FINAL REPORT

GEOTHERMAL POTENTIAL OF THE RIO GRANDE RIFT:
A CRITICAL ASSESSMENT

by

UNIVERSITY OF UTAH
STUDENT GEOTHERMAL TEAM

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1. EXECUTIVE SUMMARY

In accordance with the project plan, we began our critical assessment of the geothermal potential of the Rio Grande Rift by making a complete inventory of all printed and web resources for the region. The assessment followed principles learned in a Fall Semester, 15 week course “Geothermal Systems for Geoscientists” at the University of Utah. For the Rio Grande Rift a base map was assembled and through extensive data mining, spatial correlation of relevant demographic, infrastructure, and geothermal datasets was done using ArcMAP.

Of the more than 40 spatial data sets available, we determined the following data to be most useful in making a critical geothermal assessment: (1) heat flow measurements and mapping, (2) geochemistry of spring and well waters, (3) geologic mapping focused on young volcanics and intrusives, and (4) regional and local hydrology. Infrastructure (power plant, power line, population centers, and highway locations) became important once the geothermal resource was identified.

By critical assessment using geology, spring and water well chemistry, heat flow and geophysical anomalies the team identified four potential geothermal reservoir sites having potential

![Figure 1: ArcMap image with sites of recommended geothermal reservoir development.](image-url)

for geothermal power production or direct heat applications: Mt. Princeton, Valles Caldera, Magdalena,
and the Hueco Basin.

Two of these sites were chosen for detailed reservoir quantification and geothermal development plans. Thermal energy in each reservoir was calculated and compared to results computed with GEOFRAT. The Mt Princeton site is considered as an example of a high temperature reservoir suitable for binary plant power generation. The power potential for a 30 year use is estimated to be 8.5 MW_{electric}. The second system is more appropriate for direct heat application. Land-use regulations limit access for geothermal development of the Valles Caldera system to a low temperature reservoir in Jemez Springs. We estimate a 1.1 GW_{thermal}. Also within this system, an analysis was made of the Los Alamos Hot Dry Rock (HDR) Development Program at Fenton Hill with a proposal of improvements for a successful enhanced geothermal system.

This student driven project achieved all goals set out in the project plan. In making the geothermal potential assessment, we developed an ordered hierarchy for data importance (heat flow, spring and well geochemistry, geology, hydrology) in the exploration phase. We identified that, mapping and further geophysical exploration surveys are needed for the Magdalena and Hueco Basin sites. The project also provided multiple data sets in ArcMap format that could be included as case studies in future geothermal curricula, for example in a modification of the University of Utah course “Geothermal Systems for Geoscientists.”
2. THE STUDENT GEOTHERMAL TEAM (G-TEAM)

The University of Utah assembled a multidisciplinary student geothermal team (G-Team) to produce a comprehensive assessment of the geothermal energy potential of the Rio Grande Rift geologic province. The G-Team had three faculty members with extensive geothermal experience to act as resource personnel: David Chapman, Distinguished Professor in the Department of Geology and Geophysics, at the University of Utah who is an expert in heat flow studies; Rick Allis, Director of the Utah Geological Survey, adjunct Professor of Geology and Geophysics at the University of Utah, and previously geothermal geophysicist at Wairakei Geothermal System, New Zealand; and Joe Moore, Research Professor at the Energy and Geoscience Institute of the University of Utah, a world expert on geothermal system geochemistry. There are seven student members of the G-team.

**Danielle D’Alfonso** is currently working on her M.S. in the Department of Geology and Geophysics with a focus on structural geology and geomorphology. Her geographical interests in remote sensing are critical in layering multiple maps of geothermal interest and in exploring some of the social science dimensions (economics, transportation, environmental issues) of the Rio Grande Rift assessment.

**Christian Hardwick** is a first-year graduate student pursuing a master’s degree in Geophysics. He works in the Thermal Geophysics Research Lab and is currently delineating geothermal resources in southern Utah for his Master’s thesis focused on gravity anomalies and magneto-telluric signatures. Prior to completing his bachelor’s degree he worked for 4 seasons as a carpenter based at McMurdo Station, Antarctica for the U.S. Antarctic Program.

**Becky Hollingshaus** is a second year master’s student in the Department of Geology and Geophysics after receiving her B.S. in Chemistry at the University of Utah. She worked for three years as a lab technician at the Stable Isotope Ratio Facility for Environmental Research (SIRFER). Becky’s thesis research involves developing methods for quantifying groundwater flow systems using a bromide tracer test as well as age dating, water chemistry, and thermal characteristics of the reservoirs.

**Michal Kordy** is a first-year Ph.D. student in Mathematics. He received master's degree in mathematical statistics at Wroclaw University of Technology and worked three years in the industry mostly on statistical modeling for telecommunications' company in Poland. Currently he is working on robust algorithm for MT measurements taking into account topography.

**Ruthann Shurtleff** is a student in her final year of undergraduate studies in geoscience with a geology emphasis. She has been taking classes in geothermal, groundwater and petroleum geology giving her familiarity with geothermal systems, groundwater flow and fluid reservoirs. She is also employed by the Bureau of Land Management as a physical science technician in the Fluid Minerals (oil, gas and geothermal) Branch.

**Kevin Smith** is a graduate student pursuing his doctorate in Mechanical Engineering from the University of Utah with a focus on renewable/sustainable energy systems. He is studying geothermal systems for direct use applications. Specific areas of interest include geothermal heat pumps and seasonal underground thermal energy storage. He has B.S. and M.S. degrees in Mechanical Engineering from the Rochester Institute of Technology in Rochester, NY.

**Stan Smith** is a second-year graduate student working towards a master’s degree in Geology. He is working with Professor Kip Solomon, a world expert on groundwater dating. Stan is currently researching fluid flow through cap rocks above potential carbon sequestration aquifers. He completed his undergraduate degree at the University of Utah in Geoscience.
3. METHODS FOR ASSESSING GEOTHERMAL POTENTIAL

The team approach to this assessment was to compile and correlate available information on the Rio Grande Rift geologic province, identify potential geothermal resource sites, and develop proposals for geothermal use. A literature search and inventory of available resources was conducted and an EndNote library created. All datasets were spatially correlated using ArcGIS and geochemical reservoir analyses done with available water chemistry. The SMU Geothermal Lab heat flow database was used to interpolate the regional heat flow. Potential sites were selected and thermal energy in each reservoir was calculated and compared to results computed with GEOFRAT.

3.1 ArcGIS

For analyzing the Rio Grande Rift at the regional scale and the local scale, the ability to manage and create spatial datasets proved to be very useful. The software program ArcMAP was used and while licensing is required to create and modify a project, data viewers are freely available. This program was used to perform multiple functions: visually correlate datasets, interpolate data points, perform mathematical operations on layers, and produce figures. The final project includes publicly available datasets such as topography, geology, geophysics, hydrology, and civil data such as population and land status as well as data produced by the G-Team, which are discussed below.

3.2 Powell-Cummings geochemical analyses

A geochemical analysis of the OIT (Oregon Institute of Technology) springs dataset was conducted using the Powell-Cumming method [Powell and Cumming, 2010]. A MATLAB code was written to process the 1262 water samples included in the Colorado and New Mexico datasets. A charge balance within 5% error was computed to determine the validity of the chemical analyses. Major anions were used to characterize water samples as sulfate, chloride, or bicarbonate waters (Figure 7); ten geothermometer temperatures were calculated for each water including the silica geothermometers (amorphous silica, chalcedony, and quartz with both conductive and adiabatic cooling) and the cation or alkali metals geothermometers (Fournier’s Na-K-Ca geothermometer with Mg corrections, the Fournier, Truesdell, and Giggenbach versions of the Na-K geothermometer, and the K-Mg geothermometer of Giggenbach). The most appropriate reservoir temperatures from samples in the potential geothermal sites were determined using the Na-K-Mg ternary plot developed by Giggenbach and the cross-plot of the K-Mg and the quartz (with conductive cooling) geothermometers developed by Giggenbach and Goguel. The ternary plot was used to assess equilibrium of the water with the host rock and the cross-plot to compare low temperature geothermometers.

3.3 Heat flow interpolation

Heat flow measured at different locations in Colorado and New Mexico, taken from the database of SMU Geothermal Lab is presented as an interpolation of these data, so that for each point in those two states a heat flow value is estimated. There is no claim that the interpolated heat flow is the true value of heat flow at all points, as there are many areas with insufficient data. The interpolation was carried out so that in those regions where there is not enough data the value of estimated heat flow is close to median of all measured values 84 mW/m$^2$, and all estimated values not equal to this value are such as a result of heat flow measured in the vicinity, not a result of the interpolation method used. Heat flow was estimated for Colorado and New Mexico and for four regions selected by the G Team as regions with geothermal potential. For the details of the method used see Appendix.
3.4 GEOFRAT

Thermal energy in the reservoir was calculated using GEOFRAT, a geothermal financial risk classification and assessment tool developed by the Energy and Geoscience institute at the University of Utah. Using the resource estimation module, the reservoir temperature range (from geothermometry temperatures and measured spring temperatures), rock properties and reservoir volume were input to a Monte Carlos simulation that yields a recovery factor and the probability of heat in place and thermal power potential over 30 years.

4. GEOTHERMAL ASPECTS OF THE RIO GRANDE RIFT

4.1 Energy market

4.1.1 Demographics

The Rio Grande Rift geologic province includes south central Colorado and New Mexico. The 2010 U.S. Census reports from New Mexico show that the five most populous incorporated places and their 2010 Census counts are Albuquerque, 545,852; Las Cruces, 97,618; Rio Rancho, 87,521; Santa Fe, 67,947; and Roswell, 48,366. Albuquerque grew by 21.7% since the 2000 Census. Las Cruces grew by 31.4%, Rio Rancho grew by 69.1%, Santa Fe grew by 9.2%, and Roswell grew by 6.8%. All but the city of Roswell are in the Rio Grande Rift region. Data for Colorado show that the five most populous incorporated places and their 2010 Census counts are Denver, 600,158; Colorado Springs, 416,427; Aurora, 325,078; Fort Collins, 143,986; and Lakewood, 142,980. Denver grew by 8.2% since the 2000 Census. Colorado Springs grew by 15.4%, Aurora grew by 17.6%, Fort Collins grew by 21.4%, and Lakewood decreased by 0.8%. None of these cities are within the physiographical boundary of the Rio Grande Rift, but all are possible recipients of geothermal power coming from the Rift area. The 2010 census has not yet made population projections for these areas.

4.1.2 Infrastructure and power production

The main source of power in New Mexico & southern Colorado, like most of the US is powered from coal. The utility company of New Mexico, PNM, owns power plants that are fueled by coal (41%), nuclear power (16%), natural gas (22%) and wind (8%) [PNM, 2011]. The specific numbers per industry are 119.7 trillion BTUs for commercial uses, 212.3 trillion BTUs for industrial uses, 101.6 trillion BTUs for residential uses and 229.4 trillion BTUs for transportation. The total generation of the entire state is 35.1 TWh, ranking them 37th in the nation [eRedux, 2011]. The distribution of power plants in the Rio Grande Rift area is shown in Figure 2A.

New Mexico has one of the largest resources of coal and natural gas of the 50 states, and continues to develop its conventional resources along with new renewables. The states renewable energy portfolio calls for 20% of the total energy to come from renewable resources by 2020, a good sign for the burgeoning wind industry in the state. Southern Colorado has similar statistics and shares some electrical grid connections with New Mexico. Natural gas pipelines are another valuable resource for an investigation into power potential because they show important corridors that electrical lines can be run to for new power plant facilities. There are few pipelines in New Mexico, but some extend into the area of interest around Mt. Princeton in Colorado (Figure 2C).
Figure 2: a) Distribution of power plants; red dots indicate power plant location and black lines are state borders. b) Distribution of power lines. c) Distribution of natural gas pipelines.
4.1.3 Current geothermal use

The need to reduce the environmental impact of current energy production is motivation to develop geothermal resources. Current geothermal use is solely direct-use applications such as greenhouses, aquaculture, spas, etc. as shown (Figure 3) for locations and details on these places in New Mexico. The San Luis Valley in south central Colorado has good low temperature geothermal resources. More than a dozen resort spas, several fish farms, one district heating system, and one greenhouse use geothermal water in this region.

![Table 1. Geothermal Utilization in New Mexico](image)

<table>
<thead>
<tr>
<th>Site</th>
<th>Max. T (°F)</th>
<th>Peak Flow (GPM)</th>
<th>Energy 10^9 Btu/yr</th>
<th>Capacity MWt</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catron County</td>
<td>120</td>
<td>50</td>
<td>1</td>
<td>0.2</td>
<td>Resort &amp; Spa - Bubbles Hot Springs near Glenwood (Lower Prisco Hot Springs)</td>
</tr>
<tr>
<td>Dona Ana County</td>
<td>148</td>
<td>250</td>
<td>36</td>
<td>6.0</td>
<td>District Heating (NMSU)</td>
</tr>
<tr>
<td>Las Cruces Area</td>
<td>148</td>
<td>60</td>
<td>3</td>
<td>0.3</td>
<td>greenhouse - STDI (NMSU)</td>
</tr>
<tr>
<td>Radium Springs</td>
<td>135</td>
<td>25</td>
<td>&lt;1</td>
<td>&lt;0.1</td>
<td>Aquaculture - STDI (NMSU)</td>
</tr>
<tr>
<td></td>
<td>145</td>
<td>200</td>
<td>10</td>
<td>3.1</td>
<td>greenhouse - J &amp; K Growers</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>1,000</td>
<td>77</td>
<td>12.9</td>
<td>Greenhouse - 2nd largest nationally, Masson Radium Springs Farm</td>
</tr>
<tr>
<td></td>
<td>112</td>
<td>10</td>
<td>1</td>
<td>0.1</td>
<td>Baths - Radium Hot Springs Resort</td>
</tr>
<tr>
<td>Grant County</td>
<td>130</td>
<td>50</td>
<td>1</td>
<td>0.2</td>
<td>Resort &amp; Spa - Paywood Hot Springs</td>
</tr>
<tr>
<td></td>
<td>135</td>
<td>50</td>
<td>1</td>
<td>0.2</td>
<td>Resort &amp; Spa - Minnees Hot Springs</td>
</tr>
<tr>
<td></td>
<td>165</td>
<td>75</td>
<td>3</td>
<td>0.4</td>
<td>District Heating / Resort &amp; Spa Gila Hot Springs</td>
</tr>
<tr>
<td>Hidalgo County</td>
<td>230</td>
<td>2,000</td>
<td>184</td>
<td>19.0</td>
<td>Greenhouse - Largest nationally, Burgott Geothermal Greenhouses</td>
</tr>
<tr>
<td>Cotton City</td>
<td>185</td>
<td>200</td>
<td>11</td>
<td>0.7</td>
<td>Aquaculture - Americulture Inc.</td>
</tr>
<tr>
<td>Rio Arriba County</td>
<td>115</td>
<td>60</td>
<td>1</td>
<td>0.2</td>
<td>Resort &amp; Spa - Ojo Caliente</td>
</tr>
<tr>
<td>Sandoval County</td>
<td>155</td>
<td>50</td>
<td>1</td>
<td>0.2</td>
<td>Resort &amp; Spa - Jemez Springs Bathhouse</td>
</tr>
<tr>
<td>Sierra County</td>
<td>110</td>
<td>1,000</td>
<td>8</td>
<td>0.7</td>
<td>Resort &amp; Spa - Several spas in Truth or Consequences</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>339</strong></td>
<td><strong>44.3</strong></td>
<td></td>
<td></td>
<td>Note: Energy use is estimated.</td>
</tr>
</tbody>
</table>

![Table 2. Details of Geothermal Greenhouses](image)

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Product Description</th>
<th>Acres</th>
<th>Persons</th>
<th>Payroll</th>
<th>Capital Investment</th>
<th>Sales Gross</th>
<th>Energy Use</th>
<th>Energy Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burgott Geothermal</td>
<td>Animas/ Cotton City</td>
<td>Cut Roses</td>
<td>32</td>
<td>90</td>
<td>2,080</td>
<td>11,200</td>
<td>4,000</td>
<td>184</td>
<td>736</td>
</tr>
<tr>
<td>Masson Radium Springs</td>
<td>Radium Springs</td>
<td>Potted Plants and Flowers</td>
<td>16</td>
<td>136</td>
<td>1,988</td>
<td>5,600</td>
<td>7,395</td>
<td>77</td>
<td>308</td>
</tr>
<tr>
<td>J &amp; K Growers</td>
<td>Las Cruces</td>
<td>Potted Plants and Flowers</td>
<td>2</td>
<td>16</td>
<td>234</td>
<td>700</td>
<td>870</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>Sorenson Cactus</td>
<td>Las Cruces</td>
<td>Decorative Cactus</td>
<td>1</td>
<td>8</td>
<td>117</td>
<td>350</td>
<td>435</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td></td>
<td></td>
<td>51</td>
<td>250</td>
<td>4,419</td>
<td>17,850</td>
<td>12,700</td>
<td>275</td>
<td>1,100</td>
</tr>
</tbody>
</table>

*Figure 3: Applications of direct-use in New Mexico [Witcher, 1995]*
4.2 Geology & hydrology

4.2.1 Tectonic and geologic setting

The Rio Grande Rift is a series of north-south trending en enchelon grabens and half grabens at least 950 km in length. The northern part of the Rift is a distinctive tectonic and geographic feature separating the Colorado Plateau to the west from the Great Plains to the east. Within Colorado it has Basin-and-Range extensional features superimposed upon it that at times distort the Rift boundaries [Baldridge, 1994]. The Rift is characterized by two different ages and styles of extensional deformation that occurred from the Oligocene to Holocene. Early rift extension is characterized by north-northwest-striking block faults across the entire width of the southern Rocky Mountain region. The modern rift extension is characterized by north-south striking axial grabens and uplift along the rift flanks [Meyer, 1991]; this younger episode of activity caused a regional uplift of one to two kilometers [Seager, 1984].

The sediments of the Rio Grande Rift were influenced by concurrent plutonism resulting in multiple calderas and volcanic fields, the most well known being Valles Caldera in the Jemez Mountains near Santa Fe. The volcanic sediments, like the Rift, show two different stages of emplacement. The older volcanics are basaltic andesite flows while the younger are alkali-olivine basalt [Seager, 1984]. East of the Valles Caldera is one of the four major basins within the Rio Grande Rift—the Espanola Basin. North of Espanola Basin is the San Luis Basin and south is the Albuquerque and Tularosa Basins (Figure 4).

4.2.2 Hydrology

The Rio Grande Rift contains major rivers such as the Rio Grande and Arkansas River. The Rio Grande Rift Aquifer system is found in the interconnected sediment-filled basins (Figure 5). Basin thickness is variable but reaches 20,000 feet in the Rio Grande Valley near Albuquerque and 30,000 feet thick in the San Luis Valley [Robsen and Banta, 1995]. Dominant recharge to the basins occurs as mountain-block and mountain-front recharge as lower temperatures and higher precipitation reduces evaporation and transpiration. Conversely, the majority of precipitation that falls in the valleys is lost to evaporation and transpiration. For example, the southern portions of the Rio Grande Rift receive an average of 8 inches of precipitation per year but the evaporation potential exceeds 100 inches per year [Robsen and Banta, 1995].

4.2.3 Spring and well water chemistry

The OIT database compiled for the Colorado Geological Survey and Southwest Technology Development Institute was used for well and spring information in the Rio Grande Rift. There are 168 geothermal sites identified in Colorado, including 59 hot spring sites (some with multiple springs) and 34 designated geothermal well sites [Sares et al, 2009], with a total of 441 analyses in the Colorado dataset; the New Mexico dataset includes 359 geothermal sites and has 821 analyses. The Chemistry Information Database was used to determine the spatial distribution of discharge temperature and characterization of geothermal waters [Witcher, 1995; Cappa and Hemborg, 1995].

Regions with well and spring temperatures greater that 50 °C are found in the northern end of the Rift in Colorado (around Mt. Princeton and along the western edge near Creed), as well as in the Valles Caldera with isolated wells trending northwest and following an east-west trend along the southern part of New Mexico (Figure 6). The distribution of chloride waters (Figure 7) is due to groundwater interactions with evaporates in sedimentary basins; bicarbonate waters, with carbonates
Figure 4: ArcMap image of the geology of the Rio Grande Rift showing Quaternary faulting and volcanism.

Legend

- Quaternary Faults
- Quaternary Igneous

Kilometers

0  45  90  135
Figure 5: ArcMap image of the hydrology of the Rio Grande Rift

Legend
- Rio Grande aquifer system
- Lakes
- Streams
Figure 6: ArcMap image of the distribution of geothermal springs and wells in the Rio Grande Rift. Yellow and red dots indicate the locations of springs and wells.
Figure 7: 
ArcMap image of the distribution of geothermal waters by major anion characterization

Legend
- Sulfate
- Bicarbonate
- Chloride
- Chloride

Kilometers

0 45 90 135
such as limestones; and sulfate waters, with sediment fill. At the regional scale, the correlation of spring and well temperatures with geology and heat flow proved most useful in identifying areas of interest in this non-volcanic hosted thermal field.

4.3 Geophysical signatures

4.3.1 Seismicity

Seismicity, more commonly used as a monitoring technique in production and re-injection, can be studied in a region of geothermal interest in order to identify concealed faults or those that have no surface manifestations. Seismicity can be combined with other geophysical surveys such as gravity, magnetotellurics or magnetics in order to confirm the presence such fault planes. A regional seismicity map shows events of magnitude 2.1 up to 6.0 since 1973 (Figure 8a). Seismicity within the Rio Grande Rift is confined mostly to the southern half with a few small clusters of events adjacent to mountain ranges and notably a very large cluster of seismic events at the southwestern end of the Albuquerque Basin. The location of the area of high seismicity is also that of a series of normal faults related to the extension of the Rio Grande Rift.

4.3.2 Heat-flow

The background heat-flow of the Rio Grande Rift and surrounding area is 80-90 mW/m², which is characteristic of typical Basin and Range heat-flow values. There does not appear to be any correlation of heat-flow and indicated boundaries of the Rio Grande Rift at the geologic province scale (Figure 8b). However, when viewed at the continental scale, the Rio Grande Rift is a corridor of high heat-flow reaching southward from northern Colorado, through all of New Mexico and into Mexico. Within the Rift boundaries, heat-flow values range from less than 30 mW/m² to well beyond 150 mW/m². Areas that display anomalously high heat-flow were used to identify sites for potential development; such signatures are typically the first clue that there may be a geothermal system.

4.3.3 Gravity

The Bouguer gravity anomaly of the Rio Grande Rift (Figure 8c) displays good correlation with the rift boundaries. This is due to the fact that the boundaries were drawn based on geological data where sedimentary basins are typically bounded by normal faults and mountain ranges. The relative gravity lows signify a mass deficiency and are due to lower density materials such as sedimentary fill whereas relative gravity highs signify a mass excess which are due to higher density materials such as basement rock. On a regional scale (long-wave signal) the Bouguer anomaly is lower in the northern Rift and higher in the southern part of the Rift. This is caused by the effects of crustal roots on gravity- a thicker crust will have a lower gravity signature (low density crust) and a thinner crust will be higher (due to the high density of the mantle). Along the boundaries of the Rift, finger-like shapes depicted as gravity highs represent mountain ranges (short-wave signal). The key in using gravity is to identify structural controls such as faults for fluid flow within a geothermal reservoir. Later a closer look is taken at the gravity anomalies for each area of interest since a regional gravity map hides the small-scale details that are pertinent to geothermal systems.

4.3.4 Magnetics

Magnetic surveys are an effective way to map concealed fault offsets and volcanic rocks due to the magnetic anomalies they produce. Fault offsets are associated with linear anomalies bearing 5 to 15
nT amplitude signals whereas underlying basement and neighboring volcanic rocks are associated with anomalies on the order of several hundred nT [Grauch and Hudson 2007]. They also found that there are a significant number of previously unmapped faults within the Rio Grande Rift by developing a set of anomaly analysis guidelines and applying them to high-resolution aeromagnetic data in the region [Grauch and Hudson, 2007]. Colorado and New Mexico have two independently processed datasets, but are presented together in a regional magnetic anomaly map of the Rio Grande Rift (Figure 8d). It is difficult to observe the small amplitude anomaly signals that a fault would produce at this scale. Observed regional anomalies may be attributed to volcanic rocks and variation in basement rock.
Figure 8:

a) Seismic activity, b) heat flow, c) Bouguer gravity, d) Magnetics
5. POTENTIAL SITES FOR GEOTHERMAL DEVELOPMENT

5.1 Mt. Princeton

The Mt Princeton area was chosen as an area of potential geothermal resource development because spring temperatures and heat flow values are the highest seen in the Rio Grande Rift excluding the Valles Caldera. Hot water is already utilized for bathing, greenhouses, and district heating but with the observed values of heat flow an expansion of direct use or even power generation appears possible.

5.1.2 Geology and hydrology

The Mt Princeton geothermal area is situated in Colorado near the northern extent of the Rio Grande Rift tectonic region (Figure 9). Thermal springs and warm wells are located at the mouth of Chalk Creek on the west side of the Upper Arkansas Valley Basin [Healy, 1980]. The Sawatch fault zone separates the valley from the eastern Sawatch range. The Sawatch range is composed of Precambrian metamorphic and igneous rocks and Tertiary intrusions dated no younger than approximately 35 Ma. Quaternary alluvial and glacial deposits in the valley are approximately 100 feet thick and unconformable overly the aforementioned geologic units and the clastic Dry Union Formation (Pliocene - Miocene).

5.1.3 Spring and well water chemistry

Water chemistry samples from Mt Princeton and the adjacent hot springs and wells were analyzed to determine reservoir temperature. The dominant anions in charged balanced samples are bicarbonate and sulfate while chloride is low (Figure 10a), suggesting that this is a deeply circulating groundwater system with peripheral waters being heated. Discharge temperatures in the Mt Princeton area are in excess of 50 °C with substantial flow rates (Cottonwood-Merryfield Well at 54 °C and 990 L/min; Poncha Springs A at 70 °C and 760 L/min).

The Giggenbach Na/K geothermometer indicates a maximum reservoir temperature of 170°C. A more conservative interpretation using the chalcedony (the appropriate silica geothermometer for temperatures < 200 °C) and Giggenbach K/Mg geothermometers is that the reservoir is only 115°C. A ternary plot of Na-K-Mg (Figure 10b) shows the water is in partial equilibrium with the rock; all samples fall along a trend where the Na/K ratio is constant while Mg increases. This could indicate the presence of a higher temperature peripheral reservoir that has been diluted by groundwater, adding Mg. An alternative to the groundwater dilution scenario is that the samples contain water from a lower temperature reservoir sourced from high temperature peripheral reservoir waters that have moved to a shallower depth and re-equilibrated; both the silica and K/Mg geothermometers equilibrate rapidly and are in general agreement (Figure 10c) indicating the water was indeed at equilibrium at low temperature and groundwater dilution is less significant. Other interpretations could be that the reservoir never reaches temperatures over 115 °C and is perhaps also being diluted with groundwater. However, based on the magnitude of the heat flow anomaly the latter scenarios are unlikely and the first two are investigated for development.

5.1.4 Geophysical signatures

Measured heat flow at Mt Princeton is indicative of a significant heat source. Heat flow has been measured exceeding 350 mW m⁻², the highest value reported in the state of Colorado [Berkman
Figure 9:  
ArcMap image of the Mt. Princeton site showing land use.
Figure 10: 
a) Ternary plot of major anions (top),
b) Giggenbach ternary plot (middle), and
c) low-temperature geothermometer crossplot (bottom) for water chemistry at Mt. Princeton site.
This anomaly is on the order of 26 km² and is generally contained to the eastern front of the Sawatch range at the mouth of Chalk Creek (Figure 11). The thermal gradient at Mt Princeton reaches 160°C/km coinciding with high heat flow anomalies [Berkman and Carroll, 2008; Berkman and Watterson, 2010]. While it is tempting to determine drillable temperatures using this thermal gradient, it is unlikely that the 160°C/km gradient is due to conductive heat transfer. A more probable explanation is that convective outflow is responsible for the gradient and a temperature inversion would be found at depth. Surface manifestations such as boiling springs or craters left by phreatic explosions would be present if +300°C water was present just 2 km deep.

5.2 Valles Caldera and Jemez Springs

5.2.1 Geology & hydrology

The Valles Caldera is a large, Quaternary silicic volcanic resurgent caldera that is 22 kilometers across [Goff, 2002] (Figure 12). It is the center of the Jemez Mountains volcanic field and the western margin of the Rio Grande Rift. The caldera is at the intersections of the northeast trending Jemez Lineament and the north-south trending Rio Grande Rift. The Jemez Lineament is a line of Miocene to Holocene volcanic centers that is a reactivation of Precambrian structure [Goff, 2002].

The Valles Caldera was the focus of scientific and geothermal drilling from 1959 to 1988, which have provided a great deal of information regarding the subsurface of the caldera, but development of the geothermal resource proved to be unsustainable [Goff, 2002, 1990]. At that time the caldera showed a relatively small, liquid dominated geothermal resource with little fluid continuity among between drilled wells [Goff, 2002].

Part of why the resource is so small relates to the asymmetric structure of the caldera. The caldera is deeper on the east than on the west as the Miocene sedimentary rocks of the Rio Grande Rift thicken towards the axis of the rift [Goff, 2002]. This feature and the a horst that is beneath the mountains between the eastern caldera ring and the Pajarito fault bounds the western part of the Rio Grande Rift and forms two hydrologic basins [Goff, 2002]. The Rio Grande Rift if one basin and the caldera depression is another. There are multiple springs in the region surrounding the caldera that all vary temperature. The hottest are those within and west of the caldera [Goff, 2002], Jemez Springs is on of springs with high temperatures.

Due to the designation of Valles Caldera as a National Preserve, the caldera is no longer available as a potential geothermal resource. The western edge, outside of the national preserve may be a viable resource. There is a hydrothermal outflow plume southwest of the caldera that shows promising temperatures [Goff, 1988].

5.2.2 Spring and well water chemistry

Water samples from the Valles Caldera included in the OIT database indicate a complex hydrothermal plume system with the presence of three distinct waters (Figure 13a). Temperatures exceeding 200 °C are found in the Baca wells on the caldera. These mature chloride waters low in magnesium equilibrated with the host rock at high temperature and are typical of a volcanic-hosted geothermal reservoir. The Na/K Giggenbach geothermometer suggests a reservoir temperature of 270 °C (Figure 13b). This reservoir was the target of the Baca development project. Discharge temperatures > 50 °C are found in the hot springs and wells at Jemez Springs. Major anions and the presence of magnesium suggest that this second group of waters is a mixture of the high-temperature chloride reservoir water diluted by peripheral bicarbonate waters found in the limestone reservoir; the cross-plot (Figure 13c) indicates that these waters have not equilibrated at low temperatures; the K/Mg geothermometer indicates a reservoir temperature of 125 °C. The last set yields immature peripheral
Figure 11: ArcMap image of the thermal gradient at the Mt. Princeton site.
Figure 12: ArcMap image of the Valles Caldera site showing land use.
Figure 13:
a) Ternary plot of major anions (top),
b) Giggenbach ternary plot (middle), and
c) low-temperature geothermometer crossplot (bottom) for water chemistry at Valles Caldera site
bicarbonate waters at discharge temperatures < 50 ºC with chalcedony geothermometry suggesting a reservoir temperature of 80 ºC.

5.2.3 Geophysical signatures

Heat flow values for the Valles Caldera region range from greater than 1000 mW/m² to 70 mW/m² with an average around 100 mW/m² (Figure 14a). According to Goff [2002], convective heat-flow within the caldera can exceed 5000 mW/m² whereas just outside the caldera is as high as 400 mW/m². Near Jemez Springs lay a north-south trending anomaly that follows the western edge of the San Diego Canyon up to the western rim of Valles Caldera. Within this anomaly we observe average heat-flow values of 250 mW/m² with a baseline of approximately 160 mW/m². One half of this anomaly area has heat-flow of greater than 300 mW/m² and is located just north of Jemez Springs and continues northward to just inside the caldera.

The complete bouguer gravity anomaly for Valles Caldera (Figure 14b) shows a tongue-like shaped gravity low extending from the northwest and terminating at the circular ring fracture of the caldera bearing almost perfect correlation with the boundaries of the caldera. We observe a relative gravity low within the caldera which is due to the mass deficiency present within the caldera boundaries from low density fill surrounded by higher density rock and materials. The amplitude of this contrast is approximately 60 mGal with a steeper gradient in the southeast and a more gradual gradient in the north.

5.3 Magdalena

5.3.1 Geology & hydrology

The Magdalena Mountains are located in south-central New Mexico (Figure 15) in the Basin and Range, a geologic province created by crustal extension in the Early Miocene. Faults produced by faulting and tilting of this region during extension played a major role in the emplacement of Late Oligocene stocks, dikes, and served as conduits for hydrothermal solutions which altered or mineralized the adjacent country rock [Krewedl, 1974]. Silicic Tertiary volcanics overlie sedimentary rocks of Mississippian, Pennsylvanian, and Permian ages and metamorphic rocks of Precambrian age. Further details about subsurface geology in this area are unknown or unobtainable. No perennial streams exist within the Magdalena Mountains, but some intermittent springs are present at local permeability barriers in the canyons and arroyos [Summers et al., 1972].

5.3.2 Spring and well water chemistry

Warm discharge temperatures of approximately 30 ºC, water chemistry analyses from the wells and springs in the Magdalena Mountain area suggest a possible low temperature geothermal reservoir along the basin. One interpretation of major anion characterization (Figure 16a) is the heavy dilution of a chloride reservoir plume (correlating with the high heat flow anomaly to the north of the drainage) with peripheral carbonate and sulfate waters. Agreement among the low temperature geothermometers (Figure 16c) suggests that the mixed reservoir water equilibrated with the host rock at low temperatures. The chalcedony and K-Mg geothermometers indicate a reservoir temperature of 75 ºC.

5.3.3 Geophysical signatures

Heat-flow values for the Magdelena location (Figure 17a) range from 60 to 400 mW/m² with
Figure 14: a) Heat flow (left) and b) Bouguer gravity anomaly for Valles Caldera site.
Figure 15: ArcMap image of the Magdalena site showing land use.
Figure 16:
a) Ternary plot of major anions (top),
b) Giggenbach ternary plot (middle), and
c) low-temperature geothermometer crossplot (bottom) for water chemistry at Magdalena site.
Figure : 17
a) Heat flow (left) and b) Bouguer gravity anomaly for Magdalena site
an estimated average of 100 mW/m². We observe anomalously high heat-flow values in two areas. The first area is located immediately west of Tres Montosas West peak that appears to be centered on US Highway 60 with a mean of 150 mW/m² and a maximum of 410 mW/m². The second area is located due west of Mount Withington with an average of 150 mW/m² and a maximum of 255 mW/m².

**Figure 17b** displays the complete bouguer anomaly of Magdelena with a maximum range of 35 mGal. The gravity low anomaly is best described as a horseshoe opening to the east with an arm extending south. The gravity low in the north appear to be due to sedimentary basins (reflected in the topography) whereas in the south an extension creeps into the southwestern flank of Mount Withington disregarding topography and continues south into another sedimentary basin. The basin in the north harbors the lowest gravity anomaly and appears to be the greatest depth to basement in the area. The gravity highs for the most part are consistent with topographic highs resulting from mountain ranges and thus mass excesses. Overall the gravity in the area appears to be consistent with east-west extension of the Rio Grande Rift with only a few minor curves.

### 5.4 Hueco Basin

#### 5.4.1 Geology & hydrology

The Hueco Basin near the New Mexico-Texas border is an area of interest that would need additional geologic, geophysical and geochemical research. The known geology of the Hueco Basin is that it is a marginal Basin-and-Range fault-bounded basin that lies between the Franklin and Hueco Mountains [Taylor, 1980]. The Hueco Basin is the southern most extension of the Tularosa Basin, which one of the major basins of the Rio Grande Rift. There is a proposed sediment fill of 2400 meters and the temperatures of water within the sediment are generally high [Taylor, 1980]. There appears to be nearby igneous intrusions that could be a source for heat in the groundwater.

#### 5.4.2 Spring and well water chemistry

As no cation concentrations were available, the water chemistry reported from the wells in the Hueco Basin is an incomplete chemical analysis and geothermometry cannot be used. However, these high-yielding (flow rates > 1000 L/min) geothermal wells have temperatures > 50 °C with the major anion being chloride (see **Figure 19**). This, in addition to a high heat flow anomaly, suggests the presence of a geothermal reservoir.

#### 5.4.3 Geophysical signatures

**Figure 20a** is a heat-flow map of the Hueco Basin area where values range from 90 to 1154 mW/m² and with an estimated average of 160 mW/m². The high heat-flow anomalies are located between the township Newman and Cerro Alto Mountain. It should be noted that measurements are sparse however there are three heat-flow values close to and exceeding 1000 mW/m² in this area and the average is well above typical basin and range values.

The complete bouguer gravity anomaly (**Figure 20b**) of the Hueco Basin has a range of 25 mGal. A gravity high may be the outcrop of a basement high (horst block) or the outcrop of a relatively high density intrusive body. This high is surrounded by gravity lows which include the Cerro Alto Mountain.
Figure 18: ArcMap image of the Hueco Basin site showing land use.
Figure 19: Ternary plot of major anions at Hueco Basin site
Figure 20:
a) Heat-flow (left) and b) bouguer gravity anomaly (right) for the Hueco Basin site
6. RECOMMENDED DEVELOPMENT

6.1 Mt. Princeton

Geophysical and geologic mapping and geochemistry provide evidence that Mt Princeton is sitting atop an exploitable geothermal resource. The resource is being used for bathing and space heating but an expansion is possible that could include electricity generation or increased direct use depending on the reservoir temperature. Ground truth permeability and temperature needs to be determined by drilling deep wells where temperature and flow rates can be measured.

Figure 21: ArcMap image of the thermal gradient at Mt Princeton site. Extent of suggested geothermal reservoir is outlined in red.
6.1.1 Power potential

A geologic cross-section approximately 5 km north of the Mt Princeton area and oriented perpendicular to extensional faulting shows a 2700 meter wide fault zone at the range front fracturing igneous and metamorphic formations. It is unknown if the fault zone is as extensive at the Mt Princeton site due to surficial Quaternary deposits. However, hot springs and high heat flow do suggest an interconnected fracture network is present. Without open fractures the permeability would be several orders of magnitude lower, decreasing advective flow of water and heat [Schwartz and Zhang, 2003; Smith and Chapman, 1983].

The areal extent of the reservoir can be defined by the 100°C/km contour which covers 8.6 km$^2$ and generally agrees with the Sawatch fault zone (Figure 21). Because the reservoir is likely an outflow zone, the thermal gradient is unlikely to be linear and without a temperature-depth profile or a lithologic unit to constrain the thickness, 1 km will be used for calculations. The reservoir has been determined to contain waters ($T_h$) averaging between 170 & 115 °C and it is assumed that the water is returned ($T_c$) at 80 °C. The reservoir is fractured granite, and is assumed to have porosity ($\phi$) of 7.5%, the volume ($V$) is 8.6 km$^3$. The density ($\rho$) and heat capacity ($C_p$) of granite are chosen to be 790 kg/m$^3$ and 2700 J/kg-K respectively, while the same values for water at the reservoir temperature are taken to be 950 kg/m$^3$ and 4225 J/kg-K. The total thermal energy available can be found by finding the heat in both the granite and the trapped water which is shown by the following expression.

$$Q_{\text{total}} = (1 - \phi) V \rho_g C_p g (T_h - T_c) + \phi V \rho_w C_p w (T_h - T_c)$$

By substituting the above values into this expression the total thermal energy available is 17.6x10$^{14}$ kJ & 6.8x10$^{14}$ kJ for the higher and lower reservoir temperatures, and if we assume that the reservoir will operate over 30 years the heat reserve totals 1.86 GWt and 0.72 GWt respectively.

6.1.2 Power generation

Current usage of thermal waters includes bathing, space heating, and greenhouses. Water temperatures vary from 56-71°C with a combined flow rate of 315 GPM yielding 0.67 MWt (OIT). Clearly the resource is not being utilized near capacity. However the relative isolation of Mt Princeton relative to large cities Buena Vista and Salida limits usage. Direct use is impractical when kilometers separate city from resource. Therefore effective use of this resource will be from local growth or power generation. The abundance of open space can accommodate more housing as well as commercial applications like greenhouses, aquaculture, or any other industry that requires warm waters. If temperatures are indeed those shown by geothermometry, electricity generation could be possible and a construction of a binary power plant is suggested, which schematic diagram is presented on figure 22.
The electrical energy that can reasonably be extracted from the reservoir will need to be
determined; first we will find the amount of heat that is removed from the ground and reduce that
number based on conversion efficiencies. We will need to introduce a heat recovery factor ($\psi$) to
determine the amount of heat that can be removed from the reservoir, for this calculation 11% will be
used. The flow rate coming out of the ground is chosen to be 1000 kg/s. The heat removed from
the ground can now be calculated from the following expression.

$$Q = \psi \dot{m} C_{pw}(T_h - T_c)$$

From this we find that the total thermal energy removed from the ground is 41.8 MW and 16.3
MW. Using the Carnot efficiency ($1 - \frac{T_h}{T_c}$), which calculated the maximum efficiency of a heat engine,
a reasonable estimate of electrical power can be determined. The efficiencies of the higher and lower
temperature reservoirs are 20% & 9% respectively meaning that the expected electrical output of a
binary power plant are 8.5 MW and 1.5 MW for the high and low temperature reservoirs. This shows
that the system at Mt. Princeton can be expected to provide power for between 1500 & 8500 homes.

Calculation of electric power potential was done in GEOFRAT for both the high and low
temperature reservoirs at Mt. Princeton; the same input parameters were used for the comparison of
models. The output of the program, the most likely electric power, is 10MW and 5.1MW. These
values are quite close to the values calculated using a deterministic method (Appendix C).

6.1.3 Cost

To determine the initial cost estimated the procedure was used from [Sanyal, 2005], who
created a method to determine the levelized cost of geothermal power over a large range of plant sized
ranging from 5MW to 150 MW. The initial capitalized costs are estimated as $2500/kW on the small
side of the spectrum, while the operating and maintenance costs are estimated as $0.02/kWh. Neither
of these costs include make-up well drilling or transmission line costs, but for a plant less than 10 MW
it is assumed that no make-up well drilling will be needed over the 30 year life of the plant. While
transmission line costs will need to be included, with an average cost of $1,000,000 per mile of line and
the site being about 3 miles from the main line through the area an additional cost of $3,000,000, by
extracting the total investment costs of an 8.5 MW plant would total approximately $85,500,000 that
translates to an estimated electrical rate of $0.038/kWh. This cost estimate was only done for the hotter
end of the spectrum as a plant on the low temperature end of the spectrum would not be able to produce
electricity at the economical rate.

6.2 Jemez Springs

6.2.1 Power potential

Jemez Springs is part of the known geothermal resource area of the Valles Caldera, but the
caldera itself has been designated a protected land. This area lies about 50 miles from both Santa Fe
and Albuquerque, NM providing a large area to service with direct heat applications. The caldera is
host to temperatures in excess of 250 °C, but the area we have designated for our reservoir lies outside
the protected area and therefore the hottest temperatures. The reservoir is an aquifer made of Madeira
limestone, and is part of a faulting system that carries the geothermal water away from the caldera.
Owing to the lower reservoir temperatures in the Jemez reservoir it was decided to investigate the development of greenhouses in the area. With ample solar resources and sufficient water resources this was deemed the best use of the geothermal reservoir. As before the important values need to first be determined to find the total available thermal energy in the reservoir then calculations for the greenhouses will be performed. The hot reservoir temperature is 125 °C while the return temperature is 70 °C, the total volume is 9.6 km³, the porosity is 12% and the heat recovery factor is 11%. Using the same expression as Mt. Princeton the total thermal energy available was determined to be about 1.1
GW, this is larger than Mt. Princeton mainly to the much larger area encompassed by this reservoir.

6.2.2 Direct-use application

The additional values that are needed for greenhouse calculations are the inside temperature of the greenhouse ($T_i$) 20 °C, the lowest temperature expected outside of the greenhouse ($T_o$) -10 °C, the maximum wind ($v$) 40 km/hr the overall heat transfer value for a double polyester roof ($U_p$) 14.9 kJ/m$^2$-hr-°C and fiberglass walls ($U_f$) 21.6 kJ/m$^2$-hr-°C and the area ($A$) of the roof and the walls 524 m$^2$ and 296 m$^2$ for the roof and walls, the volume ($V$) is 2083 m$^3$ shown in the below figure, the arc length is calculated for a 1/4 circle at 1.12 times the width [Lund, 2010].

Figure 24: Greenhouse Design

The air changes per hour (AC/H) expected in the greenhouse is chosen to be 1.5. Now the loss calculations will be shown, these are needed to determine the heat load each greenhouse needs.

$Q_{lt} = AU(T_i - T_o)$

$Q_{li} = AC \int (H \cdot V \cdot (T_i - T_o) \cdot 1.21 \frac{kJ}{m^3 \cdot °C}$

From these the total heat loss from a single greenhouse is 540,000 kJ/hr. Now the total flow ($\dot{V}$) required covering the maximum expected heat loss can be determined from the following expression:

$\forall = Q_{l} / (15,040 \cdot (T_i - T_o))$

For a single greenhouse the required fluid flow is 0.8 l/s which for water relates to a mass flow rate of 0.76 kg/s. Thus for 100 greenhouses the total flow required would be 76 kg/s and could be provided for by a single well. This number of greenhouses covers about 5 ha, which is a significant land area, approximately 500,000 ft$^2$.

6.2.3 Costs

Now the estimated costs of geothermal heating versus natural gas can be calculated to determine how much of a benefit geothermal heating makes. First from the West Virginia University website [WVU Horticulture, 2011] the cost per square foot of greenhouse is $7.50 so the total cost for
the greenhouses themselves is $4,030,000 and this will be assumed to include the internal infrastructure to disseminate heat, for both natural gas and geothermal heat. With natural gas at $1.20/therm and the loss of one greenhouse calculated above and a 90% conversion efficiency the peak fuel cost of a greenhouse would be $28,700/year. By expanding this out for the life of 100 greenhouses the total theoretical peak fuel cost would be $81,600,000. But unlike geothermal energy where the heating costs are upfront the natural gas costs are only paid for as needed, thus introducing a capacity factor to give a more realistic fuel cost is given. For a capacity of 25% the fuel cost would be $21,525,000 and for 10% the fuel costs would be $8,610,000. Now for the geothermal costs the main costs will be pumping, piping, and the well costs. For pumping over the life of the greenhouses a cost of $1,000,000 will be assumed as well as $1,000,000 for the piping and $500,000 for maintenance of the pipes and wells. Now for the well costs from estimates one well will need to be drilled to provide the necessary flow rate and at approximately 1.5 km deep the well will come in with a cost of $3,000,000. Thus the total investment is $5,500,000, which comes in significantly less than even the 10% capacity factor case. This provides a strong case for developing the greenhouse potential near the Valles Caldera, which will provide for a good source of jobs in a tough economy.

6.3 Fenton Hill

The aim of this section is to assess Hot Dry Rock (HDR) development that took place at Fenton Hill the early 1970s and late 1990s and, as it is no longer continued, to approximate Fenton Hill geothermal potential for future development.

6.3.1 Historical development at Fenton Hill

The Los Alamos HDR development program at Fenton Hill was sponsored by the U.S. Atomic Energy Commission for work on the western flank of Valles Caldera where geothermal gradient is on the order of 65 °C/km. The idea was to have two wells connected through a system of cracks in hot rock, where cold water injected in one well could pass through hot rocks and produce hot water at the other well. Two reservoirs existed, a Phase I reservoir and a Phase II reservoir, along with the re-drilling of a few existing wells. As it was difficult to establish connectivity between injection and production wells, two wells were drilled first and then a connection between them was tried by pumping cold water under pressure. Given this experience, EGS reservoirs are now created by drilling one well that is stimulated with pressurized cold water. Using seismic measurements an estimation of the stimulated region is evaluated and two production wells are drilled at both sides of the injection well.

A power plant was built, which pumped water from a production well, decreased its temperature through a heat exchanger (no energy production), and pumped it back to an injection well supplied with surface water (water losses in the reservoir). Pressures were controlled at both production and injection wells. The plant operated for extended periods with no on-site personnel. Some facts about HDR Fenton Hill development argue that this site is a good place for EGS development. The final reservoir was located at depths around 3500 m and produced water at the temperature around 183 °C. From 1992-1995 total production time totaled about 8 months and the temperature drop in the reservoir was not significant. Average water losses were around 12-18%, decreasing significantly to around 2.5% at the steady state, during a time when the reservoir porous volume was filled with water [Brown, 1995]. A two rate production plan was successfully tested. By proper pressure changes each day there was a period of 4 hours when 60% more fluids were produced than during the remaining 20 hours of the day, so that the site might be used to meet peak electricity demand during the day. Yet if flow rates are considered, the amount of heat that was produced was not enough for commercial production of electricity.
6.3.2 Electric power that might have been produced at Fenton Hill

Flow rates at the production well are \( \frac{dv}{dt} = 90 \text{gpm} = 5.67 \frac{m^3}{s} \), which gives mass flow rate of \( \frac{dm}{dt} = 5.67 \frac{kg}{s} \). The amount of heat power produced, if the water is cooled to 83 °C is calculated as follows:

\[
P_{th} = \frac{dm}{dt} c_w \Delta T = \frac{5.67 \frac{kg}{s}}{4.18 \times 10^3 \frac{J}{kg\,\text{K}}} 90 \text{gpm} \times 5.67 \frac{kg}{s} = 2.37 \text{MW}
\]

If the efficiency of the power plant is 10%, the amount of electric power will be

\[
P_{el} = P_{th} \eta = 2.37 \text{MW} \times 10\% = 237 \text{kW}
\]

The amount of (electric) power needed to produce the pressure difference from the pressure at the production well is \( p_a = 1400 \text{psi} = 9.653 \times 10^6 Pa \) to the pressure at the injection well \( p_b = 3960 \text{psi} = 2.73 \times 10^7 Pa \), assuming efficiency of the pump at 80%, \( P_{pump} \) will be:

\[
P_{pump} = \frac{(p_b - p_a) dv}{\eta_{pump}} = \frac{(2.73 \times 10^7 Pa - 9.653 \times 10^6 Pa) 5.67 \times 10^{-3} \frac{m^3}{s}}{80\%} = 125 \text{kW}
\]

So if the electric energy produced at the plant was used to supply the pump, the amount of electric power that would have been produced at Fenton Hill will be:

\[
P_{el, res} = P_{el} - P_{pump} = 237 \text{kW} - 125 \text{kW} = 112 \text{kW}
\]

6.3.3 Means of improvement of productivity at Fenton Hill

a) Pressure difference increase

The amount of heat produced is much too small for commercial production of electricity. The best way to extract 10 MW of power at Fenton Hill would be to increase water flow rate. The easiest way to do this is to increase the pressure difference in the reservoir. To calculate how much pressure difference is needed to increase productivity we use Darcy's Law, which relates velocity and pressure in a porous media, can be applied.

\[
Q = \frac{-kA}{\mu L(p_b - p_a)} = -g(p_b - p_a)
\]
Where $Q = \frac{dv}{dt}$ is flow rate (measured in $m^3/s$), $k$ is permeability of the medium ($m^2$), $A$ is cross sectional area of the medium ($m^2$), $L$ length of the medium ($m$), $\mu$ is the viscosity ($Pa\ s$), $(p_b-p_a)$ is the pressure drop in the medium ($Pa$). Coefficient $g$ is the hydraulic conductivity. The amount of produced power as a function of hydraulic conductivity $g$ and pressure drop in the reservoir $\Delta p=p_b-p_a$ is presented below:

$$P_{el, res} = P_{el} - P_{pump} = P_{th} + \frac{\Delta p}{\eta_p} = \frac{\Delta v}{\eta_p} \rho_w c_w \Delta T \eta - \frac{\Delta p}{\eta_p} \frac{\Delta v}{\eta_p} = \Delta p \rho_w c_w \Delta T \eta - \frac{\Delta p}{\eta_p} \Delta p \rho_w$$

Where $\rho_w$ is the density of water and other symbols are same as above.

The formula presented above as a function of $\Delta p$, for the value of hydraulic conductivity $g$ for the current reservoir is plotted on a figure 25:

![Figure 25: Graph of electric power output as a function of pressure drop in the reservoir at Fenton Hill](image)

It clearly shows in figure 25 clearly shows that the pressure difference value tested at Fenton Hill is very close to optimum, so although increasing pressure difference between injection and production wells would increase the water flow, it will not increase the electric power output significantly. The reasonable solution is to try to increase the value of hydraulic conductivity ($g$), thus to reduce the resistance to flow within the reservoir.

**b) Hydraulic conductivity increase**

Permeability ($k$) is dependent on the average pressure in the medium. It was observed at Fenton Hill [Brown, 2002], that the bigger the pressure, the broader the flow paths between production and
injection wells, decreasing resistance to flow and thus increasing permeability and increasing value of hydraulic conductivity. One simple idea using this property was applied at Fenton Hill, by setting high values of backpressure.

It has been suggested that if there were two production wells on two sides of the ellipsoidal reservoir, the productivity of the reservoir would be larger [Brown et al. 1995]. The productivity would increase not more than twice, which is still not enough.

The biggest resistance to flow through a HDR reservoir is near the production well where the pressure change rate is largest [Brown et al., 1996]. From this fact it can be seen that increasing the size of the reservoir will only result in minimal increases in resistance to flow. To explain this phenomena consider the area that the flow close to the well encounters. This area is the surface area of a cylinder surrounding the segment of a well and it shrinks as we get closer to the well. As this area $A$ shrinks, so does hydraulic conductivity $g$, according to the Darcy’s Law. This explains that the region very close to well has the biggest resistance to flow and acts as a bottle-neck. The easiest way to increase the overall hydraulic conductivity is to increase the hydraulic conductivity in the close proximity of the wells.

One possibility is to stimulate the wells with pumping cold water at very high pressures (much higher than the ones tested so far) for a short period of time to fracture the region at the bottom of the borehole. Unfortunately this may produce seismicity and that fractures will close after the pressure is decreased to operational values.

Another suggestion is to drill more branches of the well in the lower parts, so that at the very end the well resembles Figure 26. If there were ten branches of the well and two production wells on two sides of the injection well it is likely that the hydraulic conductivity would increase by an order of magnitude, and as a result both flow rates and electric output would increase tenfold, so to produce 10 MW of electric power one would need ten systems of three wells instead of one hundred.

![Figure 26: Recommended HDR reservoir. One injection well, two production wells, each well has a number of branches the bottom of the borehole.](image-url)
7. CONCLUSIONS

Our assessment of the geothermal potential of the Rio Grande Rift provided some interesting results. From the investigation a potential $8.5 \text{MW}_e$ power plant is proposed at Mt. Princeton, and a large (100 house) greenhouse complex is described for Jemez Springs near the Valles Caldera. To find these results a base map was assembled and through extensive data mining was performed, spatial correlation of relevant demographic, infrastructure, and geothermal datasets was done using ArcMAP.

From the more than 40 spatial data sets available, the following data was found to be most useful in making a critical geothermal assessment: (1) heat flow measurements and mapping, (2) geochemistry of spring and well waters, (3) geologic mapping focused on young volcanics and intrusives, and (4) regional and local hydrology. Infrastructure (power plant, power line, population centers, and highway locations) became important once the geothermal resource was identified.

By critical assessment using geology, spring and water well chemistry, heat flow and geophysical anomalies the team identified four potential geothermal reservoir sites having potential for geothermal power production or direct heat applications: Mt. Princeton, Valles Caldera, Magdalena, and the Hueco Basin. Ultimately only Mt. Princeton and Valles Caldera were chosen because of the richness of the data sets. The other locations were not fully investigated because of a lack of data, a sign that more densely populated data is needed for more thorough investigation. Also detailed geologic maps are needed, specifically quads with surface geology and cross-sections to better identify promising reservoirs.

This project has been a valuable learning experience for the group, applying what we learned in “Geothermal Systems for Geoscientists” to the Rio Grande Rift. The combination of data mining and design calculations allowed the group to start from a broad topic of study and arrive at solid recommendations for future study. This experience has positively affected our educations here at the University of Utah.

8. ACKNOWLEDGEMENTS

NREL, David Chapman, Rick Allis of UGS, Joe Moore of EGI, Varun Gowda of EGI, University of Utah Geothermal group
9. REFERENCES


10. APPENDIX A

Powell-Cummings spreadsheet

Hydrogen chloride (HCl), sulfur dioxide (SO₂), hydrogen sulfide (H₂S), and carbon dioxide (CO₂) are gases, originating from a magmatic heat source, which can be found dissolved in geothermal waters. Identifying the major anion of discharging water can be used to characterize its source. Typical geothermal reservoir waters, having matured in the aquifer, are neutral (due to degassing and geochemical reactions) chloride waters, with low concentrations of Mg (<1 ppm). Acid sulfate waters, if they are very acidic (pH < 2), can be directly from a magmatic source (as in a near magmatic environment or crater lake) as the following reaction occurs under such conditions:

\[ 4\text{SO}_2 + 4\text{H}_2\text{O} = 3\text{H}_2\text{SO}_4 + \text{H}_2\text{S} \]

They can also be non-magmatic with a pH ~3 as a result of the surficial oxidation reaction of upward migrating hydrogen sulfide gas with perched aerated groundwater or percolating meteoric water as follows:

\[ \text{H}_2\text{S} + 8\text{O}_2 = 4\text{H}_2\text{SO}_4 \]

These non-magmatic sulfate waters are produced near the surface and can discharge in springs or percolate to recharge the geothermal reservoir. Similarly, bicarbonate waters are indicative of peripheral thermal waters, formed as rising CO₂ gas is dissolved in a perched groundwater aquifer. Both non-magmatic sulfate and bicarbonate waters can mix in the subsurface and/or be diluted with meteoric waters prior to discharge or recharge.
11. APPENDIX B

Heat flow interpolation, description:

To produce heat flow layer, the data from Blackwel's database was used:
http://smu.edu/geothermal/heatflow/heatflow.htm

From the database, points (latitude, longitude) with measured heat flow values were obtained. A heat flow map calculated for the region of two states: Colorado and New Mexico was obtained as a minimizer \( f \) of the functional:

\[
J(f) = \frac{1}{\#\Omega} \int_{\Omega} (f(x, y) - f_0)^2 \, dx \, dy + \frac{1}{\#\Omega} \int_{\Omega} |\nabla f(x, y)|^2 \, dx \, dy + \frac{1}{\#D} \sum_{(x_i, y_i) \in D} (f(x_i, y_i) - d(x_i, y_i))^2
\]

where

- \( f(x, y) \) is interpolated heat flow at point \((x, y)\)
- \( f_0 \) is the median from all heat flow values measured,
- \( \nabla f \) is gradient of function \( f \)
- \( D \) is a set of coordinates \((x_i, y_i)\) for which there is a measured heat flow value \( d(x_i, y_i) \) in the database
- integration is over \( \Omega \) - the region of two states Colorado and New Mexico
- \( \#\Omega \) is the area of \( \Omega \), \( \#D \) is the number of points in \( D \)
- \( \alpha, \beta, \gamma \) are parameters, positive weights associated with each term in the functional

Explanation of the formula:

The functional consists of three terms, the last one:

\[
\frac{1}{\#D} \sum_{(x_i, y_i) \in D} (f(x_i, y_i) - d(x_i, y_i))^2
\]

is the average squared distance of the heat flow map \( f \) to the data value \( d(x_i, y_i) \). This term measures how well the function \( f \) satisfies the data.

The second term

\[
\frac{1}{\#\Omega} \int_{\Omega} |\nabla f(x, y)|^2 \, dx \, dy
\]

is the average squares magnitude of the gradient. It measures how smooth the function \( f \) is. The smaller this value, the smoother the function is.

The first term:

\[
\frac{1}{\#\Omega} \int_{\Omega} (f(x, y) - f_0)^2 \, dx \, dy
\]

is the average squared distance of the value of the function from a reasonable average heat flow value \( f_0 \)--this term when minimized makes sure that in regions, where there is no data available, the value of \( f \) is close to \( f_0 \).

In calculation of heat flow map for the whole region value the values of the parameters were taken:

- \( \gamma = 200 \) – so that in the first place we want the function to be fitted to the data.
- \( \alpha = 1, \beta = 0.05 \) – regions of high heat flow are represented as “peaks with steep slopes”.

For minimization of the functional \( J(f) \) Conjugate Gradient Method was used.

To produce a map of heat flow for the whole region, before minimization was undertaken, all values of heat flow were “cut” at the level \( 200 \frac{mW}{m^2} \):

\[
d(x_i, y_i) = \min \left( d_{true}(x_i, y_i), 200 \frac{mW}{m^2} \right)
\]

The map of heat flow that is produced by this procedure shows regions where higher heat flow was measured as relatively small peaks.
12. APPENDIX C

*GEOFRAT model inputs*

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