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Preliminary Evaluation of Geothermal Potential at the Cheyenne River Sioux Reservation, South Dakota

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ABSTRACT

A geochemical investigation of well waters from the Cheyenne River Sioux Reservation in South Dakota revealed considerable diversity in the chemistry of the fluids and indicated that waters from the Dakota Formation were the best candidates for direct-use geothermal applications. Geothermometry calculations for all wells suggest that formation temperatures are < 90°C. Potential scaling problems from utilization of the waters would most likely be restricted to carbonate scale and could be offset by maintaining CO₂ gas in solution.

Introduction

A request to evaluate the space-heating and greenhouse-heating potential of warm to hot artesian well waters from the Cheyenne River Sioux Reservation prompted a brief field expedition to South Dakota during late March 1999. The wells which were originally drilled for drinking water supplies have been left open to flow for decades (C. Roepke, personal communication). As the need for potable water has been a major concern for the tribe, an earlier hydrologic investigation focused on evaluation of the shallow ground-water and deep bedrock aquifers for drinking water and livestock supplies. Although the presence of the thermal waters is common knowledge, little effort has been made to characterize or utilize their thermal potential. This report summarizes the initial data collected and reflects on potential direct-use applications of the thermal waters.

Background

The Cheyenne River Sioux Reservation (CRSR) located in north-central South Dakota extends across approximately 4,230 mi² of prairie in the Great Plains physiographic province (Howells, 1979) (Figure 1, overleaf). The reservation is bordered to the east and south by the Missouri and Cheyenne rivers and the northern portion is cross-cut by the eastwardly flowing Moreau river. The surficial geology is composed primarily of the Upper Cretaceous Pierre Shale and the Fox Hills and Hell Creek Formations which were sculpted by Pleistocene glaciation and erosion to the present-day rolling upland topography

(Howells, 1979). Deeper bedrock units are a mixture of continental and marine sedimentary deposits that include several artesian aquifers that are part of the southeastern limb of the Williston basin (Howells, 1979). A generalized lithologic section appears in Figure 2, overleaf.

Research by Gosnold documented a large heat flow anomaly in central South Dakota (1988, 1990, 1991). He predicted that in general, all aquifers in the Great Plains have warm enough waters for geothermal exploitation. No thermal springs were observed in the CRSR by the field team and it is uncertain if thermal springs exist within the reservation boundaries. Thermal waters were collected from two artesian wells in the SW corner of the reservation near Cherry Creek, and from three wells in the Lantry oil field (Figure 1). Daytime surface water temperature along the edge of a large creek measured 8.5°C. During the sampling period only small patches of snow existed in a few protected areas. Groundwater samples were collected from two domestic wells completed in the Hell Creek Formation (≈ 15 meters deep), and a surface water sample was collected from Little Moreau Creek in the northern part of the reservation.

The deep water wells and oil wells sampled in this study were completed in the Dakota and Red River Formations, respectively (Figure 2). These formations consist of Lower Cretaceous deltaic and near-shore facies sandstones interbedded with shale, and Ordovician marine dolomites and dolomitic limestones. Waters from the Lantry oil field are derived from depths of ≈ 1500 meters. Water temperatures ranged between 36 and 52°C. Samples FBTH #2 and FBTH #3, collected from a discharge pipe and a wellhead, contained minor traces of oil. Water from Lantry 1 stock tank flows continually from a 4" diameter pipe. The water is iron-rich (Table 1, page 457) and forms a bright red precipitate of what is assumed to be Fe(OH)₃ on the bottom of the tank.

The two thermal artesian wells are free flowing. The wellheads are wetted constantly by the flow and show obvious signs of corrosion. Both wells are leaking small amounts of water from cracks in the casing near the ground surface. Evaporation of water from cracks in the line at the Red's Scaffold Well produces a precipitate of what tastes, and appears to be, NaCl.

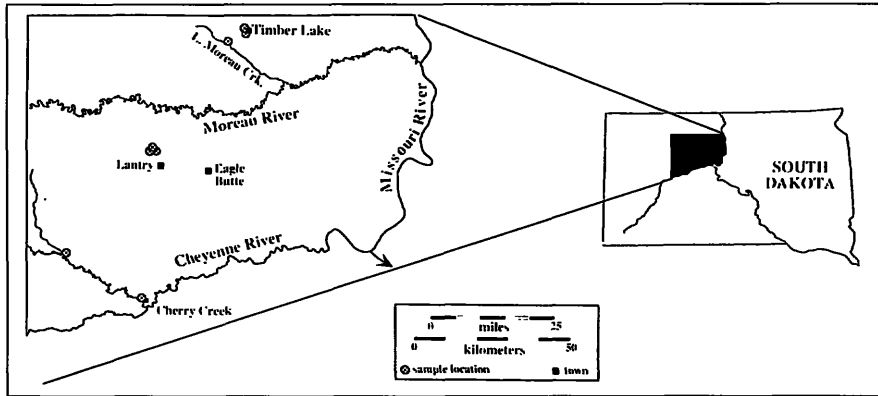


Figure 1. Map showing sample locations on the Cheyenne River Sioux Reservation.

Figure 2. Generalized stratigraphic section for the Cheyenne River Sioux Reservation (after Howells, 1979). Section shows bottom hole formations for oil field (OF), thermal artesian (TA) and groundwater wells (DG) sampled in this study. Maximum thicknesses reported by Howells are plotted because thicknesses of units vary across the region. Depths of the wells are therefore not drawn to scale.

Methods

Samples were collected according to procedures outlined in Trujillo *et al.* (1987) and were analyzed at Los Alamos National Laboratory (Table 1). Water samples were taken as close as possible to the wellhead. Well flow rates were estimated using a stop watch and a container of known volume. Water flow at the Cherry Creek artesian well was restricted by a valve manifold and so flow rate was estimated from observation of apparent flow combined with anecdotal reports. Measurements for alkalinity, conductivity, Eh, and pH were taken in the field. Special samples were collected for monomeric Al analysis according to procedures outlined in Barnes (1975). Geochemical modeling was performed using the Geochemist's Workbench software package (Bethke, 1996) and version V2-EQ8 of the GEMBOCHS thermodynamic data base (Johnson and Lundeen, 1997).

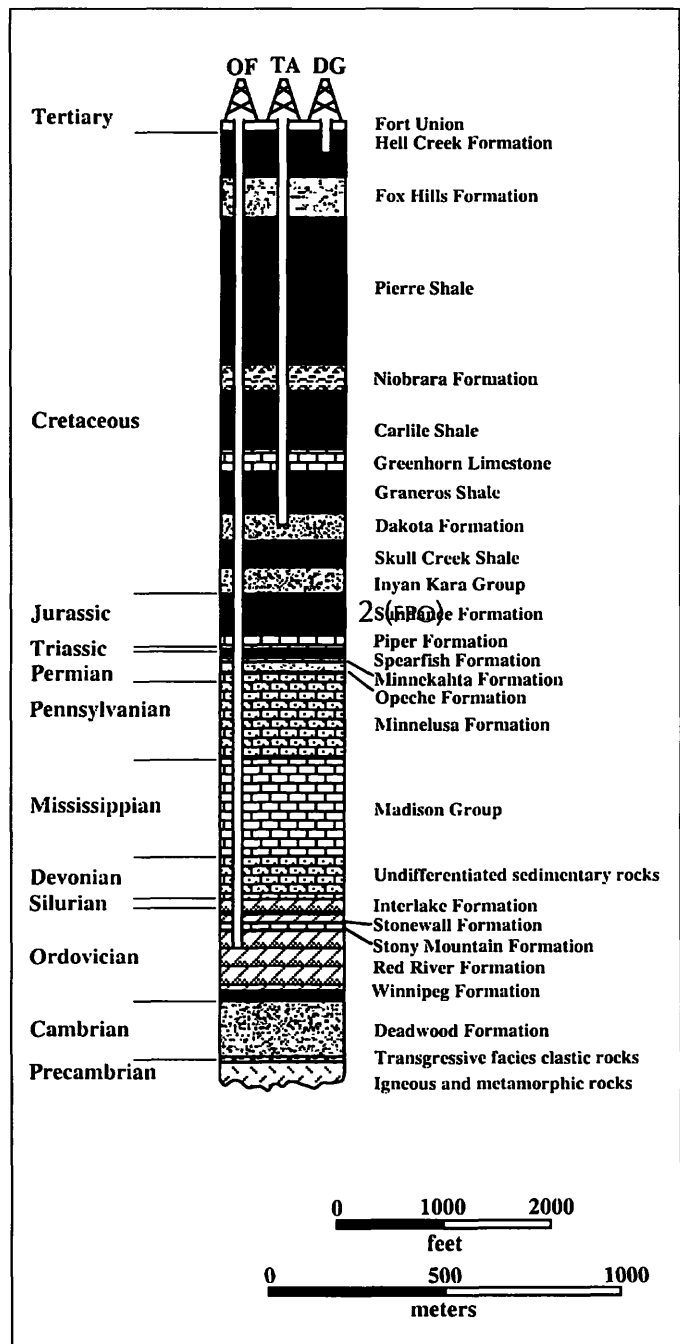
Geochemistry

Waters collected on the CRSR are varied, consisting of dilute ground waters (DG), oil field waters (OF), and thermal artesian waters (TA). Although waters within each group are geochemically similar, the three groups of waters are geochemically distinct (Figures 3 and 4). TA waters have the highest total dissolved solids concentrations of the three groups. DG waters contain more Ca and Mg than TA waters. OF waters are SO₄-rich, TA waters are Cl and HCO₃-rich. All water types are Li-poor reflecting the paucity of volcanic rocks in the stratigraphy. Hotter waters have more B than cold waters. TA waters have high concentrations of iodide.

When compared to high-temperature geothermal reservoirs such as Valles Caldera (Goff and Gardner, 1994), the CRSR waters have comparably less Cl and less Li.

Geothermometry

Table 2 (page 458) lists calculated subsurface reservoir temperatures from chemical geothermometry. Because the waters have relatively low silica, temperatures can be no more than about 90°C. Cation geothermometers suggest subsurface temperatures of no more than 70 to 80°C. A plot of Na-K-Mg (Figure 5, overleaf) shows that both OF and TA values are characteristic of relatively low-temperature fluids, and are unlike high-temperature geothermal fluids such as found at Valles Caldera.



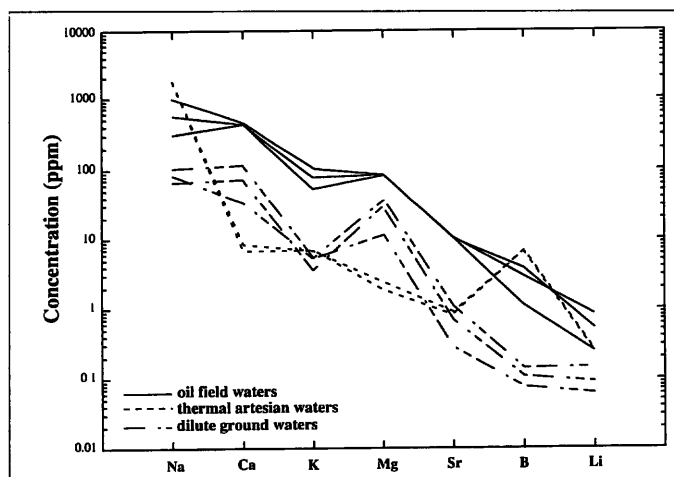


Figure 3. Plot of the logarithm of the concentrations of the major cations for oil field waters, thermal artesian waters and dilute groundwaters showing differences among groups.

Scaling

The potential for scaling in surface facilities depends on changes in the physical and chemical state of the fluids caused by production. Geochemical modeling was used to evaluate scaling potential by taking explicit consideration of the effect on mineral solubility of decreases in temperature and pressure during production and the loss of CO_2 and increase in pH that occurs during degassing.

Silica scaling in water treatment systems is expected only when silica concentrations equal or exceed amorphous silica saturation (ASTM, 1993). Silica concentrations must be limited to less than 120-150 mg/L to avoid silica scaling in low temperature systems (Amjad *et al.*, 1999; Amjad, 1993). SiO_2 concentrations in the CRSR waters range between 6 and 40 mg/kg (Figure 6, overleaf), whereas 116 mg/kg is required to precipitate amorphous silica at 25°C, according to equilibrium calculations. Thus precipitation of silica is not expected even if the temperature of the CRSR waters decreases to earth surface conditions. Silica precipitation might occur if the solutions were significantly concentrated by evaporation or other processes.

Under in-situ conditions, the CRSR waters are saturated with respect to calcite or are supersaturated by a factor of 2.5 or less. Calcite supersaturation and CO_2 fugacities well above atmospheric are common in near-surface, low temperature waters. With the exception of Little Moreau Creek, CO_2 fugacities of CRSR waters range from $10^{-1.4}$ to 10^{-2} bars. Little Moreau Creek has a CO_2 fugacity of $10^{-2.8}$ bars, which is closer to atmospheric CO_2 pressure of $10^{-3.5}$ bars. Calcite supersaturation has been attributed to a number of factors, including degassing, grain size and kinetics (Morse and Mackenzie, 1990; Herman and Lorah, 1988).

Predictions of the maximum mass of scale that can precipitate per kilogram of produced water is shown in Figure 7 (overleaf) for the OF and TA waters. For the models, each fluid was reduced from its measured temperature to 25°C. Although silica is not expected to precipitate owing to kinetic inhibitions at low temperature, it was allowed to precipitate until equilibrium

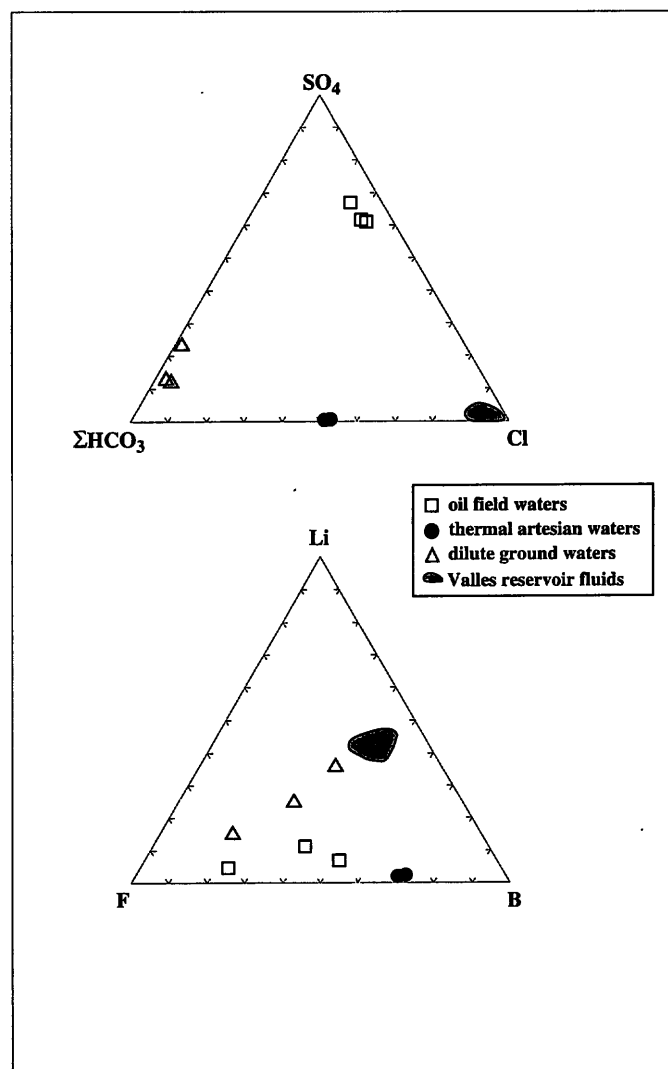


Figure 4. (a) SO_4 - ΣHCO_3 -Cl ternary diagram shows the differences in major anion fluid geochemistry among the three groups of CRSR waters ($\Sigma\text{HCO}_3 = 2 * \text{CO}_3 + \text{HCO}_3$). CRSR waters have a relatively low Cl content unlike geothermal waters of Valles Caldera. (b) Li-F-B ternary diagram shows the relatively low Li concentration for most

with chalcedony was achieved. The total mass of scale is overestimated to ensure a conservative evaluation of scale formation.

The mass of carbonate scale was estimated using two approaches based on the variation of $\text{CO}_2(\text{g})$ fugacity and the total carbonate content as the waters are brought to the surface and cool. The bars labeled "Atm" illustrate the volume of scale produced if the fugacity of $\text{CO}_2(\text{g})$ decreases to atmospheric values owing to CO_2 loss during production. The bars labeled "Fixed C" in Figure 7 illustrate the volumes of scale precipitated if the total carbonate in solution remains constant (i.e. no CO_2 loss). The scales are dominated by calcite and chalcedony.

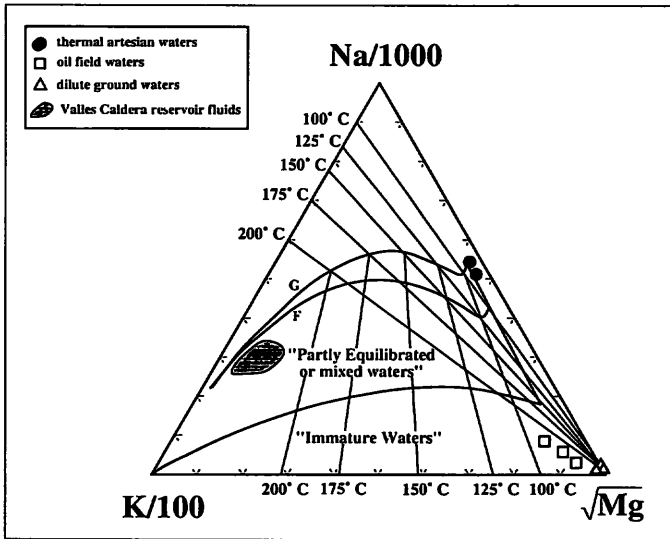


Figure 5. Na-K-Mg ternary diagram for evaluating equilibrium temperatures of CRSR geothermal fluids (after Fournier, 1990). G= Giggenbach full equilibrium line, F= Fournier full equilibrium line. Valles Caldera cloud uses data from Shevenell et al. (1987).

Calcite scale contains relatively minor amounts of strontium and magnesium. The increase in pH caused by CO₂ degassing results in the formation of greater quantities of carbonate scale. TA waters produce less scale because they possess relatively low calcium concentrations. It is apparent from the above calculations that pressure maintenance will help to minimize scale formation by preventing CO₂ degassing.

Scaling calculations using the analyzed monomeric aluminum concentrations indicate that various aluminosilicates such as clays and zeolites were supersaturated with respect to the waters under in-situ conditions. However, it is not expected that aluminosilicates will precipitate owing to kinetic limitations at low temperatures. Even if aluminosilicate scales formed, their mass would be totally overwhelmed by the mass of carbonate scale owing to the small concentrations of aluminum in solution, whether monomeric or total. The aluminum might be more likely to co-precipitate with the silica scale (Gallup, 1998; Goguel, 1976).

Predictions of scaling potential and masses of precipitates must not be taken too literally. Although calculations have proved to be useful guides to system behavior, it is still necessary to couple model predictions with careful monitoring of fluid chemistry and scale growth. Our predictions of mass of scale precipitated neglected the influence of kinetic inhibitions to precipitation; calcite and chalcedony were assumed to precipitate until their equilibrium was achieved.

Energy Potential

Table 3 lists pertinent information for the five thermal wells that we sampled at CRSR. Produced energies were calculated by multiplying the mass times the enthalpy for discharge conditions. Because the TA wells are artesian, are relatively shallow, and have the least scaling potential, it is our opinion that new

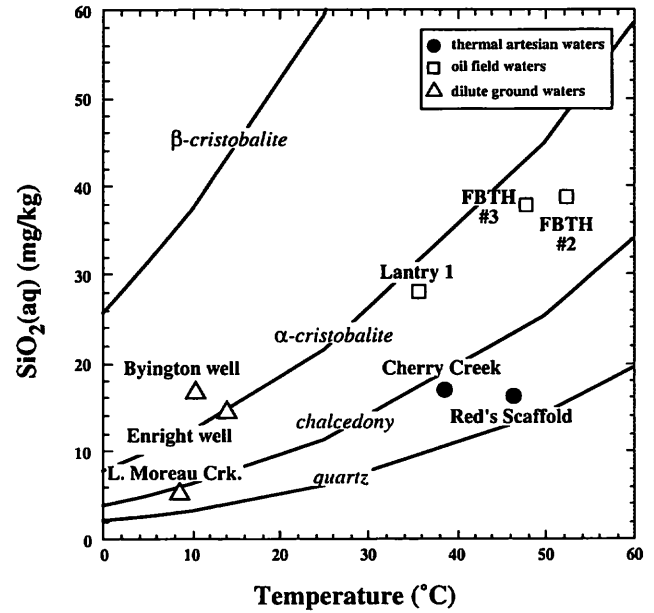


Figure 6. Concentration of aqueous SiO₂ (mg/kg) as a function of temperature in produced waters compared to the solubility of various SiO₂ polymorphs. Most waters are approximately saturated with either chalcedony or α -cristobalite.

wells completed in the Dakota Aquifer have the best energy potential for low-temperature geothermal applications. Even though the Red River Formation aquifer is slightly hotter, deeper wells will require higher costs for drilling, completion, and pumping, and Red River Formation fluids have a higher scaling potential.

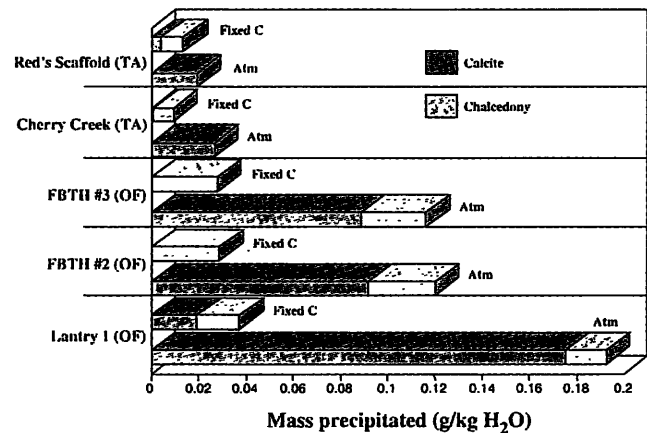


Figure 7. Mass of scale (grams/kg H₂O) formed during cooling of OF and TA waters to 25°C. Atm assumes CO₂ fugacity decreases to atmospheric levels. Fixed C assumes the total carbonate content of the fluid remains constant during cooling. No chalcedony was produced in the Red's Scaffold and Cherry Creek "Atm" simulations, in contrast to the "Fixed C" simulations, owing to the alkaline pH generated by CO₂ degassing and its effect on the aqueous complexation of silica in solution.

Table 1: Selected chemical analyses for warm and cold waters from the Cheyenne River Sioux Reservation, SD and the geothermal reservoir at Valles Caldera, NM (values in ppm unless otherwise specified). Mono= monomeric, n/r=not reported, n/a=not analyzed. Valles Caldera data from Shevenell et al., 1987.

Sample Location	OIL FIELD WATERS			THERMAL ARTESIAN WATERS			DILUTE GROUND WATERS			VALLES RESERVOIR	
	Lantry 1 water well	FBTH #2 oil well	FBTH #3 oil well	Cherry Creek water well	Red's Scaffold water well	Little Moreau Creek surface water	Byington Well water well	Enright Well water well	Baca-13		
<i>Field Parameters</i>											
Temp °C	35.7	52.4	47.7	38.6	46.3	8.5	10.3	13.8	279		
Alk. (ppm CaCO ₃)	258	150	122	1294	1264	210	493	326	n/r		
Cond. (µS/cm)	n/a	n/a	n/a	7830	8300	620	1210	860	n/r		
Eh (mV)	380	-205	-190	208	217	469	418	254	219		
pH	7.01	6.76	6.73	7.61	7.78	8.08	6.97	7.55	7.20		
<i>Major Species</i>											
SiO ₂	28.5	39.4	38.5	19.6	21.2	5.69	16.9	14.9	680		
Na	971	571	315	1760	1800	85.8	104	65.5	1540		
K	105	71.8	54.0	6.87	6.02	4.78	5.14	3.52	255		
Li	0.84	0.53	0.24	0.24	0.24	0.06	0.14	0.09	20.5		
Ca	452	436	435	8.28	6.73	34.2	119	71.0	4.3		
Mg	87.7	83.5	83.5	2.45	1.87	11.6	37.4	28.8	0.19		
Sr	11.0	10.3	9.7	0.87	0.71	0.28	1.14	0.68	0.22		
F	3.45	3.03	3.47	2.33	2.76	0.26	0.11	0.16	9.60		
Cl	987	748	476	1814	1925	4.91	18.6	21.5	2594		
Br	0.93	1.78	0.91	12.4	13.5	<0.02	0.05	0.11	7.01		
HCO ₃	280	172	170	1584	1569	257	681	440	236		
CO ₃	0	0	0	71.1	79.2	13.9	0	0	n/r		
SO ₄	2075	1464	1328	0.21	0.06	89.4	107	66.0	47		
B	2.83	3.71	1.12	6.32	6.77	0.077	0.14	0.11	18.0		
TDS	5023	3612	2918	5294	5438	508	1092	714	4644		
<i>Trace Species</i>											
Al	0.13	0.15	0.09	0.02	<0.02	<0.02	0.04	<0.02	0.34		
Al Mono	0.003	0.003	0.003	0.002	0.002	0.002	<0.001	0.002	n/r		
As	0.0019	<0.0002	<0.0002	<0.0002	<0.0002	0.0008	<0.0002	<0.0002	3.0		
Ba	0.034	0.045	0.046	0.35	0.26	0.041	0.18	0.090	0.02		
Cs	0.010	0.003	0.005	<0.002	<0.002	<0.002	<0.002	<0.002	n/r		
Fe	14.3	0.1	0.3	0.05	0.03	0.06	<0.01	0.44	0.02		
Hg	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	n/r		
I	0.09	0.07	0.04	7.03	6.68	<0.01	<0.01	<0.01	n/r		
Mn	0.250	0.009	0.160	0.003	0.004	0.18	0.041	0.048	<0.01		
NH ₄	3.07	1.90	1.26	4.61	4.19	0.13	0.65	1.09	0.21		
NO ₃	<0.05	<0.05	<0.05	<0.05	<0.05	0.09	0.09	0.04	<0.1		
Pb	<0.002	<0.002	<0.002	0.012	0.014	0.006	<0.002	<0.002	<0.01		
PO ₄	<0.1	<0.1	<0.1	<0.1	<0.1	<0.05	<0.05	0.12	<1		
Rb	0.072	0.071	0.052	0.008	0.007	0.004	0.007	0.005	3.0		
S	0.06	4.62	0.55	<0.02	0.05	0.02	<0.02	<0.02	n/r		

Table 2: Calculated subsurface reservoir temperatures, using a standard suite of chemical geothermometers (Urbani, 1986). Values in °C; parentheses means calculation violates rules of application.

Sample Location	OIL FIELD WATERS			THERMAL ARTESIAN WATERS	
	Lantry 1 stock tank water well	FBTH #2 oil well	FBTH #3 oil well	Cherry Creek artesian water well	Red's Scaffold artesian water well
Measured Temp °C	35.7	52.4	47.7	38.6	46.3
Chalcedony	45	60	59	30	33
Quartz-no steam loss	77	91	90	63	66
Na/K (Fournier)	(224)	(237)	(268)	(40)	(34)
Na/K (Truesdell)	(196)	(214)	(254)	(-11)	(-16)
Na/Li dilute	69	73	63	-5	-5
Mg/Li	59	49	31	73	77
K/Mg	99	90	82	75	75
NKC 1/3	188	187	193	82	78
NKC 4/3	(142)	(119)	(100)	(148)	(149)
R	22	23	23	25	24
NKCM	81	80	79	77	78

Table 3: Power calculations for wells on the CRSR. Enthalpy data from steam tables of Keenan et al., 1969. Well depths are estimated from Howells, 1979. Flow rate for Cherry Creek artesian well estimated from observation and local reports.

Well Name	OIL FIELD WATERS			THERMAL ARTESIAN WATERS	
	Lantry 1 water well	FBTH #2 oil well	FBTH #3 oil well	Cherry Creek artesian water well	Red's Scaffold artesian water well
Bottom Hole Formation	Red River	Red River	Red River	Dakota	Dakota
Well Depth (m)	1497	1498	1499	620	727
Surface Water Temp.	35.7	52.4	47.7	38.6	46.3
Flow Rate (gal/min)	5	25	8	50	100
Enthalpy (kJ/kg)	151	218	201	163	193
Power (kJ/sec)	47	333	94	511	1201

Conclusions

Geochemical analyses of well waters and equilibrium geochemical calculations suggest that CRSR waters produced from the Dakota Aquifer offer the best potential for low-temperature geothermal applications such as space-heating, greenhouse-heating, aquaculture, and resort use. δD and $\delta^{18}O$ isotope analyses are in progress to evaluate reservoir recharge sources. Gas analyses could improve our predictions on scaling and corrosion, although gas discharges are very small. Additional investigative efforts should evaluate the areal distribution of the aquifer, underlying temperature variations, and geohydrologic properties, and should assess the preliminary costs for various applications.

Acknowledgments

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