

THERMAL CHARACTERISTICS OF THE CHENA HOT SPRINGS ALASKA GEOTHERMAL SYSTEM

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ABSTRACT

Chena Hot Springs is located in the east-central part of the Alaska within the Yukon-Tanana Plateau, about 75 km east of Fairbanks. It is a moderate temperature deep circulation system typical of interior Alaska. The main shallow upflow zone is about 2000 ft long and 300 ft wide. The system is located at the edge of a granitic body where deep circulating geothermal waters reach the surface by way of fractures along the contact with surrounding host rocks. The hot springs discharge at temperatures around 165 °F (74 °C); nevertheless, the geochemical data suggest the source temperatures to be around 250 °F (121 °C). With current drilling activities to 1020 ft (311 m), temperatures of up to 176 °F (80 °C) have been measured.

The temperature and pressure data from the current wells show that the geothermal system is similar to the Basin-and-Range type geothermal systems. This similarity allowed application of most of the exploration methods that are used in other fault/fracture related systems. These include a detailed geological study of the area, AMT, an airborne gamma ray spectroscopy, EM and magnetic survey, and drilling with reservoir analysis. The small size of the system has enabled us to apply the conventional exploration methods with better control. The system is attractive as it is smaller in scale compared to most of the Basin-and-Range systems, but still showing a similar complex hydrologic character.

So far, 11 exploration wells have been drilled as part of a DOE-GRED contract and 7 wells by the resort with depths 300ft-1000 ft. The highest temperatures in the 700-1000 ft depth range are found about 1000 ft west of the main hot springs vent area and the geothermal waters here show highest concentration of helium and dissolved solids. The location and size of the deeper high temperature system are not clearly understood with current drilling data because of the high permeability zone at shallow depth. The wells at

both ends of the shallow convective zone have gradients two or three times the regional background which suggests the deep source is spread in a much wider area relative to the shallow zone. Currently, one 700 ft deep well with flow rate of 500 gpm has been used for running a 250 kWh power unit. Further deeper drilling has been proposed in order to understand the deep thermal regime. If the high target temperatures are reached at exploitable depths with sufficient flow rates, the production capacity could be 1-10 MW. The electricity production is possible in this low enthalpy system as a result of low surface temperatures relative to the moderate subsurface temperatures.

INTRODUCTION

Chena Hot Springs (CHS) is located 96 km north-east of Fairbanks, Alaska in the central part of the Yukon-Tanana Upland. It is one of the thirty low to moderate temperature hot springs in Alaska (Waring, 1917). These hot springs lie along a band in interior Alaska extending from the Seward Peninsula in the west to the Yukon Territory of Canada in the east. The locations of the springs are generally associated with the contacts of rounded granite bodies of Mesozoic to Early Tertiary age within the matrix of the pelitic metamorphic rocks (Wilson et al., 1998). CHS is located in the center of a 40 km long and 5 km wide pluton. Kolker et al. (2007) suggested a Cretaceous age (80-90 Ma) to the pluton with later partial resets of early Tertiary (60 Ma) period. No quaternary volcanic rocks have been found within hundreds of miles of the CHS.

The vicinity of CHS is not associated to any kind of regional structural feature. The seismicity shows a typical pattern of inactive regions in Alaska. The hot springs are located where the Monument Creek (Figure 1) valley changes orientation from east-west to northwest-southeast. Previously, the hot springs were inferred to be associated with a fault at the south edge of the valley (Wescott and Turner, 1981) or a couple of faults intersecting at the location of the

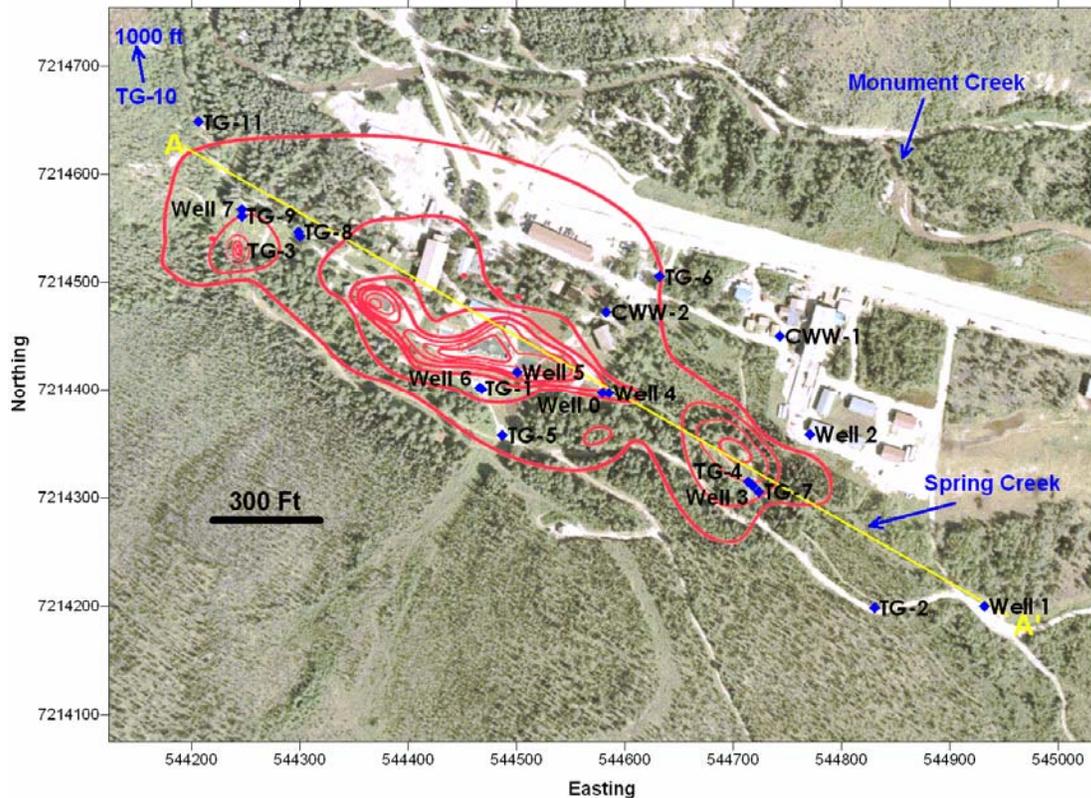


Figure 1. The general aerial view of the Chena Hot Springs with well locations. The contour map shows the result of the 1979 study for the shallow (0.5 m) thermal anomaly. The contour interval is 5 °C with the outermost contour representing 10 °C.

hot springs although no faults have been mapped so far (Kolker et al, 2007).

The plutonic body is further classified with interfingering subunits consisting of coarse-grained granite, tonalite, granodiorites and diorite (Kolker et al., 2007). The interfingering character may indicate historic internal deformation within the pluton which resulted in the juxtaposition of different units. Slickensides and brecciation in the south edge of the valley also indicate the existence of shear zones within the pluton which may be responsible for the inferred southeast-trending faults or fractures.

CHS is privately owned and has been used as a resort since 1907. Geothermal water with maximum temperature of 165 °F reaches the surface naturally and is used to heat pools, buildings, and running greenhouses. The thermal waters are also used to keep an ice hotel standing year-round using ammonia absorption chiller technique (Erickson et al., 2005). Since 2005, extensive exploration activities continue with the support of the Department of Energy as part of the Geothermal Resource Exploration and Definition (DOE-GRED) program in order to produce electricity from the geothermal system (Holdman et al., 2007). A power plant with 0.25 MW rating was installed and activated in August 2006 as a

result of the first stage of the exploration activities. Due to the remoteness of the area, resort electricity was supplied by diesel generators at a very high cost. Although currently exploited water temperatures are moderate, off-the-grid location and low surface temperatures makes geothermal electricity production economically and physically feasible.

Geothermal resource assessment of Chena Hot Springs started in 1973 as a M.S. thesis project in University of Alaska-Fairbanks (Biggar, 1973). Before this study, the only data were some geochemical studies of the hot springs by the USGS (Waring, 1917). Since then geochemical analysis of all hot springs, wells and creek water was done at various times. In general, the concentrations of dissolved solids are as low as 300-350 mg/l (Yoshikawa, 2006; Holdnam et al., 2007). An abnormally high concentration is only seen on flourine, reaching 19 ppm. Two end member compositions are the deep mineral rich geothermal waters in the western end and very dilute meteoric waters coming from Monument Creek eastern end. All other waters are mixtures of these two end members.

In 1980, in order to investigate other geothermal anomalies around the Chena area, a regional study of

helium and mercury concentrations in the soil was done by collecting 50 samples around the Chena pluton (Wescott and Turner, 1981). Except the Chena area, all helium concentrations in the samples reflected the atmospheric concentration (within 4% of 5.2 ppm). Within the Chena area, a very sharp and narrow anomaly was found north-west of the main hot spring area (> 750 ppm) (TG-8 site in Figure 1). Along the south-east end of the hot springs, He concentrations were relatively lower (~ 200 ppm), but dispersed in a wider zone. This could be result of mixing with the ground water in the south-east as will be discussed later. Very high He concentrations in the north-west were interpreted to be related to direct connection of the deep thermal source to the surface in the north-west of the main anomaly (Wescott and Turner, 1981).

A number of geophysical studies were carried in 1979 (Wescott and Turner, 1981). Both shallow electrical conductivity (10 m) and shallow temperature (0.5 m) surveys outlined the main shallow permeability zone as a narrow north-west to south-east trending anomaly along Spring Creek. 1D seismic refraction experiments along the central valley revealed that the valley fill is about 40 m thick at the center and is only 2-15 m thick at the location of the hot springs. In 2005, extensive geophysical studies including AMT survey (Reed and Liu, 2006), airborne geophysics (Pitchard, 2005) were carried out. The airborne geophysics included a combination of electromagnetic, radioactivity and magnetic surveys. Airborne geophysics was particularly useful in order to better understand the geology of the region. The airborne radioactivity pattern depicted a highly radioactive body north of the Monument Creek valley and the hot springs area. The hot springs are located where this high radioactive body contacts a less radioactive unit.

TEMPERATURE DEPTH DRILLING

Temperature-depth measurements started in 1979 with eighty holes 0.5 m in depth (Wescott and Turner, 1981). Their 0.5 m isotherm map shows an elongated thermal anomaly around the hot springs area with main boundaries about 1000 ft long and 300 ft wide with a maximum temperature of 118 °F (Figure 1, red contour lines). Prior to 2005, eight wells with depths between 200 and 300 ft were drilled by the resort (Figure 1 wells designated by W). Deeper geothermal exploration and precision temperature logging started in late 2005 by measuring the temperatures in these existing wells. Following this study, eleven new temperature-gradient wells were drilled through August, 2006 as part of a GRED III program (Figure 1, wells designated by TG). Five of these wells reach depths of 600-1020 ft while the others are 200-300 ft deep. The wells were drilled into granitic bedrock capped

by a thin weathered layer of alluvium less than 30 ft deep. Most of these wells are at least weakly artesian with hydraulic heads less than 5 ft above ground level.

Table .1 Well information drilled in the Chena Hot Springs. Surface temperature was taken 32 °F.

<u>Well Name</u>	<u>Drill Date</u>	<u>Depth</u>	<u>Shallow Gradient</u>	<u>Interval</u>	<u>Tmax</u>
		(feet)	(°F/100 ft)	(feet)	(°F)
WELL 0	1998	80	N/A	N/A	N/A
WELL 1	2003	196	6.90	147-196	44
WELL 2	1998	250	25.30	65-249	101
WELL 2b	2005	800	22.00	33-203	124
WELL 3	2003	43	201.7	0-49	132
WELL 4	2003	280	44.2	16-148	145
WELL 5	2003	275	N/A	N/A	N/A
WELL 6	2005	131	248.1	0-66	163
WELL 7	2006	715	28.90	250-400	169
CWW 1	N/A	N/A	N/A	N/A	N/A
CWW 2	N/A	59	51.90	0-59	63
TG-1	2005	246	201	0-66	163
TG-2	2005	194	30.8	98-194	79
TG-3	2005	197	43.2	0-197	117
TG-4	2005	197	201.7	0-49	132
TG-5	2005	282	53.8	16-98	131
TG-6	2005	74	25.60	0-74	51
TG-7	2005	702	148.9	0-66	153
TG-8	2005	1020	23.60	0-606	176
TG-9	2006	800	24.40	0-558	169
TG-10	2006	300	3.30	52-300	45
TG-11	2006	315	13.80	52-315	86

The wells are often pairs or clusters reflecting up to three stages of drilling activity. The initial drillers had difficulty reaching below 300 feet so this was the maximum depth of the first shallow temperature gradient (TG) holes. Later, some of the TG wells were re-drilled or a new well was drilled in the same location to depths of 600 to 1020 ft. The multi-stage drilling turned out to be advantageous. It enabled analysis of the effects of intra-well flow between different horizons, which can be very complex when flow zones with different pressures are connected. This can be very difficult to sort out using a TG well drilled in a single stage. In the following discussion, the deep wells are discussed with their shallow partners in order to see the effect of multi-stage drilling.

Static logs of shallow wells

The wells located along the perimeter of the drilled area (Well 1, TG-6, and TG-10) stand out as having

the lowest temperature gradients (Figure 1, and blue tones in Figure 2). The easternmost well, Well 1, has a temperature gradient of 6.9 °F/100 ft which is approximately four times the regional value (~ 2 °F/100 ft). In the western end, TG-10 is about 1000 ft west of the main cluster and has a temperature gradient of 3.5 °F/100 ft, almost twice the expected regional background. TG-6 in the north has the lowest temperature gradient with 2.6 °F/100 ft but shows its proximity to the hot springs area by being about 10 °F hotter at the surface than Well 1 or TG-10. The relatively low gradients in TG-6 tend to support the narrow width of the anomalous zone defined by the 0.5m holes (Figure 1) defined by Wescott and Turner (1981). If the gradients in these surrounding wells are showing the deep thermal conditions, the target temperatures of about 250 °F anomaly could be encountered at depths of 2000 to 4000 ft. This would include the entire area so far examined by thermal gradient drilling.

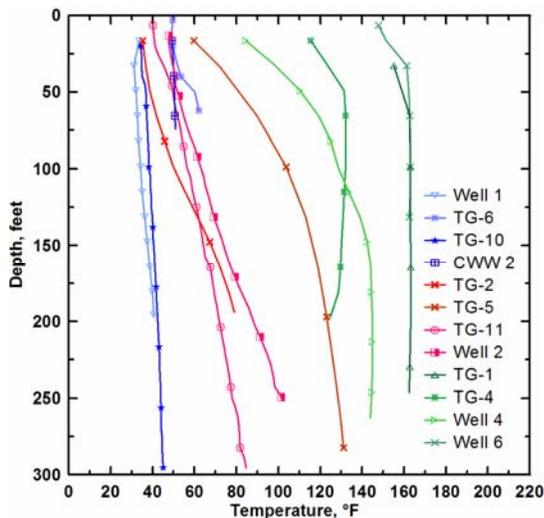


Figure 2 Static TD curves for the shallow wells. The outer area wells (tones of blue), the wells near the margins of the central anomaly (tones of red) and the wells within the central shallow anomaly (tones of green) are shown for comparison. See Figure 1 for well locations.

The wells between the central anomaly and the edges have all relatively higher temperature gradients compared to the previously discussed wells (Red tones in Figure 2). Temperature gradients in this group of wells ranges from 13.8 °F/100 ft in TG-11 to 31 °F/100 ft in TG-2. All of these wells are closer by hundreds of feet to the center of the thermal anomaly than the previously described “remote” wells. However, they do not have extremely high temperature gradients as seen in the other wells in the hot springs area. In Well 2 and TG-11, linear temperature curves continue to depths of up to hundreds of feet showing conductive behavior.

However, since the western end of the main geothermal anomaly is not clearly defined, TG-11 could either be within the main high temperature zone at shallow depths or reflect deeper conditions.

The relatively higher gradients in all of these wells may decrease at greater depths because of proximity to the margins of the thermal anomaly. These wells however are more likely to overlie high temperatures at depth than the remote wells.

The central shallow area is the apex of the shallow anomaly where the surface leakage is located and the wells are hot at very shallow depths (Figure 2, green tones). No wells have been drilled below a depth of 300 feet in this area. Well 0 and 5 are used for the direct use thermal needs of the resort therefore equilibrium temperatures logs are not available. The TG-1 well encountered 165 °F water at very shallow depths. It was drilled almost entirely in unaltered but fractured granite. TG-1 and Well 6 are artesian and therefore have essentially isothermal temperature profiles. Temperature-depth data from this group of wells show characteristics of highly fractured and permeable rock at shallow depths with upward moving thermal fluid bringing high temperatures close to the surface. All of these wells have extremely high near-surface temperature gradients. Only one well in this group, Well 4 in the eastern end of the fractured hot springs area, shows lower temperatures with increasing depth with a slight overturn below 200 ft. This might be due to the semi-horizontal movement of water toward the east end of the main shallow anomaly. Very slight shallow overturns are also observed in TG-1 and Well 6, but temperature reversals are more profound in Well 4 toward the east.

At the south edge of the main hot springs area, TG-5 shows conductive rollover behavior at depths of 100-150 ft. The shape of the temperature depth curve is diagnostic of the footwall portion of a flow system along a planar fault or fracture zone dipping to the north-east. Thus, this well defines the southern edge of the shallow thermal anomaly. In spite of TG-5 being only a few hundred feet from the TG-1 site where a temperature of 165 °F at 60 ft is present, the projected depth to the 165 °F isotherm at the TG-5 site is about 1000 ft implying strong fall in isotherms toward the south. Although the shallow part of TG-5 shows conductive behavior, the projected deep temperatures below 150 ft are still consistent with high temperatures at reasonably shallow depths.

Eastern area deep wells

Wells in the east are characterized by relatively low temperatures and show effects of lateral flow toward the east. Well 2 (Figure 3) was drilled in 1998 and deepened in late 2005. The log made in October 2005

just before the hole was deepened shows a high and generally linear gradient of 31 °F/100 ft to a depth of 250 ft and a bottom hole temperature of 110°F. However, after the well was deepened to 820 ft, the 110°F temperature at that depth has not been repeated. This area would be impossible to define if there was only one deep well. Therefore the staged drilling has helped to decipher the distribution of pressure and permeability in this area. During the second stage of drilling, deeper fracture zones were encountered at lower pressures. As shown on the Dec. 2005 injection logs, the water in the well bore flows down the well from an entry point at about 110 ft and exits at depths between 270 and 770 ft. The temperature profiles of Well 2 show a classic pattern of flow in a fractured rock. The two major fracture “thief” zones are at 270 ft and 770 ft, although there may be smaller fracture zones at other depths. Multiple fractures in the well are clearly seen in the temperature logs.

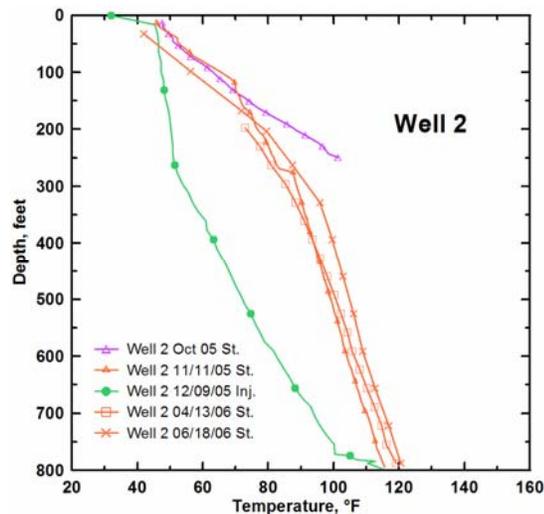


Figure 3. T-D curves for Well 2, in the eastern side. Green curves show injection log. Purple curve show the data for the first-stage of drilling

As a result of the downflow of water, the bottom hole temperature of the formation has not been established. However, a 10 °F rise between January and June 2006 (orange curves) logs illustrate that the bottom thief zone has sealing itself off and the downflow is diminishing. There is clearly a decrease in the thermal gradient in the depth range of about 250 to 300 ft, but the gradient below this zone continues to appear positive with a gradient of at least 5.7°F/100 ft. The actual bottom hole temperature is undeterminable with the present data but is almost surely in excess of 140°F. The heating behavior of the well and the possible maximum temperature offers insight to the overall resource size. Both this well and the well complex near by TG-7 have bottom hole temperatures of over 140 °F at depths of about

800 ft. These temperatures are comparable to the temperatures seen in the hot spring area. Therefore there is a significant possibility that the higher temperature resource may occur at greater depths in this area. This would increase the size of the resource at depth if the area were not confined to the east of the central anomaly.

TG-4 and TG-7 are on the eastern edge of the main shallow anomaly. The area is complicated in terms of the temperature-depth curves (Figure 4). The 702 ft deep TG-7 has maximum temperature of 156 °F which indicates that the temperatures of the main shallow anomaly dissipate toward the east of the hot spring area. As in the nearby Well 4, these wells also show shallow temperature overturns but they are larger and shallower compared to Well 4. In TG-7 there are two overturns, one at the 50-150 ft depth interval and another between 280 ft and 450 ft. A similar zone from about 60 to 200 ft is seen in nearby TG-4. This pattern is a further indication of lateral flow of water toward the east in this area.

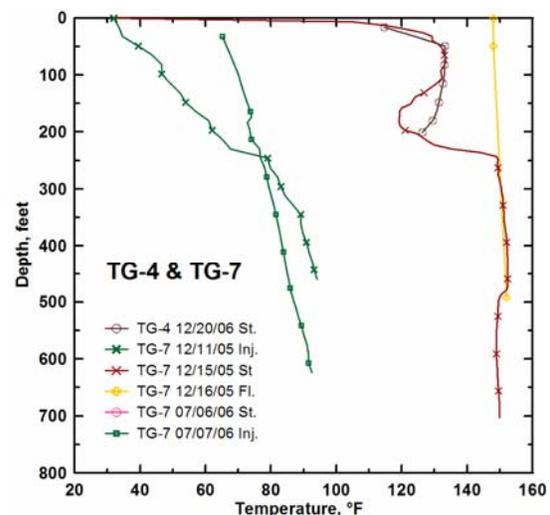


Figure 4. T-D curves for TG-4 and TG-7 in the eastern side. Green curves show injection logs. Yellow curve show the data for flowing log. TG-4 is the first stage of TG-7

The isothermal section on the flow zone in TG-7 below a depth of 250 ft is problematic as it could be an intra-bore flow region rather than a continuous permeable region. There are seems to be suggested by the fact that the well accepted injection at 250 ft and below 450 ft in the test of Dec. 11, 2005. Also the well produced from about 450 ft when it was flowed on Dec. 16, 2005. Because of penetrating high permeability zones with relatively low deep pressures, TG-7 is currently being used as an injection well for the power plant.

Western area deep wells

In the summer of 2005, TG-3 was the first well drilled in order to investigate the potential toward the west of the hot spring area (Figure 5). After drilling, this well had a BHT of about 80 °F but it quickly warmed up to 117 °F. The well had a weak artesian flow with a head of about 3 ft. This well has high projected temperatures at depth with a slight leakage of thermal water to the surface from about 100 ft.

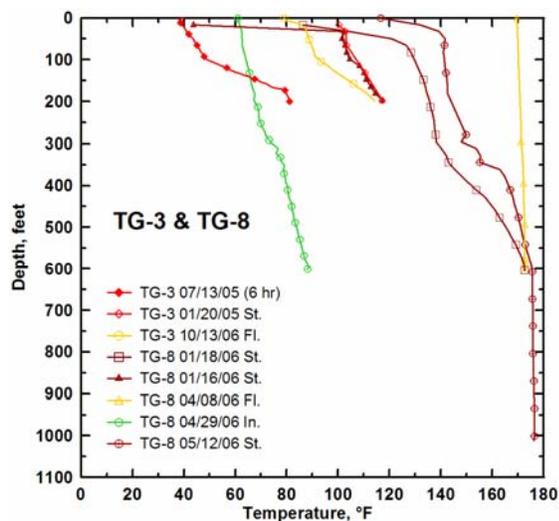


Figure 5 T-D curves for TG-3 and TG-8 in the western side. Green curves show injection logs. Yellow curves show flowing logs. TG-3 (red) is the first stage of TG-8 (brown).

Promising gradients in TG-3 led to the drilling of the nearby well TG-8 to a depth of 1020 ft. The temperatures follow the projection of the data from TG-3 to a depth of about 600 ft. The temperatures are near isothermal below this depth at 176 °F. Above 300 ft, the static temperature profiles in TG-8 are strongly influenced by rising water within the wellbore. The BHT is just over 176 °F at 1016 ft. This is the highest temperature measured at Chena to date. The temperature in the bottom 400 feet of the well increases by only 1 °F and is presumably impacted by fast fluid movement within or adjacent to the wellbore.

TG-9 was drilled a few hundred feet to the west of TG-8 (see Figure 1). TG-9 encountered a highly permeable fractured interval at 457 ft where a fluid-entry temperature of 163 °F was measured during a short flow test (Figure 6). After testing this zone, the well was deepened to 800 ft where a maximum temperature of 168.9 °F is present. The temperature-depth curve shows a sharp toe above 800 ft so projecting temperatures at greater depths is subject to considerable uncertainty.

Well 7 is located about 40 ft south of TG-9 and is being used as the production well for the power plant. A log made before the casing was cemented at 450 ft and logs made after the well was completed are shown in Figure 6. The shallow part of the well is very hot, apparently hot water is leaking from somewhere near by. The overturn is so sharp that it doesn't seem likely that this is the situation in situ. This same sort of overturn was seen in an early log in TG-9, but at a different depth. It is hypothesized that the depth difference is not real and the upper part of TG-9 should look like Well 7 at similar depths.

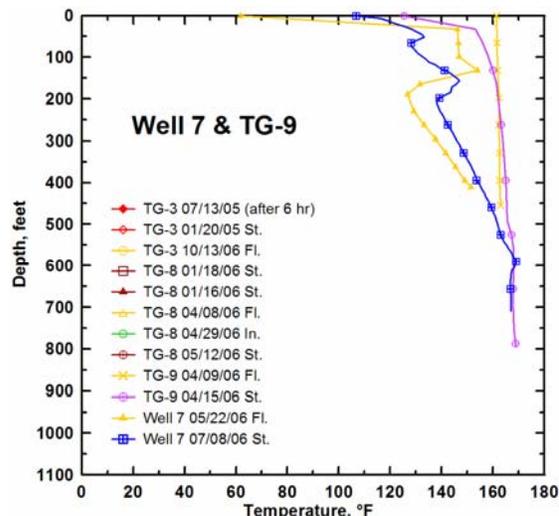


Figure 6 T-D curves for Well 7 and TG-9 in the western side. Yellow curves show flowing logs.

Geothermal system heat loss

The heat loss in Chena was calculated using the shallow thermal gradients that are tabulated in Table 1. A thermal conductivity of 2.7 W/m/K was assumed for the granitic rocks which are characteristic of the area. The loss was calculated for heat flow based on two assumptions for the surface temperature which are 0°C and -2.2°C. The heat flow was calculated over the depth interval of 0-50 ft. Only the area with thermal data was included in the calculation so the values should be conservative.

The natural heat loss calculated varies between 4.67×10^6 to 5.02×10^6 W depending on the selected surface temperature. This value compares well with other hot spring systems. Wisian et al. (2001) proposed an electrical production rate of 1 to 10 times the natural heat loss as a reasonable figure based on the existing highly developed fields around the world. However, most basin and range systems (deep circulation) that might be comparable to Chena have not been developed at such high values to date. Furthermore the temperatures in the other systems examined are typically over 350 °F so that the efficiency of energy conversion is much greater. A

reasonable estimate range for the power generation at Chena might be from 1 to 10 MW. The highest output is probably only reachable if the higher temperatures indicated by the geochemical thermometers occur over most of the anomaly region and at economic depths, probably less than 3000 ft.

Ions, isotopes and mixing models

Deep water samples from the wells show a similar chemical characteristic hot spring waters. The most saline and therefore the most primitive waters are found in the vicinity of TG-8 and TG-9, where highest temperatures were found. The high salinity wells are highly clustered in the western part of the anomaly from Well 4 to TG-9. The low salinity wells are located east of Well 4. The low salinities in the eastern wells are likely due to mixing with the surface water. Interestingly, although the deep well TG-7 is the hottest in the eastern part ($T \sim 153$ °F), water samples from depth of 450-500 ft show very low salinity which might indicate a great amount of mixing occurs in this area even at great depths. This could imply larger temperatures in the deeper parts than what is observed by temperature logs.

Although the highest temperature found so far is 176 °F, both Na-K-Ca and SiO_2 geothermometers suggest temperatures of 260 ± 10 °F. Samples from both eastern and western wells show the same high geochemical temperatures. Previous studies of hot spring waters estimated temperatures around 266 °F based on the same methodology. Therefore, the geochemical studies clearly indicate higher temperatures somewhere in the CHS geothermal system.

In order to understand the possible source of deep waters and timing of the circulation, a stable isotope study based on ^{18}O was carried out at SMU. Small $\delta^{18}\text{O}$ shifts from the meteoric line (0.5 mil) shows that the deep water is meteoric in origin and has a relatively recent recharge history. ^{14}C analysis shows the age to be less than 3000 yr (Yoshikawa, 2006).

Static well pressures

The well pressures show varying characteristics with increasing depth (Holdman et al., 2007). Shallow pressures in wells up to 200 ft deep (at a constant elevation of 1120 ft) change gradually from 52.5 psi in Well 1 to 31 psi in TG-3 which follows the general topography (decreasing to the west). In the west, the pressures are slightly higher compared to the hydraulic head associated with the deep geothermal system. In deep wells TG-8 and TG-9, the static increase of pressures with depth is well above the corresponding hydrostatic head. A pressure map below 300 ft shows increase opposite to the shallow regime and the topography that is toward the east. In the southeast part, deep well TG-7 has a pressure

which is 17 psi less than TG-8. This clearly indicates that the recharge of the shallow geothermal system is in the west. This is in agreement with the temperature logs which indicate eastward flow of deep fluids by overturns.

THE COMBINED CONCEPTUAL MODEL

Both temperature and pressure data indicates that the deep thermal waters enter the shallow system at depths below 600 ft at a distance of 300 ft west of the main hot springs (TG-8 and TG-9 sites). Upon entry to shallow levels, the thermal waters migrate toward the east where the pressure due to the deep geothermal systems declines. The thermal waters find ways to the surface at the current location of the hot springs where rocks are highly permeable. Part of the water continues to flow toward the north-east along the shallow fractures. Geochemical analysis of the waters shows that a substantial amount of mixing between groundwater and geothermal water occurs here. This makes the deep resource estimation in the eastern end even more difficult.

In the west, at TG-11, the projected depth for 250 °F is about 1500 ft assuming conductive T-D behavior. Here, if the gradients are lower at greater depths the source temperatures could be deeper.

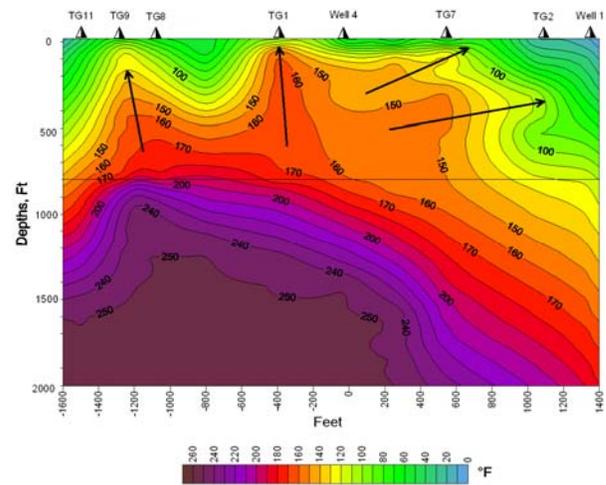


Figure 7 Conceptual model for temperatures in CHS

The wells in the main cluster are likely reflecting a shallow convective flow pattern. Therefore a single deep thermal model of the area would not be possible. This is especially the case in the east where lateral flow of geothermal water screens deep thermal regime. A good approach is to give bracket for the possible scenarios. Figure 7 shows a 2D representation of the best possible scenario based on results of subsurface temperatures from the existing wells. According to this, the gradients in the wells

stay constant at depth. The arrows show the main flow regimes based on temperature and pressure data.

In the less optimistic scenario, the wells would show smaller gradients at depth which result in a smaller resource size at a deeper level. A reasonable depth for the target temperature would be 3000 ft at the site of TG-8 and TG-9. Lastly, the worst case scenario could occur by only considering thermal data and excluding the geochemical data. According to this model the 250 °F isotherm would be far below exploitable depths and would not have any interaction with the circulating fluids.

These source models assume the gradients in the eastern wells are representative of the deep thermal regime but it is also possible that the deep high temperature source might be totally screened by the presence of shallow cold waters. This could increase the size of the resource toward east.

CONCLUSIONS

Stable isotope analysis shows that thermal waters in CHS are in meteoric in origin. The ¹⁸O and ¹⁴C analysis of the spring waters indicates that the circulation time of the meteoric water is less than 3000 yr. The depth of circulation must be about 11,000 ft in order to get temperatures of 250 °F based on a background temperature gradient of 2 °F/100 ft. High background heat flow, deep circulation of thermal waters along the fractures, relatively recent age of the circulating waters, complexity of the fracture patterns, and the distribution of complex pressure regimes makes Chena geothermal system a typical fault/fracture driven geothermal system. This is true in spite of the fact that the system is only 3000 ft long and 300 ft wide.

One of the unique applications in this prospect was taking advantage of multi-stage drilling. Although it was not intentionally applied for scientific purposes in Chena, the procedure turned out to be an advantage by greatly increasing the understanding of the flow regimes.

So far the drilling activities have been successfully accomplished by delineating production and injection zones and a 0.25 MW power plant has been successfully operated. One of the ultimate goals in development of a production unit is to establish a system that does not allow intrusion of the cold groundwater into the energy conversion cycle. Well communication testing showed that the western end is in close connection with the deep circulating thermal waters (Holdman et al., 2007). The western area is characterized by high permeability and pressure which allows rapid recharge of the hot fluid to the system below depths of 400 ft. The eastern end wells have low deep pressures which is good for

injection of the waste water in order to establish a sustainable power source.

The high artesian flow rates of the western wells (500 gpm) indicate that the system has a large potential at greater depths and temperatures. Considering the geochemical evidence for temperatures of over 250 °F, further drilling in this area could result in higher temperatures. Thus, even though the system appears relatively small in its surface manifestations, it is quite capable of producing significant geothermal energy if properly managed.

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