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## GEOCHEMISTRY OF THE WENDEL-AMEDEE GEOTHERMAL SYSTEM, CALIFORNIA

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ABSTRACT

The fluid chemistry of the geothermal system that feeds Amedee and Wendel Hot Springs in eastern California is complex. Two thermal fluids have been identified based on the concentrations of the conservative elements Cl and B, fluid enthalpies, and the application of chemical geothermometers. One is characterized by temperatures above 120°C and a TDS content of 1300 ppm, and will be used by GeoProducts Corporation to produce electricity. The second is lower in temperature, 75°C, and has a TDS content of 650 ppm. This fluid may be used for direct heat application at the Susanville Correctional Institute. Both Amedee and Wendel Hot Springs discharge waters which are mixtures of these two types. Warm waters discharged from some of the shallow wells in this area have temperatures of 20°-30°C and appear to be conductively heated groundwater. Cold groundwaters range in TDS contents from 200 to 2000 ppm. This variation in salinity may be due to fluid contact with saline lake deposits.

INTRODUCTION

Amedee Hot Springs is perhaps the best known of the hot springs that actively deposit mercury sulfides (White, 1981). A geothermal test well drilled at Amedee Hot Springs in the early 1960's (White, 1967, p. 598) showed that the hot spring waters are composed of 107°C fluid which mixed with a cooler fluid at 122 m, resulting in a 104°C fluid.

Amedee and the nearby Wendel Hot Springs discharge boiling fluids of 96°C from Lake Lahontan sediments. The total flow from all Amedee Hot Springs vents has been estimated as 67.6 l/s (White, 1981). During the last several years the geothermal system which feeds Amedee and Wendel Hot Springs has been the subject of renewed exploration because of its potential for producing geothermally generated electricity. To date this program has resulted in the drilling of one deep production well and numerous supporting geologic and geophysical studies (Zeisloft et al., 1984). Chemical analysis of fluids discharged from wells and springs in the area indicate that the geothermal system is part of a complex hydrologic regime which includes waters of varying chemistries. The

purpose of this paper is to present geochemical data on these fluids and a model of the geothermal system. This model has been developed through a comparison of the conservative elements within the fluids, fluid enthalpies, and the application of chemical geothermometers.

## GEOLOGIC SETTING

The Wendel-Amedee geothermal system is located in Honey Lake basin near the junction of three major physiographic provinces: the Basin and Range, the Sierra Nevada and the Modoc Plateau (Fig. 1). Honey Lake basin is a closed basin that contains approximately 600 m of volcanic flows and tuffaceous sediment, intercalated with sediment from Lake Lahontan (Zeisloft et al., 1984). The basin is underlain by fractured Mesozoic intrusive rocks.

Several hot spring vents are active within Honey Lake basin. These vents exist as two closely clustered groups and have been designated as Wendel and Amedee Hot Springs. Although both hot spring groups are associated with travertine mounds deposited during Lake Lahontan time (Zeisloft et al., 1984), neither appear to be presently depositing calcite. Amedee Hot Springs, however, are actively depositing mercury sulfides on Lake Lahontan sediments (White, 1981).

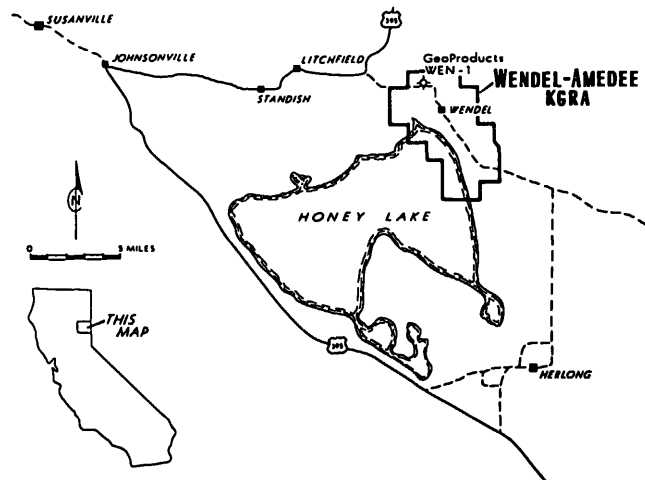


Figure 1. Location Map.

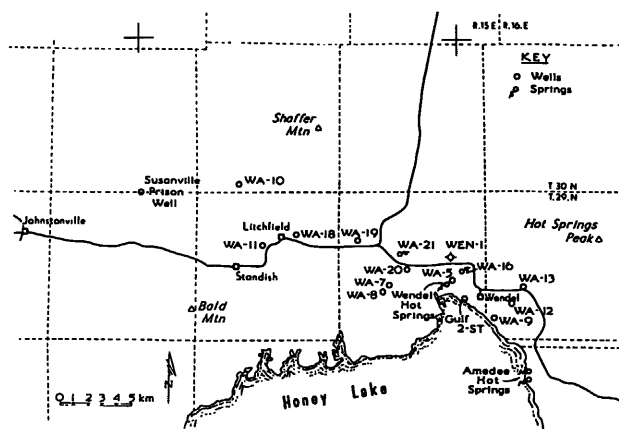


Figure 2. Sample Location Map

## METHODS OF INVESTIGATION

Water samples, collected during the winter of 1982, were taken from the hot and cold springs, irrigation and domestic wells, and geothermal wells shown in Figure 2. The samples were filtered through a  $.45\mu$  membrane filter with a peristaltic pump and stored in polyethylene bottles. The containers were precleaned with 20% nitric acid and deionized water and rinsed with filtered sample water. An untreated sample and two acidified splits (one with 1% HCL and one with 20%  $\text{HNO}_3$ ) were collected at each sample site.

The pH and bicarbonate concentration were determined at the time of collection on pressure filtered samples using a selective ion meter with a Ag/AgCl combination pH electrode and by sulfuric acid titration (Presser and Barnes, 1974), respectively. Potassium, fluoride, chloride, sulfate and total dissolved solids were determined on filtered samples by atomic absorption spectrophotometry, specific ion electrode, silver nitrate titration and gravimetry, respectively. The remaining major and minor elements listed in Table 2 were determined by inductively coupled plasma spectrometry using methods described by Christensen et al. (1980). All samples were analyzed within one month of collection.

## RESULTS

Chemical compositions and calculated geothermometer temperatures of the samples collected are listed in Table 1. Five of the samples were taken from hot springs, two from cold springs, two from irrigation wells, two from deep (> 300 m) thermal wells, and twelve from cold and warm domestic wells. A water sample of the geothermal production well, WEN-1, was collected by GeoProducts, Inc., during the spring of 1982 and analyzed by the Earth Science Laboratory.

A trilinear plot (Fig. 3) of major ion ratios was used to characterize the water samples by the method of Piper as discussed in Hem (1970). In addition Cl/B ratios have been plotted against  $\text{Na}/\text{SO}_4$  (Fig. 4) and  $\text{Na}/\text{Cl}$  (Fig. 5).

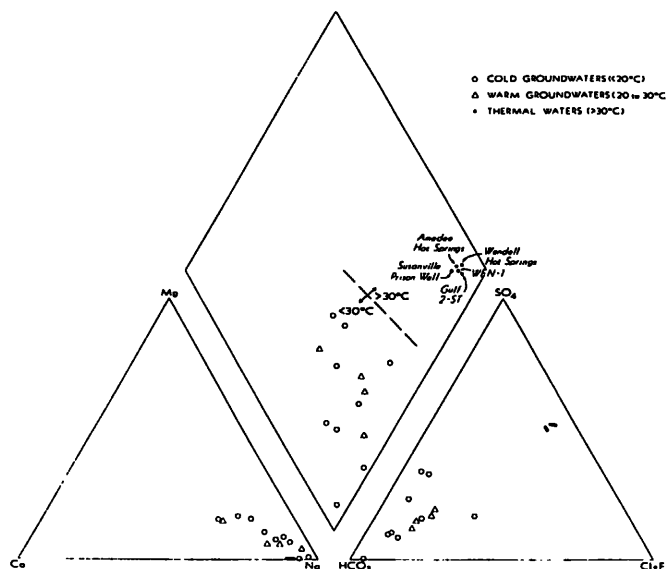


Figure 3. Piper Plot of thermal and nonthermal waters sampled in this study.

## DISCUSSION

## Characterization of water types

All waters collected with measured temperatures above  $30^\circ\text{C}$  group closely on the trilinear plot and are sodium sulfate in character, while those below  $30^\circ\text{C}$  are scattered and are sodium bicarbonate in character (Fig. 3). The total dissolved solids contents (TDS) of the waters with measured temperatures between  $20^\circ$  and  $30^\circ\text{C}$  are almost identical (200-260 ppm) (Table 1). The TDS values for waters with measured temperatures below  $20^\circ\text{C}$  range from 180 to 1940 ppm, suggesting heterogeneous source rocks for the cold groundwaters.

Stefansson and Arnorsson (1975) used B/Cl ratios in fluids to define the areal extent of geothermal reservoirs. Ratios of B and Cl for the Honey Lake basin fluids do not separate thermal from nonthermal fluids. However, when  $\text{Na}/\text{SO}_4$  and  $\text{Na}/\text{Cl}$  ratios are used as an indicator of water character, and are plotted against B/Cl ratios, thermal, warm and nonthermal fluids separate well (Figs. 4 and 5).

Relationships between the Cl,  $\text{SO}_4$ , Na, and B concentrations in the waters sampled are shown in Figure 4 and Table 1. Inspection of the  $\text{SO}_4/\text{Cl}$  ratios (Table 1) show that these waters do not display trends found in most geothermal systems. Ratios of  $\text{SO}_4/\text{Cl}$  in geothermal fluids decrease as temperature increases because of the retrograde solubility of calcium sulfate minerals and the increased scavenging of Cl by the fluids at elevated temperatures. Steam heated hot or warm waters display an increased  $\text{SO}_4/\text{Cl}$  ratio as a result of increasing  $\text{SO}_4$  from  $\text{H}_2\text{S}$  oxidation (Mahon et al., 1980). However, steam heated waters will also show an increase in  $\text{HCO}_3$  that is not present in the thermal waters sampled in the Honey Lake basin.

TABLE 1. CHEMICAL ANALYSES AND GEOTHERMOMETER TEMPERATURES

Sample	THERMAL WATERS (>30°C)					WARM WATERS (20°C to 30°C)					COLD WATERS (<20°C)								
	Amedee HS	Wendel HS <sup>1</sup>	Prison Well	Gulf 2-ST	WEN-1 <sup>2</sup>	WA-9	WA-12	WA-16	WA-21	shallow	WA-5	WA-7	WA-8	WA-10	WA-11	WA-13	WA-18	WA-19	WA-20
Well Depth (m) or Spring(s)	S	S	~600	1532	1758	30	91	S	shallow	25	155	155	30	91	30	shallow	shallow	shallow	
Measured Temp(°C)	96	96	75	35	96	22	27	27	22	17	14	13	14	15	14	14	14	14	
pH	8.8	8.3	8.7	8.7	8.3	7.8	7.3	7.9	7.3	7.9	8.8	8.8	7.6	7.6	7.3	7.3	7.4	7.9	
TDS <sup>3</sup>	838	1021	660	1010	1320	206	216	204	258	180	818	636	492	400	264	378	378	1940	
Na <sup>3</sup>	224	280	159	271	349	48	44	37	58	39	288	241	101	98	55	68	80	588	
K	6	8	3	5	20	10	9	6	3	8	4	2.3	13	5	7	8	10	18	
Ca	20	20	16	16	38	6	8	14	3	8	2	6	28	14	5	28	10	39	
Mg	0.02	<.1	0.11	0.13	<.5	2	3	5	1	5	2	2	14	7	3	10	4	22	
SiO <sub>2</sub>	108	125	83	93	130	43	44	33	49	36	45	36	58	66	59	55	48	55	
Li	0.09	0.11	0.05	<.05	0.26	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	
B	4.5	5.6	3.5	6.6	7.7	0.3	0.3	0.2	.2	0.1	1.2	0.7	0.5	0.7	<.125	0.1	0.3	2.1	
SO <sub>4</sub>	282	340	247	346	410	26	28	20	19	23	58	2	121	29	41	13	20	260	
Cl	153	185	96	205	284	20	19	14	16	15	49	13	23	15	8	15	11	367	
F	4.7	4.2	3.9	3.8	6.5	0.2	0.2	0.2	0.3	0.2	1.0	1.0	0.3	0.3	0.2	0.4	0.3	0.8	
SO <sub>4</sub> /Cl	1.84	1.64	2.57	1.69	1.44	1.3	1.47	1.43	1.19	1.53	1.18	.15	5.26	1.93	5.13	.87	1.82	.71	
Alkalinity (HCO <sub>3</sub> )	54	53	66	78	73	122	120	120	150	122	668	701	266	302	149	297	197	1015	
Na-K-Ca (-Mg) <sup>4</sup>	123	128	69	112	158	83	63	63	69	32	30	62	32	45	39	60	54	29	
Chalcedony <sup>5</sup>	115	125	99	106	127	64	66	52	71	56	67	56	79	86	80	77	70	77	
Quartz <sup>5</sup>	136	143	124	129	152	95	96	83	101	87	97	87	109	115	110	106	100	106	

<sup>1</sup> Analysis U-2, taken from Mariner et al. (1976).

<sup>2</sup> Sample taken after water flashed at atmospheric pressure, bottom hole temperature was 124°C.

<sup>3</sup> TDS and element concentrations are in ppm.

<sup>4</sup> Method of Fournier and Truesdell (1973) and Fournier and Potter (1979); Temperatures are in °C.

<sup>5</sup> Method of Fournier (1973); Temperatures are in °C.

The silica and cation geothermometers were calculated for the waters sampled and are listed in Table 1. According to Fournier (1973) the quartz geothermometer works best for well waters where subsurface temperatures are above about 150°C and the wallrock has an excess of normative quartz. Fournier further states that in some aquifers below 100°C, and perhaps up to 150°C, chalcedony rather than quartz apparently controls the dissolved silica content. Subsurface temperatures higher than 125°C have not been recorded in the vicinity of Wendel and Amedee Hot Springs. Furthermore, mafic volcanics are predominant in this area down to about 1200 m. This would suggest that the silica geothermometer polymorph most applicable to thermal waters flowing through mafic rocks in the Wendel-Amedee area is chalcedony. The thermal water from WEN-1, however, flows from silicic intrusive rock at a depth of about 1660 m and may be in equilibrium with quartz.

The chalcedony and quartz geothermometer temperatures for the thermal waters are plotted vs. B in Figure 6. The general trend of increasing temperature from the Susanville Prison well to Amedee H.S., Wendel H.S., and WEN-1 is similar to the trend shown on the Cl vs. B plot for these thermal waters (Fig. 7). The best fit for the regression line shown in Figure 6 was obtained using chalcedony geothermometer temperatures for the Prison well and the hot springs, and the quartz geothermometer temperature for WEN-1. Gulf 2-ST falls off the trend, and its predicted temperatures are substantially higher than the measured temperature of 35°C. These disparities may be due to reequilibration of fluid in a low permeability formation.

Cation geothermometer temperatures show a greater scatter (Fig. 6) than silica for the thermal waters. Both the quartz and cation geothermometers indicate an original temperature of 150° to 160°C for WEN-1 fluid.

Geothermometer temperatures for cold and warm water from Honey Lake basin should be viewed with caution. Fournier (1979) states that cation geothermometer results are dubious when applied to magnesium-rich waters. In addition the magnesium correction factor (Fournier and Potter, 1979) is not calibrated for waters with an RMg (= magnesium to total major cation ratio, exclusive of Na) over 35. The RMg values for the warm and cold waters in Honey Lake basin range from 23 to 45.

#### Cl/B AS AN EXPLORATION TOOL

The atomic ratio of Cl/B has been used in several areas to characterize geothermal aquifers. Stefansson and Arnorsson (1975) utilized the Cl/B atomic ratio to define the areal extent of geothermal systems in the Southern Lowlands of Iceland. In New Zealand, Mahon (1970) combined Cl/B atomic ratios in reservoir rocks with Cl/B data from experiments on rock/water interactions to predict vertical and areal changes in the geothermal composition of the reservoir rocks. These predictions were subsequently verified by drilling. Upwelling geothermal fluid at the Roosevelt Hot Springs KGRA was mapped by Ross et al. (1982) by plotting and contouring boron and chloride contents of groundwaters.

All of these studies have assumed negligible contributions of boron from cold groundwaters which mix with the thermal fluids. For most areas

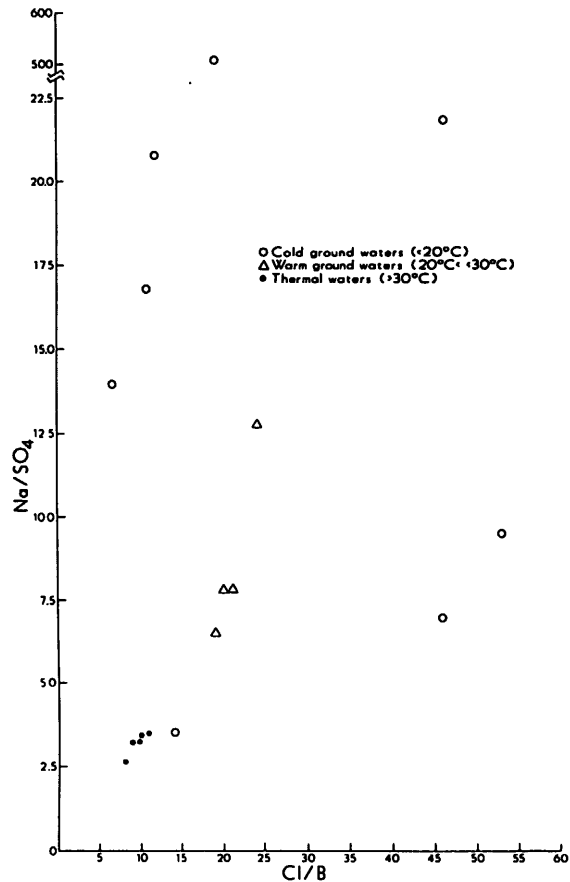


Figure 4. Water character ( $\text{Na}/\text{SO}_4$ ) vs. conservative elements ( $\text{Cl}/\text{B}$ ) of sampled waters.

this is a valid assumption. For example, median boron concentrations for streams in the U.S.S.R (Turekian, 1969) and the U.S.A. (Livingstone, 1963) have been estimated as 0.01 and 0.0116 ppm, respectively. This is much less than the range found in hydrothermal waters (Gmelin, 1954), 0.5 to 1000 ppm. Saline lakes also range from 0.5 to 1000 ppm in boron concentration (Gmelin, 1954). However, in an arid closed basin such as Honey Lake, there is a strong likelihood that the sediments will contain highly soluble borate minerals. Borax deposits are found exclusively within these environments (Kistler and Smith, 1975). Thus a very low concentration of B in the cold groundwaters in Honey Lake basin cannot be assumed. Under these conditions ratios of B to Cl should plot as a straight line if the cold and warm fluids are related by mixing.

B and Cl have been plotted for the Honey Lake basin fluids in Figure 7. Regression lines based on B and Cl concentrations were calculated for cold, warm and thermal waters. Inspection of this plot shows a distinct linear trend among the thermal waters, indicating that the thermal fluids are related by mixing and/or boiling. However, there is no evidence of subsurface boiling at Honey Lake

basin and therefore it is not considered in the following discussion.

The regression line calculated for the cold groundwaters does not pass near any thermal water points, suggesting that significant mixing between these cold waters and the thermal waters has not occurred. The regression line based on the warm waters does not intersect any thermal water points, and the warm and thermal regression lines are almost parallel. The near parallelism of the two trends suggests that: 1) no simple mixing relationship exists between the thermal and warm waters, 2) similar processes control the B/Cl ratios in warm and thermal waters, and 3) the concentrations of B and Cl are roughly temperature dependent.

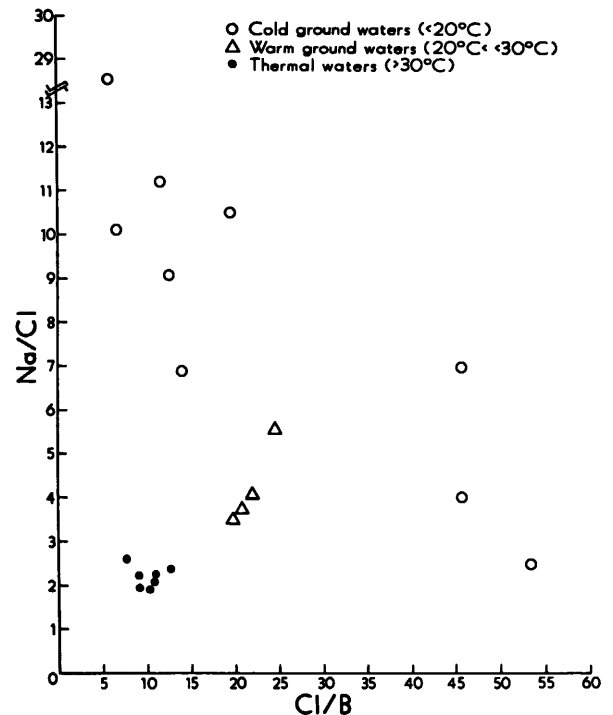


Figure 5. Water character ( $\text{Na}/\text{Cl}$ ) vs. conservative elements ( $\text{Cl}/\text{B}$ ) of sampled waters.

The Cl/B ratios can be used to calculate the proportions of the various end member fluids which may have combined to produce the thermal springs and wells. Mixing proportions were calculated for three cases (Table 2). Case 1 involves mixing the WEN-1 production fluid at its measured temperature with a hypothetical 14°C groundwater. The Cl and B concentrations for the hypothetical groundwater were determined by the intersection of the thermal water regression line and the average groundwater chloride concentration (Fig. 7). Case 2 involves mixing WEN-1 production water with the Susanville Prison well water at their measured temperatures. Case 3 uses WEN-1 fluid at its average chemical geothermometer temperature and Susanville Prison well fluid at its measured temperature as

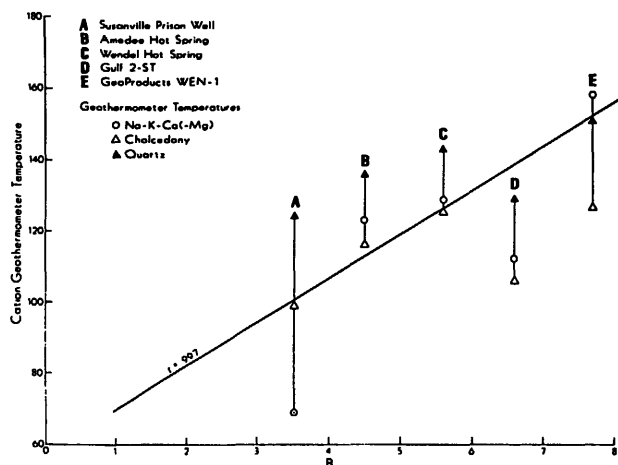


Figure 6. Geothermometer temperatures vs. boron concentrations for thermal waters. Regression line based on chalcedony geothermometer temperatures of samples A, B, and C, and on quartz geothermometer temperature for D.

end-members. These three hypotheses can be further tested by using measured enthalpies to calculate the temperatures of the fluids that would be produced by mixing the various end-members. Results of these calculations as well as measured temperatures are listed in Table 2.

It can be seen from the calculations that Case 1 mixing proportions do not give a good fit for temperatures indicating that the linear B vs. Cl trend exhibited by the thermal waters is not due to simple mixing of thermal fluids with groundwaters. Similar results were obtained when actual groundwater enthalpies and compositions were used. For Case 2 the calculated temperatures are more reasonable but still below measured temperatures in some areas. Case 3 provides the closest fit. However, the 107°C measured subsurface temperature of the fluid which discharges from Amedee Hot Springs can be matched by raising the temperature of the Susanville Prison water by 10°C (Case 3b). Case 3 predicts that fluids which discharge from Wendel Hot Springs have a higher subsurface temperature than those discharging from Amedee Hot Springs. This relationship is consistent with the temperatures predicted by chemical geothermometers for the hot spring fluids (Fig. 6).

TABLE 2. FLUID MIXING CASES

	CASE 1		CASE 2		Measured Temp (°C)	CASE 3	
	% Dilute Component	Predicted Mixing Temp (°C)	% Dilute Component	Predicted Mixing Temp (°C)		% Dilute Component	Predicted Mixing Temp (°C)
MEH-1	0	124	0	124	124	3a 155	3b 155
GULF 2-ST	24	98	30	109	35	30	131
Wendel H.S.	35	86	50	100	96+	50	115
Amedee H.S.	49	70	70	90	96+	70	99
Prison	68	49	100	75	75	100	75
Groundwater	100	14			-		

The largest discrepancy between measured and predicted temperatures is for the Gulf 2-ST well. The permeability in this well has been shown to be very low (McNitt and Wilde, 1980).

Thus, conductive cooling would be a reasonable interpretation for this water.

CONCLUSIONS

Interpretation of a hydrogeochemical survey of the northeastern portion of Honey Lake basin indicates that fluids from thermal wells and hot springs are composed of mixtures of two or more chemically and thermally distinct fluids. Mixing proportions were estimated from B and Cl, conservative elements which display an excellent linear trend among the thermal waters sampled. The high temperature end-member appears to be similar to the fluid from GeoProducts production well WEN-1. Silica and cation geothermometers indicate a temperature of 150°-160°C for

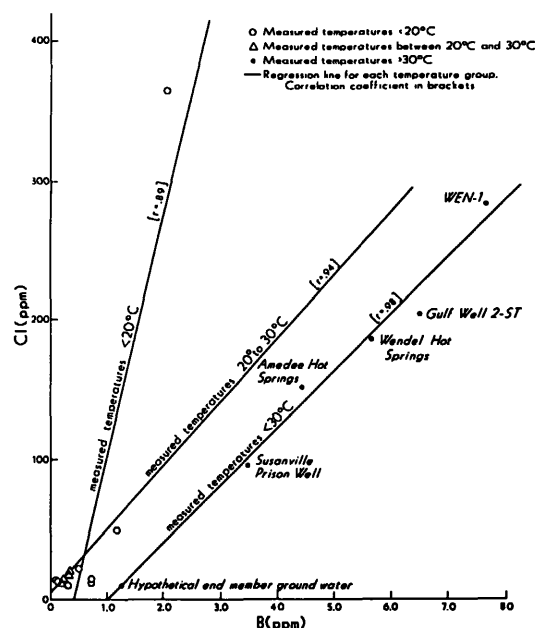


Figure 7. Cl/B relationships of waters sampled in eastern Honey Lake basin.

this fluid, although the present down-hole temperature for this well is 124°C. The low temperature end-member has a temperature close to 85°C and is similar in temperature and fluid chemistry to the Susanville Prison well. This may indicate the presence in eastern Honey Lake basin of a low salinity medium-temperature fluid source distinct from the reservoir being tapped by WEN-1. Shallow medium-temperature stratabound aquifers are known to exist (Benson et al., 1980) below Susanville on the western edge of Honey Lake basin.

Mixing relationships indicate that fluid produced from the Gulf 2-ST well has cooled from approximately 130°C to its measured temperature of 35°C by conductive cooling in a low permeability formation.

Warm (20° to 30°C) waters in eastern Honey Lake basin appear to be conductively heated groundwaters. Quantification of cold and thermal water mixing in Honey Lake basin based on B and Cl is complicated by the probable presence of boron minerals in Lake Lahontan sediments.

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