Geothermal Assessment of Archuleta County and the Pagosa Springs Aquifer, Colorado

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ABSTRACT

A reassessment of geothermal potential in Archuleta County reveals that there are no thermal aquifers with electrical generating potential (>150°C). Instead, isolated thermal aquifers are scattered throughout the county which may have future potential for greenhousing and aqua-culture, as well as bathing and heating. Maximum estimated reservoir temperatures are 110-120°C for the Pagosa Springs Aquifer and 110-140°C for the Piedra Hot Spring system which circulate through Precambrian basement; however, estimated depths to the source reservoirs are 1 to 3 km. Maximum estimated reservoir temperatures for other thermal aquifers, which circulate in Mesozoic sedimentary rocks, are ≤75°C. Additional observations made at Pagosa Springs show that present exploitation of the aquifer exceeds natural recharge during the months of September through May causing temperature declines in several wells and the famous Big Spring.

INTRODUCTION

In the summer of 1990 the Commissioners of Archuleta County, Colorado determined that an assessment of the energy potential of the geothermal resources within the county was needed by public, private, and commercial enterprises to increase the county's light industry. A project was formulated whose objectives were to: (1) provide a data base of geothermal aquifer characteristics for planning and development decisions; (2) train county personnel in geothermal exploration, evaluation, and management; and (3) collect data on direct use applications in space heating, horticulture, and aqua-culture to be used for public education and to assist developers and engineers. The Colorado State Department of Local Affairs provided a grant of $40K to the county in November, 1990. This was matched with $15K of county funds. Los Alamos National Laboratory provided chemical analyses of waters, miscellaneous laboratory support, field sampling equipment, and geothermal expertise, and the project was conducted during 1991. This report is a summary of findings resulting from objectives (1) and (2).

GEOLOGICAL SETTING

The geology of the Archuleta County region (Fig. 1) has been mapped by Wood et al. (1948), Steven et al. (1974), and Galloway (1980) among others. Regional geology consists primarily of Mesozoic and Paleozoic sedimentary units of the Colorado Plateau overlying Precambrian crystalline basement. Paleozoic rocks are found in the western part of the county west of the crest of the Archuleta Anticlinorium suggesting that a Precambrian high once existed in the east. In the northern and eastern sectors of the county, these older rocks are overlain by mid-Tertiary domes, flows, tuffs, ignimbrites, and associated sediments of the San Juan volcanic field dated at 40-22.5 Ma (Steven and Lipman, (1976). Mafic dikes believed to be contemporaneous with this extensive period of volcanism intrude large areas of older rocks in southern Archuleta County.

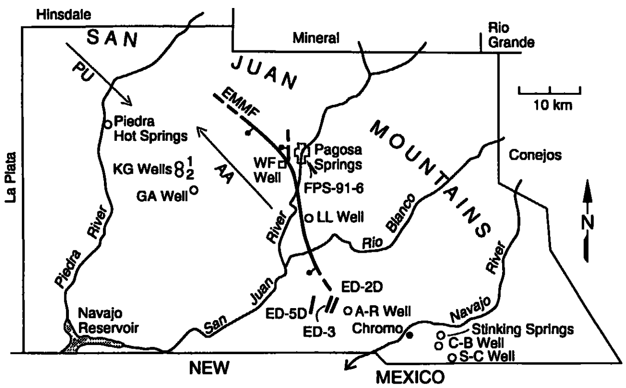

Figure 1. Map of Archuleta County, Colorado showing locations of thermal aquifers and mafic dikes described in this report: EMMF = Eight Mile Mesa Fault, AA = Archuleta Anticlinorium (plunge NW), PU = Piedra Uplift anticlinorium (plunge SE).

The older rocks were broadly folded and faulted during Laramide time (65-55 Ma) into NW-trending structures such as the Archuleta Anticlinorium and Piedra Uplift. It is widely believed that the anticlines formed over reactivated Precambrian faults (i.e. Muehlberger, 1967). The most significant fault from a geothermal perspective is the Eight Mile Mesa Fault (Galloway, 1980) which cuts all exposed Mesozoic units and which may have been active into Miocene time (Dunn, 1964).

PREVIOUS GEOTHERMAL ASSESSMENTS

A state-wide assessment of Colorado geothermal areas was published by Pearl (1979). This report described several thermal sites in Archuleta County but did not identify high-temperature resources or suggest possible uses for lower temperature fluids. A detailed geothermal assessment of the Pagosa Springs area was undertaken in the late 1970's (Coury and Associates, et al., 1980; Galloway, 1980) and resulted in the drilling of two wells. The deeper well (P-1) penetrated Precambrian basement at about 425 m (1400 ft) but the hottest water and best producing fracture was encountered in Dakota sandstone at about 76 m (250 ft). Samples of water from both the Dakota and Precambrian zones were essentially identical in chemistry and isotopes. This well was re-engineered to become the Town Well #5 which presently supplies space heat for many buildings in Pagosa Springs. Galloway (1980, p. 37) noted that the P-1 flowing zone in the Dakota occurred at a small displacement fault but that "...this flow had such a drastic effect on existing wells and the spring that the well had to be cased as soon as possible..."

ADDITIONAL GEOLOGIC OBSERVATIONS

During our reassessment of geothermal potential in Archuleta County, we found that thermal waters were not associated with obvious faults or fracture zones at any locations, even at

Pagosa Springs. This is noteworthy because most geothermal reservoirs and their hot springs have obvious structural control observable at the surface or with geophysics. Many thermal waters in the county are known only because they occur in old oil exploration wells which were drilled into presumed sedimentary traps, not into fault zones. A considerable amount of geologic and geophysical work was done at Pagosa Springs in the late 1970's but no fault zone, fracture zone, or other structure of consequence was found at the surface or at depth. We also collected and analyzed eight samples of ancient and modern alteration deposits from springs, wells, dikes, veins, and faults in the region. In all cases the deposits were either aragonite, calcite, gypsum, or iron-oxides (and various mixtures). No sinter (SiO_2) deposits were found which are an indication of reservoir temperatures ≥150°C (White et al., 1971; Goff et al., 1987). All existing spring deposits are travertine ($CaCO_3$) indicating reservoir temperatures <150°C or mixing of reservoir fluids with $CaHCO_3$-rich waters.

HEAT SOURCES

To eliminate volcanism as a viable heat source for the region, we obtained four dates on samples of the many mafic dikes that constitute the Archuleta Dike Swarm (Table 1). The oldest date (~35 Ma) was obtained from a basanite dike (Fig. 1) exposed on Light Plant Road, about 1.5 km south of Pagosa Springs. Three dates (~25 Ma) were obtained on lamprophyre dikes exposed along Montezuma Mesa Road about 25 km south of Pagosa Springs. The two types of dikes have different trends as well as different ages and compositions suggesting changes in the paleostress regime during this time period (Aldrich et al., 1986). Although magmas of the compositions dated have their origins in the mantle, the dikes are much too old to provide heat for any present geothermal systems in the region (Smith and Shaw, 1978); thus geothermal fluids in Archuleta County are heated by deep circulation into shallow Precambrian basement having relatively high background heat flow (2.5 HFU, 45°C/km gradients) as concluded earlier by Galloway (1980).

GEOCHEMISTRY OF THERMAL WATERS AND GASES

Approximately 100 samples of thermal and nonthermal waters were collected in Archuleta County during 1991 to obtain additional information for a county-wide geothermal evaluation. Very few thermal waters occur in the county outside of Pagosa Springs (Fig. 1, Table 2) and many of these are tapped only by wells. In general, the thermal waters can be classified compositionally as either Na-Ca-SO_4-HCO_3-Cl or Ca-SO_4-HCO_3 types (referred to hereafter as "Cl-type" and "SO_4-type", respectively). The former type occurs only at Pagosa Springs and Piedra Hot Spring, is closely associated with Precambrian rocks, and is relatively rich in F, a characteristic of fluids that flow through volcanic/plutonic rocks. The SO_4-type is more widely distributed, is affiliated with Mesozoic rocks, particularly Mancos shale and Dakota sandstone, and contains less F. The Cl-type waters also contain substantially more B, Br, Li, and other trace elements indicative of higher temperatures of equilibration and deeper circulation. On the other hand, all waters contain moderate to low concentrations of SiO_2 and large concentrations of Ca+Mg+Sr, suggesting equilibration temperatures less than 150°C or substantial mixing of different water types. A major exception to the above generalizations is the composition of the Archuleta Ranch well. This 63°C water contains unusually high pH and HCO3 and very low SiO_2 and SO_4; thus it appears to be heavily contaminated with drilling fluids and cannot be reasonably evaluated. None of the waters resemble the Na-K-Cl type fluids typical of high-temperature (>200°C) geothermal systems (Fournier, 1981; Nicholson, 1993).

Table 1: Potassium-Argon Dates on Volcanic Dikes in the Pagosa Springs Region, Colorado[1]

Sample No.	Rock Type	Material	%K	ppm *Ar (x 10⁻⁴)	% *Ar	Age (Ma)	Strike
FPS-91-6	Basanite	W/R	0.372	9.03	34.7	34.7±1.8	N14W
ED-2D	Lamprophyre	Phlog.	7.071	123.4	69.4	25.0±0.7	N23E
ED-3	Lamprophyre	Phlog.	6.864	117.9	53.1	24.6±0.6	N29E
ED-5D	Lamprophyre	Phlog.	6.205	104.8	73.7	24.2±0.6	N13E

[1] Dates by Geochron Laboratories, Cambridge, MA; * Ar refers to radiogenic argon.

Additional differences, similarities, and trends can be observed in the Cl variation diagrams of Fig. 2. Waters from each site have unique chemistry showing they do not constitute one huge reservoir. Interestingly, all waters have similar Br/Cl ratios relatively close to seawater, indicating recharge and/or flow within marine sedimentary rocks. The Pagosa Springs aquifer (PSA) is by far the most interesting site geochemically. Cooler wells in the margins of the PSA show mixing of Cl-type reservoir fluids with dilute surface water (Poma #2) or SO_4-type water (D/S Well). It is very clear that the PSA mixes with SO_4-type water above Precambrian basement because there is a strong inverse correlation between Cl and SO_4.

Free gas occurs only at Pagosa Springs. The gas from Big Spring is probably most representative because it was collected directly from the vent at the summit of the travertine. Three analyses of gas (Table 3) show that it is composed mostly of CO_2, N_2, CH_4, and He. The gas at Spa Motel was collected at the surface of the pool, many meters from the source wells. Enrichment of CO_2 relative to other gases is probably caused by conversion of HCO_3 to CO_2 as water is pumped to the pool. The gas samples are poor in H_2 and H_2S, although the odor of H_2S is present and dissolved S (ranging from 1.5 to 15 mg/kg) occurs in reservoir fluids. High-temperature geothermal gases usually contain 1-6 mol-% H_2S and considerably more H_2. The PSA gas is similar to low temperature gases found in sedimentary basin aquifers and some oil/gas fields, and has a geothermometer temperature of ≤70°C.

RESERVOIR RECHARGE AND AGE

Selected stable isotope (δD, $\delta^{18}O$) and tritium (^3H) determinations on the waters appear in Table 4. All stable isotope data are plotted on Fig. 3. As expected, stable isotopes of cold springs collected in the San Juan Mountains have more depleted isotope values than cold waters emerging at lower elevations (Vuataz and Goff, 1986). Thermal waters from various locations in Archuleta County do not form any consistent pattern. They exist as separate aquifers as indicated by chemistry. The three waters comprising the Stinking Springs group are closely related but they display no oxygen-18 enrichment indicative of high-temperature isotopic exchange. Piedra Hot Spring water also shows no isotopic exchange. In contrast, the isotope values determined for the PSA form a large cloud with a definite oxygen-18 enrichment of at least 1‰, due possibly to higher-temperature conditions. The irregular outline of the cloud suggests that the waters are complicated mixtures of Cl-type fluids and other water types as shown by the chemistry. Importantly, the δD values of samples in the PSA are similar to the δD values of cold waters collected at higher elevations. Probably, recharge to the PSA (and most other county thermal waters) ultimately originates from the San Juan Mountains.

Tritium is useful in determining the relative ages of groundwaters because it has a short half-life of 12.4 yr and was produced in large amounts during atmospheric nuclear tests in the 1950's and 1960's. Meteoric precipitation in the southern Colorado-northern New Mexico region contained about 10-12 T.U. from 1991 to present (Shevenell and Goff, in press). To make quantitative estimates of mean residence times of water in underground reservoirs requires derivation of analytical solutions as a yearly function of ^3H content for two end-member types of reservoirs: piston-flow (minimum age) and well-mixed (maximum age). The theory, equations, and derivation of input functions can be found in Shevenell (1991).

As can be seen from Table 4, cold meteoric waters generally contain much more ^3H than thermal waters indicating the former have much shorter residence time underground. Except for the Wirt Frank well (which is cold but has similar chemistry to SO_4-type waters), most cold waters are best modeled as piston-flow aquifers and their calculated minimum age is most accurate. Note that the San Juan River contains more ^3H than present precipitation indicating considerable input from slightly older groundwater.

County thermal waters including the PSA are mostly ^3H dead indicating long residence times underground. Deep aquifers

Table 2: Representative Chemical Analyses (mg/kg) of Thermal Waters in Archuleta County, Colorado[1]

Sample No.	Name	Date	Temp (°C)	pH (lab)	SiO_2	Na	K	Li	Ca	Mg	Sr	F	Cl	Br	HCO_3	SO_4	B	As
County Thermal Waters																		
CH91-16	Shahan/Crowley Well	05/14/91	70.5	7.83	39	14.2	4.40	<0.01	151	15.5	1.03	0.30	6.37	0.02	110	354	<0.01	<0.1
CH91-21	Stinking Springs	05/14/91	26.7	7.73	24	19.7	11.4	0.02	213	27.0	2.23	0.51	6.67	0.02	165	493	<0.01	<0.1
CH91-22	Crowley/Barsonti Well	05/14/91	46.9	7.73	33	21.6	9.62	0.02	309	24.4	2.52	0.47	7.53	0.02	125	737	<0.01	<0.1
SB91-9	Loma Linda/Eoff Well	05/14/91	38.7	7.67	47	165	20.9	0.31	614	31.0	6.81	2.28	17.9	0.08	144	1757	0.19	<0.2
DM91-085	Piedra Hot Spring	06/26/91	53.7	8.06	98	571	40	2.85	76.0	5.97	1.86	6.79	116	0.60	328	934	0.86	<0.1
LC91-07W	Keyah Grande Well 1	07/17/91	44.8	7.98	21	153	9.98	0.30	64.7	11.8	3.02	1.83	2.23	<0.01	254	308	<0.01	<0.1
LC91-08W	Keyah Grande Well 2	07/17/91	27.5	7.94	16	81	6.21	0.13	98.4	21.0	4.15	1.01	1.21	<0.01	223	293	<0.01	<0.1
ED91-15W	Archuleta Ranch Well	08/30/91	63.0	9.58	7	575	10.6	0.21	1.4	0.32	0.14	1.45	235	1.45	1120	2	<0.01	<0.1
Pagosa Springs Aquifer																		
PS91-1A	Town Well #5	06/05/91	64.8	7.53	59	766	73	2.89	225	25.0	4.37	3.72	167	0.76	680	1480	2.10	<0.1
PS91-2A	Archuleta Co. #1	05/29/91	56.2	7.64	55	760	74	2.70	250	24.1	4.29	3.58	157	0.71	669	1520	2.10	<0.1
PS92-3A	Rumbaugh Well	06/05/91	58.0	7.56	58	802	79	2.78	228	25.6	4.10	3.85	157	0.71	629	1550	2.06	<0.1
PS92-4A	Montroy Well	05/29/91	48.7	7.61	55	825	75	2.77	239	25.4	4.08	3.66	152	0.68	751	1560	2.10	<0.1
PS91-5A	Big Spring	05/29/91	53.7	7.66	57	732	69	2.40	248	27.5	4.33	3.63	152	0.70	676	1545	2.06	0.2
PS91-6A	Spa Motel #1	05/31/91	50.3	7.65	52	786	77	2.74	216	22.8	3.98	3.69	139	0.67	635	1590	2.13	<0.1
PS91-7A	Spa Motel #3	05/31/91	45.1	7.59	48	767	72	2.57	245	24.3	4.23	3.55	136	0.65	697	1590	2.09	0.1
PS91-8A	Spa Motel #2	05/31/91	50.0	7.67	49	784	72	2.61	217	22.8	4.00	3.84	141	0.69	639	1575	2.08	0.1
PS91-10A	Dugan/Sanders Well	05/31/91	33.0	7.70	32	786	73	2.46	214	27.6	4.05	3.37	105	0.55	570	1690	2.09	<0.1
PS91-11A	Poma #2	06/03/91	44.8	7.83	48	620	61	2.12	181	22.8	3.46	3.64	107	0.49	638	1145	1.56	<0.1
PS91-12A	Poma #1 (drain)	05/23/91	>49.2	7.70	55	764	71	2.81	257	26.7	4.33	3.62	165	0.75	713	1535	2.03	0.1
PS91-13	Buhler Well (drain)	01/03/91	>53.6	7.26	56	783	76	2.78	247	27.0	4.37	5.00	168	0.68	792	1620	1.76	<0.1
PS91-14A	Los Banos Well (fct)	05/23/91	>56.6	7.70	57	794	74	2.87	249	26.4	4.26	3.54	164	0.75	775	1505	2.08	0.1
PS91-17A	Methodist Well	06/05/91	55.4	7.66	53	782	72	2.81	261	23.9	4.16	3.66	152	0.75	758	1495	2.10	0.1
PS91-18	Mees Spring Vent	09/30/91	41.0	6.97	54	750	70	2.65	232	26.6	4.35	4.07	161	0.75	740	1555	1.89	0.2
PS91-19W	Morgan Well	10/03/91	22.0	6.74	27	730	82	2.57	275	37.9	4.16	3.03	72.8	0.40	596	1700	1.31	<0.2

[1] Analyses by P.E. Trujillo and D. Counce, Los Alamos National Laboratory.

are probably best modeled as well-mixed reservoirs; thus their calculated maximum age is most accurate. The PSA consistently produces ^3H dead waters that may be >10,000 yr old. In contrast the Piedra Hot Spring, and Gail Adams well contain relatively high ^3H. The former is probably mixed with young river water (springs issue from edge of river) and the latter is probably mixed with drilling fluids (sample was collected after the well was completed).

CHEMICAL GEOTHERMOMETRY

Chemical geothermometer temperatures are listed in Table 5. The reader should consult Fournier (1981) for a generalized discussion of chemical geothermometers and their application. Most geothermometers are empirical, that is, a temperature-dependent equation is determined from the chemistry and temperature of fluids produced from high-temperature geothermal reservoirs; thus, chemical geothermometers work best and show best agreement for high temperature waters (>150°C). The last column of Table 5 shows the best estimate of reservoir temperature based on our experience with geothermal systems and knowledge of the region. Only the Cl-type fluids from Piedra Hot Spring and the PSA indicate subsurface equilibration temperature >100°C. Because the heat source for these aquifers is non-volcanic, a maximum depth of circulation can be calculated based on a regional conductive gradient of 45°C/km and an ambient temperature of 10°C. Depths to these two reservoir are ≤3 km.

OBSERVATIONS AT PAGOSA SPRINGS

The city of Pagosa Springs is presently involved in a lawsuit regarding water rights and the possible impact of Town Well #5 on the PSA (Sheftel, 1991). The city claims that TW#5 has minimal

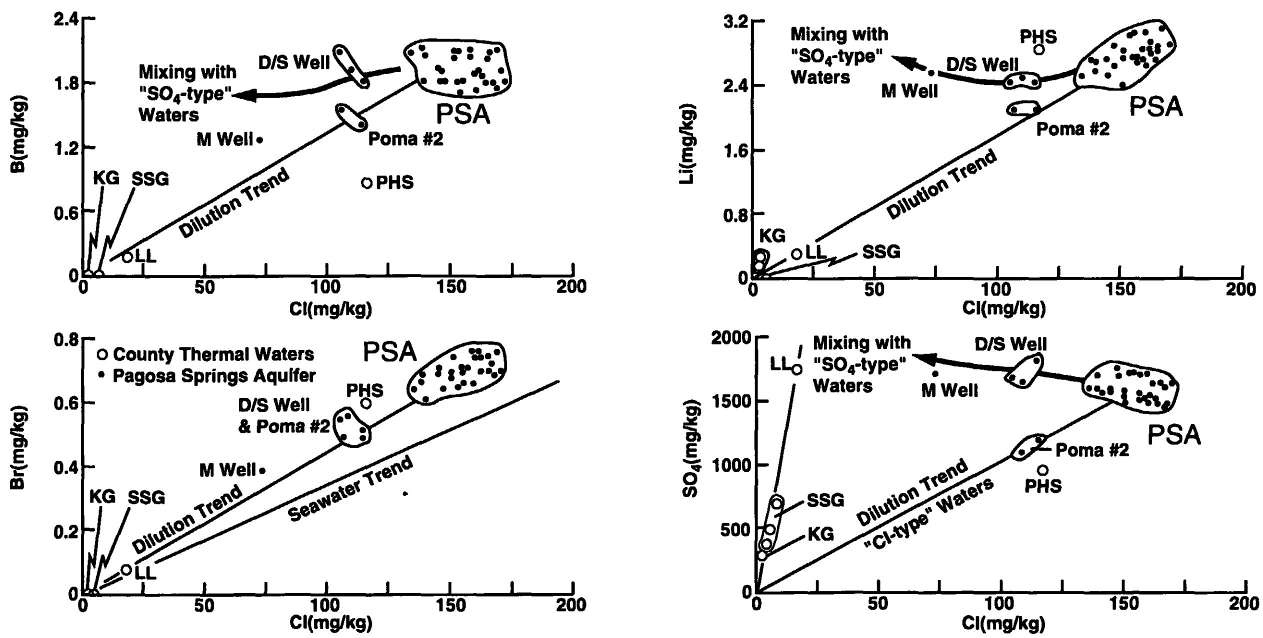

Figure 2. Plots of B, Br, Li, SO4 versus Cl for thermal waters in Archuleta County, Colorado; all thermal samples collected during this study are plotted.

Table 3: Gas Analyses (mol-%) of Pagosa Springs Aquifer, Colorado[1]

Sample No.	Name	Date	CO_2	H_2S	He	H_2	Ar	O_2	N_2	CH_4	C_2H_6	NH_3	Total	D-P[2] (°C)
PS91-5-1	Big Spring	01/03/91	48.5	0.0000	2.14	0.031	0.664	0.242	43.4	4.41	0.247	0.0031	99.6	67
PS91-5-2	Big Spring	01/03/91	49.5	0.0000	2.24	0.000	0.622	0.258	42.8	4.28	0.253	0.0038	99.9	67
PS91-5-3	Big Spring	01/03/91	49.4	0.0000	2.30	0.000	0.647	0.081	42.8	4.46	0.268	0.0034	100.0	67
PS91-9	Spa Motel Pool	01/03/91	66.3	0.0000	1.69	0.000	0.519	0.755	26.9	3.72	0.115	0.0024	99.9	63

1 Analyses by P.E. Trujillo, Los Alamos National Laboratory.

2 D'Amore and Panichi (1980); assumes H_2S = 0.003 mol-% (using gas equilibria and sulfide concentration of 1.5 ppm) and H_2 = 0.03 mol-% for all samples.

Table 4: Representative Isotopic Analyses of Thermal and Nonthermal Waters in Archuleta County, Colorado[1]

Sample No.	Name	Date	Temp (°C)	δD (‰)	$\delta^{18}O$ (‰)	^3H (T.U.)	Min. Age (yr)	Max. Age (yr)
Cold Waters								
HL91-025	Opal Lake Spg	06/04/91	4.9	-100.5	-14.00	28.0	20	20
DM9`-095	One Mile Spg	06/19/91	7.2	-99.4	-13.71	13.9	8	100
CR91-0205	Lower Cpgd. Spg	07/17/91	15.2	-99.5	-13.89	14.2	8	100
OH91-12W	Wirt Frank Well	08/07/91	14.8	-102.1	-13.68	1.99	35	850
OH91-041S	Gomez Spg	10/14/91	11.2	-103.0	-13.56	18.0	14	75
WC91-013S	Lost Lake Spg	07/05/91	5.6	-98.3	-14.14	21.5	18	50
SB91-016W	Valley View Well	10/15/91	11.1	-95.4	-12.61	12.7	5	125
PS91-15	San Juan River	01/04/91	0.4	-94.2	-12.23	17.1	12	75
County Thermal Waters								
CH91-16	Shahan/Crowley Well	05/14/91	70.5	-98.9	-13.84	0.00	>100	>10,000
CH91-21	Stinking Springs	05/14/91	26.7	-99.1	-13.83	0.01	>100	>10,000
SB91-9	Loma Linda/Eoff Well	05/14/91	38.7	-101.3	-13.88	0.02	100	>10,000
DM91-085	Piedra Hot Spg	06/26/91	53.7	-100.5	-13.65	3.51	35	500
CL91-07W	Keyah Grande Well	07/17/91	44.8	-103.8	-13.77	0.00	>100	>10,000
LC91-017W	Gail Adams Well	11/15/91	>38.9	-92.7	-11.99	8.33	35	150
Pagosa Springs Aquifer								
PS91-1	Town Well #5	01/03/91	64.6	-99.7	-13.15	0.00	>100	>10,000
PS91-1A	Town Well #5	06/05/91	64.8	-103.0	-11.58	0.01	>100	>10,000
PS91-1B	Town Well #5	09/27/91	64.3	-98.3	-13.77	0.02	100	>10,000
PS91-5	Big Spring	01/03/91	52.5	-100.6	-12.81	0.05	85	>10,000
PS91-5B	Big Spring	07/27/91	57.6	-101.0	-12.92	0.00	>100	>10,000
PS91-8	Spa Motel #2	01/03/91	50.3	-99.3	-13.15	0.00	>100	>10,000
PS91-10	Dugan/Sanders Well	01/03/91	33.5	-97.3	-13.38	0.00	>100	>10,000

1 Stable isotope analyses by M. Colucci, Southern Methodist University; tritium analyses by H. Gote Ostlund, University of Miami.

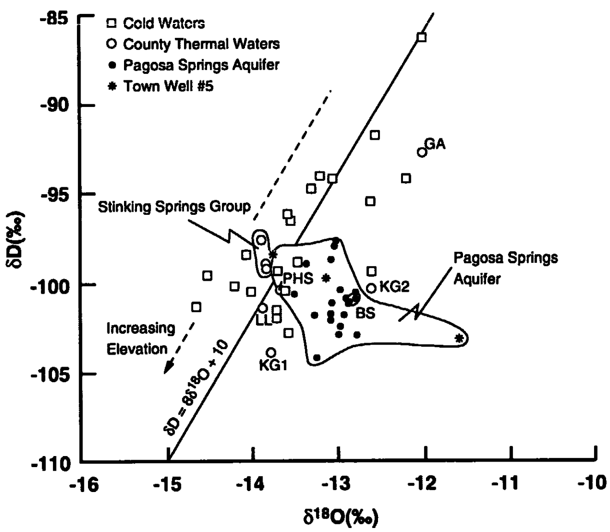

Figure 3. Plot of δD versus $\delta^{18}O$ for thermal and nonthermal waters in Archuleta County, Colorado.

impact whereas other users claim the impact is substantial during the months of September to May when TW#5 is pumped. The observations of Galloway mentioned above suggest that TW#5 taps a major feeder zone of the aquifer within the Dakota sandstone and that production of the well has a direct impact on other wells and Big Spring.

Historically, the Rumbaugh Well (Table 1), when pumped at high flow rates, caused the water level in Big Spring to drop drastically and pressures to decrease in other wells (B. Lynn, retired Water Commissioner, Colo. Div. Water Res. Dist. 7). The second author of this report witnessed a 45 cm (18 in) drop in the water level of Big Spring on June 5, 1991 after the Methodist well was pumped for only 30 minutes that same day. It is noteworthy that these wells, the TW#5 well, and Big Spring all lie on a strike of roughly N15W. This is the same strike direction as the mafic dike south of town and the projection of the dike trend points towards the general vicinity of Big Spring. Another dike of similar strike and composition occurs about 1 km west of town indicating that this direction is an important trend.

In the 1970's, Big Spring had a consistent flow rate of 850-1000 ℓ/min (225-265 gal/min) and a flowing temperature of about 58°C (Pearl, 1979), but the spring has not overflowed since TW#5 went on regular service. During 1991, several temperature measurements were made of TW#5, Big Spring, and area wells (Fig. 4). The results show that all features have a temperature rebound of 2-5°C during the summer months when TW#5 is turned off.

Table 5: Calculated Subsurface Temperatures (°C) for Thermal Waters in Archuleta County, Colorado Using a Standard Suite of Chemical Geothermometers[1]

		Measured	Silica		Na-K-Ca		Na/K	Na/Li	Mg/Li	K/Mg	Na-K-Ca (Mg)		Best
		Temp (°C)	QC	CH	1/3	4/3	WE	Cl<7000			R	Mg-Corr	Estimate
CH91-16	Shanan/Crowley Well	70.5	91	60	—	19	(353)	59	<0	38	25	19	≤75
CH91-21	Stinking Springs	26.7	70	38	—	39	(508)	77	8	77	4.3	39	≤75
CH91-22	Crowley/Barsonti Well	46.9	83	52	—	29	(435)	72	2	65	5.8	29	≤75
SB91-9	Loma Linda/Eoff Well	38.7	99	68	—	55	(214)	114	52	76	5.3	55	≤70
DM91-085	Piedra Hot Spring	53.7	136	109	171	(144)	(152)	189	140	110	9.3	137	110-140
LC91-07W	Keyah Grande Well 1	44.8	65	33	—	78	(146)	116	59	65	21.8	78	≤60
LC91-08W	Keyah Grande Well 2	27.5	55	23	—	49	(161)	104	32	49	25	49	≤60
	Pagosa Springs Aquifer (average of 28)	≤65	111[2]	81[2]	183	(143)	(182)	159	113	107	13.1	120	110-120

[1] Temperatures are calculated from the GTHERM code of Urbani (1986). Equations for many geothermometers are found in Fournier (1981), except where noted; QC = quartz conductive; CH = chalcedony; 1/3 and 4/3 refer to the beta factor of the Na-K-Ca geothermometer; Na/K (WE) = White-Ellis equation (Truesdell, 1976); Na/Li (Cl<7000) = equation for dilute water of Fouillac and Michard (1981); Mg/Li = equation of Kharaka and Mariner (1989); K/Mg = equation of Giggenbach (1986); R and Mg-Corr refer to the R factor and corrected value of the Na-K-Ca geothermometer of Fournier and Potter (1979). Values in parenthese violate rules of application.

[2] Silica value of 60 mg/kg was used.

A mass-balance method (Goff et al., 1987) was used to estimate the total discharge of thermal water into the San Juan River during early January, 1991 (Table 6). At this time of year, the river has a relatively low flow rate, but withdrawal from the PSA is at a maximum. Because all thermal water is dumped into the river through well drains or natural conduits, the river chemistry upstream and downstream of Pagosa Springs can be used to determine the discharge from the PSA. The calculated percent of thermal fluid entering the river was 2.2% and the total flow of the river downstream was 85.8 cfs (measured by Colo. Div. Water Resources); thus, the total discharge of thermal water was 1.9 cfs (3220 ℓ/min). This is the total discharge obtained by summing the amount of water produced by all wells tapping the PSA, indicating that there is no natural discharge into the river from the aquifer during winter months.

A model of the PSA geothermal system is shown in Fig. 5 which combines information obtained from various sources cited herein and our own work. The deep aquifer rises from Precambrian basement along a fracture zone that may or may not be intruded by a mafic dike. The probable strike direction of this structural zone is N15W but because the dike is only 1.5 wide where exposed it is unlikely that it could be drilled without an angled hole. Deep Cl-type fluids enter and form a pool of water within the Mesozoic sediments

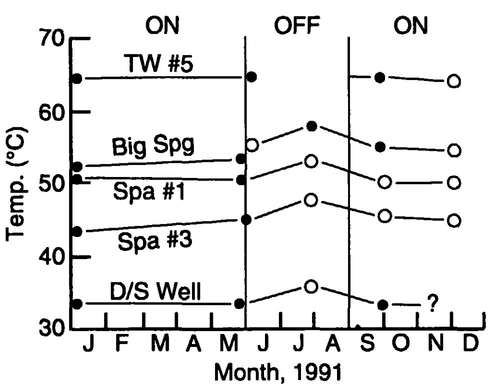

Figure 4. Plot of temperature versus date for several wells and Big Spring, Pagosa Springs aquifer, Colorado; data for Spa Well #2 overlies Spa Well #1; points indicate that a chemical analysis is available from samples taken during the time of measurement; circles indicate no sample.

above basement. Cooler SO_4-type waters and dilute near surface waters mix with deep fluids around the top and side margins of the aquifer. During peak exploitation, cooler fluids at the margins of the aquifer are drawn toward the various wells and Big Spring because the recharge rate of deep fluid is less than the exploitation rate.

CONCLUSIONS

Several conclusions can be made from this investigation. Many of them concur with the earlier report of Galloway (1980):

1. There is no young volcanic heat source for thermal waters in Archuleta County. The thermal waters are heated during circulation into sedimentary horizons of the Colorado Plateau and during deeper circulation into Precambrian basement.
2. No thermal aquifers (or associated gases) have the deposits and geochemical characteristics of high-temperature geothermal systems. Thermal waters in each area of the county are geochemically different indicating relative isolation from each other.
3. Most thermal aquifers are probably recharged from sources in the San Juan Mountains and most have mean residence times (underground) of >10,000 yr.
4. Maximum reservoir temperature is ≤120°C for the PSA at ≤3 km depth in Precambrian basement. Aquifers in overlying sedimentary rocks are cooler. These fluids are too cool for electrical power generation, but could be used effectively for greenhousing and aqua-culture as well as heating and bathing.
5. Thermal fluid from the PSA is presently exploited at a rate greater than natural recharge during September to May each year.

Table 6: Calculated Percentage of Geothermal Fluid in San Juan River Downstream of Pagosa Hot Springs and Wells (Jan. 3-11, 1991)

Component	Upstream (PS91-15)	Downstream (PS91-16)	Difference	"End-Member"[1] Fluid	Percent Thermal Fluid
B	<0.02	0.04	0.04	1.80	2.2
Cl	1.83	4.95	3.12	162	1.9
Cs	0.005	0.009	0.004	0.25	1.6
F	0.11	0.25	0.14	5.04	2.8
K	1.1	3.1	2.0	78	2.6
Li	<0.01	0.05	0.05	2.95	1.7
Na	11.6	29.4	17.8	800	2.2
SO_4	21.3	65.1	43.8	1690	2.6
					Average of Components = 2.2±0.4

[1] Based on average of eight most concentrated springs and wells sampled on Jan. 3, 1991.

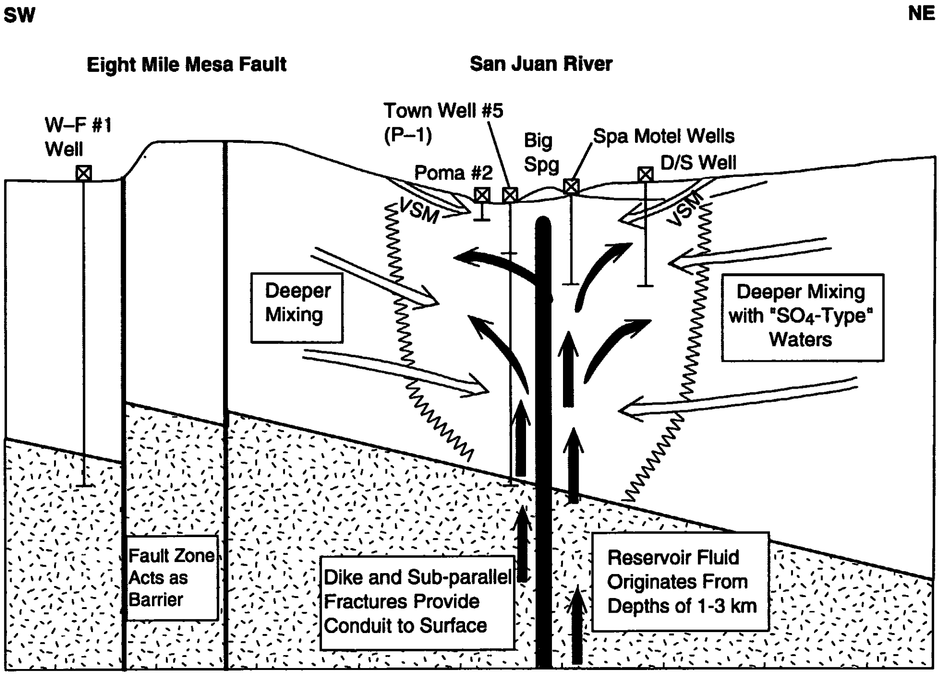

Figure 5. Proposed hydrologic model of Pagosa Springs aquifer, Colorado; pattern indicates Precambrian basement; blank indicates mostly Mesozoic sedimentary rocks of Colorado Plateau; well locations are partly arbitrary and the presence of the mafic dike remains to be proven; VSM = very shallow mixing.

Quantitative measurements of temperature at several wells and Big Spring during 1991 clearly show a direct impact by Town Well #5 on the rest of the aquifer. Every well and spring tapping this aquifer should be monitored for temperature, pressure, draw-down, and flow rate, on a daily to weekly basis where possible. Waste water from the PSA should be used more efficiently.
6. All thermal waters in Archuleta County display poor structural definition. As a result, it is difficult to determine appropriate drilling sites to best explore these resources and reveal their deeper plumbing.

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