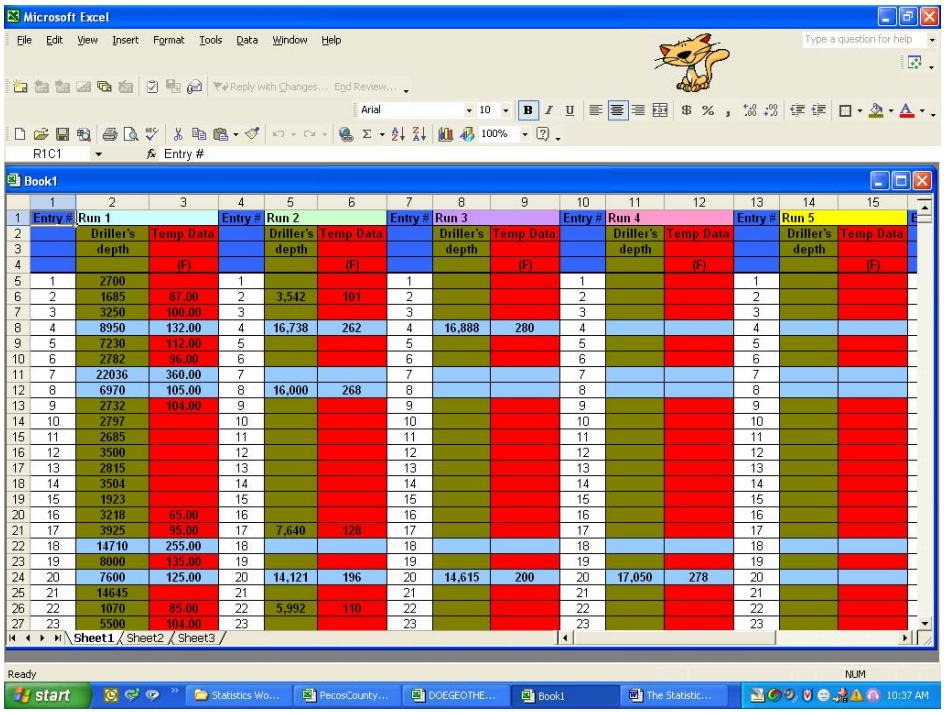
Appendix 2

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 felt 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.

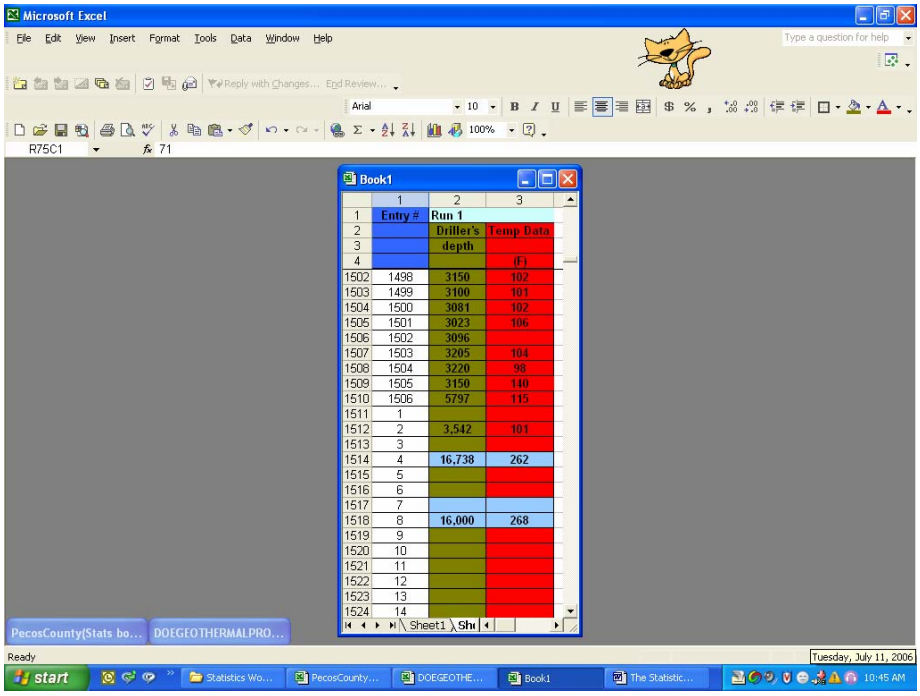
Note: (the print screen insert below does not show all the runs for workbook from which it was copied. This is just an example)



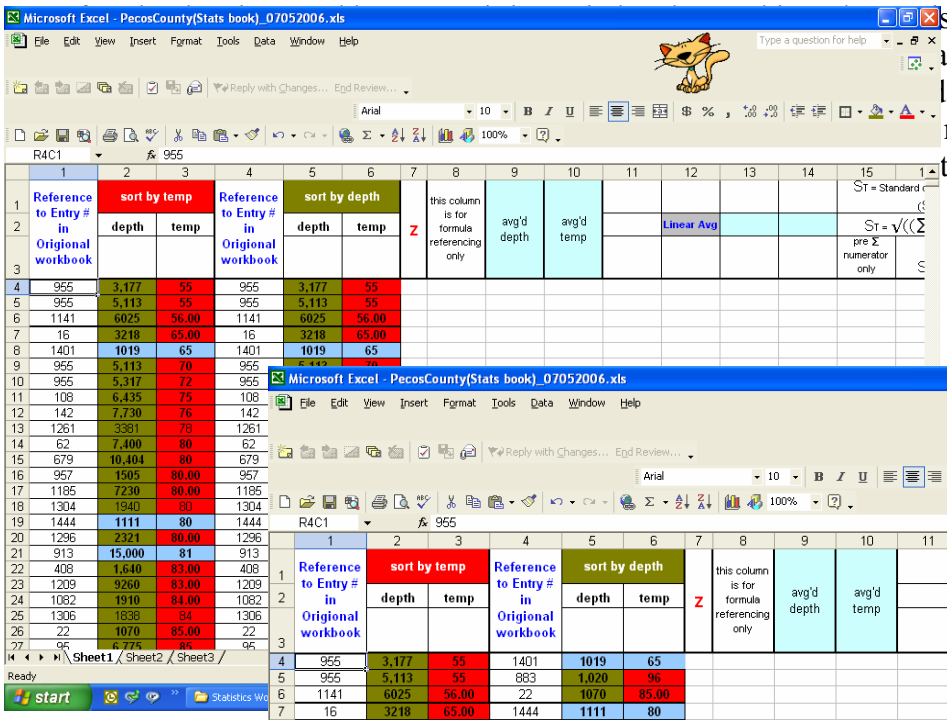
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Entry #	Run 1		Entry #	Run 2		Entry #	Run 3		Entry #	Run 4		Entry #	Run 5	
2		Driller's	Temp Data		Driller's	Temp Data		Driller's	Temp Data		Driller's	Temp Data		Driller's	Temp Data
3		depth			depth			depth			depth			depth	
4			(F)			(F)			(F)			(F)			(F)
5	1	2700		1			1			1			1		
6	2	1685	87.00	2	3,542	101	2			2			2		
7	3	3250	100.00	3			3			3			3		
8	4	8950	132.00	4	16,738	262	4	16,888	280	4			4		
9	5	7230	112.00	5			5			5			5		
10	6	2782	96.00	6			6			6			6		
11	7	22036	360.00	7			7			7			7		
12	8	6970	105.00	8	16,000	268	8			8			8		
13	9	2732	104.00	9			9			9			9		
14	10	2797		10			10			10			10		
15	11	2685		11			11			11			11		
16	12	3500		12			12			12			12		
17	13	2815		13			13			13			13		
18	14	3504		14			14			14			14		
19	15	1923		15			15			15			15		
20	16	3218	65.00	16			16			16			16		
21	17	3925	95.00	17	7,640	128	17			17			17		
22	18	14710	255.00	18			18			18			18		
23	19	8000	135.00	19			19			19			19		
24	20	7600	125.00	20	14,121	196	20	14,615	200	20	17,050	278	20		
25	21	14645		21			21			21			21		
26	22	1070	85.00	22	5,992	110	22			22			22		
27	23	5500	104.00	23			23			23			23		

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 starts over.

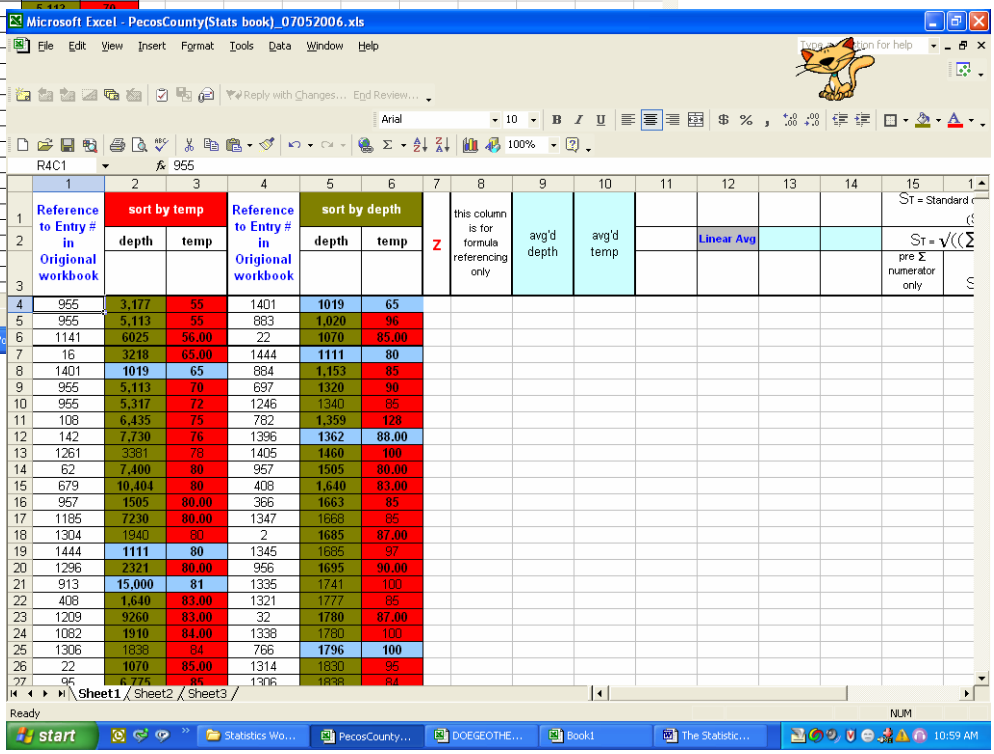


	Entry #	Run 1	
		Driller's depth	Temp Data (F)
1502	1498	3150	102
1503	1499	3100	101
1504	1500	3081	102
1505	1501	3023	106
1506	1502	3096	
1507	1503	3205	104
1508	1504	3220	98
1509	1505	3150	140
1510	1506	5797	115
1511	1		
1512	2	3,542	101
1513	3		
1514	4	16,738	262
1515	5		
1516	6		
1517	7		
1518	8	16,000	268
1519	9		
1520	10		
1521	11		
1522	12		
1523	13		
1524	14		



Reference to Entry # in Origional workbook	sort by temp depth	sort by temp temp	Reference to Entry # in Origional workbook	sort by depth depth	sort by depth temp	Z	this column is for formula referencing only	avg'd depth	avg'd temp	Linear Avg	ST = Standard	ST = √((Σ
											pre Σ numerator only	
955	3,177	55	955	3,177	55							
955	5,113	55	955	5,113	55							
1141	6025	56.00	1141	6025	56.00							
16	3218	65.00	16	3218	65.00							
1401	1019	65	1401	1019	65							
955	5,113	70	955									
955	5,317	72	955									
108	6,435	75	108									
142	7,730	76	142									
1261	3381	78	1261									
62	7,400	80	62									
679	10,404	80	679									
957	1505	80.00	957									
1185	7230	80.00	1185									
1304	1940	80	1304									
1444	1111	80	1444									
1296	2321	80.00	1296									
913	15,000	81	913									
408	1,640	83.00	408									
1209	9260	83.00	1209									
1082	1910	84.00	1082									
1306	1838	84	1306									
22	1070	85.00	22									

stics Workbook in the
can be sorted by depth
lata with depth and
no use in the
t have depth and temp



Reference to Entry # in Origional workbook	sort by temp depth	sort by temp temp	Reference to Entry # in Origional workbook	sort by depth depth	sort by depth temp	Z	this column is for formula referencing only	avg'd depth	avg'd temp	Linear Avg	ST = Standard	ST = √((Σ
											pre Σ numerator only	
955	3,177	55	1401	1019	65							
955	5,113	55	883	1,020	96							
1141	6025	56.00	22	1070	85.00							
16	3218	65.00	1444	1111	80							
1401	1019	65	884	1,153	85							
955	5,113	70	697	1320	90							
955	5,317	72	1246	1340	85							
108	6,435	75	782	1,359	128							
142	7,730	76	1396	1362	88.00							
1261	3381	78	1405	1460	100							
62	7,400	80	957	1505	80.00							
679	10,404	80	408	1,640	83.00							
957	1505	80.00	366	1663	85							
1185	7230	80.00	1347	1668	85							
1304	1940	80	2	1685	87.00							
1444	1111	80	1345	1685	97							
1296	2321	80.00	956	1695	90.00							
913	15,000	81	1335	1741	100							
408	1,640	83.00	1321	1777	85							
1209	9260	83.00	32	1780	87.00							
1082	1910	84.00	1338	1780	100							
1306	1838	84	766	1796	100							
22	1070	85.00	1314	1830	95							

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 ∑ numerator column, column 16, uses column 9 in that calculation.

Column 10 & 11 – This is simply a place fro 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 ∑ 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.

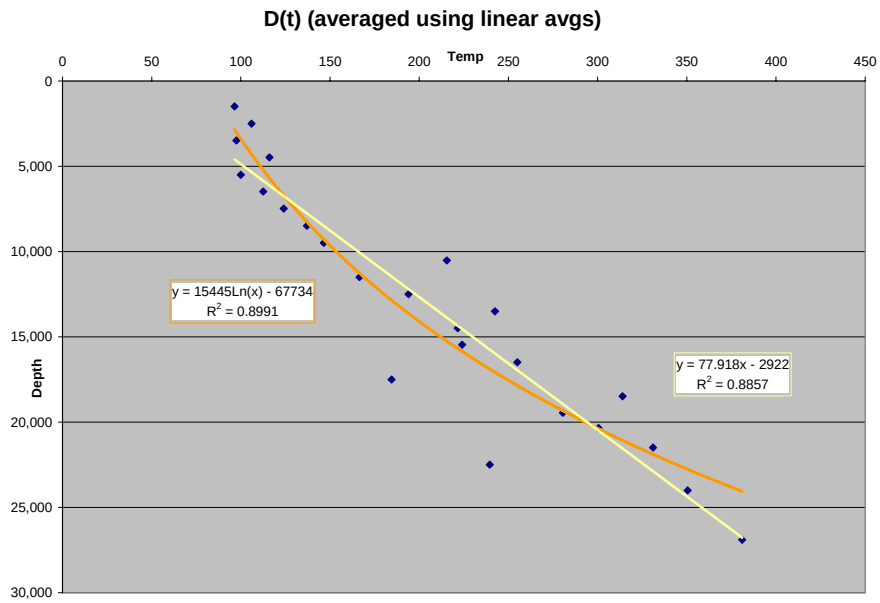
Note: Within columns 10 – 14 there are some other statistical values. The max and min for the temp and depth and the mean, median and mode for the temp. The max and min are used in setting up columns 22 & 23 which are used for the graph "D(t) avgd using linear avg." The mean, median and mode are for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

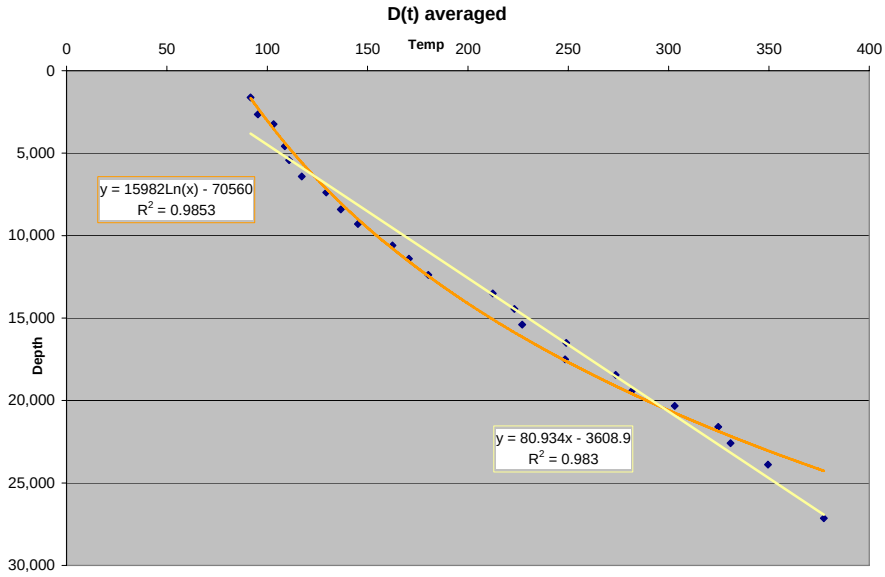
Purpose:

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

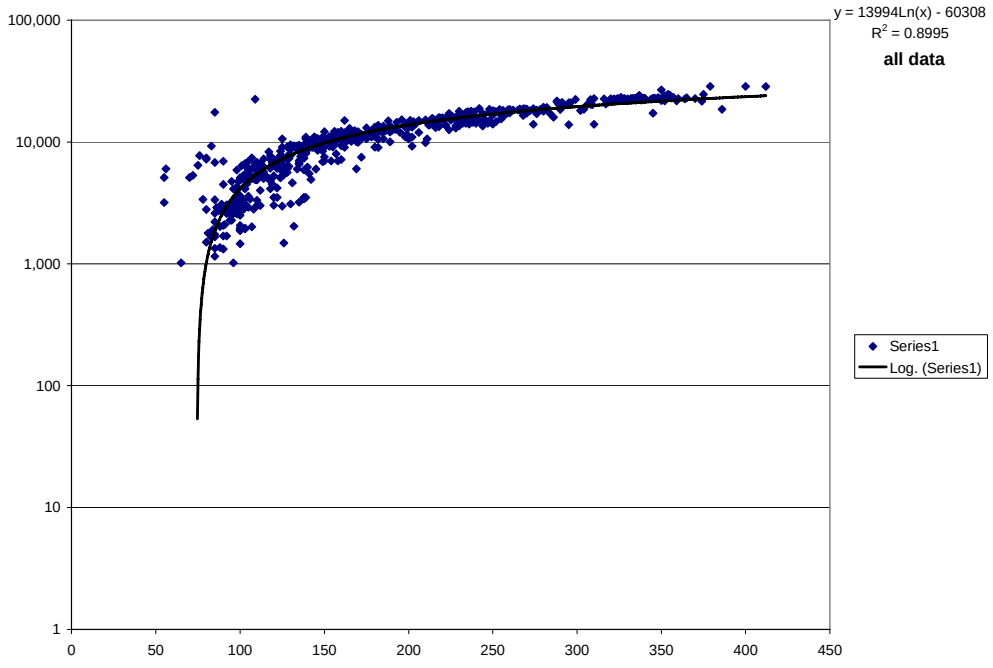
This appendix is based upon certain errors that were noted between the drillers depths and the loggers depth as observed on the log header information. Reference is made to a file named "@PecosCounty(compensated book)_07052006.xls".

July 5, 2006
Michael W. Sorensen

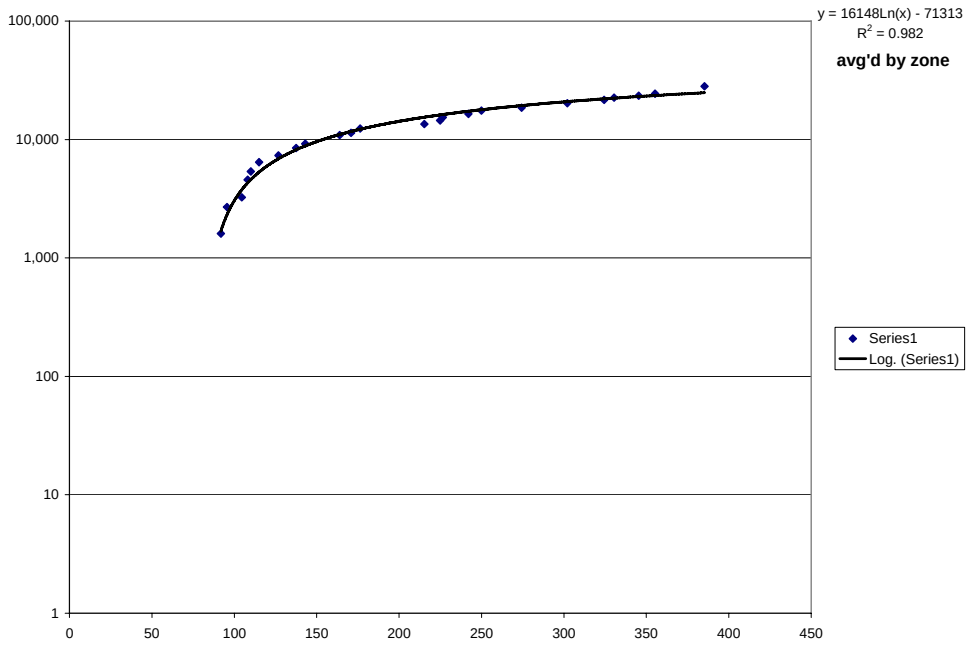
After generating a plot for the overall trend for the Pecos County data it was discovered that there were several temperatures that appeared to be abnormal for the depths associated with the points on the graph. The initial data input was, and will continue to be, input into the file "DOEGEOTHERMALPROJECT_Pecos 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 obivious. 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.



avg'd depth	avg'd temp
1606.00	91.86
2695.32	95.57
3250.60	104.51
4577.32	108.14
5365.96	110.04
6442.18	115.03
7337.47	126.79
8475.83	137.50
9229.71	143.05
10879.42	163.96
11394.82	170.82
12384.85	176.39
13514.81	215.34
14480.08	224.88
15380.65	226.56
16442.67	242.08
17518.36	249.86
18550.65	274.35
20284.29	302.00
21580.81	324.38
22592.82	330.49
23393.00	345.33
24380.25	355.25
28108.50	385.25



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