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Recovery Act: Direct Confirmation of Commercial Geothermal Resources in Colorado Using Remote Sensing and On-Site Exploration, Testing and Analysis

Prepared by Pagosa Verde, LLC

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Introduction

The geothermal resource identified in previous studies is not uniformly defined. Based on the need to understand the extent and character of the greater system, with landowner cooperation and community support Pagosa Verde proposed six thermal gradient wells to the south of downtown Pagosa Springs. Three of these wells were drilled to depths between 1400 and 1465 feet, and the results indicated geothermal potential to the west and northwest of downtown also existed. One shallow (320ft) well was drilled to evaluate this hypothesis. Three of the four wells drilled showed temperature gradients no higher than the regional background while the fourth, the furthest to the east, indicates potential for further exploration with a thermal gradient of 54.5°C/km (2.98°F/100ft)

This DOE Project was originally awarded to Flint Geothermal. It was organized into three Phases:

- Phase I - Quantify and qualify geothermal resources based on remotely sensed signatures.
- Phase II - Verify the signatures by direct on-site testing using indirect electrical and magnetic surveys including thermal gradient wells.
- Phase III- Based on the analysis of the Phase II surveys, drill deeper slim hole tests on two of the prospective resources.

Flint Geothermal completed Phase I. Pagosa Verde LLC took over the grant in April 2014 to conduct Phase II of the project in the limited time allowed due to funding expiration. This report is concerned primarily with that Phase II.

Pagosa Springs, Colorado is located approximately 400km southeast of Denver and 30km north of the Colorado-New Mexico border (Figure 1). A recognized geothermal resource since pre-settler times, the waters have been frequented by visitors and locals for hundreds of years, with the size and depth of the main spring, or "Mother Spring" causing special note from many. The current geothermal spas, resorts, and town heating system have been run for commercial and public benefit for decades.

Pagosa Springs was identified as a potential geothermal target in Colorado by the Flint Geothermal Phase 1 exploration. The Flint Project identified the Pagosa Springs geothermal system as one of the five best geothermal sites in Colorado. The study used ASTER imagery to identify structures in the Pagosa Springs area and recommended additional studies be initiated to determine the location of the upwell zone feeding the lateral flow occurring along the Dakota Sandstone. The geochemistry and geothermometry of the Pagosa Springs system was positive for the low-temperature binary geothermal power and direct use. The geothermal resource in the region has long been identified due to a large spring (also referred to as "Mother Spring, Big Spring, Hot Spring") and other surface expressions in the downtown area straddling the San Juan River.

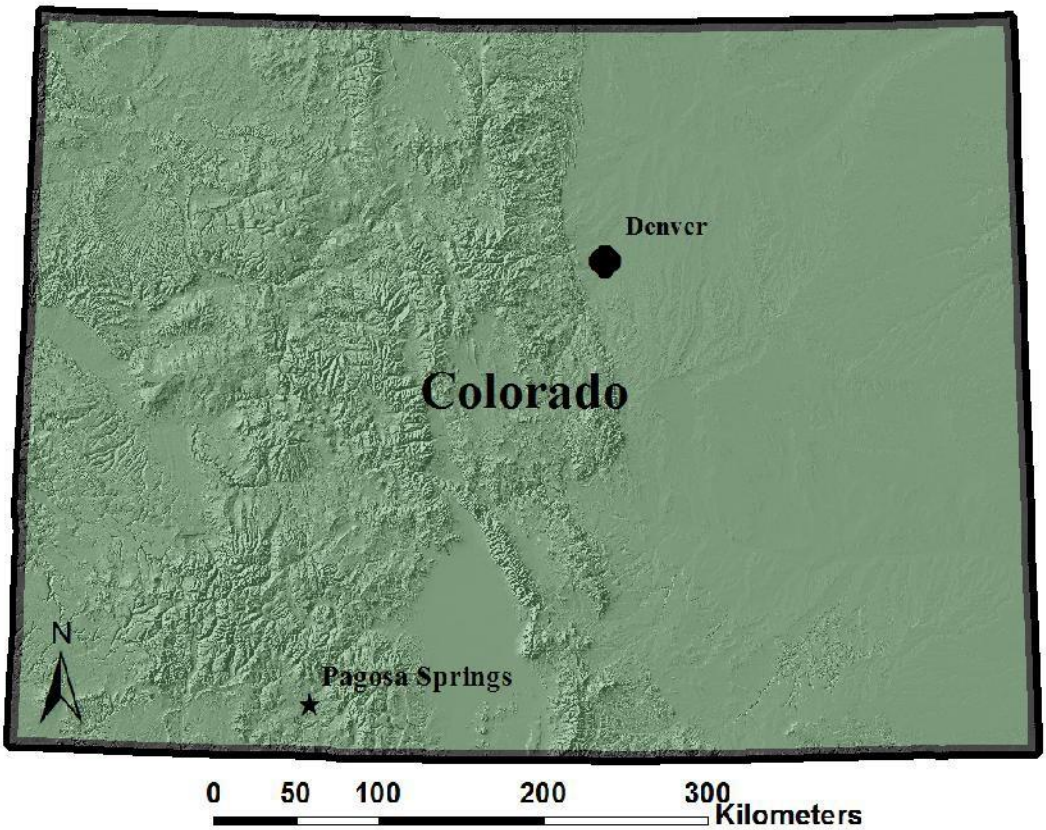

Figure 1 - State Map
Map of the State of Colorado showing the location of Pagosa Springs in relation to Denver. Pagosa Springs is nestled in the South San Juan Mountains near the border with New Mexico (to the south) at an elevation of over 2100m.

Pagosa Springs was identified as a potential geothermal target in Colorado by the Flint Geothermal Phase 1 exploration. The geothermal resource in the region has long been identified due to a large spring (the "Mother Spring") and other surface expressions in the downtown area straddling the San Juan River. This shallow resource is currently utilized as the source for a variety of commercial resorts, spas, and the Town of Pagosa Springs' geothermal district heating program. Any future geothermal development in the area cannot infringe on the geothermal water rights that currently exist and so exploration focuses on deeper, hotter resources that will not negatively affect the public and private interests in town. Regional geologic mapping was completed by the USGS in the 1930s, and has since been updated in the 1950s and again by the Colorado Geological Survey in the 1970s (Galloway, 1980). The Flint Geothermal Phase 1 cited geothermometer calculations which indicated a predicted reservoir temperatures from 73° C to 127° C suggesting a geothermal system hot enough for a binary power plant. Also MMR studies in the area south of Pagosa Springs inferred geothermal gradients of 90° C/Km and heat flow values of 120-199MW/m$^{2.}$

Geology

Sedimentary

Pagosa Springs sits above a 300-500m Jurassic to Cretaceous sedimentary package. The major sedimentary units above the Precambrian crystalline basement near town are, in order of decreasing age, the Entrada, Wanakah, Morrison, Dakota, and Mancos formations. Regionally, erosion stripped away early Laramide formations on the Archuleta Anticlinorium and deposited late Upper Createceous and Paleocene sediments such as the Kirtland Shale and Animas formation in to the San Juan Basin and San Juan Sag, respectively (Brister and Chapin, 1994). More recent erosion has exposed the Cretaceous Mancos Shale and Dakota Sandstone in the Pagosa Springs area. These units have also been identified as the two near surface groundwater aquifers (Galloway, 1980).

The sedimentary formations in the Pagosa Springs region are generally uniform in thickness and dip 5-10° to the northeast. The surface units near town are generally the Dakota Sandstone and the Mancos Shale, although small outcrops of Morrison to the south have been observed (Figure 2). Younger sediments such as the Lewis Shale outcrop to the east of town, moving progressively further up the sedimentary record (Galloway, 1980). A nonconformity between the Jurassic sediments and underlying the Precambrian granite gneiss complex generally lies between 300m and 460m below surface. The Precambrian formation in the Pagosa Springs area is currently undated.

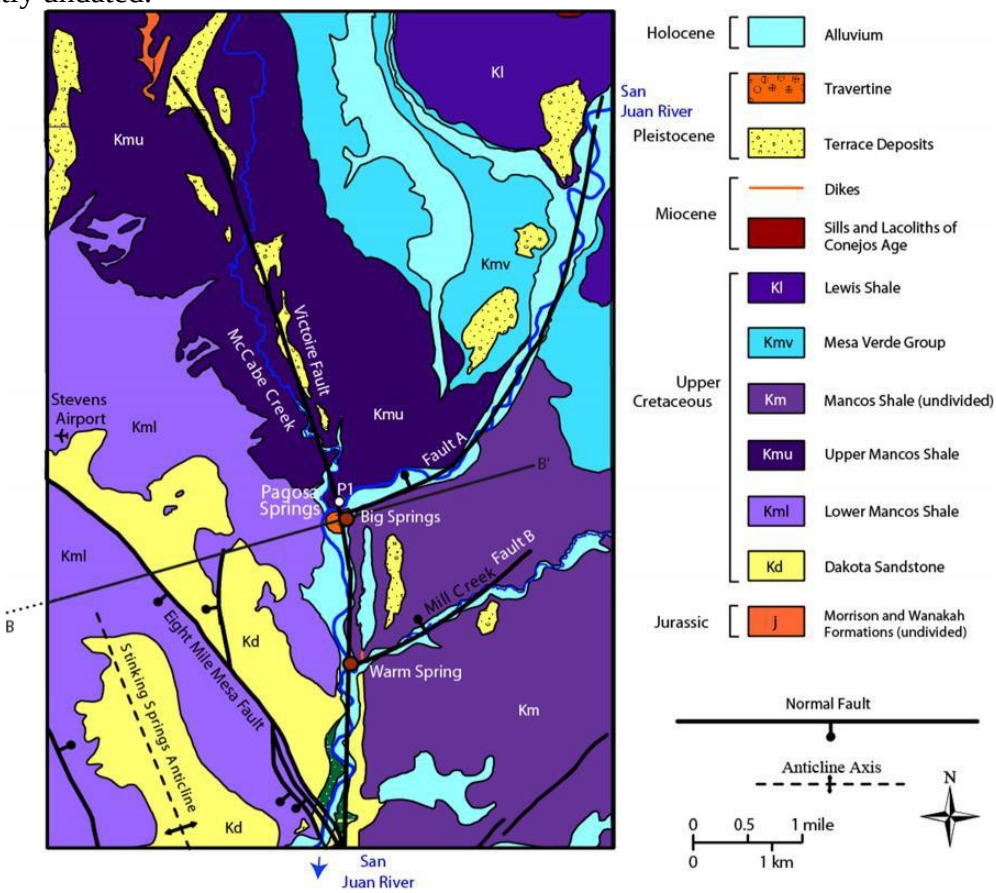

Figure 1 - Geologic Map of the Pagosa Springs Region
Geologic map of the Pagosa Springs area from Revil et al, 2013. The surface geologic units are shown, with the Mancos shale separated into the upper and lower unit in the west and north and undivided in the east. (Big Springs

and Mother Springs are the same feature)

Mancos Shale

The Cretaceous Mancos Shale is a thick (greater than 600m) dark-grey to black fissile shale interbedded with thin discontinuous sandstones and limestones found broadly throughout the southwest United States. The Mancos Shale is divided into the Upper and Lower Mancos based on the amount of calcareous material. A layer of carbonaceous dark shale separates these members (Wood et al., 1948; Galloway, 1980). In Pagosa Springs the Mancos Shale varies from a 120m section to being nonexistent in some locations.

Dakota Sandstone

The Cretaceous Dakota Sandstone is a light to dark grey generally fine to medium grained sandstone approximately 60m thick in Pagosa Springs. A highly mottled texture in some sections results from heavy bioturbation (Figure 3). The lower half of the unit has increasing shale and clay layers interbedded with the sandstones. An unconformity exists between the Dakota Sandstone and the underlying Morrison Formation (Galloway, 1980) separating the Upper Cretaceous sedimentary package from the Jurassic.

Morrison Formation

The Jurassic Morrison Formation ranges from a coarse grained conglomerate in its lower member to a fine grained sandstone in the upper member (Galloway, 1980). The sandstone members have a variable red to green mottled texture (Figure 3). Some shales are found near the upper member of the unit. Total thickness is around 210-220m in the Pagosa Springs region.

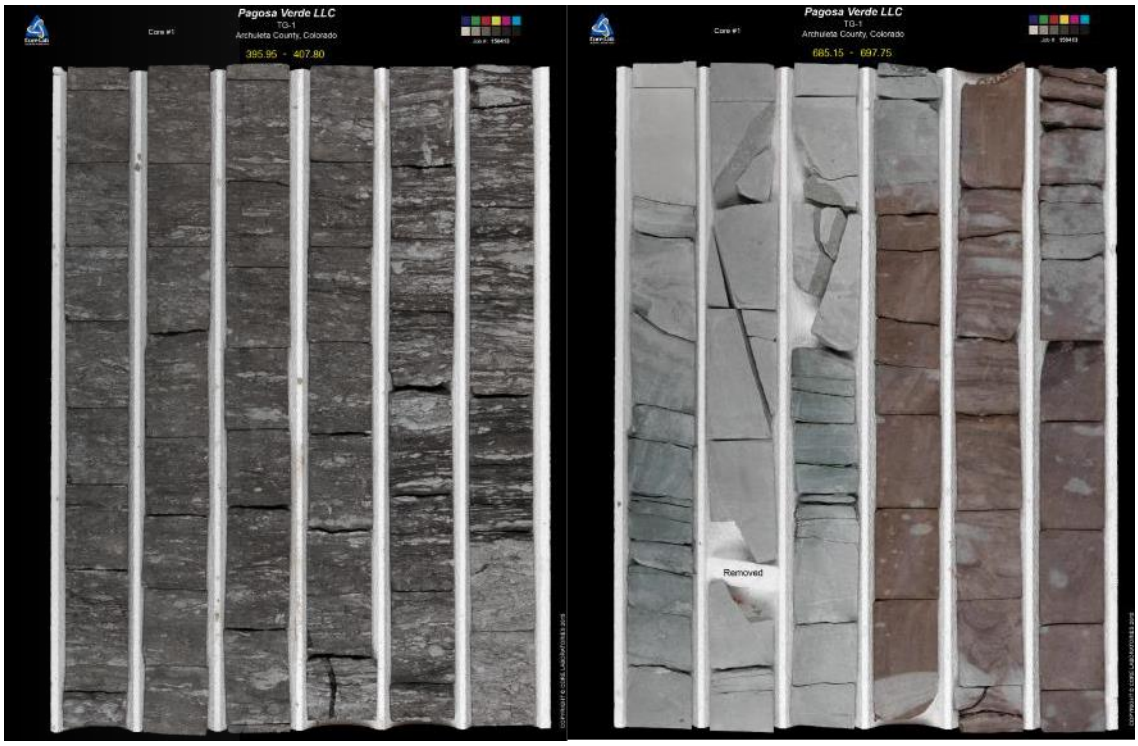

Figure 2 - Dakota and Morrison Core Photos

Photography of the slabbed core from TG-1. The left six columns are from 121-124m below surface and are Dakota sandstone, showing the mottled grey texture interpreted to be partially caused by bioturbation. The right six columns are from 209-212m below surface and highlight the red and green coloration frequent in the Morrison Formation. The complete core photography is attached in Appendix 3. Core photography by Core Laboratories in

Denver, Colorado.

Wanakah Formation

The Jurassic Wanakah formation is a white limestone-anhydrite layer ranging from 40% to 95% anhydrite (Figure 4). The P-1 well found 40-70% anhydrite in this formation (Galloway, 1980) and Pagosa Verde found 95% anhydrite. The unit thickness is 25-30m locally and it conformably overlies the Entrada formation (Galloway, 1980).

Entrada Formation

The Jurassic Entrada formation is white to grey and mottled fine to coarse grain sandstone (Galloway, 1980). The unit is massively crossbedded with sand grains typically rounded to subrounded and held with a carbonate cement (Wood et al, 1948; Galloway, 1980) (Figure 4). This unit is approximately 30m thick in the Pagosa Springs area and unconformably overlies the Precambrian basement.

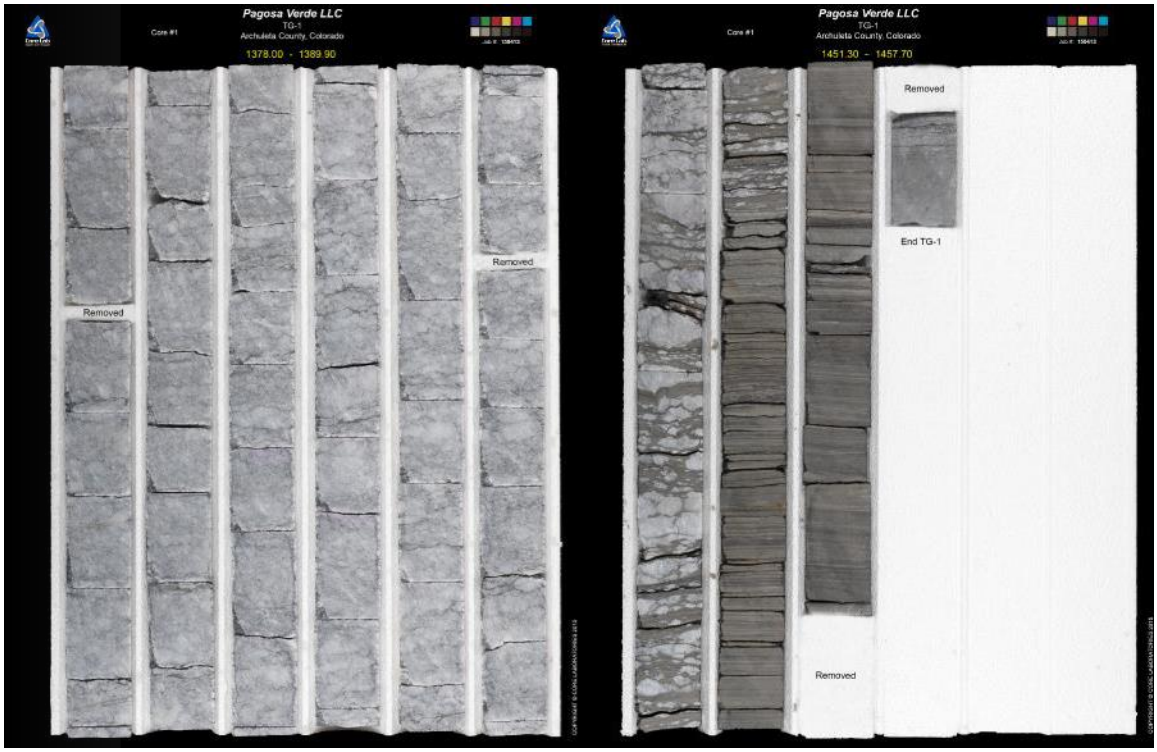

Figure 3 - Wanakah & Entrada Core Photos

Photography of the slabbed core from TG-1. The six left columns are from 420-423m below surface in the Wanakah formation, while the right three columns represent the bottom 2m of TG-1 (442-444m below surface), transitioning from the Wanakah to the Entrada formation. Core photography by Core Laboratories in Denver, Colorado.

Precambrian Basement

The Precambrian basement, while not sedimentary, underlies the sedimentary package in the region. The basement is a hornblende biotite gneiss complex with veins of light pink feldspar. Fracture surfaces in the basement show some alteration. Neither the gneiss nor granite has been dated in the area so the formation age is unknown.

Figure 4 - Basement Core Photo
The Precambrian basement granite-gneiss complex at the bottom 1.5m of TG-3 (445-447m below surface). The basement was cored in TG-3 and TG-5, but not reached in TG-1. Core photography by Core Laboratories in Denver, Colorado.

Structure

Pagosa Springs lies on the Archuleta anticlinorium, a complex 120km anticlinal feature characterized by a network of mostly northwest-southeast trending folds and normal faults with some additional northeast trending transverse faults (Woode et al., 1948; Ryder, 1977). The anticlinorium serves as a border between the San Juan Uplift northwest of Pagosa Springs to the southeast into Northern New Mexico where it terminates at the Nacimiento Uplift, Chama Basin, and Brazos Uplift. These structural features resulted from the Laramide Orogeny, the tectonic event that formed the modern Rocky Mountains.

The uplift of the Colorado Plateau initiated the Laramide Orogeny with a rise of about 3 kilometers by the end of the Miocene (Clarkson and Reiter, 1987). Localized uplifts varied in magnitude, creating highlands and lowlands that deformed the existing sedimentary packages. The Archuleta Anticlinorium resulted from loading of sediments in the San Juan Basin and San Juan Sag and northeast compression during the Eocene in the late Laramide. Other regional stresses may have also contributed to the formation of the anticlinorium. The anticlinorium lies on the southwestern boundary of the Uncompahgre Uplift, formed during the Rocky Mountain Orogeny prior to the Laramide (Figure 6). The northwestern trend of the anticlinorium is likely influenced by faults in the Precambrian basement resulting from pre-Laramide tectonics (Brister and Chapin, 1993).

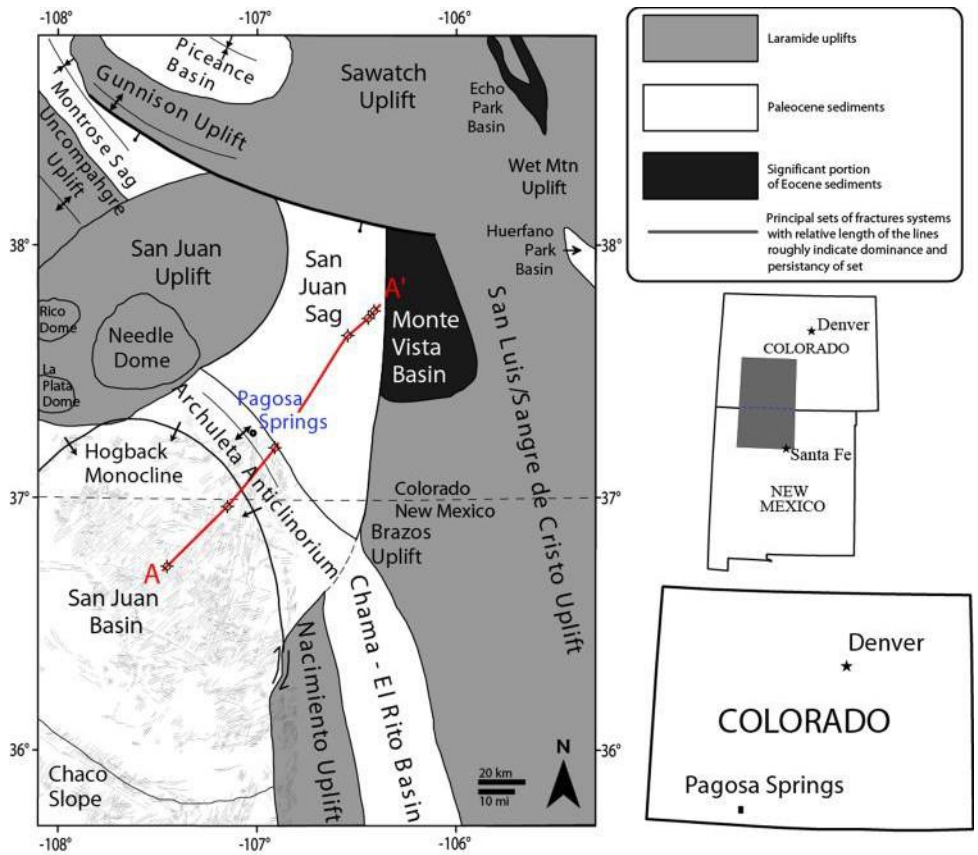

Figure 5 - Regional Structure Map

Map of the Laramide structures of the region surrounding Pagosa Springs (modified by Revil et al, 2013 from Brister and Chapin, 1994). Overlain onto the structure map are dominant fracture systems mapped by Kelley (1957). Profile A to A' indicates the location of the cross section shown in Figure 2 crossing the Archuleta anticlinorium.

The fault and fracture systems present on the Archuleta Anticlinorium emerged from a combination of competing regional stresses. This resulted in a series of predominantly near vertical normal faults in the area. The faults trending northwest-southeast along the anticlinorium likely resulted from the Eocene northeasterly compression and basin loads. Another fracture system strikes north to northeast. These faults are most likely connected with Miocene dike intrusions as indicated by the displacement of the dikes (Galloway, 1980). The dikes are likely the result of stresses unrelated to Laramide tectonic activity (Baltz, 1967), which is suggested to end prior to the Oligocene (Brister and Chapin, 1994). Another dominant fracture system was mapped in the northeasterly direction (Kelley, 1957).

Pagosa Springs exists at an intersection of these regional fracture systems, with a significant effect on the local geomorphology from underlying faults and geology. The San Juan River flows to the southwest until it reaches near the city where it flows westerly then takes a sharp turn to flow south, following an apparent change in fault trend (Figure 7.) This occurs at the intersection of the southwest trending unnamed Fault A (in Figure 7) and the north trending Victoire Fault. The sharp change in trend of the Juan River occurs in conjunction with the Mother Spring in downtown Pagosa Springs, suggesting structural control on the geothermal system and the river and indicating a thorough understanding of the structures involved to be important for properly understanding the system.

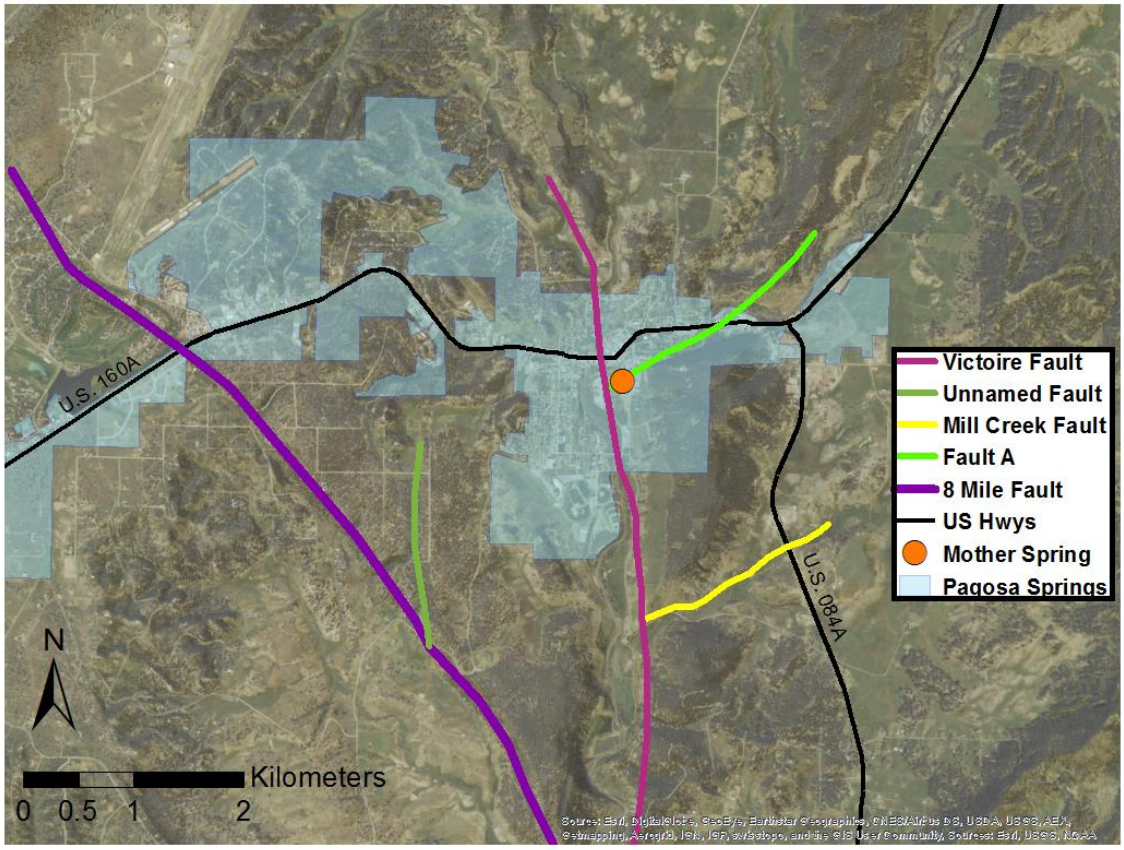

Figure 6 - Local Fault Map
Map of the Pagosa Springs region showing the locally mapped faults. The "Mother Spring" is located at the intersection of Fault A and the Victoire Fault and is the primary surface indication of the geothermal system. Faults lines represent potentially wider shear zones, not discrete planes.

The most prominent fault in the region is the southeast trending steeply dipping 8 Mile normal fault, approximately three kilometers to the southwest of Pagosa Springs. The steeply dipping Victoire Fault runs just to the east of downtown Pagosa Springs and has been thought to be a part of the structural control for the Mother Spring. The Mother Spring is the primary surface expression of the Pagosa geothermal system. The Mill Creek Fault parallels Fault A (Figure 7) and with the Victoire Fault has an intersection analogous to that at which the Mother Spring occurs.

Initial Exploration

Previous Work

The Pagosa Springs region has been the focus of geothermal exploration activities occasionally since the late 1970s with the Colorado Geological Survey drilling project to characterize the resource (Galloway, 1980). This study combined a shallow gradient well array with deeper, wider bore exploration well drilling in the downtown region surrounding the surface expression of the Mother Spring. An array of 90m shallow gradient wells was used to map the heat flow anomaly in the region and found it to be increasing west of downtown with no maximum

determined. The deeper slimhole drilled during Galloway's exploration (P-1) successfully targeted the Precambrian basement. This well caused a loss in pressure at the Mother Springs and drilling had to be stopped to prevent economic damage to the previously existing commercial infrastructure in the region.

The data gathered by Galloway served as the basis for much of the exploration in the region. A thermal gradient reversal below the Dakota was recorded in this location. Unfortunately, the raw data from Galloway's exploration has been lost so the gradients had to be recalculated from the reported information (calculations were done by the Colorado Geological Survey, courtesy of Paul Morgan). The basement core collected by Galloway was not found for additional analysis at any of the core libraries investigated (USGS Denver and University of Utah Energy and Geosciences Institute).

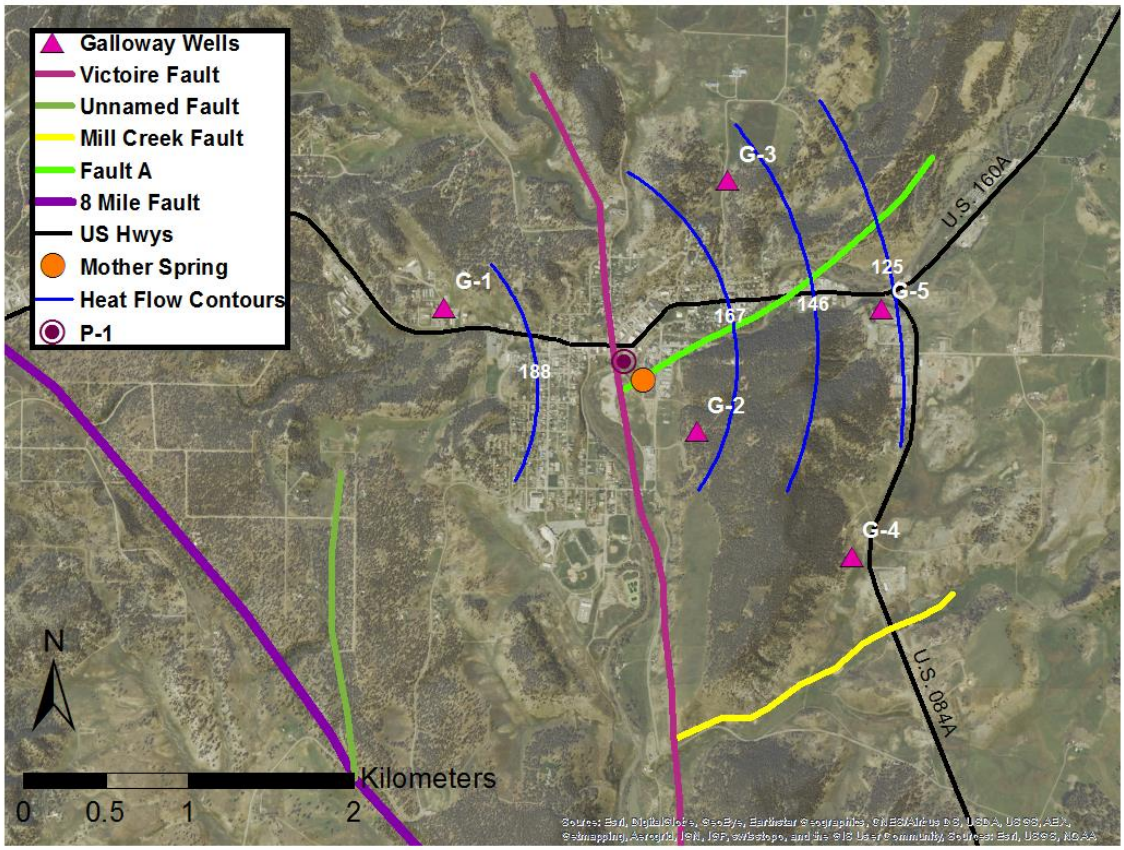

Figure 7 - Heat flow Contours
Heat flow contours and the location of the shallow gradient well array from Galloway, 1980. The confidence in the data gathered from these shallow holes was increased by the nearly matching heat flows calculated from G-4 and TG-1 as a part of the Pagosa Verde exploration.

The Town of Pagosa Springs has an operating district heating system for a variety of business and residential buildings in the downtown area. This system was installed in 1982 and has been operated through the fall, winter, and spring annually since. The town system and local resorts and spas that use geothermal heat are operating a series of shallow wells tapping in to the Dakota Sandstone, where Galloway recorded an elevated temperature in his P-1 well.

Study	Techniques	Findings/Theory	Importance
Galloway, 1980	Studied system with surface expressions, shallow gradient wells, heat flow study, and observation wells	Described a heat flow anomaly centered near downtown Pagosa Springs oriented in the NE/SW direction with the highest temperatures in the Dakota Sandstone and lower temperatures in the deeper formations in the study area, indicating the system may be controlled by a vertical fault/fracture system extending in to the basement.	Potential geothermal resource to the south of the city with a fracture controlled system requires additional geophysical testing and drilling to evaluate.
Lund & Huttrer, 2010	Desktop study of surface expressions and shallow thermal wells in Pagosa Springs	Fluid heated in Precambrian basement and rises along faults before moving laterally in the Dakota and Mancos formations. Major upflow region of the system may be to the south and southwest of downtown.	The geothermal system may be more extensive than previously thought and indicates structures to the south of downtown could be worth targeting for our exploration
Klingel, 2011; Klingel, 2012	Studied area to the south and southeast of town with geochemistry, geothermometry, and MMR.	Characterized the area southwest of Pagosa as an inferred geothermal resource based on gradients of 90°C/km, heat flow rates of 120-199 mW/m^2, and geochemistry indicating potential reservoir temperatures of up to 140°C.	Thermal anomaly to the south of Pagosa Springs merits further investigation as a potential geothermal resource.
Huttrer & Galloway, 2012	Studied surface expressions and shallow thermal wells, desktop study, static test, flow test on the direct use system	Observed interference in the wells in town during the flow test.	Shallow drilling (<1000ft) within ½ mile of existing wells or the spring will likely affect existing flow rates.
PGA, 2012	Installed water level/pressure monitors on wells in the Pagosa Springs area	Established a system for continued monitoring of the geothermal wells in the downtown area.	Water level and pressure monitors have been used during drilling to determine impact on the geothermal system.
CSM, 2012; CSM, 2013	Deep seismic, shallow seismic, magnetic, gravitational, electromagnetic, direct current, resistivity, self-potential, and ground penetrating radar stuies.	Conducted a variety of geologic and geophysical surveys in the Pagosa Springs region mapping the subsurface structures present.	Identified potential structural controls in the Pagosa Springs region that extend in to the basement that may be conduits for upwelling deep geothermal fluid.

Revil, 2013	Combined SP and electrical resistivity data in the area to investigate fundamental structures and fluid flow paths in geothermal fields.	Used data fusion techniques and image guided inversion to infer most of the hot water circulating along the Victorie Fault has discharged to the Mother Spring north of the study area from CSM, 2012 and CSM, 2013.	Propose future exploration is necessary to clarify the resource potential to the south and north of town. Previous evidence indicates potential to the south, this should be the focus of investigations.
Klingel, 2014	MMR soil gas investigation of the region.	The constituents found in local springs and wells are consistent which lends support to a reservoir at depth that has a vertical pathway from the Precambrian basement to the surface or near surface.	Continues to suggest structurally controlled circulation for the geothermal system with a basement source for the heat.

Table 1. Summary of previous exploration work in the Pagosa Springs Region, along with brief descriptions of how the data and results influenced the Pagosa Verde decision making process for identifying thermal gradient well sites and continuing exploration activities.

Goff and Tully reported on the geothermal potential of Archuleta County in 1994 at the request of the County Commissioners. The report focused on the geochemical analysis of surface waters in the region to determine geothermometry of the reservoirs present. This report collected and analyzed water samples from a variety of local springs and geothermal wells. Geothermometry calculations and chemical analysis indicated up to 120°C geothermal reservoirs in the Precambrian basement, since updated to 130°C by the Colorado Geological Survey.

Surface Geophysics

The Colorado School of Mines geophysics department summer field camp students completed surface geophysical studies in the region under the supervision of several professors and graduate students (Appendix 9). Local landowners and government supported these studies through access to the area. The students completed a variety of techniques including shallow seismic, deep seismic, magneto-telluric, ground penetrating radar, self-potential, resistivity, magnetics, and gravity surveys (Figure 9). These surveys helped determine potential structural flow controls on the geothermal system. Identification of faults and bedding beneath the Mill Creek and 8 Mile Fault regions allowed inferences to be made about the offset and fracture potential in these areas. The geophysical data significantly improved understanding of the Mill Creek and Victoire Faults.

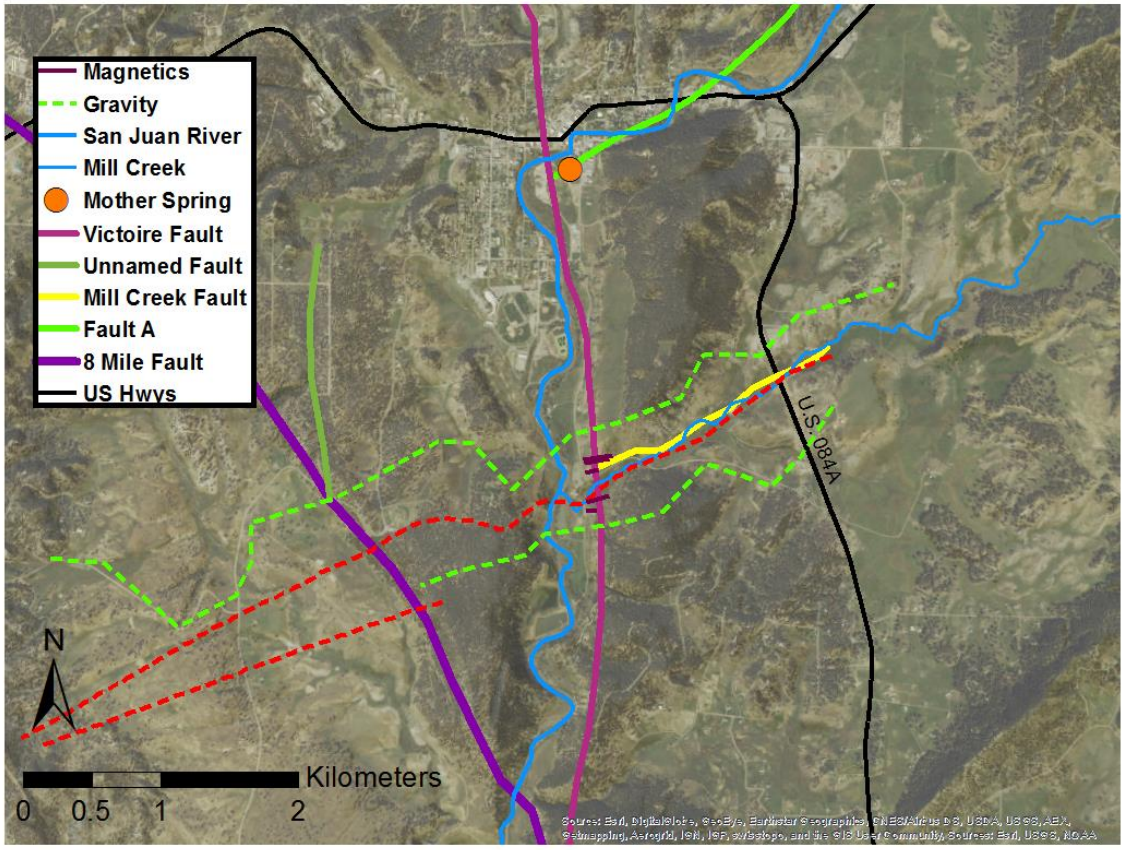

Figure 9 - Surface Geophysical Survey Lines
Surface geophysical surveys completed by the Colorado School of Mines in the area just south of downtown Pagosa Springs and along Mill Creek. An additional deep seismic survey was completed north of US 160 and cutting across the 8 Mile Fault (Colorado School of Mines, 2012; Colorado School of Mines, 2013).

Additional analysis of the geophysical data was performed by Revil, et. al using image guided inversion of the MT data. This image-guided inversion allows for more accurate analysis of the data and a more defined subsurface image. The geophysical data collected combined to indicate the presence of faulting running along Mill Creek between Highway 84 and the San Juan River. This fault, called the Mill Creek Fault (Figure 7), runs parallel to the fault intersecting the Victoire Fault at the Mother Spring, setting up a comparable structural environment to the spring's location that could be an upwelling source for geothermal fluid.
An important aspect of the Colorado School of Mines study was the 6km deep seismic profile run from Highway 84 to the west along the Mill Creek Fault and across the Victoire Fault and San Juan River. This profile indicates substantial fracturing near the TG-1 location as well as significant offset along the north-south trending faults in the region (Colorado School of Mines, 2012). These faults and fault intersections became the target of the thermal gradient drilling program, as the potential was high for structurally controlled flow of the geothermal fluid from deep, basement penetrating features.

MMR Soil Gas Samples

The Magmatic, Mantle, and Radiogenic technique applied during this project is a relatively untested method attempting to use the soil gas chemistry to determine temperature anomalies at depth. Each site tested used a combination of gas geothermometers to determine an average temperature from which the anomalies can be mapped. The measurements were taken near the

originally proposed drilling locations on the River Ranch property and were analyzed by the University of New Mexico in Albuquerque.

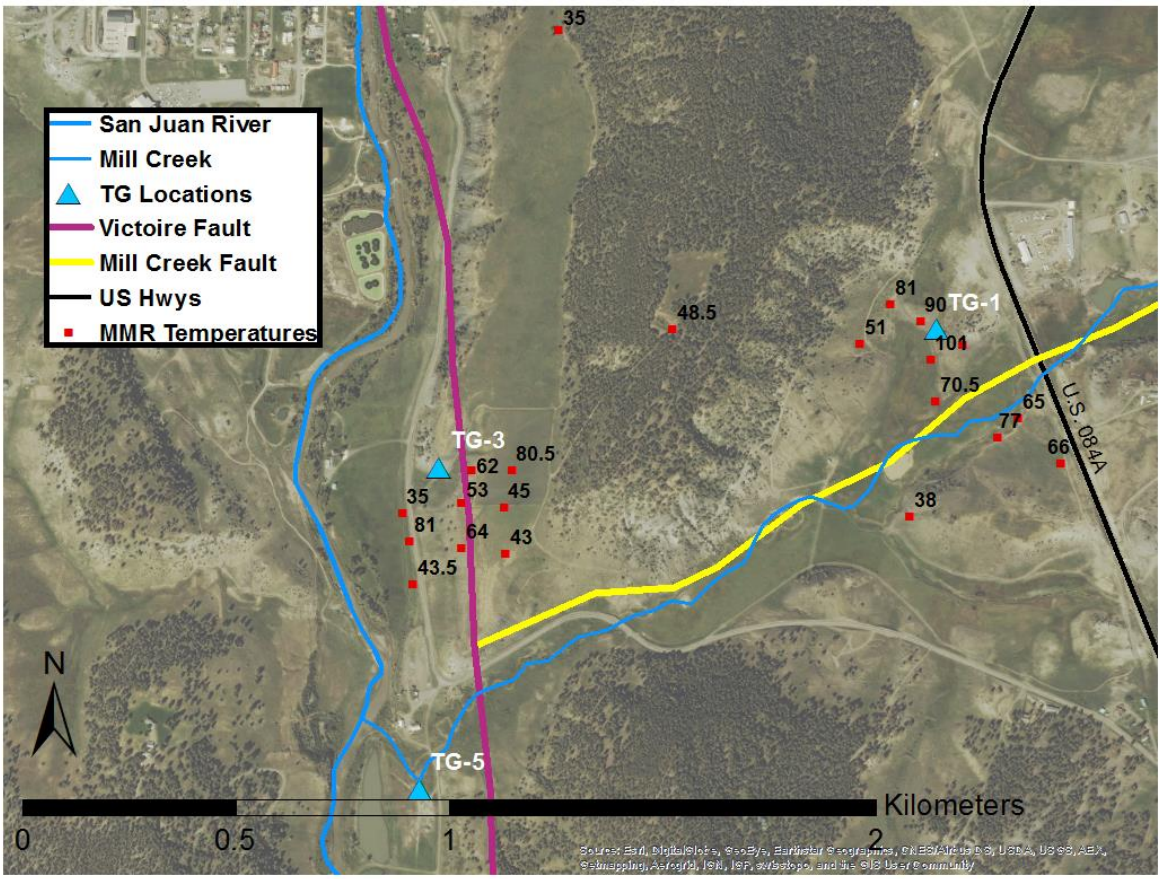

Figure 10 - MMR Sample Locations
Locations of the MMR soil samples taken on the River Ranch Property. The temperatures anomalies are in °C averaged from the CO_2/N_2, and H_2/Ar geothermometer calculations for each location. The complete report is attached in Appendix 6 with the location identities and other geothermometery calculations.

Two separate areas south of Pagosa Springs were chosen for application of the MMR technique, one located just west of US Highway 84 and north of Mill Creek and the other straddling the Victoire Fault near TG-3. The Highway 84 location is Pagosa East and TG-3 location is Pagosa West. Ten sites in the east region and nine sites in the west region were sampled for their soil gasses and three geothermometers were calculated for each site: CO_2/CH_4, CO_2/N_2, and H_2/Ar. Each of these geothermometers was calculated based on the soil gas ratios collected at each site from a shallow depth with a vacuum s a m p l e tube. A more thorough description of the technique is present in Appendix 6.

The CO_2/CH_4 geothermometer consistently returned results dramatically higher than those of the CO_2/N_2, and H_2/Ar samples, as well as the geothermometers calculated from the water samples. The CO_2/CH_4 results are considered inaccurate at these locations.

River Ranch MMR Gas Geothermometer Temperatures				
Sample ID	CO2/CH4 (°C)	CO2/N2 (°C)	H2/Ar (°C)	Average Co2/N2 and H2/Ar
BG-2	188	44	53	48.5
BG-Dup-1	192	44	26	35
W-1		86	42	64
W-1 Dup		42	47	44.5
W-2		45	62	53.5
W-3		42	48	45
W-4	32	57	41	49
W-5	227	81	43	62
W-6	171	90	71	80.5
W-7	153	42	45	43.5
W-8		110	52	81
W-9		48	22	35
E-1	164	78	102	90
E-2	199	92	62	77
E-3		95	67	81
E-4	175	42	60	51
E-5		76	54	65
E-6	265	82	50	66
E-7	142	97	105	101
E-8	185	68	73	70.5
E-9	190	63	54	58.5
E-10	194	43	33	38

Table 2. Geothermometer calculated temperatures from the MMR gas soil survey. BG-2 and BG-Dup- 1 were on the top of reservoir hill. Those with a Sample ID beginning with W were from the west region and those beginning with E were from the east region (Figure 10). The average calculated here ignores the CO_2/CH_4 geothermometer due to high variability and inconsistency with other calculations. The BG labeled measurements from Reservoir Hill are background values for the dataset.

A limitation in assigning much weight to this data regards the high variability in the observed geothermometer calculations and the small sample size. Although the average and median temperatures of the eastern data points are15°C higher than the western, with only ten data points taken for each region there is a significant risk in assessing the quality of the data in regards to the technique's method of determining a temperature anomaly and geothermal resource potential. A more rigorous statistical analysis of the geothermometry data may provide more information going forward but lacking a higher volume of data points any conclusions are limited at best.

Thermal Gradient Drilling Program

Introduction

Six thermal gradient drilling locations were chosen based on surface exploration and geophysical data. These sites targeted structural intersections as potential flow pathways for geothermal fluid on and around the River Ranch Property at the south end of Reservoir Hill. The order of drilling was determined through evaluation of geothermal potential and the data needs to enable scientific clarification. Three of the six originally proposed sites were drilled, as well as one additional site based on gradient measurement results. TG-1, TG-3, and TG-5 were completed to depths of 1458 feet, 1465 feet, and 1404 feet respectively. Planned sites TG-2, TG-4, and TG-6 were not drilled.TG-1 reached the top of the Entrada Formation while both TG-3 and TG-5 succeeded in reaching the Precambrian Basement. Temperature gradients in these wells were quick to equilibrate and showed very little change after the first week post drilling. TG-5 has been plugged and abandoned (P&A) due to an uncontrolled artesian flow to surface.

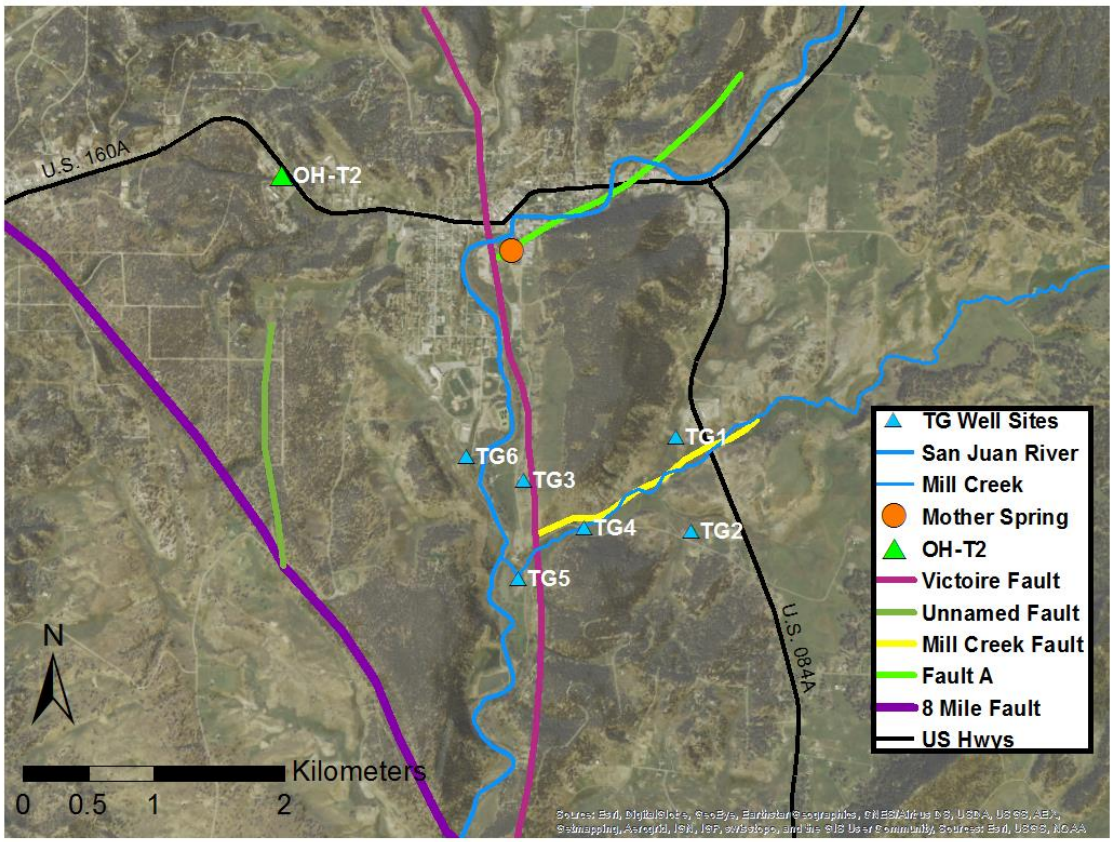

Figure 8 - TG Well Locations
Thermal gradient wells proposed by Pagosa Verde. Of these, TG-1, TG-3, TG-5 and OH-T2 were drilled. The TG series were the originally proposed wells, OH-T2 was suggested later based on the initial results from the three TG wells drilled.

During drilling, budget constraints and time limitations due to artesian flows reduced the value of continuing with the originally proposed schedule and suggested a change in the exploration strategy.

Results from the thermal gradient measurement in TG-1 closely matched with the shallow gradient well measurement nearby and increased confidence in the heat flow map developed as a result of the shallow well array (Figure 8) (Galloway, 1980). Combined with the thermal gradient measurements in TG-3 and TG-5, three new exploration targets were chosen to the

west of downtown Pagosa Springs. The shift to the west of Pagosa Springs was driven by the geologic data but exact well locations were controlled by surface environmental considerations and land availability. Before the termination of field activities OH-T2 was drilled to the west of downtown to a depth of 98m (320ft) penetrating 15m (49 ft) into the Morrison

Site Preparation

Two endangered species had to be considered when selecting the drilling locations in addition to standard environmental concerns: Pagosa Skyrocket and the New Mexico Jumping Mouse. Ecosphere Environmental Services completed a biological survey for each proposed drill site in June and July 2015 to identify skyrocket plants. The TG-1 site had to be moved to prevent negative effect on Pagosa Skyrocket. A major time delay to the drilling program occurred due to the seasonal skyrocket bloom restricting when a biological assessment could occur. Six months were removed from the drilling schedule and the project was pushed into undesirable and expensive winter drilling. Sites other than TG-1 remained in the proposed locations.

Figure 12 - Pagosa Skyrocket
Flower of the Pagosa Skyrocket, only found in Pagosa Springs and listed as a federally endangered species. Protection of Pagosa Skyrocket habitat was critical to planning the drilling program. Photo by US Fish and Wildlife, Mountain Prairie region.

Original planning had TG-1 being drilled to a depth of 610m (2000ft) with the other five wells being drilled to a depth of 305m (1000ft). TG-1 was specifically targeted the Precambrian Basement. TG-1 was cored from the surface casing shoe at 61m (200ft) to TD. TG-3 and TG-5 were spot cored as deemed necessary to allow a better evaluation of the prospect. Monitoring well permits were obtained from the state to allow for future transition to water wells if desired by the property owner and geothermal lease holders.

The selection of the drilling contractor was done by competitive bid, with DOSECC Exploration Services (DES) selected to drill the three deep thermal gradient wells. The straight

cost competitive bidding did not result in selection of the party necessarily most qualified for the expected drilling conditions, and therefore may not have been the best value for the project. The drilling was performed under the drilling license of Fred Rothauge of HydroResources. This arrangement was necessary because DES lacked the Colorado State drilling license required to work in the state.

Geothermal water rights to the shallow aquifer underneath downtown have been previously claimed with the town of Pagosa Springs providing geothermal district heating for 15 customers in the downtown region and several private wells supporting commercial geothermal resort operations (Rafferty, 1989). To prevent any damage or economic loss to the current geothermal water rights owners and operations pressure and temperature monitors were installed at the well heads of five actively used geothermal wells in town. If a negative effect on the town system occurred the thermal gradient drilling would have terminated.

The shift to the west of Pagosa Springs required a second round of environmental consideration for each drill site and the limited time frame required a finding of no effect for endangered species on any proposed location. Only sites on pavement and greater than 300m from the Skyrocket potential habitat Mancos Shale could be considered, significantly limiting the drilling options. Of the three proposed sites meeting the required criteria only one (OH-T2) was drilled due to time constraints.

Site Selection

The six drilling sites originally chosen and the justifications for each follow below. These sites were chosen to maximize the potential of intersecting the structurally controlled up flow zone and correlate subsurface geology with that interpreted from the geophysical surveys. The first six thermal gradient sites were given the identifiers TG-1 through TG-6 based on location and potential drilling order. Of these sites only TG-1, TG-3, and TG-5 were drilled. TG-2, TG-4, and TG-6 were permitted but no drilling activities occurred.

Well	Initial Reasoning for selection	Drilling Order
TG #1: Central Mill Creek	This site corresponds to several anomalies: a high temperature anomaly from MMR testing, a positive SP anomaly, and high conductivity values from DC Resistivity testing. Geologically, CSM 2013 detected a possible series of small faults running through the area in addition to the larger series of faults detected immediately north and south of Mill Creek. A stratigraphic well could confirm the depth of the Mancos and whether or not this is a horst graben system in the north-south direction. This information could help us confirm and extrapolate the placement of rocks elsewhere in the region without drilling.	1

TG #2: South Mill Creek	Similar to TG #1, this site corresponds to temperature anomalies and conductivity anomalies that could indicate geothermal fluid. Also, this area had a much higher SP anomaly than the surrounding area, and corresponds to a fault trace detected by the DC Resistivity data. If significant, this could be the location/source of upwelling water that discharges into the Mill Creek area.	Not Drilled
TG #3: Warm Springs	This may be close to Victoire Fault. The basement is at shallow depth if the fault angles as the cross section suggests. This site corresponds closely with a warm spring that discharges into the San Juan River. Allows us to examine this known source of geothermal water and evaluate if this water is fault-controlled and/or being allowed to flow through the Dakota Sandstone through fracture porosity as a local aquifer. The specific location is chosen in order to answer these questions while staying off of high value land closer to the river. This location is also near an interpreted fault and was a significant area of interest in the MMR survey (although measured temperatures in this area were not as high as Mill Creek). An understanding of conditions here could give us insight into the extent of the geothermal system and how drilling in Mill Creek may affect geothermal wells elsewhere in the area.	2
TG #4: Light Plant Road	This site falls between sites #1/#2 and sites #3, as well as falling along an interpreted fault plane. It is also near a significant SP anomaly as well as a conductive area between faults as interpreted by the DC data. This well could give us insight of the geology (throw of the Victoire fault, depth to Dakota) as well as providing insight between the connectivity of any geothermal fluid found in Mill Creek (#1 and #2) with the geothermal water coming to the surface at the Warm Springs (#3) and perhaps the Mother Spring.	Not Drilled
TG #5: San	We infer that the basement may be relatively shallow. Although its proximity to Victoire fault is somewhat speculative a good test hole in that area will sharpen our understanding of that fault. This site corresponds to where the CSM seismic line ran through the area in May 2013. It is close to two interpreted faults from DC Resistivity and seismic data and just south of the Warm Springs. This area gave us a more direct stratigraphic reference for the seismic line and allowed us to interpret this dataset in conjunction with CSM. It may also provide some insights to the structure of the area that will allow us to extrapolate to areas we cannot drill and determine a working hypothesis (based on stratigraphy instead of geophysics) with which we can justify fluid flow and the presence of geothermal water.	

TG #6: High School	This location behind the high school will provide geothermal gradient data in the vicinity of existing geothermal discharge area. It will also provide sub surface geologic data to better characterize the geology of the Pagosa Springs area. The well could also be used in the future as a monitoring well for the Pagosa Springs geothermal system. The well would be useful to determine conditions on the west side of a north/south San Juan Fault along the San Juan River and east of the Victoire Fault. This is the least helpful well and by being last is at risk of not being done.	Not Drilled
OH-T2: Northwest Region	This location was chosen after the completion of the first three thermal gradient wells and the analysis of the temperature data from the wells. This well was chosen as a potential site for its location between the 8 Mile Mesa Fault and the downtown shallow geothermal system. The 8 Mile Mesa fault is a potential structural control on deep up-flow of the geothermal water feeding the shallow system. Environmental and time constraints effected the location of this drill site as it had to be located where a finding of no effect on the endangered species the Pagosa Skyrocket and New Mexico Jumping Mouse be made. It is also located west of town in the direction of the increased thermal gradient and heat flow mapped by Galloway.	

Table 3. Summary of the proposed drilling locations and the reasons each was suggested the. The location of these sites is mapped in Figure 12.

Drill Program Summary

Drilling of TG-1 began November 6, 2014 and the bottom hole depth was reached December 3, 2014. The first 50ft (15m) were drilled with a 10-5/8" tri-cone bit and a 6-5/8" SWT casing was cemented in place. From 50 to 204 feet below surface (fbs) (15 to 62 meters below surface (mbs)) was drilled with a 5-5/8" tri-cone bit and 4-1/2" HWT casing was cemented in place, per State of Colorado regulations. From 204fbs (62mbs) through the total depth (TD) at 1458fbs (444mbs) was cored with an HQ (3.97 ") bit. A 2-3/8" steel liner was cemented in place to TD and filled with a static column of water for thermal gradient measurements. TD was reached on December 3, 2014, drill crew de-mobilized on December 16, 2014. The 13 day delay was caused by difficulty in dealing with artesian flow and creating a successful seal around the 2-3/8" liner to keep the artesian zones separated.

Prior to the arrival of the core rig onsite, a separate local driller drilled and installed the 50ft (15m) conductor at TG-3, so the DES crew was able to begin from this depth. From 50fbs through 200fbs (15mbs through 60mbs) was drilled with the 5-5/8" tri-cone bit and a 4-1/2" HWT casing was cemented in place by December 20, 2014. HQ coring was done from 200fbs to 370fbs, (61mbs to 113mbs) at which point artesian flow management became a priority. Mud rotary drilling commenced at 370fbs with a PDC bit. HQ coring was performed from 1436fbs to 1465fbs (438mbs to 447mbs) to confirm penetration of the basement. The 2-3/8" #/ft grade steel liner was cemented in place to TD on January 19, 2015.

A local driller attempted to set the 50ft (15m) conductor for TG-5, but difficulties drilling through the surface alluvium prevented that from being completed. This resulted in DES having to start the hole from surface on January 21, 2015. Significant caving issues occurred in the 50

ft. A succession of tri-cone bits were used starting with an 8-1/2" and ending with a 10-5/8". The 6-5/8" HWT conductor was set on January 25 and cemented in place. From 50fbs through 200fbs (15mbs through 61mbs) was drilled with a 5-5/8" tri-cone bit, and the HWT surface casing was cemented in place January 29, 2015. 200fbs to 267fbs (61mbs to 81mbs) was cored with an HQ bit before artesian difficulties forced the return to mud rotary with a combination of PDC and tri-cone bits. Weighted mud control of artesian with a PDC bit proved difficult due to the high rotation speed of the bit causing separation of the mud components. A core sample was drilled from 1142fbs to 1152fbs (348mbs to 351mbs) and another from 1400fbs to 1404fbs (426mbs to 427mbs) where drilling was completed and the 2-3/8" steel liner cemented in place February 20, 2015.

Drilling for OH-T2 commenced June 15, 2015, with 47ft (14m) drilled prior to encountering water at which point the hole was filled with accelerated cement and allowed to set for 12 hours prior to restarting drilling A tri-cone bit was used to drill the original hole, which was then widened with an air hammer. A Surface casing was set to 180fbs (54.864mbs), and then air hammer used to drill to TD at 320fbs (97mbs). The 2-3/8" steel liner was hung in the well but not cemented in place to allow for abandonment activities later. This well was drilled under a monitoring hole permit, and so may only stay open for one year under State of Colorado law.

The daily drill logs and data sheets are attached in Appendix 7 for a more thorough analysis of the day to day activities and difficulties.

DRILLING SUMMARY				
NAME	LOCATION (NAD 83)	DEPTH	FORMATION AT DEPTH	DWR PERMIT #
TG1	37.251811, -106.996206	1458FBS	Wanakah & Entrada	293537
TG3	37.248229,-107.00964	1465FBS	Basement	294130
TG5	37.241819,-107.00933	1404FBS	Basement	294128
OHT2	37.269241,-107.030577	320FBS	Dakota Sandstone	53844-MH

Table 4. Summary of drilling location, depth and permit number.

Difficulties and Strategies

The drilling phase of exploration during this project ran well over expected timing and budget. There are several causes for this and the most important will be considered with their effect. Of primary concern was high volume artesian flows encountered in the Dakota and Morrison formations. These flows required time and money to effectively control and allow continued drilling. Winter drilling conditions, with frequent snow, daytime highs just above freezing and nighttime lows well below it, caused additional time delay.

A water chemistry analysis was completed on each of the encountered artesian aquifers. This analysis allowed for geothermometry calculations and comparison with other local known thermal features and aquifer system. The high sulfur content of many of the artesian zones encountered combined with the large flow volumes observed may have been a contributing factor in the continued difficulties with cementing. Sulfur acts as a retardant to standard cement (Type I and II cements)so even after 150% of the suggested wait time cement jobs on TG-5 were not properly set. Using an accelerant such as calcium chloride helped some, but

specialized calcium aluminate cement (Type V) with a rapid set time and a reduced effect of sulfur proved to be the best option in combatting these difficulties.

Core drilling was deemed important for scientific value added to the project. However, high volume artesian flows caused issues with the core drilling. The artesian flows encountered in each of the TG wells with the pressures and temperatures are presented in Table 3. Each encountered artesian flow was cemented before drilling could continue, unfortunately some flows had to be cemented multiple times. Standard cement jobs (no accelerant) require a 24 hour wait per state regulations prior to the continuation of drilling so each artesian flow encountered added a minimum of 24 hours to the drilling time.

TG-1 was the only well cored continuously from the surface casing to its total depth. Subsequent wells incorporated a combination of core and rotary techniques to maximize core recovery and artesian control capabilities while reducing the time and cost for the well. Mud-rotary allows for a heavy mud to suppress the artesian flow when drilling. The rig used to drill TG-1, TG-3, and TG-5 was a core rig. This rig could not supply the necessary weight on bit (WOB) for rotary drilling. The mud system also proved to be inadequate for weighted muds.

Artesian Occurrences				
Well	**Depth (FBS)**	**Pressure (PSI)**	**Flow (GPM)**	**Temp (°C)**
TG-1	356	N/R	N/R	N/R
	978	60	N/R	26
	1287	high	800	warm
TG-3	235	N/R	30	12
	344	28	N/R	12
	750	51	N/R	14
TG-5	204	N/R	200	11
	404	60	250	13
N/R - Not Reported				

Table 5. Artesian zones encountered during the thermal gradient drilling process. There were no artesian zones in OH-T2, all water had a static level somewhere below surface. Missing data generally was a result of malfunctioning equipment on the drill rig and qualitative assessments have been included where possible.

When used for some of the rotary drilling a polycrystalline diamond compact (PDC) rotary bit, operated at high RPM and low WOB was most effective. When using the PDC bit, the drill mud was discovered to be losing weight between when it was pumped in to the hole and circulated back to the surface. A major source of this loss was separation of the mud components in the drill rod between the surface and the bit due to the centrifugal force from the high rotation speed. This necessitated the use of a lower RPM and tri-cone bit when drilling with a weighted mud, stressing the torque capabilities of the rig. The small annulus limited recovery to very fine cuttings, reducing the ability to accurately log the cuttings in the field for sections drilled with this technique.

Figure 13 - Driller Dealing with Artesian Flow
The drill crew working to control artesian flow from TG-5. While this instance did not have the high volume of some of the others, the high sulfur content still proved a difficulty for cementing and control.

Artesian flow was the primary cause of delays and cost over-runs. Of the 43 days with a drill rig on TG-1 only 14 were spent actually drilling. For this well, 421.5 hours of delays and $123,000 of associated costs are attributed to the artesian flows. Although the core was scientifically important, a capable drill rig with sufficient mud rotary abilities may have allowed the TG program to progress faster, and more cost efficiently. As a result of the artesian flows and associated core drilling cost TG-1 was unable to reach the targeted Precambrian basement.

Grout plugs (HQ VK Packer-Grout Plug A387-L) and inflatable packers were used to seal artesian zones for cementing. Cementing each encountered artesian flow allowed for continuation of core drilling through all of TG-1 and portions of TG-3 and TG-5. Packer failure was a recurrent problem, particularly when attempting on TG-1. The slim HQ hole limited the downhole equipment used and generally smooth sidewalls from the core bit did not allow the packers to seal effectively against the borehole wall.

The experience with artesian flows encountered in TG-1 is discussed below. The first encountered artesian was at 356fbs, at which point core drilling with mud was attempted. Coring continued to 387.7fbs to provide a cement seal across the artisan zone. , 15.5ppg cement was placed across the zone and shut in with the blow out preventer (BOP). Drilling commenced after a 24 hour cement curing period and proceeded to 438.7fbs until the artesian flow could no longer be managed. A packer was installed at 335fbs and the zone from 335 to

438 cemented with 15.4ppg cement. After a 24 hour wait period, the packer was drilled through and flow did not restart.

A second artesian was encountered at 948fbs. A packer was placed above the zone and the zone cemented, but during cementing high pressure in the pump (up to 1200psi) and a low flow rate (less than 5gpm) indicated an issue. The rod was removed from the hole and the packer determined to have failed but the cause of the malfunction was undetermined. The second packer and cement job required to seal this artesian zone caused the program to reach Thanksgiving break, and the extra several days of drying time were allowed.

A third artesian zone was encountered at 1287fbs, and core drilling continued to 1458fbs (TD) due to the belief the basement was close. When the flow rate required cessation of drilling activities the closure of the zone proved to be difficult. The first packer hung up in the hole at only 360fbs. The packer set at 365fbs was pushed to the bottom of the hole by the drill rod. A replacement bridge plug was set at 1285fbs but the packer to be set above it hung up at 365fbs again and pieces of rubber bushing returned through the BOP. Artesian flow was noted within three hours. A new plug of different design (Van Ruth CW) was attempted, but the packer placed at 1250fbs was encountered at only 800fbs, having forced its way up the well, likely due to smooth sidewalls not allowing for adequate purchase.

The cement job on TG-1 eventually succeeded and the 2-3/8" liner was properly placed and cemented, but the time and budget overruns as a result of the artesian, cement, and packer difficulties proved to be a large cost for the project.

In scoping the drilling program at the beginning of the project, high artesian flows were anticipated in the Dakota Sandstone and at the top of the basement rocks based on Galloway and other well reports, but not expected in the Morrison and the Wanakah formations. The benefit of core and assessment of high artesian flows only in two zones which could be dealt with standard cementing technologies led to the decision of going with core drilling for the TG wells.

Sampling and Data Collection

Core and Cuttings

Through the thermal gradient drilling program core and cuttings were collected to maximize the geologic data of each formation and to provide the best characterization of the geothermal system. The emphasis on core aligns with the best practices in geothermal drilling but had to be reduced when the high volume artesian flows were encountered.

Figure 14 - Fractured Core from TG-3
Fractured core from TG-3. This core was from an artesian zone between 220fbs and 230fbs. The arrow in the bottom left points in the downhole direction, with 220fbs in the bottom left corner and 230fbs in the upper right corner of the image. This core section is from the Dakota Sandstone.

All core recovered was 3" core from an HQ bit. Core was cut in 2 foot sections and boxed. Core was stored in a local temperature controlled building. The core was washed with soft sponge and water as necessary due to the drilling fluid on the surface of the core.

Cutting collection occurred every 10 feet during conventional rotary drilling. Cuttings were collected from the returning drill fluid. The fluid was routed to a fine mesh screen to collect the samples. When using the PDC bit in TG-5 the cuttings were small sand sized grains. The cuttings returned from OH-T2 had a larger chip size and greater volume than those from TG-3 and TG-5 due to the larger annulus and the nature of the air hammer technique utilized.

Each cutting sample filled a one quart bag where return volume allowed. Each sample was split with half washed for easier analysis. A binocular scope was used for observation of samples, especially were only fine sand was returned.

Artesian Water

Artesian aquifers were sampled when encountered. To get a clean and representative sample the zones were allowed to flow until the water returning to the surface was clear. The samples were filtered through a 45 micron screen to prevent particulate contaminations. The temperature of the water at the well head was recorded at the time of sample collection.

Filtered samples were collected in three bottles supplied by the analytical lab. One bottle was empty, one contained nitric acid, and one contained sulfuric acid. The bottles were filled and refrigerated until they could be sent back to the laboratory. The time delay between collection and arrival at the lab was not more than two days, with one day being preferred. The samples were tested for a full range of parameters (Appendix 5) and results returned within two weeks.

Borehole Geophysics

TG-1, TG-3, and TG-5 all had borehole geophysical logs run to TD. OH-T2 was not geophysically logged as little scientific value would be added to the project. The borehole geophysical tests run included natural gamma, spontaneous potential (SP), resistivity, compensated density, P-wave velocity, S-wave velocity, caliper, short wave sonic, long wave sonic, and spherical density. The nuclear tests were run through the drill rod. The remaining logging was done in openhole.The surface casing had been cemented in place that limited the return of geophysical data in the first 200 ft.

The geophysical logging was contracted to COLOG and completed before the 2-3/8" liner was installed and cemented. Weighted mud and a lubricator were used to prevent artesian zones from flowing during logging. The geophysical logs were sent to Ben Barker and the Colorado School of Mines for analysis. The geophysical logs proved rapidly useful for determining correlation between the core in TG-1 and the formation boundaries in the other wells post drilling. Geophysical log analysis also helped with the understanding of fracture permeability in units where rotary drilling left little evidence in the cuttings.

Town of Pagosa Springs Well Monitors

In 2011, existing geothermal well owners, concerned private citizens, the Town of Pagosa Springs, and Archuleta County installed monitoring equipment on the existing geothermal wells in downtown Pagosa Springs. The monitored data includes temperature and pressure at the well heads and is collected by the town Geothermal Manager. The data is publically available but well owners have requested the specific wells remain anonymous to prevent any commercial or competitive difficulties.

The data loggers are submerged in the well and measure the pressure at the surface due to the artesian flow. The devices are left in the wells and record pressure and temperature over time and are removed periodically for the data to be extracted. The loggers are generally (with one exception) not placed in the main flow line and so the temperatures recorded are not representative of the temperature of the resource. The one data logger in the main flow line does provide representative temperatures for the water produced by that well.

Before drilling began in the TG program, the well loggers were checked for accuracy and the times synchronized. The Town of Pagosa Springs collects the data monthly but was prepared to collect more frequently if there was any indication of interplay between the existing wells and the thermal gradient drilling. The TG-1 artesian zone at 1287fbs was the highest encountered flow and temperature during the drilling program and resulted in no discernable effect on the town system through the logs. Any variability in the readings was considered normal for the seasonal and daily fluctuations of the geothermal resource.

Thermal Gradient Measurements

In TG-1, TG-3, and TG-5 the liner has been cemented in place for the entire length of the well and filled with a static column of water. TG-5 was later P&Ad due to leakage. Each liner had a cap on the bottom and the only communication with the surrounding lithology is through thermal transfer. In OH- T2 the two inch liner has been hung in the well and not cemented to facilitate future P&A of the well. The static column of water in this well matches the peizometric potential surface of the surrounding aquifer at 50m.

The temperature of the column of water in the two inch liner has been measured with a probe capable of withstanding well beyond the expected temperatures and pressures at the base of the 2-3/8" liner. The probe is attached to a cable run through a depth counter and lowered in 7.6m (25ft) increments until it reaches TD. A delay of five minutes at each 7.6m (25ft) increment is to allow the temperature probe to stabilize. An additional stabilization period of 10 minutes is allowed at the bottom of the hole for complete equilibration. For OH-T2, 3m (10ft) increments were used due to the shallow depth of the hole and the extra limitation as a result of the lack of a complete column of water.

Exploration Results

Introduction

The suite of geophysical techniques completed in the region by the Colorado School of Mines proved valuable information in identifying structural features and potential drilling locations.

The MMR gas surface technique was evaluated for its potential in identifying subsurface heat signatures, although no depth could be interpreted from the data. Continued evaluation of this technique is necessary as the results presented here are non-conclusive. The MMR reports prepared have been included in Appendix 6. Subsurface geology has been interpreted from a combination of the core, cuttings, and borehole geophysics. Borehole geophysical log comparisons between the completely core drilled TG-1 and the partially rotary drilled TG-3 and TG-5 wells allowed for more accurate interpretations of the units in TG-3 and TG-5 sections with minimal cuttings recoveries. Borehole Logs and digital files are included in Appendix 4.

The temperature gradient measurements have been completed in the four wells over a period of time to determine if any changes have been occurring. TG-1, TG-3 and TG-5 each equilibrated rapidly and showed little change over time after drilling. The temperature gradients have been extrapolated from these measured temperatures with attention paid to the differences in thermal conductivity between the formations.

Core and Cuttings Logs

The geology of each thermal gradient well is presented below in Figure 16. For simplification purposes during drilling and discussion, the Wanakah and Entrada formations have been combined. Drilling in TG-1 finished less than 1.5m (5ft) in the Entrada formation. TG-3 and TG-5 were both completed into the Precambrian basement. OH-T2 was completed in the Morrison formation. The complete core and cuttings logs of each well are in Appendix 2.

The core sections drilled have proven useful for geologic interpretation of the formations, fractures, and subsurface features. Coring the basement was considered a priority of the thermal gradient drilling program and as such greater emphasis was put on coring in wells TG-3 and TG-5 into the basement because TG-1 was un successful in reaching the basement.

Formation thickness was relatively consistent across all wells including well P-1 (Table 4) (Galloway, 1980). The differences in the depths to the units are a combination of the regional dip of the bedding and faulting present between boreholes (Figure 16). Artesian flows were related to sandy, poorly cemented layers within the Dakota Sandstone as well as fractured regions in the deeper portions of both the Dakota and Morrison Formations and formation boundaries.

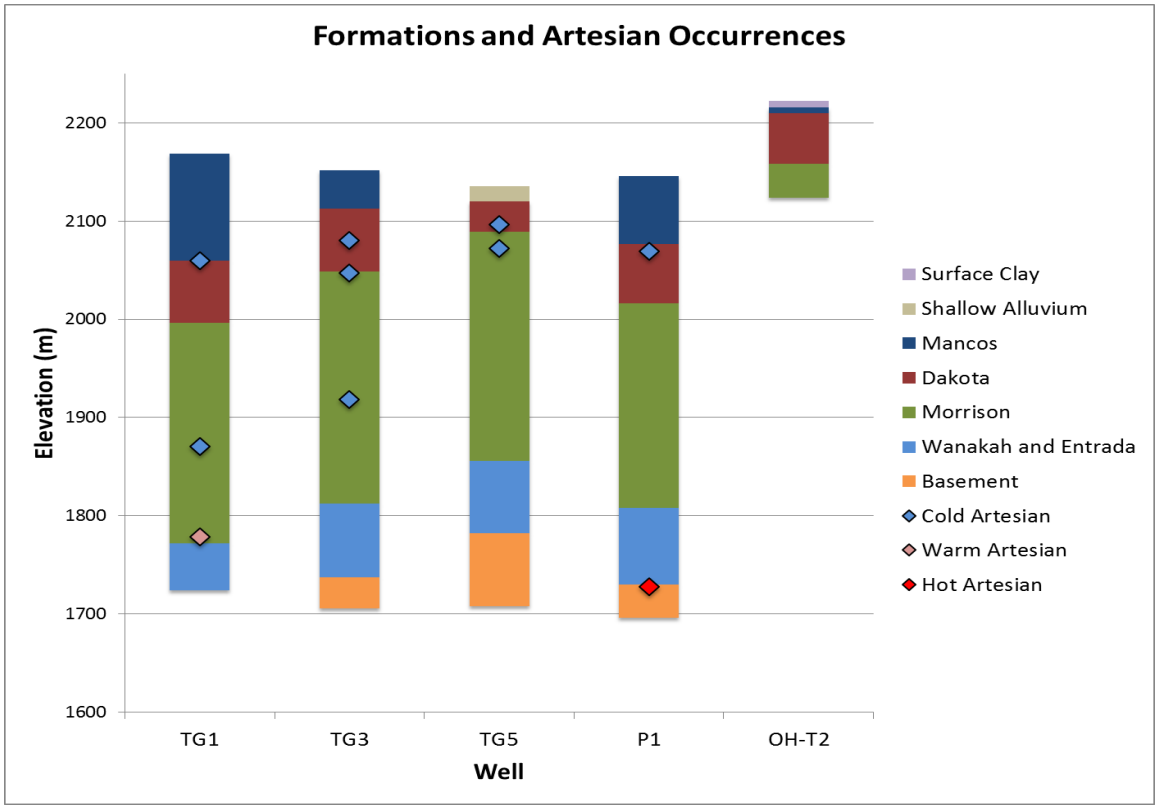

Figure 15 - Borehole Geology
Subsurface geology determined from a combination of core, cuttings, and borehole geophysical logging. The geologic formations and well surface and total depth elevations are presented as determined by the depth below surfaces measured during drilling. Artesian flows are marked with diamonds and colored according to temperature.

Formation Thickness in Pagosa Springs Wells (ft)					
Well	**TG-1**	**TG-3**	**TG-5**	**OH-T2**	**P-1**
Dakota SS	200	212	NA	170	198
Morrison	786	774	766	NA	681
Wanakah	96	56	30	NA	95
Entrada	NA	190	210	NA	160

Table 4. Formation Thicknesses as recorded by geologic and borehole geophysical logging on each of the wells drilled by Pagosa Verde as well as the Galloway deep well. Thicknesses are not represented where the well ends in one of the units, either at the surface or at the bottom of the hole, and the Mancos is not shown as no wells drilled the entire thickness of this unit, all started in its lower member or below it entirely.

The core from TG-1, TG-3 and TG-5 intersects both open and closed fractures in the sedimentary and Precambrian formations. Typical fracture mineralization varied by depth but open fractures were frequently found with pyrite, quartz, and aragonite, and calcite. Fractures surfaces in the Precambrian basement had alteration but whether the cause of this alteration was weathering or geothermal has not been determined. The complete cuttings and core logs are located in Appendix 2.

Borehole Geophysics

The geophysical logs from the TG-1, TG-3 and TG-5 were consistent with the structural model previously described for the region. The formation thicknesses are consistent between units, and the variations in depths to the tops of the formation units are consistent with seismic results (CSM, 2012; Revil, et. al.). TG-1 has a strong indication of fracturing in the Dakota 108-172m, (356-566ft) and Morrison 172- 412m, (566-1352ft) formations with severe borehole erosion observed on the caliper log. While washouts are created by poor drilling practices, they may also indicate a fractured or unconsolidated zone. With the Wanakah formation being truncated in TG-5, the abundant washouts may indicate TG-5 is on or very near a fault intersection. A stratigraphic comparison of TG-3 and TG-5 shows the equivalent rocks are 48m (160ft) higher in TG-5. The variations in unit elevations between TG-3 and TG-5 indicate offset on the Mill Creek Fault when accounting for the offset between the KB elevations for the two wells.

Thermal Gradient Measurements

Temperature gradient data from the drilling of TG-1, TG-3, and TG-5 provided valuable information on the geothermal system South of Pagosa Springs. TG-1 was drilled to a depth of 444m (1458 ft.) and had a bottom hole temperature of 36.8°C (98.2°F.) The thermal gradient varied from 5.3°F/100ft (96°C/km) in the Mancos Shale to 2.47°F/100ft (44.9°C/km) in the Morrison Formation. The overall thermal gradient of TG-1 excluding the Mancos shale region was 2.91°F/100ft (48°C/km).

Temperature gradient wells TG-3 and TG-5 were drilled to depths of 447m (1465 ft.) and 428m (1404 ft.) respectively. Both TG-3 and TG-5 penetrated into the basement Precambrian gneiss. Bottom hole temperatures of TG-3 and TG-5 were 26.7°C (80°F) and 26.3°C (70°F) respectively. The temperature gradients of the two wells are very similar with an overall value of 2.03°F/100ft (37°C/km). These lower gradients are within range of normal thermal gradients for this area of Southern Colorado. Gradient measurements are shown in Figure 17.

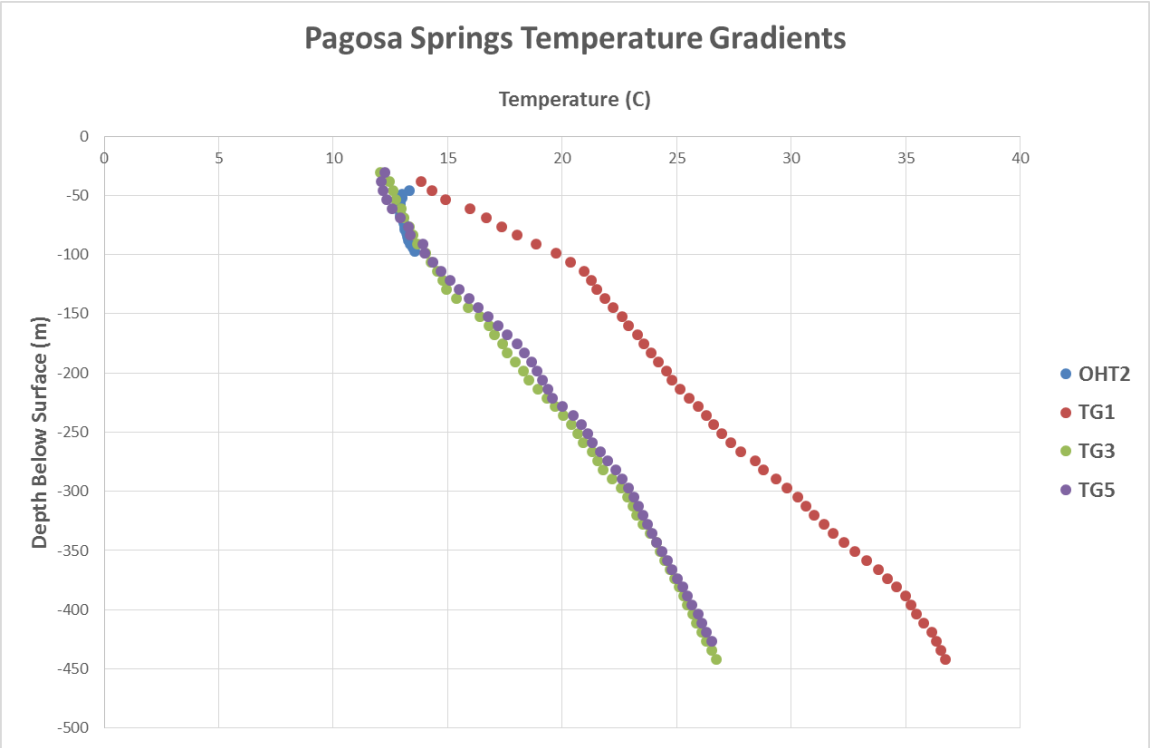

Figure 96 - Temperature Gradient Measurements
Temperature gradient measurements from the thermal gradient wells drilled by Pagosa Verde. Each well equilibrated quickly after drilling was completed, with temperatures not changing significantly after the first week. The complete temperature gradient measurements over time are available in Appendix 1, with only the most recent shown in this figure. The top 50m of OHT2 were recorded in air and as such are not considered an accurate representation of the subsurface temperature. Below 50m the static column of water was measured.

Extrapolation of the gradient data from these wells provides an estimate of the temperatures expected at the depth of a deeper exploration well as shown in Table 5. TG-1 has the highest gradient and therefore would be expected to have the highest temperature at depth; predicted to be 70°C (158°F) at 3500 feet below surface (fbs) and 93°C (200°F) at 1525m (5000fbs). This compares to temperatures of 51°C (124°F) at 1067m (3500fbs) and 69°C (155°F) at 1525m for wells at TG-3 and TG-5 locations. The subsurface temperatures at 1525m for TG-5 and TG-3 locations is approximately the same as the subsurface temperature at TG-1 at only 1067m. Predicted temperatures within a reasonable drilling depth at TG-3 and TG-5 are too low for power generation given today's ORC binary technology but could be adequate for direct use geothermal applications. The TG-1 location extrapolated temperature of 93°C (200°F) at 1525m is marginally within the technical feasibility range for low temperature binary power production but will likely require tandem development with direct use to make it economically feasible.

An issue regarding development of the geothermal resource in the deeper basement formations is the likelihood of intersecting fractures in the Precambrian gneiss. Drilling data from TG-1 indicated high water flow in the Dakota Sandstone and at the base of the Wanakah formation but the well did not penetrate the Precambrian basement. Wells TG-3 and TG-5 penetrated the top of the Precambrian basement with TG-5 reaching a total depth 200ft below the contact with overlying sedimentary units. The core from TG-3 and TG-5 did show significant fracturing at the top of the basement indicating a high potential for flow however the temperature within the basement did not show the existence of a thermal aquifer given the measured bottom hole temperatures. The lack of an increased gradient in the basement rocks at TG-5 and TG-3

locations provided an indication the basement rocks in that area are not hosting a significant geothermal reservoir. Deep seismic studies suggest some fracturing in the area of TG-1, but less near TG-3 and TG-5.

Well	Depth	Temperature Gradient	Depth to 70°C (160°F)	Temp at 1066m (3500ft)	Temp at 1524m (5000ft)
TG1	444m (1458ft)	54.5°C/km (2.98°F/100ft)	1075m (3539ft)	69.5°C (157°F)	93.2°C (200°F)
TG3	446m (1465ft)	36.0°C/km (1.97°F/100ft)	1557m (5110ft)	51.3°C (124°F)	68.7°C (156°F)
TG5	428m (1404ft)	35.9°C/km (1.97°F/100ft)	1557m (5110ft)	51.3°C (124°F)	68.7°C (156°F)
OHT2	98m (320ft)	30.9°C/km (1.7°F/100ft)	2260m (7400ft)	32.9°C (91.2°F)	47.1°C (116.8°F)

Table 5. Temperature gradients and extrapolations from the TG drilling program in Pagosa Springs. The temperature gradient for TG1 was calculated excluding that portion measured in the Mancos shale due to the significant difference from the underlying sedimentary units. TG1 also excluded the last 4 measured depths due to the unweighting of the measurement cable indicating the last several data points may have been all at the same depth. Temperatures at depths below the drilled maximums of the wells have been extrapolated from the best fit thermal gradients.

TG-1, TG-3, and TG-5 do not show the temperature reversal present in Galloway's P- 1 well (Galloway, 1980). TG-1 has a gradient higher than the regional background, and when combined with the geochemical observations this indicates the wells likely overlie fractures of deep fluid circulation.

The worldwide background gradient recorded in OH-T2 suggests a sharp boundary on the western edge of the Pagosa Springs shallow geothermal system. The gradient found in well G-1 (Galloway, 1980) was significantly elevated over that found in OH- T2 and with the short distance between the two a structural barrier for the flow is suggested. One possible feature is the unnamed fault trending north from its intersection with the 8 Mile Fault towards the space between the two wells (Figure 7). The lack of an elevated gradient to the west of downtown suggests the up-flow controlling structure for the shallow geothermal system is not the 8 Mile Fault. Another structure can be implied as the source of this fluid flow from the deep reservoir.

Geochemistry

Geochemistry data from three temperature gradient wells have been analyzed using standard geothermometry techniques to estimate source temperatures for the waters. Basic geochemistry of the water from the Mother Spring and the wells with respect to geothermometry are very similar. From the results with the Pagosa Springs/Pagosa Verde samples, the silica estimate is thought to yield a reliable conservative estimate of the source temperature with the range of 75 to 95°C (167 to 203°F). Excluding the higher estimates, the Na-K-Ca geothermometer with the Mg-correction probably yields a maximum possible source temperature with the range of 115 to 135°C (239 to 274°F) (Appendix 5). The depth at which these temperatures exist cannot be deduced from the water geochemistry alone.

The observation that the application of geothermometry to the geochemistry from samples from the three temperature gradient wells predicts estimated source temperatures essentially the same as the geothermometry estimated source temperatures for the town spring and wells is a surprising result as the water from the temperature gradient wells was much cooler than the water from the town thermal spring and wells. One simple explanation for this result is that the water collected from the temperature gradient wells and from the town thermal spring and wells has a common source but cools before it reaches the temperature gradients wells. However, although cooled, the temperature gradient well waters do not appear to have sufficient time for their chemistry to re-equilibrate to yield lower geothermometry temperatures before collection at the temperature gradient wells. The difference in measured temperatures may be a result of an en-echelon fault system at a shallow level with a variety of flow pathways to the surface available.

Cultural Impacts and Strategies

Collaboration between federal, state and local governmental entities, a private business, and local landowners and citizenry catalyzed the grant award and enabled all the project work to follow. This collaboration overcame cultural factors inhibiting prior geothermal exploration or development efforts in Colorado. The strategy developed in aligning cultural factors should be considered a valuable outcome to the DOE commitment.

The Colorado geothermal market does not conform to conventional geothermal development targets. The resource is typically modest and occurs in economically and environmentally sensitive locales. Most Colorado geothermal surface expression occurs in or near well known destination resort communities. In most of these same areas there are visible reminders of a history of unpleasant experience with extractive industries in Colorado. These are key factors in the active and influential interest groups and industries resistant to all physical resource development. These groups include environmentalists, outdoor recreation, the tourist industry and residential property owners. Additionally, Colorado county and state regulations are inconsistent regarding resource development and the state agencies have had little experience in supporting geothermal projects.

For those reasons large companies that have invested in California, Nevada and other geothermal fields worldwide expressed little interest in investing in Colorado. The Colorado factors contributed to the time-to-production issue that makes geothermal development less attractive than other forms of energy development. This was expressed to Pagosa Verde directly by the major developers in 2010. Post the 2008/9 recession, the appetite for risk by investors has contracted. Presently the likelihood of private investment sufficient to develop a Colorado geothermal market without significant public financial support is very low. Direct confirmation of commercial geothermal resources in Colorado cannot occur without engaging these economic, historical and public perception factors.

In response to this Pagosa Verde developed a value proposition unique to Colorado. It has attracted an additional investor class: local, regional and state governments whose goals are economic health and jobs, rather than high financial rates of return. It mitigates exploration risk by stressing rigorous resource evaluation targeting power-worthy resources, but if unsuccessful, provides a high probability of yielding economically beneficial direct-use opportunities. The model defines the advantages of geothermal power development in terms of environmental concerns, esthetic and property values, security issues, and local income and

control. The delivery of this value proposition to the public culture, both the citizens and institutions, involved investment in education and a dialog with the people of Colorado.

Cultural alignment for this project evolved as much as it was managed. More detailed information is contained in the Pagosa Waters Project Timeline. The following are cultural communication guidelines.

Pagosa Verde built public understanding from the grassroots up through one-to-one engagement and in presentations to groups. In Archuleta County we had the benefit of other geothermal efforts preceding ours. Early on they offered their support.

At every level we attempted to identify the influential individuals or groups most likely to oppose the project. They were important to engage and until they were on- board, we did not attempt to move up the demographic chain. Our goal was, if not to persuade them, to identify their needs and objections and refine the model or our presentation. We believed that the intrinsic value of the project deserves and earns broad support when presented correctly.

In this way the model evolved in sophistication while maintaining its values and technical goals. In the early days this commitment to refining the model often led to repeat engagements. Until we'd succeeded in finding the model refinement required to earn approval we considered the problem ours – not that of the audience. Stamina, consistent messaging, agile listening, and re-analysis of our "product" was paramount.

For each discussion or presentation we tried to anticipate the issues most important to that audience and modified presentation emphasis accordingly. For example, in rural Colorado speaking to ranchers and farmers we emphasized an air-cooled model. Though water-cooling may be possible and more efficient, in rural Colorado water issues are taken very seriously and the lack of pollutants and the minimal use of water in binary plants was a key point and shortened the time to acceptance.

Once we felt comfortable with a broad base of citizen support we approached the local regional economic agency and local government officials. Jobs and economic stimulus were their key issues, as was their awareness of public support. This led to our first significant financial investment. Local financial and popular support led to acquiring federal and state support.

At each level we encountered a unique culture. Popular, local government, federal and state government – each has its own cultural behavior, history and needs. Thoughtful consideration of these different needs lead to a more effective project.

At each level, and in each institution, we encountered professionals that understood the value of the project. Once the project was understood we left it to the professionals to manage its advance through their own culture.

In the course of this process we learned that most agencies were consulted too late in a project. If the project is presented early, in our experience, the agency professionals not only contribute to its refinement, but facilitate the regulatory or procedural progress.

Concurrent with our community and institutional dialogs we sought every opportunity to present the model to the community, to the geothermal industry and to other venues that expressed an interest in understanding the implementation of renewable and sustainable technologies.

This cultural communications strategy yielded several important results that now provide impetus for geothermal development throughout Colorado:

1. The adaptation of the Geothermal Activity Bond Statute (Colorado S 30-20- 1203) providing a tax exempt, state guaranteed bond program for geothermal plant and transmission financing. This bond program provides low-cost finance for geothermal power without adding a liability to rural citizens. The program gives Colorado a significant advantage in geothermal development economics.
2. The Pagosa Waters, LLC public/private structure composed of the Town of Pagosa Springs and Archuleta County investing in the Pagosa Area Geothermal Water and Power Authority, and the Authority investing with Pagosa Verde LLC. in the Pagosa Waters Project. This allowed Pagosa Verde to channel the Award monies into the project in combination with State monies channeled through the Authority. This also allowed the citizens of Archuleta County to be majority owners of the project and to maintain control of environmental standards.
3. Strengthened relationship between the U.S. Department of Energy and the State of Colorado.
4. Creation of a Colorado geothermal regulation template designed to stimulate exploration in Colorado. This template has now been adopted by two counties and elements included in new land use codes in other counties. This process of standardization will include all of Colorado over the next few years.
5. Creation of a geothermal handbook by the Colorado Water Division to clarify geothermal regulations for developers.

These examples of the power of cultural communication were all empowered by the Pagosa Verde award from the DOE. All of these contribute to the commercial development of geothermal power in Colorado.

Discussion and Conclusions

Initial analysis of the Pagosa Springs Geothermal System was presented by Galloway in his 1980 report. The data at that time focused on the central thermal area within the Town of Pagosa Springs. The information on well and spring data indicated a central upwelling of thermal water in the mother spring area with more thermal seeps along the banks of the San Juan River. Drilling data outside the Pagosa Springs area indicated only colder ground water was intersected. Thermal gradient data collected by Galloway indicated a heat flow anomaly increasing from east to west with open thermal gradient contours to the south. A deep production well drilled in 1979 intersected thermal water within the Dakota Sandstone with a temperature reversal in the Morrison formation below the Dakota Sandstone. (Galloway, 1980)

Subsequent work by Lund and Huttrer indicated a potential geothermal system extended to the south of Pagosa Springs based on a reported thermal seep along the San Juan River two miles south of town. Also the Victoire Fault trended north-south along the river and passed near both the mother spring and the thermal seep area. (Lund, J. and Huttrer, G., 2010)

This area was the focus of both MMR work by Klingel and geophysical and geological work by the Colorado School of Mines in the summer of 2012 and 2013. During these investigations several potential thermal targets and new subsurface fault structures were identified which were thought to be controlling fractures for geothermal fluid within the Precambrian basement to upwell along the fracture penetrating the upper Morrison, Dakota, and Mancos formations. The

conceptual model formed from the studies suggested geothermal targets for drilling would be the fault intersections and splayed fracture area at the terminus of a fault. This was the basis for locating the temperature gradient holes in the area south and southeast of town to provide additional information on the potential of a geothermal reservoir and controlling subsurface conditions. (Klingel, 2012, 2013, 2014), (CSM Field Camp reports, 2012-2013)

Drilling three gradient holes found no elevated thermal gradients in TG-3 and TG-5 located along the Victoire Fault. TG-1 had an elevated gradient indicating a potential thermal system at depth in the area. Results of the TG-3 and TG-5 drilling closed the Galloway heat flow contours to the south (Figure 8) but left an undefined the western boundary. The conceptual model was modified to eliminate upwelling of thermal fluids along the Victoire Fault to possibly upwelling along the 8 Mile Fault west of the town with outflow within the Dakota Sandstone and discharge in the Pagosa Springs and Mother Spring area. This matched the data from the Galloway thermal gradient wells, the reversal of temperature in the Galloway deep well, and temperature gradients of the Pagosa Verde wells TG-1, TG-3 and TG-5.

As a result of this new data, future drilling was moved away from the south where TG-2, TG-4, and TG-6 were scheduled to the west between the city of Pagosa Springs and the 8 Mile Fault. The drilling of OH-T2 to a depth of 98m (320ft) was completed in June. Though this well has not likely fully equilibrated, the apparent lack of an elevated gradient to the west Galloway's G-1 well suggests the up-flow controlling structure for the shallow geothermal system is not the 8 Mile Fault. The sharp difference between OH-T2 and G-1 indicates a defined boundary to the shallow geothermal resource to the west of town. This boundary to the east of the 8 Mile Fault restricts the up flow from the deep reservoir to the west. A structure other than the 8 Mile Fault may be the source of this fluid flow from the deep reservoir.

Although the deeper reservoir and source of the shallow geothermal resource underneath Pagosa Springs has not yet been determined, several structures have been identified as unlikely to be the control on the system. The South, East, and West have been considered unlikely directions for the geothermal upwelling providing the town resource with hot water.

Lessons learned about the geothermal system of Pagosa Springs are quite varied. Through the activities and analysis of the data collected during the study new insights were gained from the exploration here through drilling activities. During the exploration a focus was placed on the area to the south of Pagosa Springs based on access and previous geologic and geophysical data. New structural data was gathered using a variety of geophysical techniques that indicated potential reservoir conditions might exist in the Precambrian Basement. The planned 610m depth of the thermal gradient holes was a result of the attempt to target the basement. Several of the geophysical techniques were not designed to image in the basement although they gave good interpretation for the shallow formations, but well data on deep structures was limited. Further work to identify these deep structures is suggested.

Designing the geophysical surveys to image the deeper formations and basement structures across the area of interest would have helped place the thermal gradient wells. Taking a closer look at our first well TG-1 and comparing this data to earlier data by Galloway provided evidence we may not need to drill into the basement to get reliable temperature gradient data. In looking at the data the Colorado Geological Survey's Paul Morgan indicated reliable gradient data could be obtained in a thermal gradient well 100-150m deep rather than the 610m

originally planned. This resulted in changing the depth target in the OH-T2 well.

During drilling significantly higher pressure artesian zones were encountered. This proved to be a problem for the core drill rig used as these fluids could not be controlled so each flow zone had to be cemented resulting in higher cost. Changing to a crude mud rotary operation on the coring rig allowed fluid density to be modified for control of artesian pressure and flow resulting in improved drilling and reduced cost. Up to 15 pound per gallon mud weight was required to control artesian flow during the thermal gradient drilling program. The ability to mud rotary the wells to control the higher pressure artesian flows while selective coring would be the best solution. This would increase drilling rate (ROP) and limit water disposal issues while allowing for spot coring for geologic interpretation.

The higher gradient at TG-1 and G-4 warrants further exploration. To make exploration economically feasible exploring and developing for direct use is recommended. An 8 inch diameter well to 2500 feet with sufficient flow and anticipated temperature of 128°F would be adequate for direct use. That size and depth will also provide a feasibility go/no-go for the possibility of sufficient heat and flow for power generation. The subsurface plumbing of the Pagosa Springs geothermal system, though better defined, is still unknown. As described earlier, the conceptual model of the resource being controlled by faulting to the south of Pagosa Springs has been shown to be incomplete by data provided by TG-3 and TG-5.

It is recommended two to four additional temperature gradient wells be considered to the west and north of the city to tie into the well network constructed by Galloway in 1980 and recently by Pagosa Verde.

This area could also be a candidate for additional geophysical surveys, either conducted by the Colorado School of Mines or a contracted geophysical firm. Recommended surveys include gravity and magnetics to tie into the work conducted by the Colorado School of Mines to the south and southeast of Pagosa Springs. Also an additional seismic line near Pagosa Springs in a southwest to northeast orientation would be effective in determining the deep structures in the area of the thermal upwelling. This line should start from the 8 Mile Fault southwest of town and go through the thermal area to the northeast. The line would be parallel to the Mill Creek seismic line done by CSM in 2013. The information would be valuable in determining the subsurface plumbing of the Pagosa Springs geothermal system and be helpful in assessing the potential target for a deeper exploration well to target high temperature and permeable fracture basement rocks for potential geothermal power production.

The Colorado Geological Survey currently has core samples awaiting thermal conductivity measurements. Gathering water chemistry to the west-northwest will further define the extent of the similar geochemistry and may help understand the geochemistry and temperature similarities between the city geothermal area and areas to the east and west to help understand the deeper geothermal system in the area.

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