Rico Geology Report

Prepared for
Professor Masami Nakagawa
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1 Location

Rico is located in the southwest part of Colorado on the eastern side of Dolores County. It is 28 miles southwest of Telluride and 83 miles northwest of Durango, Colorado (see figure 1).

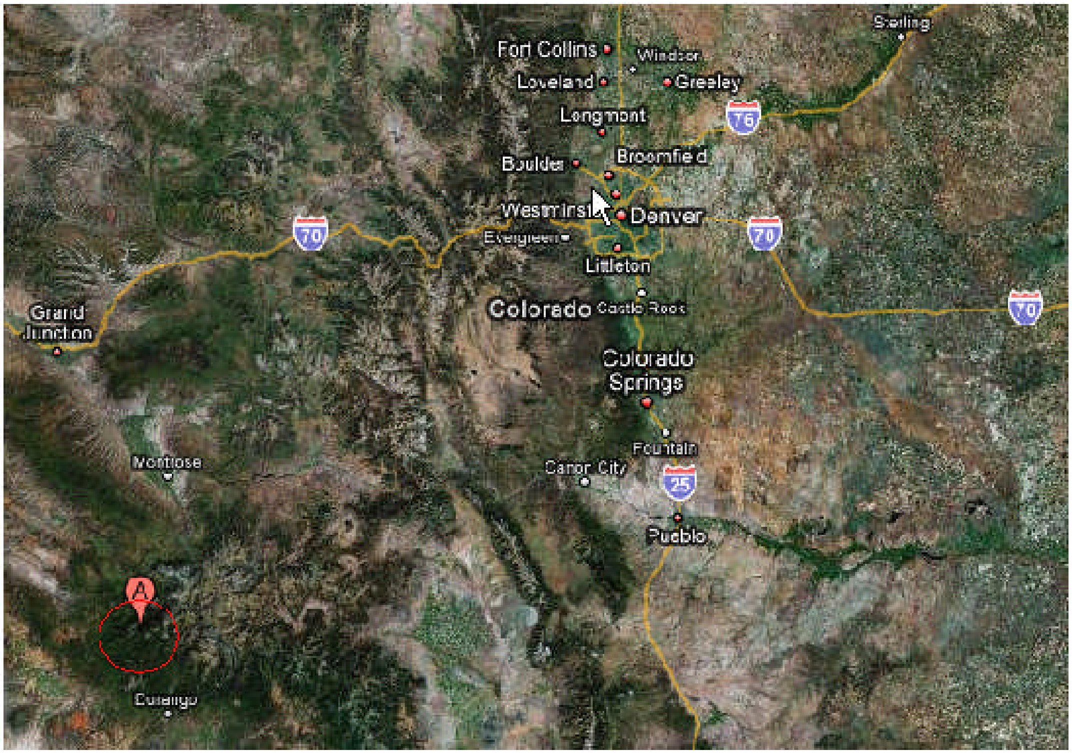


Figure 1 Location of Rico, Colorado

The town of Rico is located in the isolated Rico Mountains. Rico can be classified as a once booming mining town which has survived and maintained its identity through tourism and cultural centers.

2 Rico, Colorado

2.1 Rico General Discussion

The town of Rico sits atop a geothermal resource that has the potential for both direct heating and electrical generation ability. The geothermal resource underneath Rico has the second largest heat flow, ranging from 217 to 288 mW/m^2, making Rico an excellent geothermal exploration candidate (MegaMoly, 2009).

The resource was discovered in the 1980's after wells were installed just north of the town. Along with the know existing hot springs that are present in Rico and north of Rico, these indicators have caused more attention to the geothermal potential of the area (MegaMoly, 2009).

The Rico community has an interest in developing its geothermal resources, first focusing on smaller direct use projects. Assuming adequate resources are available and accessible, the community would like to have a geothermal power plant that could provide power locally and generate revenue from power exports beyond the existing community needs (Rico Community Meeting, March 2008).

This project has been completed as a part of the MNGN 598 Pilot Introduction to Geothermal Energy class as a part of a more comprehensive class project. This portion of the report focuses on the geology of the Rico area. It is designed to give the Rico community and potential investors a better understanding of the regional and local geology. It will also be helpful to see what data and research exists and what next steps might be in further assessing the geothermal potential moving forward.

2.2 **Mining History:**

Rico, the Spanish word for "rich", is the perfect name for this town blessed with natural resources. Ore deposits which stimulated mining development consisted of large gold strikes and silver veins as well as some copper and lead-zinc discoveries (NMGS, 1968). The Rico district has produced in excess of 14,500,000 ounces of silver, 84,000 tons of lead, 83,000 ounces of gold, 83,000 tons of zinc, and 5,600 tons of copper (McKnight, 1974). Beyond that, recent exploration activity has looked at resurrecting exploration efforts that the Anaconda Mining Company pursued for molybdenum in the mid-1970's, assuming prices rise again. The demand and interest in mining for silver also fluctuates with the upticks in the price.

The first gold was discovered in 1866 by Colonel Nash, a Texan who led a team of 18 prospectors. In 1869, Shafer and Fearheller came across Nash's gold discovery then considered the pioneer lode. This was later developed into the Shamrock and Potter Mines becoming the first profitable, ore producing property in the district (NMGS, 1968). The establishment of the Pioneer Mining District in 1876 led to an abundance of mining, and in the spring of 1879 rich oxidized silver was discovered on Blackhawk and Telescope Mountains (Rico website). The Enterprise Lode was struck in 1887 by David Swickhimer expanding the silver mining in the Rico area. Rico experienced growth in the years from 1879 to 1890 despite being very remote, a factor which increased shipping costs dramatically (Rico website).

Historical Rico, Colorado mining activity

Rico's mining activity peaked in 1892 only to bust with the silver panic of 1893. The population of Rico naturally would rise and fall with the investment in the local mining industry with populations nearing a low of 200 and a high at nearly 5,000. Local mining occurred in the early 1900's with a strong resurrection occurring in 1926. Bob Pellet and the Rico Company began to revitalize the area mining industry, and in 1937 the Rico Argentine Mining Company constructed a new mill. A sulfuric acid plant brought better economic fortune from 1953 until 1965 when the mining industry shifted focus to lead and zinc ores up to 1971 (Rico website).

2.3 Basic Mining Geology:

The ore deposits of the Rico district consist of:

1. *Massive sulfide replacement deposits* in Pennsylvanian limestone of the Hermosa formation;
2. *Contact metamorphic deposits* of sulfides, specularite, and magnetites of the Devonian Ouray and Mississippian Leadville limestone, but also of the Hermosa Formation;
3. *Veins on fractures and small faults* in the Hermosa sandstones and arkoses; and
4. *Replacement deposits in residual debris* resulting from solution of a gypsum bed where broken by fissures in the lower Hermosa Formation.

Massive sulfide replacement and contact-metamorphic deposits have been the most productive of base metals with byproduct silver in the present century. The massive sulfide replacement deposits have also yielded the pyrite for a large output of sulfuric acid. Veins on fractures and small faults and replacement deposits in residual debris were very productive of silver before 1900 (McKnight 1974). A more detailed discussion of the stratigraphy follows under the Rico stratigraphy section that describes the lithology (for the Pennsylvanian Hermosa, Devonian Ouray and Pennsylvanian Leadville formations).

2.4 Major Mines of 1920 to 1974:

Major mines that existed from 1920 on include (McKnight, 1974):

1. *The Mountain Spring and Wellington tunnels* on the slope of CHC Hill, on the east side of the Dolores River about 1.5 miles north or Rico have altitudes of 9,433 and 9,725 respectively.
2. *The Pigeon tunnel* portal is 1,800 feet north of the Mountain Spring portal at an altitude of 9,320 feet.
3. *The St. Louis tunnel* was driven by the St. Louis Smelting and Refining Company during 1930-31 to explore for deep ore horizons below CHC Hill with an altitude of 8,844 feet. It is on the East bank of the Dolores River, 1 mile upstream from Rico.
4. *The Rico Argentine group of mines* is on Silver Creek, about 1.5 miles northeast of Rico. Within the Rico Argentine group are the following tunnels:
    a. Log Cabin (Blackhawk) Tunnel
    b. Blacksmith Tunnel
    c. Argentine Tunnel
    d. Rico Consolidated Tunnels
    e. James G. Blaine Tunnel (levels 200, 300, 400, 500 and 600)
5. *The Yellow Jacket (Phoenix) Group of mine* workings is largely in the block of ground between the Last Chance and Nellie Bly faults on the southeast slope of Nigger Baby Hill with an altitude just above 9,600 feet.

6. *The Falcon mine* workings consist of three tunnels on the nose of Nigger Baby Hill a short distance above the mine road up Silver Creek, with altitudes of 9,175 and 9,250 feet.
7. *The Aztec mine* is west of the Dolores River north of Rico, on the north bank of Aztec Gulch. The lowermost tunnel has an elevation of 9,540 feet and the upper one at 9,592 feet.
8. *The Nora Lily mine* consist of two tunnels, now caved; drive eastward on the Last Chance fault zone from the west side of Nigger Baby Hill with the original mine at an altitude of 9,072 feet.
9. *The Pro Patria and Revenue tunnels* are nearly parallel crosscuts that enter the northern part of Newman Hill at altitudes of 9,425 and 9,576 feet respectively.
10. *The Forest Payroll mine* is at an altitude of 10,137 feet, on the spur leading northwest from Dolores Mountain, high on the left slope of Allyn Gulch.
11. *The Iron Clad (Silver Clad) mine* is below the Engel's mine road on the west side of the Dolores River southwest of Rico, in the first hundred feet above the valley floor; there are two tunnels with altitudes of 8,725 and 8, 800 feet each.
12. *The Jones gold mine* is on the west side of the Dolores River southwest of Rico, just above the Engel's mine road, at an approximate altitude of 8,845 feet.
13. *The Atlantic Cable mine* is in the town of Rico just west of the main street and just north of Silver Creek. The mine has 3 levels at 45, 62, and 183 feet. It has lead, zinc, copper, and iron-sulfides.

(The vast majority of mines through 1974 are shown on the geologic map in the McKnight, 1974 publication.)

3 General Geology of Rico Area

The Rico area is on the western most edge of the Rio Grande rift system, a system that comes up through the south central part of Colorado nearly on top of what is now the Sangre De Cristo range. This system is characterized by late Cenozoic volcanism, tensional block faulting and thick graben-fill, thermal springs and wells and abnormal high heat flow (Pearl, 1974).

The town of Rico occurs within a massive geological structure known as the Rico Dome considered to be an east-west anticlinactic fault which is Precambrian in age (see figure 2). The dome is elliptical in shape and is approximately 5 kilometers long. Amongst other constituents including carbonates and clastics, the Rico Dome's center is comprised of a quartzite core (MegaMoly, 2009).

The area surrounding the Rico Dome has abundant faulting systems. These faults feed the high temperature geothermal fluids up towards the surface, heating the bedrock as it rises. The fluids are initially heated deep within the earth where magmatic activity uses the method of convection to transfer its heat.

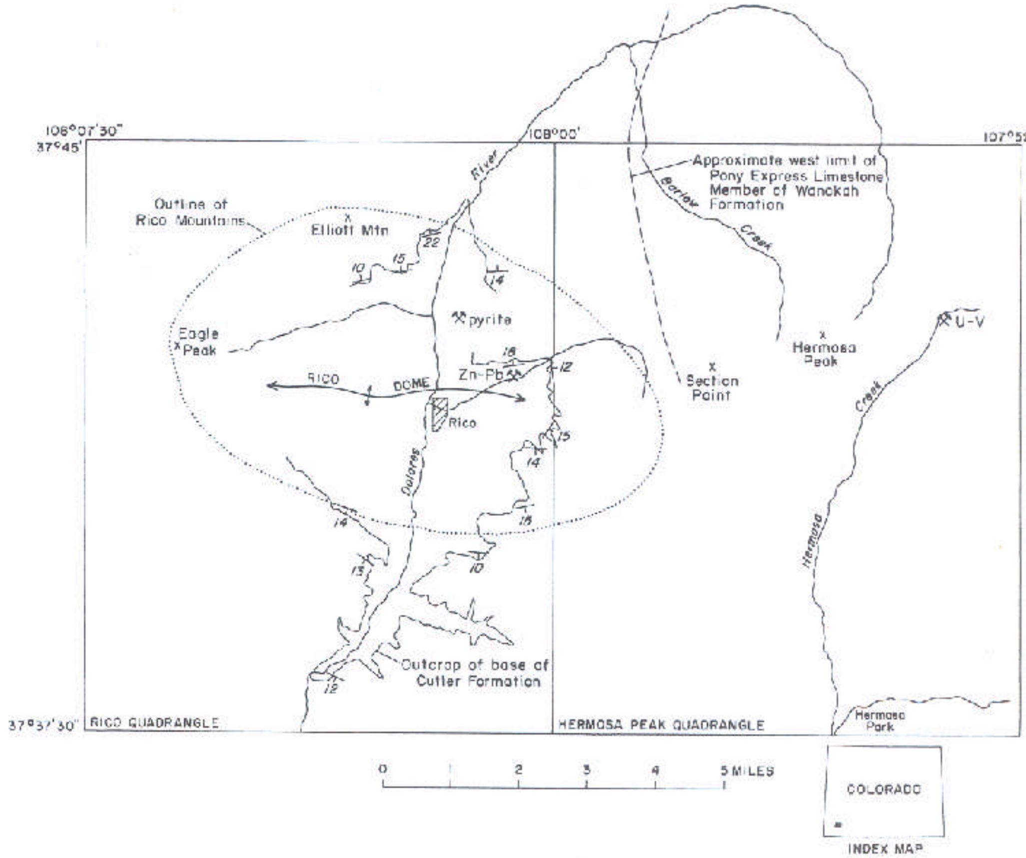


Figure 2 NMGS map showing location of Rico, CO and Dome outline

4 General Tectonism

Tectonic activity occurred during the Laramide orogeny in Eocene time just prior to the extensive volcanic activity of the period. Most of the structural relief (but none of the physiographic relief) of Colorado occurred during this time-period. In Colorado, the morphotectonic expression of the system extends northward from New Mexico through the San Luis Valley and the upper Arkansas Valley to Leadville (Pearl, 1974).

The geometry of the normal faults within the grabens of the Rio Grande rift system is not well known. This area is covered with a complex of intra-rift hosts and grabens indicating a pattern of crustal extension – one of the geothermal features associated with many economic geothermal activities.

The continuing development of the Rio Grande rift system in Colorado continues as evidenced by the many fault scarps. The occurrence of active faulting in, and peripheral to, the Rio Grande rift system during the last few million years points up a pattern of crustal extension and thinning characteristic of the Basin and Range geothermal province covering much of the Cordillera farther west. The Rio Grande rift system appears to be an extension of the Basin and Range province northward into Colorado caused by a westward movement of the Colorado Plateau block relative to the Great Plains block (Pearl, 1974).

5 Rico Area Faulting

The Rico Dome area consists of many high angled, east-west trending fault systems (Knight, 1974). The fault that moves with the most frequency and has the longest movement history is named the Last Chance Fault.

It is believed to be Precambrian in age and originally was as a wrench fault during that period (MegaMoly, 2009). The Last Chance Fault exerts significant control on the occurrence of Laramide and Pliocene aged intrusions, alterations, and hydrothermal activity. In addition to the Last Chance, the Blackhawk Fault is localized near the surface. The Blackhawk is northwest trending and has a lead-zinc-gold mineralization making it much like the surrounding faults (MegaMoly, 2009).

Further faults that account for considerable displacement are recognizable at the surface and/or within the mines themselves. These faults have likely had a major impact on fracturing and minor faulting and include the Smelter, Futurity, Nellie Bly, Yellow Jacket, Silver Creek, South Park, Knob Hill, Sandstone Mountain, Princeton, Honduras, Alaskite, 210 Drift, Hidden and the faults o f the Dolores Mountain and Deadwood Gulch area. The majority of the faults are of normal displacement, but a few are steeply reverse. Approximately one-half of these faults trend east-west and are downthrown on the north. The remaining faults favor a northeast-southwest trend with only two faults having a northwest-southeast trend (McKnight, 1974). (See Appendix for geologic map and cross-section of the Rico area.)

6 General Volcanic Activity

The south central part of the southwest quadrangle of Colorado is an area that was covered by volcanics during the Cenozoic – this area is designated as the San Juan Volcanic Field (see figure 3). Delores County, the county which the town of Rico is located in, is on the western most edge of the field. The volcanic activity occurred from 40 million to 20 million years ago. This age of volcanism has had little influence on the existing geothermal resources today (Pearl, 1974).

There was a second phase of volcanism that continued into the Quaternary. Eruptive centers were small, isolated and widely scattered in the southwest quadrant of Colorado. In west-Central Colorado small cinder cones and associated flows having erupted during the last 1.5 million years and are found at five localities (Pearl, 1974).

7 Rico Dome Intrusives

The Rico Dome area has previously undergone two distinct periods of magmatic activity. The first dates back to the Cretaceous period which put in place the Rico monzonite. This Rico monzonite, also known as augite monzonite, was emplaced just west of the Dolores River. In addition, hornblende latite porphyry was created as various dikes and sills throughout the area (Larson 1994).

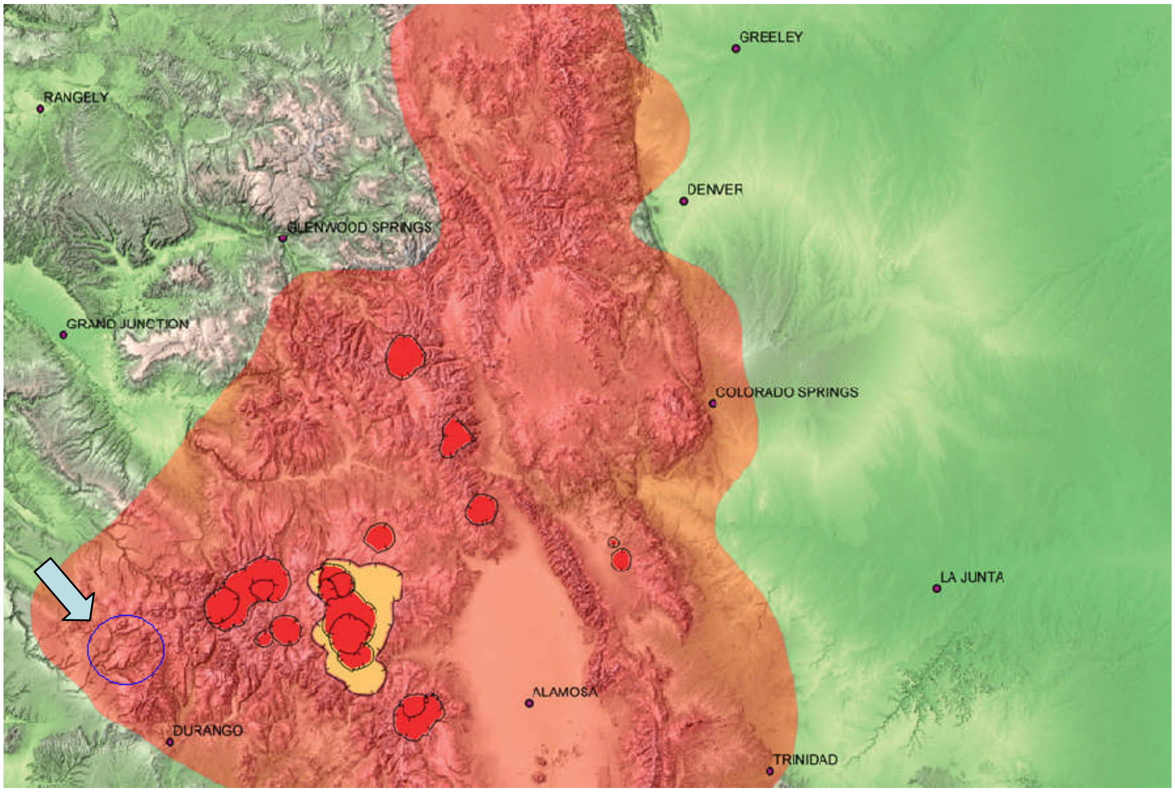


Figure 3 Tertiary volcanics for Colorado

Following this Cretaceous event was a second event, which took place during the Pliocene era when basaltic, lamprophyric, and rhyolitic dikes were formed. These dikes are associated with hydrothermal systems and precious metals mineralization. The hydrothermal mineral deposits include gold-zinc-gold epithermal veins and occur a couple meters north of the town of Rico. In addition to the veins, they also formed a hydrothermal plume (Cameron, 1985). This plume, termed the Rico Paleothermal Anomaly (PTA), produced alteration patterns that extended out up to approximately 8 km in length (Larson, 1994). The PTA alteration also produced potassic, phyllic, and propylitic zones in non-calcareous rocks, and garnet zones in various carbonates within the plume. The PTA is centered at the intersection between Blackhawk Fault and the Last Chance Fault, which provided conduits for hydrothermal fluid to rise towards the surface (MegaMoly, 2009).

This is important because it further enabled the partial conduction and convection of the extremely energized magma to rise in elevation, making the potential geothermal fluids become closer to the surface. The Rico Dome is bisected by the valley of the Dolores River and produces a slope greater than 3,000 feet. This relief exposes a sedimentary sequence of the previously mentioned Precambrian quartzite (USGS 83).

8 Stratigraphy

The stratigraphy consists of the following chronological sequence (see detailed descriptions of sedimentary section in table 1): Proterozoic greenstone, Precambrian Uncompahgre Quartzite, Mississippian Leadville Limestone, Pennsylvanian Hermosa and Rico Formations, and Permian Cutler Formation (MegaMoly, 2009). The Hermosa Formation can then be subdivided into three separate members comprised of upper, middle, and lower layers. The upper layer is composed of sandstones, shales, and conglomerate; the middle member is comprised of inter-layered limestone with some arkosic sandstone; and the lower layer is completely dominated by coarse-grained marine clastics. Next, the Rico and Cutler Formations are composed of sandstone, siltstone, and arkose red beds, which only occur on the absolute flanks of the Rico uplift. The layers of contact between the Greenstone/Uncompahgre Quartzite and Uncompahgre Quartzite/Hermosa seem to be the conduits for the mineralizing constitutes within the fluids (Cameron, 1985).

The igneous intrusions within the Rico area can be categorized into three separately distinctive groups: porphyritic hornblende latite, augite monzonite, and quartz-bearing biotite trachyte; the former 2 of the 3 have been mentioned earlier. To describe in more detail, the porphyritic hornblende latite is the predominate porphyry present in the area encompassing Rico. It has formed sills, laccoliths, and dikes within the Rico Mountains (USGS, 86). The augite monzonite is the second type of igneous intrusion and cuts the latite to form part of the Rico Dome. The augite monzonite has been useful to assist in determining the relative geologic age of the intrusives, which significantly aids in the overall mapping of the Rico subsurface. The final intrusion, biotite trachyte bearing quartz, can be seen on the eastern slope of the Rico Mountains in the form of sills and is the predominate of the three igneous rock groups (USGS, 86). The ages of these rocks are known only as post-Mancos and pre-Pleistocene although the porphyritic hornblende is thought to be Tertiary in age. The reason for the uncertainty is the lack of radiometric dating, even though the collected specimens have appeared to be fresh enough for a reliable dating trial. Work is currently being done to the stated igneous rock groups and scientists are optimistic on discovering the K-Ar ages, which would further increase our background on the history of the Rico area to aid in the future geothermal exploration (MegaMoly, 2009).

Table 1 Mesozoic and Older sedimentary & metamorphic rocks (NMGS, 1968)

AGE	FORMATION	DOMINANT LITHOLOGY	APPROXIMATE MAXIMUM EXPOSED THICKNESS (ft)
Late Cretaceous	Mancos Shale	Dark-gray shale.	3,000
Late and Early (?) Cretaceous	Dakota Sandstone	Light-gray and tan sandstone, minor black shale.	300
	Unconformity		
Late Jurassic	Morrison Formation	Brushy Basin Shale Member: light-green and brown shale.	500
		Salt Wash Sandstone Member: light-gray and brownish-gray sandstone with greenish clay galls; Junction Creek Sandstone equivalent at base in western part of area.	300
Late Jurassic	Wanakah Formation	Limy siltstone above, fine-grained sandstone below; Pony Express Limestone Member at base in eastern part of area.	200
Late Jurassic	Entrada Sandstone	Light-brown or gray massive sandstone; locally contains coarse frosted quartz grains near base.	80
	Unconformity		
Late Triassic	Dolores Formation	Light-reddish-brown very fine-grained sandstone and siltstone; thin beds of gray limestone pebble conglomerate.	1,000
	Unconformity		
Early Permian	Cutler Formation	Interbedded reddish-brown siltstone and purplish-brown coarse-grained arkose and conglomerate.	2,100
Middle Pennsylvanian	Rico Formation	Sandstone and arkose, in part conglomeratic, and subordinate shale and shaly limestone; various shades of greenish- reddish-, and brownish-gray. (Included in upper member of Hermosa Formation in eastern part of region.)	325
Middle Pennsylvanian	Hermosa Formation	Upper member: greenish-gray to brownish-red arkose, sandstone, shale, conglomerate, and minor limestone.	830
		Middle member: gray massive limestone beds separated by gray or brownish-red sandstone and shale.	650
		Lower member: greenish-gray sandstone, siltstone, and arkose; minor shale and limestone.	880
Middle Pennsylvanian	Quartzite of Larsen tunnel area	Gray to brown coarse-grained quartzite.	80
	Unconformity		
Lower Mississippian	Leadville Limestone	Light-gray crystalline limestone and dolomite	170
Devonian	Ouray Limestone	Crystalline limestone; in subsurface only.	
	Unconformity		
Precambrian	Uncompahgre Quartzite	Light-gray well-indurated quartzite.	1,000(?)
Precambrian		Metadiorite.	?
Precambrian		Greenstone.	?
		Total	11,415

9 Elements Needed for Successful Geothermal Development

There are at least six geologic elements that need to be assessed to ascertain the geothermal viability of Rico and the surrounding area. These include:

1. *Recent volcanism* – preferably Quaternary aged or within the last 1 million years

2. *Recent tectonism* – that is folding, fracturing and faulting – preferably Quaternary aged or within the last 1 million years

3. *Direct evidence of geothermal activity at the surface* – with geysers, fumaroles, or warm/hot springs

4. *Water* , ideally large quantities of warm to hot water

5. *Heat flows* that are higher than average

6. *Reservoir rock* with permeable and porous beds which the water can flow through and that are capped to minimize upward release of heat

10 Volcanism and Tectonism Evidence for Prospecting

From the discussions in the earlier part of this paper, it is abundantly clear that the Rico area has had recent volcanic activity indicative by the various intrusives present. Along with this volcanic activity, significant tectonic activity has occurred on a regional level as evidenced by the vast number of major and minor faulting that has been recorded.

11 Direct Evidence of Geothermal Activity (Pearl, 1979) and Water Flow

There is also direct evidence of geothermal resources based on the location and study of several warm/hot springs. The warm/hot springs that are known for which there is recorded information include the Dunton Hot Springs, Paradise Warm Springs, and Geyser Warm Springs (see figure 6 for location of hot springs).

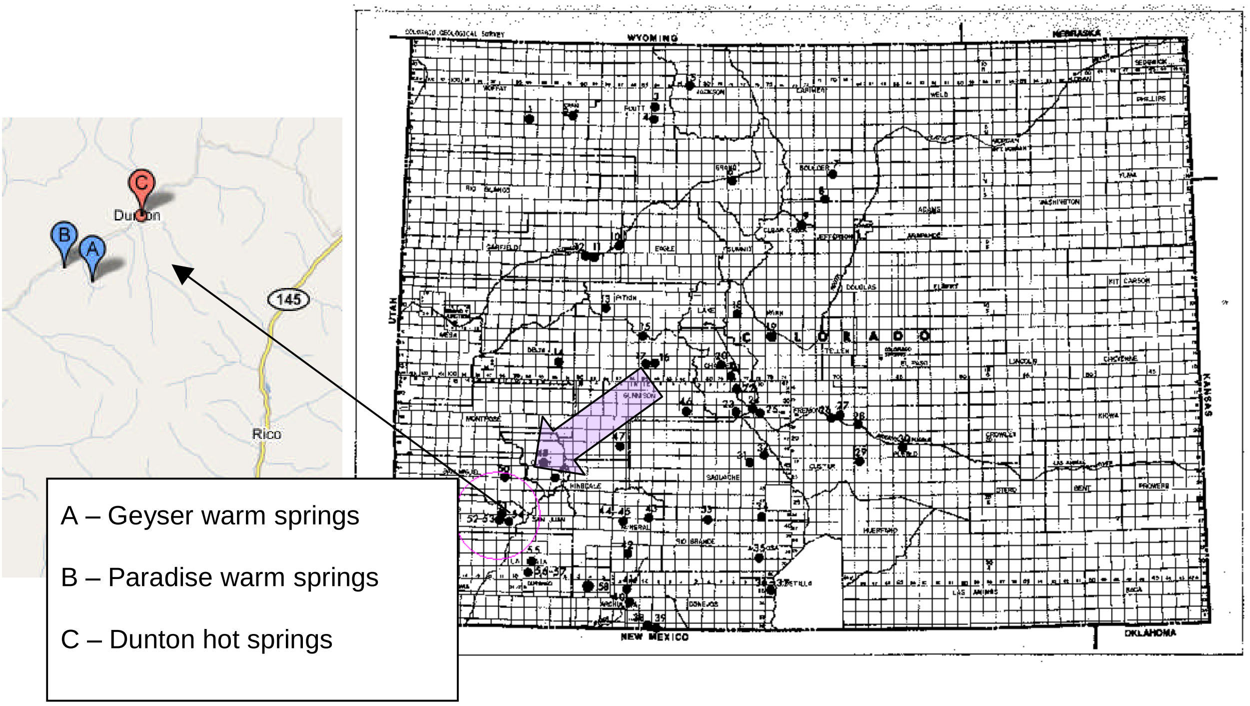


Figure 4 Location of several warm/hot springs in the Rico area – Colorado Geological Survey

Details of these hot springs include:

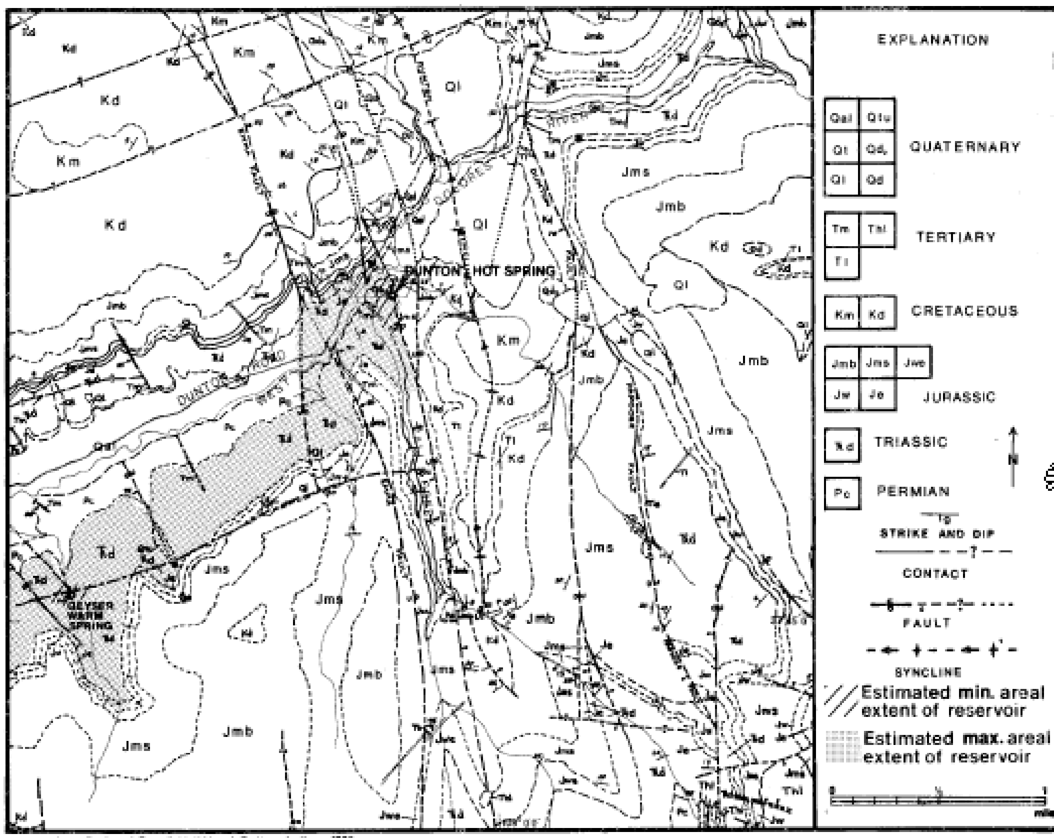
Dunton Hot Springs:	Temperature:	-42C at the surface; estimate subsurface at between 50C and 70C
	Discharge rate:	-25 gpm (96 l/m in CGS open file report 95-1)
	Bedrock surroundings:	-red sandstones/siltstones/shales - Delores Formation
	Tectonism:	-several north-northwest trending faults w/offset
	Recharge area:	-unknown – though likely to the south
	Water:	calcium bicarbonate w/lots of iron and manganese
Paradise Warm Sprgs:	Temperature:	-40C to 46C at the surface; -estimate subsurface at between 39C and 56C based on amorphous silica; 245C to 252C based on Na-K and Na-K-Ca geothermometers – suspect due to magnesium
	Discharge rate:	-26 to 34 gpm (114 l/m in CGS open file report 95-1)
	Bedrock surroundings:	-reference had no geology; suggests it is similar to Dunton Hot Springs as this is due South
	Tectonism:	-assume similar to Dunton Hot Springs
	Recharge area:	-unknown
	Total Dissolved Solids:	-6,070 to 6,530 mg/l
Geyser Warm Springs:	Temperature:	-28C at the surface;
	Discharge rate:	-estimate 20 to 250 gpm (428 l/m estimate in CGS open file report 95-1)
	Bedrock surroundings:	-waters emerge from the Dolores Formation, which overlies the Pennsylvanian Cutler Formation. Dolores consists of red siltstones, sandstone, shale and a few limestone-pepple conglomerate beds;
	Tectonism:	-spring located at the intersection of a northeast and northwest trending fault
	Recharge area:	intense faulting makes reliable predictions of recharge areas difficult.
	True geyser:	-eruptions vary – about 30 minute intervals – only 12 to 15 inches above the ground
	Water:	-sodium bicarbonate
	Total Dissolved Solids:	-1620 mg/l

These three hot springs – being in relatively close proximity – are hypothesized to be all part of one larger system. The system could be at such extreme depth that it is uneconomic.

Some work done in 1978 by Barbara Coe (CGS Information Series #9) looked at these three hot springs and estimated their areal extent at about 1.16 square miles with a thickness of approximately 400 feet. Additionally, she postulated that these were from stratigraphic reservoirs that might yield a volume of

.0262 total British thermal units (10^{15}). This complex of hot springs was given the highest potential of the “no-current activity” areas in the state.

One of the requirements for geothermal exploration entails tectonic activity. The geologic overview shows that there is broad faulting and folding throughout the Rico Dome area. On closer inspection, relative to Dunton and Geyser Hot Springs (see figure 5), significant north-south faulting has occurred with close spacing of faults in the range of 1/8th to ½ mile apart for more than 6 faults. A minor set of faults trend northeast-southwest, but far fewer of these fault traces exist at the surface. Such tectonism likely has yielded many faults and fractures at depth creating avenues for potential geothermal resources. The surface rock and postulated reservoir rock of the Geyser Warm Spring is believed to be the Dolores Formation, which overlies the Pennsylvanian Cutler Formation. At this location, the Dolores Formation consists of red siltstones, sandstone, shale and a few limestone pebble conglomerate beds.



Adapted from Bush and Bromfield, 1966 and Pratt and others, 1969

Figure 5 Geologic map of Dunton and Geyser Warm/Hot Springs

There are other warm/hot springs which are listed below. These are not believed to be connected as the 3 above appear to be. Details on these hot springs yield the following data:

Rico Hot Springs (DDH): Temperature: -44C at the surface

Discharge rate: -15gpm

Water: -Calcium bicarbonate-sulfate w/large amount of

		manganese
	Total Dissolved Solids:	-2,250 mg/l
Big Geyser Warm Spgs:	Temperature:	-34C to 36C at the surface;
	Discharge rate:	-8 to 12 gpm
	True geyser:	-6 feet in height
	Water:	-calcium-bicarbonate w/large amounts of iron and manganese
	Total Dissolved Solids:	-2,750 mg/l
Geyser Warm Spring:	Temperature:	-38C
	Discharge rate:	-13 to 15 gpm
	Water:	-calcium-bicarbonate w/large amounts of iron and manganese
	Total Dissolved Solids:	-2,790 mg/l
	*Radium Content:	-38 picocuries/liter of Radium 226 – the highest of any thermal waters in the Colorado
Little Spring:	Temperature:	-38C
	Discharge rate:	-15gpm
	Water:	-calcium-bicarbonate-sulfate w/a lot of iron and manganese
	Total Dissolved Solids:	-2,745 mg/l

All the above thermal waters are located along the east side of the road leading to the Argentine mine on the East side of the Dolores River.

Some work done in 1978 by Barbara Coe (CGS Information Series #9), looked at these four closely spaced hot springs and estimated their areal extent at about 1.74 square miles with a thickness of approximately 1000 feet. Additionally, she postulated that these were from a fractured reservoir that might yield a volume of .1407 total British thermal units (10^{15}). This area was given moderate potential of the "no-current activity" areas in the state.

In the 1992-1993 Low Temperature Geothermal Assessment Program, Colorado Geological Survey (Open File Report 95-1) report that the Geyser hot water well is flowing and bubbling with a slight geyser effect. It has built a substantial tufa mound, approximately 6-ft high, and a semi-circle shaped apron, approximately 25 feet in diameter, around the drill hole. Limonite staining is prominent in the tufa. The waters remain unused. The chemistry of the geothermal waters in the Rico area is too complex for an accurate estimate of subsurface reservoir temperatures.

While the Rico Hot Spring does not have the number of faults evident on the surface as those present at Dunton Hot Springs and Geyser Warm Springs, the Rico Hot Springs well is located on the crest of the Rico Dome. East of the well there is evidence of faults trending east-west and also northwest-southeast.

Likely any additional faulting is covered by Quaternary aged talus and landslide deposits or by Tertiary instrusives.

12 Heat Flow

12.1 Heat Flow (Morgan, 2009 and Barrett and Pearl, 1976) and Indicators of Heat Flow

The Colorado Geological Survey has a variety of different maps showing the heat flow or temperatures in the state of Colorado as well as in Rico itself. In the mapping shown below, the heat flow was color coded by heat flow intensity. The dark orange is the highest heat flow shown in mW/m^2. Several hot spots appear on the statewide map with one of the strongest anomalies shown in the southwest part of Colorado and inclusive of the Rico area hot springs (see figure 6).

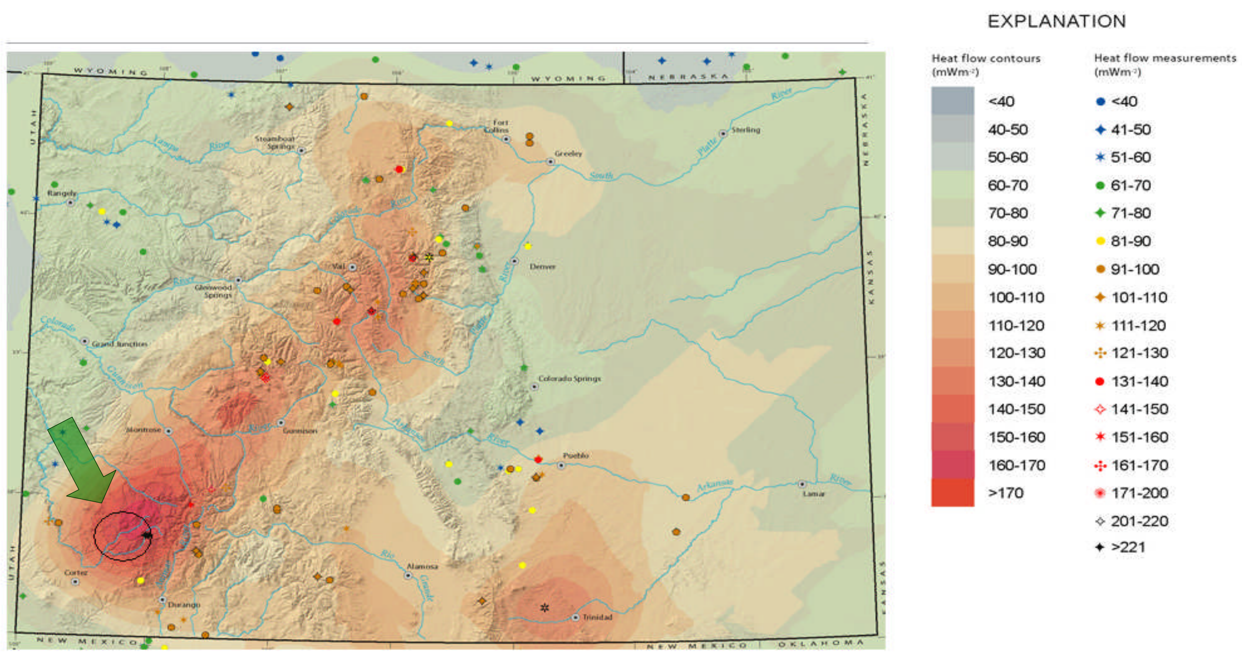


Figure 6 Heat flow in Colorado – Colorado Geological Survey

A closer look at the heat flow at Rico shows heat flow levels of 228, 238 and 243 mW/m2 (see figure 7).

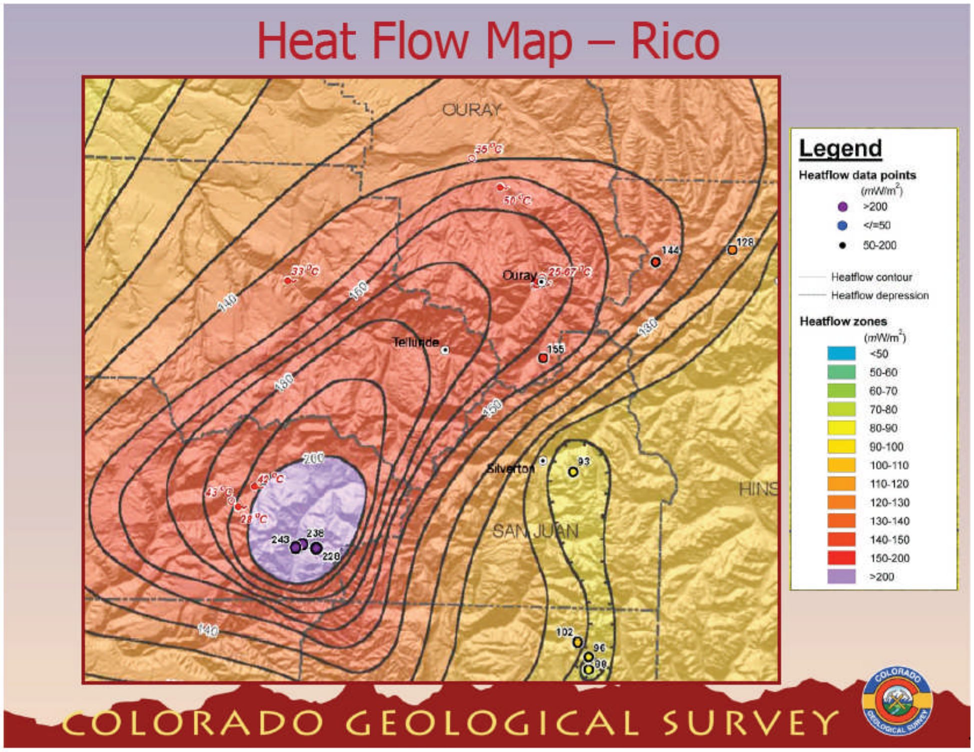


Figure 7 Heat flow map of Rico

Additionally, the content of 38 picocuries/liter of Radium 226, is the highest of any thermal water in the state of Colorado. One of the elements the CGS suggested is a good indicator of heat source is radioactive decay - thus the presence of radium (and potentially radioactive strontium below) are indicators of heat sources of significant magnitude.

The data gathered in the Hydrogeochemcial Data of Thermal Springs and Wells in Colorado (Information Series 6) reports the amount of 17 different elements in waters at each hot springs or well. Strontium is slightly elevated (relative to the rest of the well data) at Dunton Hot Springs and Paradise Hot Springs with readings of 3,000 and 3,800 ug/L. Geyser Warm Springs, where the small geyser erupts periodically, has the highest strontium reading reported for any Colorado hot spring at a level of 12,000 ug/L. The Geyser Warm Springs also has anomalously high readings of barium at a level of 1,000 ug/L – a level of 4 to 500 times greater than other Colorado wells.

12.2 Heat Flow Thesis Work for Rico Area from University of Wyoming

Eric Medlin from the University of Wyoming wrote a Master of Science Thesis titled, "Modeling Local Thermal Anomalies: Constraints from Conductivity, Gravity, and Heat Flow," in December, 1983. Medlin's research provided a bit more data on the heat flow availability in the Rico area.

Medlin begins his report by investigating the heat flow of the area. He discovered that the heat source was caused by continuous and discontinuous faults and intrusives both small and large scale throughout the area. Core data suggests that the average density of all the formations in the area is 2.67g/cm^3. An elongated dome sits in the middle of Rico that has been uplifted 1800m. Overall, it consists of an uplifted Mississippian to Cretaceous with a Precambrian core. Two intrusives associated with the Dome exist. One of these intrusive episodes is Cretaceous-Paleocene in age while the other is Pliocene-Miocene in age. Simply, the first intrusion is 2.5 km west from the heat site: 3.4$\pm$ .3 MY and the second is 1.5 km east from the heat site: 3.9$\pm$.4 MY^2 (Medlin, 1983). Based on gravity modeling and assuming a density of .1 g/cm^3, the San Juan area was interpreted as a batholithic complex with accompanying calderas and intrusives.

Per Medlin, Rico displays a nonconstant thermal gradient along with isothermal sections based on three drilled holes within the area (which he was able to access, but did not put in total into his thesis). This indicates that Rico is thermally disturbed. Anaconda Minerals mining company drilled three surface holes and one in the Blaine Tunnel located in or around Rico. As seen from previously drilled holes, the thermal gradient was inconsistent with no visible signs of heated water flow. The following is the data collected for each well log (Medlin, 1983):

SC-1: Non constant thermal gradient above 600m indicates a thermal disturbance 44 C/km to 27 C/km. High measured heat flow value decreased down hole.

SC-2: Most stable, 30 C/km average gradient. Measured heat flow value is very high and stable.

SC-4: Thermally disturbed by water flow, exhibits isothermal behavior in upper part of hole, and extremely high gradient in low areas. Not used for heat flow determinations.

SC-7: Hydrologically disturbed. May exhibit effects of fracture controlled hydraulic nature of the area; water may be coming into the hole by fracture zones; large temperature jump at 640m and isothermal section at bottom of hole.

Medlin explains that the corrected heat flow anomaly of 1.5 Hfu collected from the well logs is explained by the convective groundwater system, radioactive decay, a large cooling body which also caused the gravity anomaly northwest of the area, and from a small, younger, isolated cooling body near Rico. Medlin continues to explain that no surface manifestations or serious gradient perturbations are reflective of the major convective system operating in the area (Medlin, 1968).

Other site investigations in Rico found flowing hot water in several drill holes. Medlin determined that the water flow is common in fault controlled hydraulic regimes but do not indicate that this is a large scale system. In fact, this may result in high measured heat flow. A challenge that Medlin crossed was the idea that the hydrologic convection may remain hidden. If the convection was contacted by drilling, greater magnitude geophysical anomalies would result. The convection would have to be 50km thick for this to take place. Therefore, the cooling body that causes Rico's heat flow anomaly needs to be further investigated.

13 Geothermal Geology

13.1 Geothermal Geology at the Prospect Level:

The prospect elements include having hot rocks, permeable and porous beds, a fluid (water, vapor or gas) that can circulate the heat and a cap rock to enclose or limit the loss of heat to the surface.

Unfortunately, at this time, very limited data was located as electrical logs or sample logs from the mining drill holes were not readily accessible. Such data would assist in identifying the formations with the best porosities, primary and secondary permeability and some information about water resources.

Within a radius of approximately 2 miles of Rico, as described above, the following elements critical for geothermal development present include:

> Indication of water resources – given by the presence of geysers and the amount of fluid they produce
>
> hot rocks based on the heat flow maps (regular and interpretive) done by the Colorado Geological Survey
>
> other evidence of hot rocks based on the evidence of high amounts of the radioactive elements including radium and potentially radioactive strontium
>
> extensive faulting in the area both on a regional and local level (as evidenced by the USGS mapping done by Tweedy and Pratt of the Rico area and Quadrangle maps and also the CGS localized mapping at the Dunton and Geyser Hot Springs and the localized mapping of the Rico Hot Spring).

13.2 Reservoir Rocks:

Because the surface rocks are a menagerie of metamorphic, sedimentary and igneous rocks – and the geology is very complex – it is extremely difficult to predict the exact reservoir that the water is produced from. It could be any one of the above or any combination. While metamorphic and igneous rocks usually have very limited porosity and permeability, with the extensive faulting in the area, it is possible that these rocks have been fractured due to the tectonism and hold the waters that are heated and circulating to the surface via the springs. The cap rock could also be either metamorphic, igneous and/or sedimentary. In the sedimentary realm, we see surface evidence of dense shales at the surface which could serve as a cap rock.

13.3 Future Geologic Work Discussion:

Rock Types/Structure/Stratigraphy: Various types of interacting rock formations dominate the subsurface of the Rico area. These rock formations are controlled by their individual structure and the current data in this area is somewhat lacking. Thus, additional structural and stratigraphic geological analyzes is needed of the Rico area. A study of the surface outcrops and rock samples aid in determining stratigraphic records. Analysis of both surface outcrops and rock samples from the mining drilling (and/or new drill holes) would help in identifying the availability of reservoir rock at depth. The ideal rock would have adequate primary permeability or have the rock characteristics that would allow for the development of secondary permeability (predominately fracturing).

Rock Permeability: Permeability in flow sequences usually exists at the upper and lower boundaries or at the contacts of individual lava flows. In basin areas, much like Rico, permeability is controlled by the type of rock and by its degree of metamorphism. This metamorphism causes the rocks to become brittle and fracture under the tectonic stresses. Through gaining insight into the overall permeability of the Rico area, it can be determined how the geothermal fluids will flow and ultimately the best way for them to be utilized. The knowledge behind the structure of these rock formations is necessary to have in order to proceed with the geothermal energy process.

Faults themselves can form zones of permeability by fracturing the rock section adjacent to the fault which creates open spaces below the surface. These open spaces can remain open or be filled with a type of rock flour which is very impermeable. Faults and fractures can also be filled naturally by precipitation of vein minerals such as calcite and quartz, both of which are present in the Rico area. Mineralization can also develop along various faulting systems. This process isolates the aquifers in individual fault blocks and decreases the hydrologic communication across an area.

Alternatively, in places where faults intersect one another and fractures remain open, the overall permeability is enhanced. A structural analysis is also important when considering volcanic structures. This recognition of volcanic structures, such as calderas and vents, is important in understanding the geologic evolution of an area and can suggest where possible subsurface heat sources and permeable zone could be located. In the Rico area, knowledge of the shape and size of the basin in addition to the location of faults can be used to predict depth to permeable horizons. These permeable horizons would be the location where the potential thermal water is contained.

Hydrogeology: More hydrology and hydro geological data of the area needs to be gained in order to determine flow dynamics and possible interactions between the surface system and the deep hydrothermal system. Existing data is limited. More data would allow for a preliminary hydrologic model. The model would be conceptual at first, which would include the vertical and horizontal groundwater gradients. In addition, the model would encompass the flow directions. This model could then be used to evaluate interaction of the surface water system with the hydrothermal system overall.

Remote Sensing: Remote sensing along with other geophysical data and logs from well bores would help in creating an in depth picture of the subsurface faulting systems throughout the Rico area. Geophysical tests including resistivity and other various surveys have already been done to some of the area. This data, once obtained, should be considered when attempting to draw the system of faults within the Rico basin and range structure. The faulting system would yield the best possible location to try in order to gain the greatest amount of natural artesian pressure, which would reduce the dollars dedicated for pumping equipment.

Drill Cuttings/Samples: Geologic studies of drill samples are another great tool in the geological engineer's toolbox. Two different types of rock samples may be obtained through drill. When doing core drilling, a core of rock is cut by a hollow diamond-studded drill bit, and is collected in a core barrel which lies inside of the drilling rods. Periodically the core barrel is brought to the surface and emptied to collect the sample of rock through which the drill bit has cut. Core drilling is often used in exploration holes, in geothermal as well as oil and gas exploration.

The second type of rock sample is found from rotary drilling. In rotary drilling, the drill bit cuts rock chips from the bottom of the hole, and these chips are then transported to the surface with the drilling mud. The drilling mud is circulated down the inside of the drill string and also the wall of the hole. The purpose of this technique is to remove the cuttings while lubricating and cooling the drill bit. Once at the surface, the drill chips are removed from the mud by pouring the mud over a shaking screen, which is called a shaker table. At this point, the drill chips are revealed for hand and microscopic inspection and analysis.

Temperature Logs: Once these wells are drilled, temperature logs can begin to be created. These logs would be used to calculate the multiple geothermal gradients within the Rico area. Approximately 10 wells should suffice when performing the temperature logs. The wells should be drilled to an average depth close to 200 meters. At this depth, it is ensuring that an accurate reading of the geothermal heat is being read from the geothermometer.

14 Oil and Gas Information

The Rico area is proximal to the Paradox Basin located west of the Rico area; and the San Juan Basin located south of Rico. (see figure 8). There were several well logs including resistivity and porosity logs that were available for wells drilled on the fringes of both basins near Rico. Additional information may be garnered by a more thorough review of the logs yielding additional reservoir information (paper copies from the Denver Earth Resources Library and raster images from the Colorado Oil and Gas Conservation Commission)..

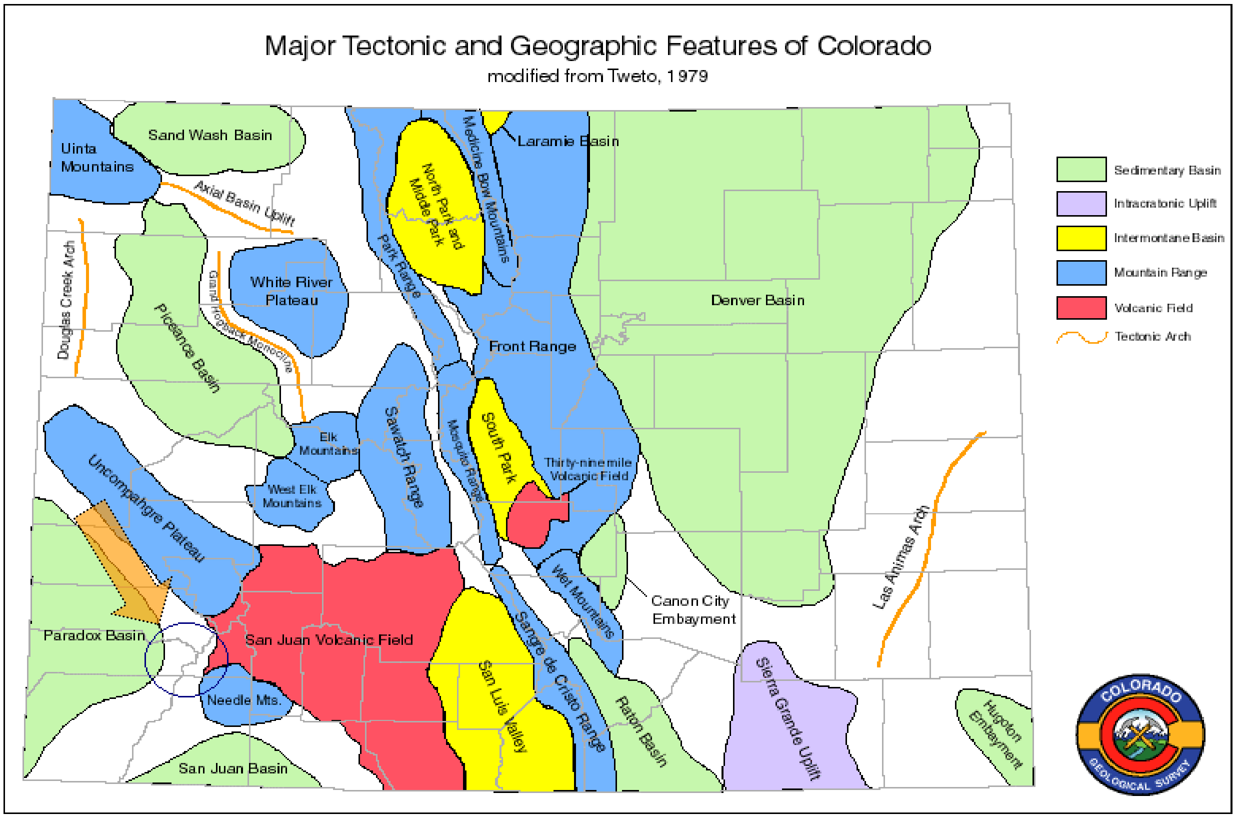


Figure 8 Location of the Paradox and San Juan Basins relative to the Rico area.

15 Summary

Rico is geologically located on the western edge of the Rio Grande Rift system. The entire Rio Grande rift system is characterized by Cenozoic volcanism with some quaternary volcanic activity. There is tensional block faulting and graben-fill. The surface rocks yield everything from Pre-Cambrian metamorphic to younger Mississippian sedimentary rocks. The pattern of active normal faulting throughout the area is an indication of traditional crustal extension and thinning. And there are thermal springs and heat flow within the region – and at Rico. Based on a first assessment level of the Rico area, we would move forward to gather more information. However, considerably more work could be done to derive the best locations for geothermal development in the Rico area.

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Mining Research to Further Delineate Rico Geology

1. Gathering of Additional Mining Data: The gathering, interpretation and integration of additional mining data would add to the ability of the Rico community and any other interested party allowing a better understanding of several key necessary factors for geothermal exploration including:
    a. *Lateral extent* of various productive horizons
    b. *Rock lithology* variations (sedimentary, metamorphic and igneous)
    c. *Porosity and permeability* of the various potential rock horizons
    d. *Faulting and fracturing* presence and its contribution to water flow
    e. *Temperatures* and thus potential heat flow
    f. *Water flow*

2. Drill Hole Data: The above mines were active at some time between 1920 and 1974. Many of the mines had drill holes drilled within the mine – some of the known drill holes are shown below on the USGS topo map (see figure 8). Tracking down the resulting information from each drill hole would no doubt prove helpful in further delineating the geothermal potential of the area.

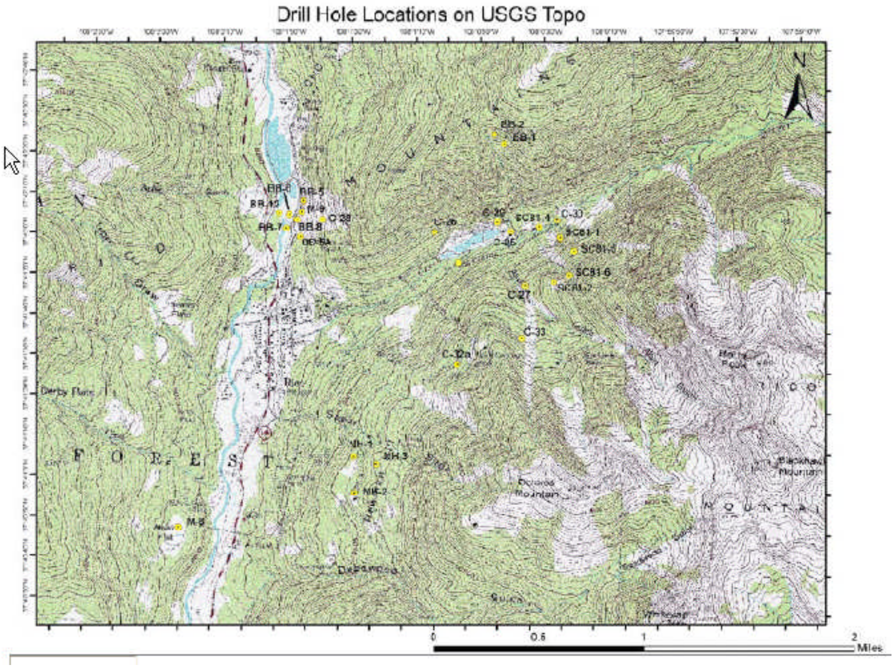

Figure 9 Drill hole locations on USGS Topo

3. Pre-1920 Mining Geology and Data: Additional mining information exists for activity in the late 1800's and early 1900's in works done by D.J. Varnes in 1943 (1944) and by Ransome (1901). Time did not permit looking at this data and it would be beneficial for future teams to research this information as well.

4. Pre-existing and Post 1974 Mining Data: Contact was made with Mr. Ramon Escure, an attorney for the Rico Renaissance Mining group, in an effort to locate and access any recent diamond drill holes or other drill holes their group has accumulated (Escure, April 2009). Follow-up with Mr. Escure may yield more data for use in future analysis.

Additional General Geologic Work

5. General Additional Geologic Data Needed: Focal points of further analysis of the following would yield better direction for the Rico community and other parties interested in developing geothermal resources both regionally and at a localized level including:
   a. Structural interpretation
   b. Stratigraphic interpretation
   c. Overall hydrology including more extensive fluid sampling of waters present in the Rico area
   d. Remote sensing

6. Well Bore Data: Well bore data gathering indicated above is recommended further research on the mining operations – with appropriate integration of analysis. This would include the oil and gas logs and their analysis nearest the town of Rico.

7. New Well Bore Drilling: Drilling of additional well bores to gather information in the areas that appear to be of highest interest and most accessible. Data to be gathered from old and new well bores include:
   a. Temperature log recordings to determine various geothermal gradients throughout the area
   b. Observations from drilling samples/cuttings taken from the wells
   c. Well logs – accessing any previous well logs and/or running well logs on new well bores

8. Field Mapping: Additional field mapping research is required with the intent of reviewing the geology with a focus on geothermal energy indicators. This can greatly aid in the overall picture of the subsurface water and heat flows. Most of the flows, in areas where the rock structures are not very permeable, travel up through the surrounding fractures. Such mapping would focus on:
   a. Thermal springs, geysers and fumaroles as these are subtle indications such hydrothermal alteration of rocks or ancient or modern spring deposits of (SiO_2) or travertine (CaC_3).

9. Integration and analysis of data gathered in 1 through 8 above

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16 REFERENCES

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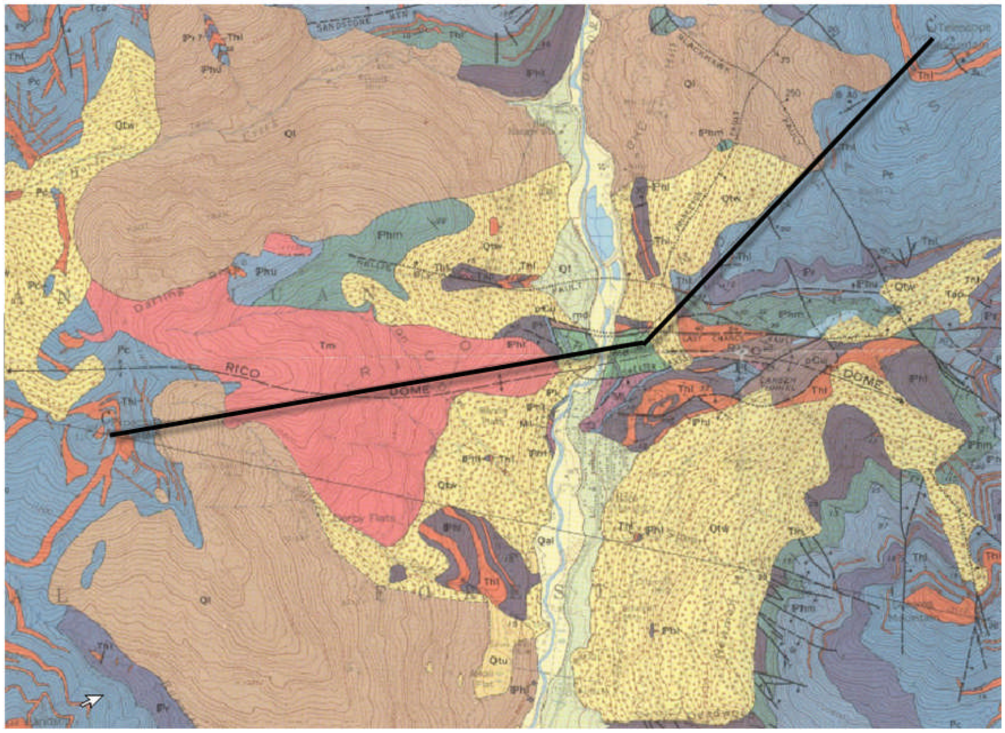
Maps:

7. Geologic Map of Colorado – compiled by Ogden Tweto, 1979, Colorado Geologic Survey

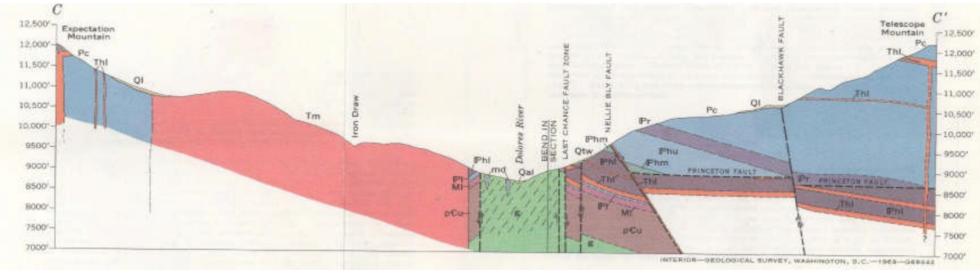
8. Geologic Map of the Rico Quadrangle

Miscellaneous Investigations Series, Map I-1039, Energy Resources Map of Colorado, United States Geological Survey and Colorado Geologic Survey, 1977.

APPENDIX I Rico Geologic Map - cross section.



Geologic map of Rico area



Cross-section C-C'