Preliminary Geothermal Resource Assessment for the Raton Basin, Colorado

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Keywords

Geothermal, Raton Basin, Colorado, sedimentary, power capacity, resource assessment

Introduction

Colorado has yet to develop a single power generation plant from geothermal energy, and it has not been for lack of thermal resources. This slow geothermal progress has primarily been due to geological complexities, rugged terrains, and NIMBY attitudes that have prevented serious development to proceed. One area, the Raton Basin, hasn't even been on the radar for exploration until recently, and this lack of excitement is understandable based on data as shown on Figure 1. I'm hoping to generate exploration interest in the Colorado portion of the Raton Basin with my MS thesis research. This paper presents a small portion of my research to date.

Geological Background

Southern Rocky Mountains

The Southern Rocky Mountain region has had a very active geological history. Four mountain-building phases created the Rockies as we know them today (Larkin *et al*, 1980). First, the Early Precambrian phase uplifted the crystalline basement rocks. The second phase occurred primarily in the Pennsylvanian and Permian, creating widespread uplifting near sea level and block faulting in Colorado during the Late Paleozoic. This activity developed the Ancestral Rocky Mountains. From the Late Cretaceous through the Eocene was the third phase, known as the Laramide Orogeny. The majority of the current structures in the Rocky Mountain region were created at this time, including the Raton Basin and the better understood Denver Basin. There was also an extended volcanic period that began in the Middle to Late Tertiary with a major center creating the San Juan Mountains. The earliest of recent dike eruptions began at the close of the Eocene and continues into the current phase. This volcanic activity provided extensive intrusion of magmatics via dikes and sills throughout the Raton Basin to this day (Hills, 1900). This fourth (current) phase consists of a post-Laramide uplift from the Oligocene to Holocene, with continued uplifting and block faulting. It is during this phase that the Rio Grande Rift Valley and the Spanish Peaks in the Raton Basin were developed.

Raton Basin, Colorado Portion

The present Raton Basin was part of the Western Interior Basin. Its Cretaceous rocks are buried except at the basin margins, and most surficial rocks are Tertiary. However, subsurface studies reflect the Greenhorn marine cycle and transgressive phases of the Niobrara marine cycle (Kauffman *et al*, 1969). These marine cycles into the Late Cretaceous generated numerous coal-bearing strata, which in turn led to current day coalbed methane production from Cretaceous and Raton formations. Subsequent uplifting gave the Raton Basin the rugged terrain and asymmetrical shape we see today. The basin is bounded by the Sangre de Cristo uplift on the west, the Wet Mountains uplift and Apishapa arch on the northeast, and the Sierra Grande arch on the southeast (Figure 2).

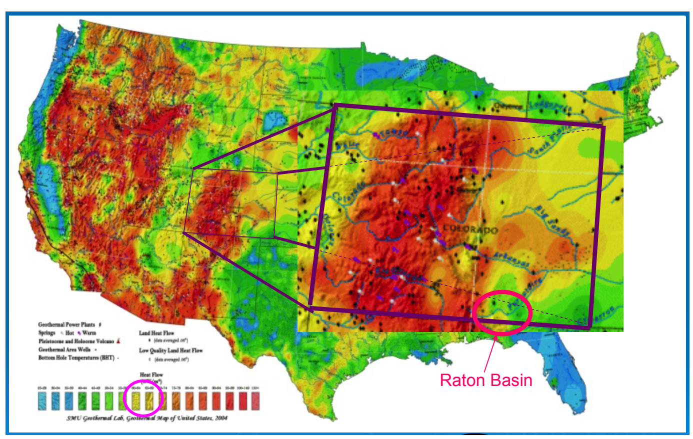

Figure 1. A heat flow map for the continental US with the Raton Basin area highlighted. The circle on the legend indicates the global continental average heat flow, indicating much higher heat flow in the western US including Colorado (Modified from Blackwell et al, 2004).

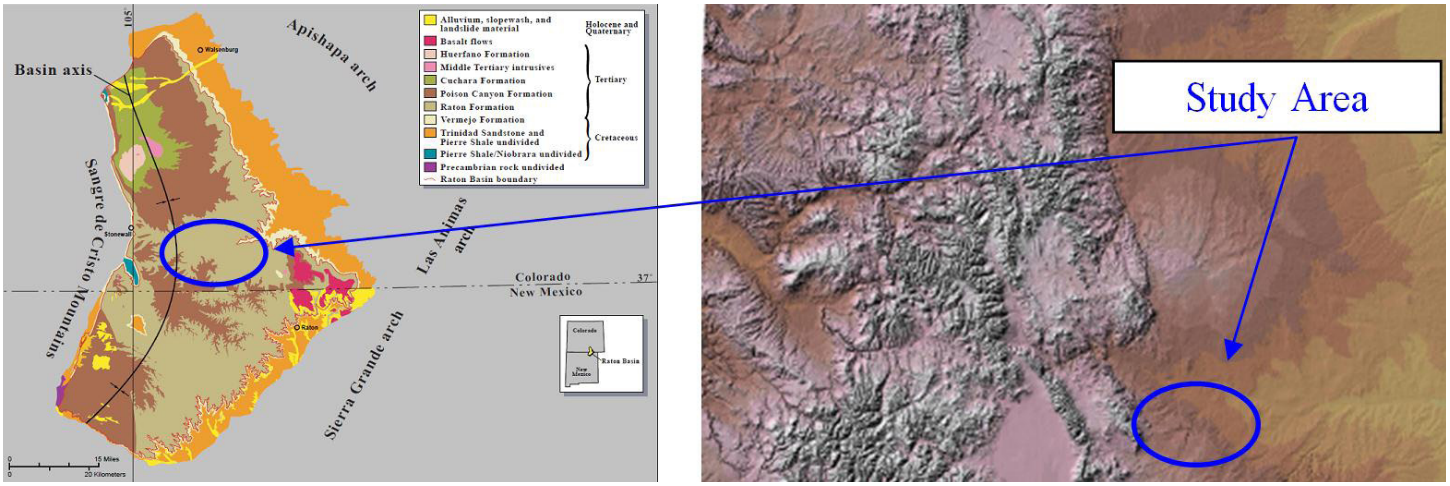

Figure 2. Schematic of the Raton Basin and its geological boundaries (Johnson and Finn, 2001) and (right) a topographical view of the Colorado portion of the Raton Basin (Aber, 2009).

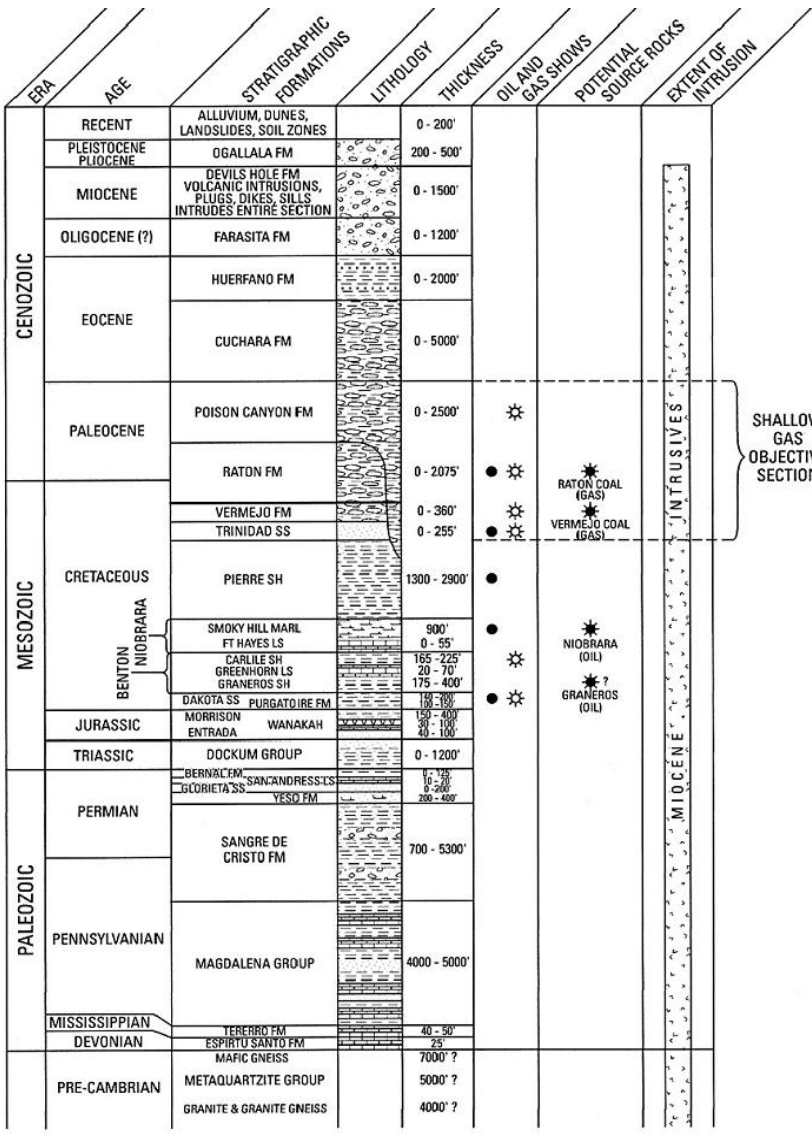

Figure 3. A general column showing stratigraphy based on well data and outcrop correlations (Johnson and Finn, 2001).

The deep subsurface geology of the Raton Basin is not well known due to the scarcity of deep test wells. The existing model of the basin is based primarily on surface geology and outcrops being compared to data from better-studied regions such as the Denver Basin.

Historical coal mining and more recently coal-bed methane production have generated well data to confirm the shallow stratigraphy of the Basin. Figure 3 shows a general stratigraphic column for the basin. Not all formations remain in all areas. In some areas, much of the Mesozoic formations are missing in the subsurface. Figure 4 shows a general cross-section of the northern Raton Basin, and Figure 5 is a revised simplistic cross-section of the study area with tremendous vertical exaggeration based on some well data.

As noted in Figure 5, much of the sedimentary rock that was to be included where the Raton Basin was formed in Colorado consists of the Sangre de Cristo formation. Due to the potential volume and depth of the Sangre de Cristo formation in the Basin, this formation could be relevant to geothermal exploration in the study area.

Sangre de Cristo Formation

The Sangre de Cristo formation is a complex suite of sediments whose lateral and vertical variations reflect several stages of formation. The exact stratigraphic position and age of the Sangre de Cristo formation is uncertain throughout most of the Raton Basin because there is a paucity of deep well data and cores. The formation is present throughout the Raton Basin except on the apex of the Sierra Grande uplift, where Sumner (Permian) rocks rest on the pre-Pennsylvanian carbonate rocks. The Sangre de Cristo formation has a consistent gradation from very course to finer grain size from west to east, and is generally no thicker than 75 meters (250 feet) along the Apishapa and Sierra Grande uplifts where it does exist.

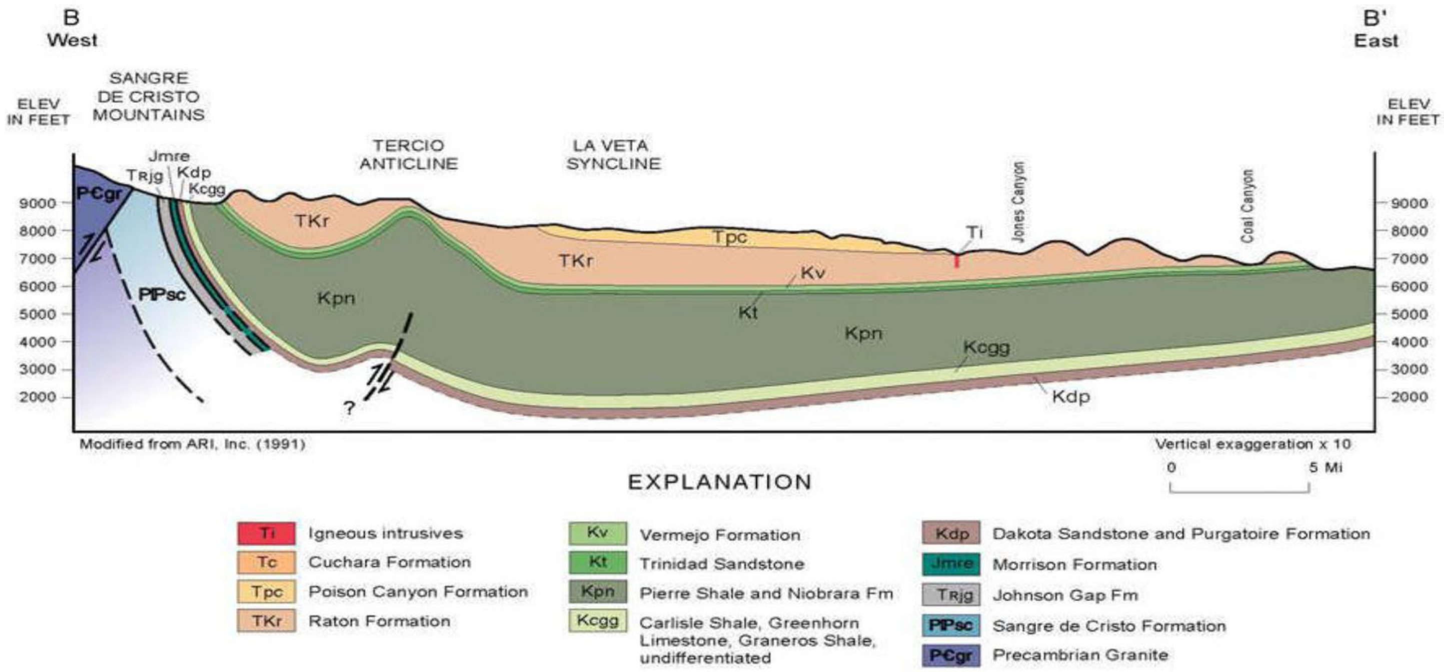

Figure 4. General cross-section of the northern portion of the Raton Basin, south of the study area (Morgan, 2009b).

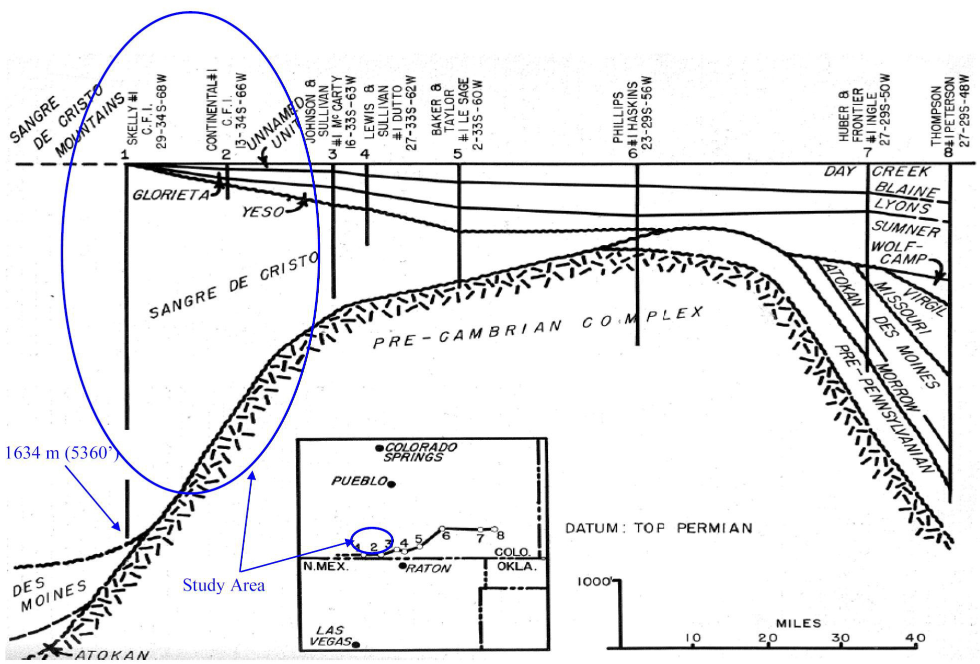

Figure 5. Cross-section derived from drilling data and well logs in the lower Raton Basin in Colorado, where 1 is south of Stonewall, 2 is midway between Stonewall and Trinidad but south of the Purgatoire, and 3 is due east of Trinidad (Shaw, 1956). Notice the depth of Well #1.

this research project, and are discussed in a later chapter.

Rock Samples

In June of 2009, a day trip was made to the area to gather rock samples. Thirty-five (35) samples were retrieved, and 58 cores were made from these (see Figure 6). The formation source was identified and density and porosities were calculated. Equipment is being developed from which to find the thermal conductivity of the cores.

Geothermal Potential Indicators

Recent tectonic and volcanic activity are generally good indicators of geothermal potential, and can lead to exploratory drilling in the most promising locations. As this critical drilling has not commenced in the Raton, some simple assessment has been performed based on thermal gradients and simple heat flows.

Thermal Gradient

Breccia and conglomerate units of the Tererro formation (Mississippian) samples were studied at outcrops, and found to be porous. The lost circulation zone where they were found at the Ocate anticline shows that some porosity and permeability may be indicated in the subsurface (Baltz, 1965). This could be a good indicator of the Sangre de Cristo formation also having porosity and permeability at depth, especially with the considerable lamination found in the formation. Some rock samples were taken for

One can look on GoogleEarth (google.org/egs) for visual presentation of the latest data available for publishing on thermal gradients. Southern Methodist University (SMU), who also published heat flow maps as seen in Figure 1, has been gathering data and subsequently updating their maps. Figure 7 shows an expanded section of the Raton Basin study area, highlighting thermal gradient in the basin based on currently available data.

Figure 6. Rock samples were taken from the area.

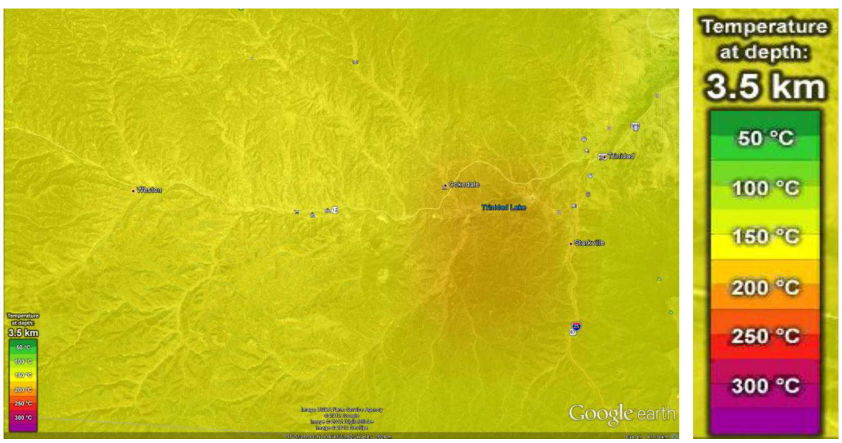

Figure 7. Published thermal gradient in the Raton Basin.

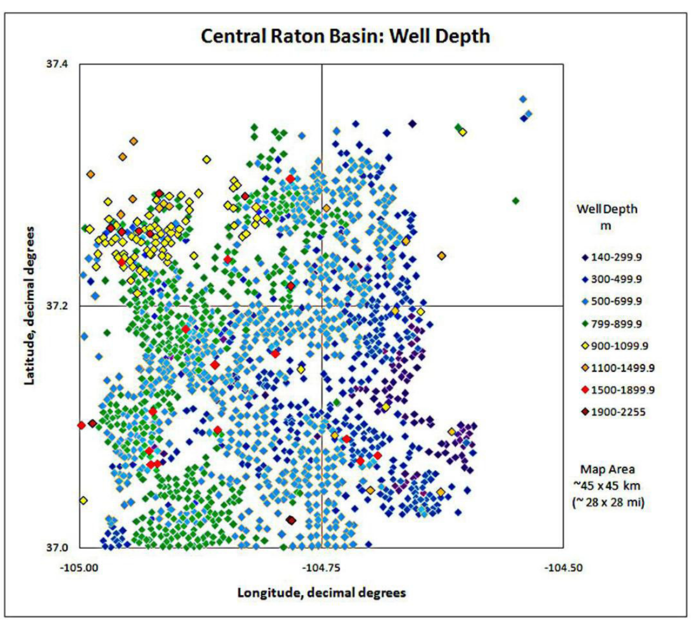

Figure 8. Study area well depths (Morgan, 2009b).

For this study, surface and bottom-hole temperatures were provided for 1172 active gas wells in the Raton Basin from the operating producer. Their total depths range from just over 200 meters to over 2200 meters. However, the majority (999 wells) are less than 1 km deep and go no deeper than the Pierre Shales. Figure 8 shows well locations and their depths. Generally the shallower wells are in the east of the study area.

The thermal gradients for the deeper wells tend to be in the 30s to 50s °C/km, while the shallower well gradients run from 40s to 80s °C/km. The vast majority of the wells (1130) have higher than 31ºC/km gradients, and three wells have gradients over 100°C/km. The average thermal gradient based only on well data is 49.2°C/km; the global continental average is 30ºC/km.

For lack of deeper well data, thermal gradients were calculated using simple linear interpolation of the known well data. These gradients were then graphed for temperatures at depths of 1-, 2-, and 3 km to show how a reservoir volume may be mapped. Many geothermal wells are not economically productive until depths at 3 km, often in basement rock. With a potential reservoir with large volume in the sediments (Sangre de Cristo) found in the Raton, this research focuses on depths remaining in this formation. As Figure 5 shows the Sangre de Cristo boundary with the pre-Cambrian basement estimated to be less than 2 km below the surface, a graph for 1.5 km temperatures was mapped as well. The temperatures at depth are depicted in Figure 9. Notice the warmer temperatures coincide with the eastern end of the study area with the exception of an anomaly just west of the center. The warmer eastern area coincides with published data seen in Figure 7. The west anomaly is near the area of Welton seen on Figure 7. Some data points, however, show temperatures approximately 50ºC higher at 3 km depth than the SMU data at 3.5 km.

Heat Flows

Heat flow can be calculated simply by multiplying the thermal conductivity by the thermal gradient. Figure 1 gave a view of heat flows across the US based on data available in 2004. In the expanded Colorado section, there does appear to be an increase in the Raton Basin compared to that general area of the state. However, it also appears to be no more than the global continental average of 65 mW/m^2.

There is no published thermal conductivity (TC) data given for all the formations found in the Raton Basin, and to date the TC has not been established for the rock samples gathered from the basin. To that end, a generic thermal conductivity of 2.5 mW/m°C was used with the linear gradient calculations (Morgan, 2009a). Given this datum, the well data provided a range of heat flows from 32.9 – 288.6 mW/m°C with an average in the study area of 122.9 mW/m°C. Only 19 of the 1172 wells provided a heat flow less than the global continental average of 65 mW/m°C.

Figure 10 shows how these heat flows mapped out in the study area. Again, just as with the temperatures at depth, the higher heat flows are found in the eastern end of the study area.

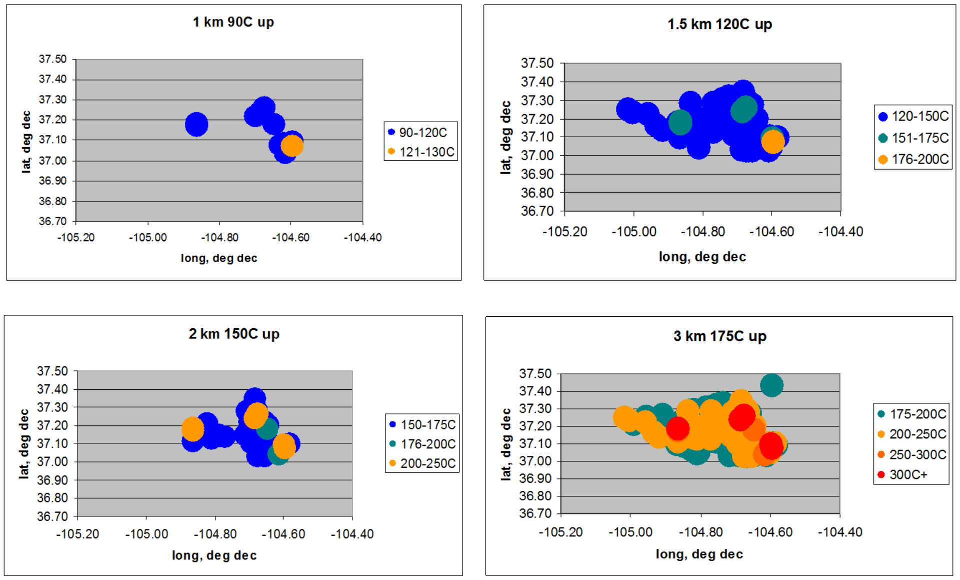

Figure 9. Temperatures at depth based on linear thermal gradients in the Raton Basin study area.

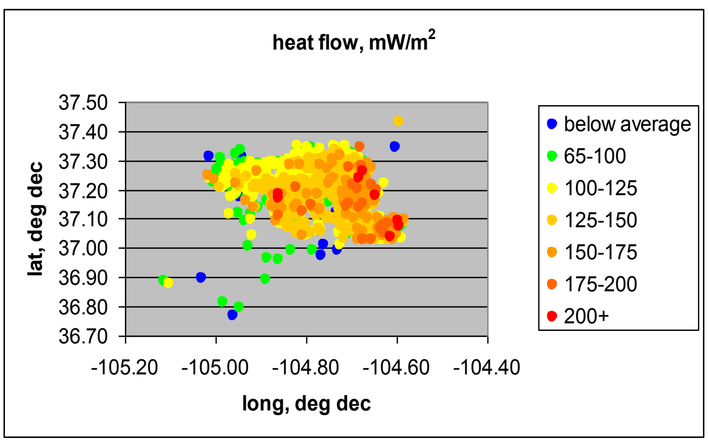

Figure 10. Study area heat flows using data available.

A high anomaly is again found near Welton, but other high heat flows are found scattered over the study area.

Much work has been performed to determine why the Raton Basin has such high heat flow. In my own rock samples, no high radiation was found ruling out the natural radioactive decay found in the subsurface. There is no known near-surface magma chamber in the Raton. While the more recent volcanic activity is to the east and south of the study area, the volcanism is still too old to typically be responsible for the high heat flows.

To date, only groundwater flow can be attributed to causing the high heat flows. Figure 4 gave a general cross-section of the basin. Hydrological studies have found that the groundwater generally flows laterally to the east within the formation strata, as shown in Figure 11. This allows meteoric water in the wetter areas on the west end of the basin to sink deep in the west before they continue to the east. This depth allows heating of the water, and the heat is maintained as the water flows to the east. Hence, the hot deep water in the west then is measured to be hot at shallower depths in the east. This phenomenon coincides with the higher thermal gradients found to the east of the basin in the shallower wells. These higher gradients in turn provide for higher calculated heat flows than the continental average.

Power Production Calculations

While the thermal gradients and heat flows look promising, even with their simplistic (possibly unrealistic) calculations, true exploration interest requires production potentials. Drilling an exploration well is a costly endeavor, so economics must be considered to further proceed. For this, some preliminary calculations were made with existing data from the area.

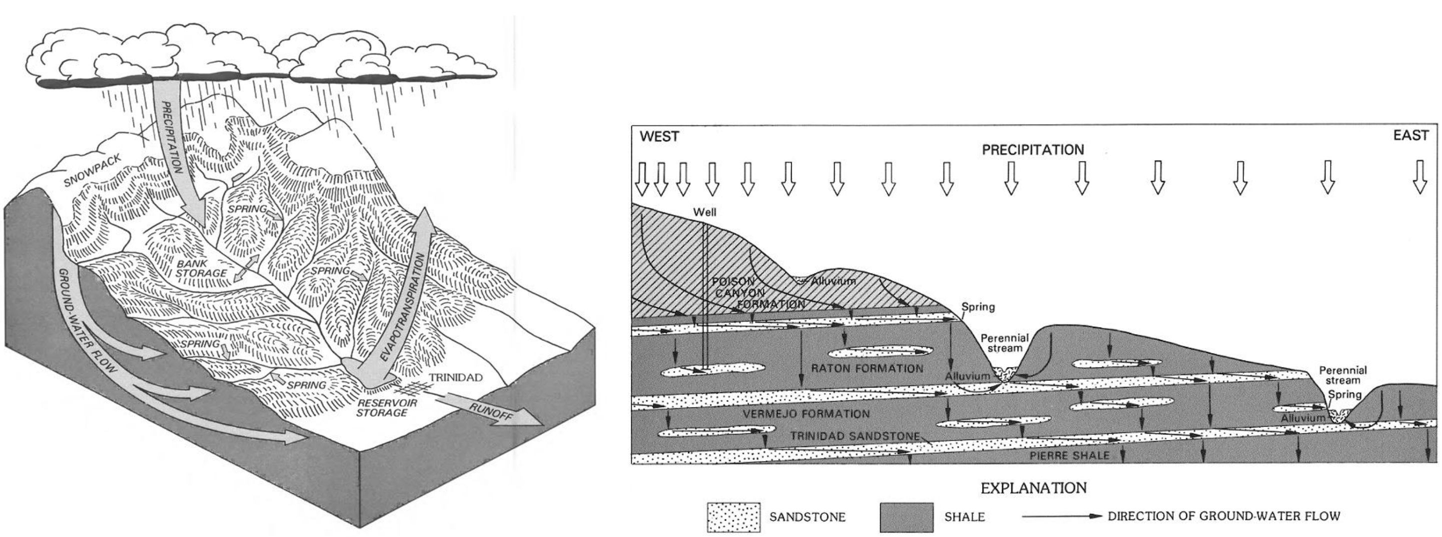

Figure 11. Generalized subsurface water flows in the Raton Basin (Geldon, 1987).

$$\Sigma Q = Q_R + Q_F \quad \text{[Eq 1]}$$
$$Q_R = \Delta Q_R\,(V) \quad \text{[Eq 2]}$$
$$Q_F = \Delta Q_F\,(V) \quad \text{[Eq 3]}$$
ΔQ_R is heat stored in rock (J/m^3)
$$\Delta Q_R = (1-\Phi)\,\rho_P\,c_R\,[T_z - T_{z0}] \quad \text{[Eq 4]}$$
T_z is temperature at depth, T_{z0} a datum temperature, will get both from gradient calculations
ΔQ_F is heat stored in pore fluid (J/m^3)
$$\Delta Q_F = (\Phi)\,\rho_L\,s_L\,[h_z - h_{z0}] \quad \text{[Eq 5]}$$

Figure 12. Simple calculations to depict heat energy stored in a reservoir.

Preliminary Calculations

Preliminary heat flow calculations were discussed above. From these data, a general reservoir location can be made, including probable depths of exploration. But to get power production potential, hot rock volumes and heat capacity, or stored heat must be considered. A basic equation can be used to find these answers: $\Sigma Q = Q_R + Q_F$. Figure 12 provides details involved to get stored heat energy results.

No water data was used in these calculations, so the fluid equations are ignored. Typically the fluid energy contributions are minimal in the overall heat capacity. Using data from the well data spreadsheets provided, and calculations on the Sangre de Cristo cores, the following was produced:

$$\Delta Q_R = (1-\Phi)\,\rho_P\,c_R\,[T_z - T_{z0}] \quad \text{[Eq 4]}$$

Sangre de Cristo data:
Avg $\Phi = 0.05$
Avg $\rho_P = 2.70$ g/cm^3 (grain density)
Typical specific heat = $0.85 < c_R < 1 = 0.85$ kJ/kgC

$$\Delta Q_R = (1-0.05)\ 2.7 * 0.85\ [50] = 1.09\text{e}8\ \text{J/m}^3$$

$1^{\circ} \sim 111$ km, 33.3*33.3*0.5 km = 554 km^3
(area based on Figure 9 data)
2*2*0.5 km = 2 km^3
(a more conservative reservoir volume considered)

$$Q_R = \Delta Q_R\,(V) = 1.09\text{e}8 * 2 = 2\text{e}17\ \text{J} \quad \text{[Eq 2]}$$

joule (J) = work required to produce
one Watt of power for one second,
or 1 J = 1 Ws, so 1 W = J/s

$$1\ \text{J} = 2.78\text{e-}7\ \text{kWh} \quad \text{[Eq 6]}$$

$$2\text{e}17\ \text{J} = 5.5\text{e}10\ \text{kWh}\ \ !!! \quad \text{[Eq 7]}$$

To put this in perspective the data provided for this model allows for ~7000 MW production sustained for an entire year.

Reservoir Model Reality Check

No existing geothermal power plant has a 7000 MW capacity. This is due to myriad reasons, some of which are listed below:

- Water picks up a fraction of available energy
- Water must not extract more energy than produced at depth
    - Residence time must be calculated for sustained production when designing the reservoir for production and injection well locations
    - Flow volume calculations must be performed to ensure sufficient hot water is produced to provide thermal energy
- Plant efficiency never at 100%
    - Depends on equipment
    - Depends on water supply flow
    - Depends on water supply temperatures

Due to the missing actual data requiring assumed values, one can reasonably assume a very conservative 1% thermal recovery rate. This would provide a 70 MW capacity plant. However, realize also that a reservoir volume of only 2 km^3 was simulated due to lack of known data. In reality this reservoir volume would be larger.

Discussion

Many assumptions were made in power calculations for geothermal potential for this paper. These assumptions prevail even today when presenting data. Figure 13 shows a more recent sketch than those provided in this paper, and is the most practical to date regarding a target area in the study area. Until exploratory drilling is accomplished, one cannot determine the true deep subsurface stratigraphy of the basin. To minimize drilling costs, would it be possible to deepen existing abandoned wells?

Little is known about water movement through the Sangre de Cristo formation due to no deep wells providing information. Again, exploratory drilling would provide information in this area and give a sense of fracturing required to allow water transport.

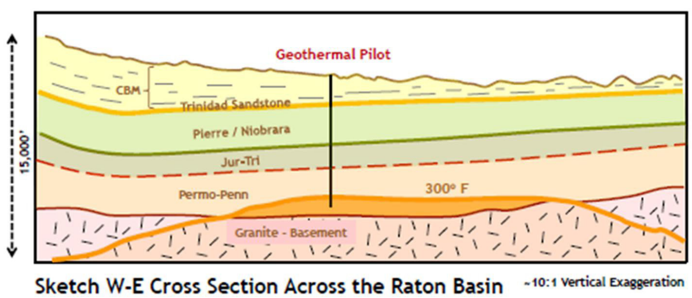

Figure 13. A recent sketch of a possible cross-section in the study area (Macartney, 2011).

Better bottom-hole temperatures could be found with exploratory drilling as well. Linear extrapolation as provided in this paper probably does not give reasonable temperatures, assuming the water travels as noted.

The natural gas operator in the area has suggested initial geothermal exploration commence in the target area provided in Figure 13. This is due to the infrastructure in place and the anomaly seen in provided figures of this paper. Is it reasonable to start exploration at this location, or focus on more data compilation in the presumed warmer eastern area?

Would electrical power produced be transportable to area of use at the target location, or would it be more economical to place the plant nearer to Trinidad where power distribution infrastructure is already in place?

Fracturing would most likely be required, but two things make this a minimal concern for the Raton: 1) the operator of the area has the equipment and expertise required to design a producing reservoir, and 2) the economics and technology required of a sedimentary reservoir vs a basement system are extremely in favor of the Raton Basin development.

In looking at the scales for depth to potential reservoir, it can be seen that developing the Raton would be about 2/3 shallower than for example, the Denver Basin. If there were an excellent choice for an initial geothermal reservoir in Colorado, the Raton Basin is it.

Conclusion

Even with minimal data presented in this paper, the Raton Basin shows excellent potential to provide geothermal power production. All indications point, however, to the need for exploratory drilling to acquire real data. Further calculations and data collection are in progress for the Raton, and new material may be available soon. Developing the Raton Basin for a geothermal power plant has several benefits. Even if production is not as economical as proposed, the Raton can become a research lab for geothermal exploration in a sedimentary basin. The economics, technology, and onsite expertise available together make this a very feasible venture. The Raton Basin could become the first EGS power plant in Colorado.

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