HYDROGEOCHEMICAL CHARACTERIZATION OF THE ALVORD BASIN GEOTHERMAL AREA, HARNEY COUNTY, OREGON, USA

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SUMMARY - The geothermal system within the Alvord basin, Harney County, Oregon discharges bicarbonate-rich water at three hot-spring areas. System recharge by meteoric water occurs in the Steens Mountain-Pueblo Mountain fault block. Water circulates to at least 2.5 km before rising along range-front and intrabasinal faults. Minimum reservoir temperature is estimated near 200' C and residence time in the system may be over 10,000 years. Flow pathways, discharge volume, and boiling account for compositional differences in spring discharges.

1. INTRODUCTION

Three hot-spring areas discharge from a geothermal system within the Alvord basin in southeastern Oregon: Borax Lake and associated springs, Alvord Hot Springs and Mickey Springs (Figure 1).

In 1989, Anadarko Petroleum Corporation drilled a geothermal exploration well to a depth of 451 m approximately 2.2 km southwest of Borax Lake. The well was flow-tested for 22 hours yielding a flow rate of 400 gpm with a measured temperature of 152°C. Listing of the Borax Lake Chub, *Gila boraxobious*, as an endangered species on May 28, 1980 under the Endangered Species Act of 1973 designates critical habitat at Borax Lake. The proximity of Borax Lake to the exploration well drilled by Anadarko Petroleum Corporation and the critical habitat the lake provides for the Borax Lake Chub has focused the greatest attention on this area. The issue of the effects of future geothermal operations on the chub habitat was one of the motivating factors for this study.

In this paper, pertinent information from previous studies and geologic, isotopic and geochemical data from fluids, gases and rocks obtained during this study are used to estimate the temperature, lithology and location of geothermal reservoirs, and to define recharge areas, residence times and circulation pathways.

2. REGIONAL GEOLOGY

The Alvord basin is in the northern Basin and Range province of the southwestern United States. The basin is a complex N-NE striking graben 112 km long and up to 13 km wide. The basin lies between the Steens Mountain and Pueblo Mountains to the west and topographically lower ranges to the southeast and east.

Suggested displacements on the Steens Mountain-Pueblo Mountains range-front faults vary from 2,500 m to 3000 m. This displacement suggests a long-term slip rate of 0.33 mm/yr for the last 9.3 Ma. Analysis of fault scarps along the Alvord segment of the Steens Mountain fault zone indicates the most recent movement occurred during the late Holocene (Hemphill-Haley et al.,1989).

Voluminous Tertiary volcanic and minor volcaniclastic rocks are exposed in the Steens Mountain range front. Mesozoic and Paleozoic metamorphic and granitic intrusive rocks, including Permian or Triassic metasedimentary and metavolcanic rocks, occur in the Pueblo Mountains, but are not exposed north of the Oregon-Nevada lineament that separates the Pueblo Mountains from the Steens Mountain.

The stratigraphically lowest units exposed on Steens Mountain are the Alvord Creek, Pike Creek, and Steens Mountain Volcanics; volcaniclastic sediments, rhyolitic ash-flow tuff, and olivine/augite basalt and andesite, respectively. These early to middle Miocene volcanic rocks are overlain by the middle Miocene Steens Basalt. The Steens Basalt exceeds 1,000 m and is composed of tholeiite to high alumina basalt (Hart and Carlson, 1985). Welded ash-flow tuffs erupted from the McDermitt volcanic field overlie the Steens Basalt (Walker and Repenning,1965; Rytuba and McKee,1984).

The Alvord basin is filled with

volcaniclastic sediments of late Miocene to Holocene age. Geophysical studies indicate the sediments are up to 0.5 km thick (Griscom and Conradi, 1975; Cleary, 1976). The basin was occupied by Pleistocene Lake Alvord which dried approximately 10,000 yr.b.p. (Hemphill-Haley, 1989). Glacial flour, diatomite, and coarse-grained shoreline facies are exposed within the basin.

The northern Basin and Range province is characterized by abnormally high heat flow and anomalous thinning of the Earth's crust (Sass et al., 1981). Estimates of regional heat flow in the vicinity of the Alvord basin range from 60-100 mWm^{-2} (Blackwell et al., 1978). Heat flow measured in drill holes in the Alvord basin ranges from 52-268 mWm^{-2} (Brown and Peterson, 1980).

The dominant hydrologic regime in the Basin and Range province is range-to-valley flow (Mifflan, 1988). The shallow ground water system is recharged by stream flow supplied by mountain precipitation that infiltrates alluvial fans. The deep ground water and thermal water systems are fed by fault-controlled deep circulation of meteoric water.

3. HOT SPRINGS OF THE ALVORD BASIN

The hot-springs areas discharge from faults along which late Pleistocene to late Holocene displacement has been documented (Hemphill-Haley, 1989; Hook, 1981; Cummings and St. John, 1993). opaline silica sinter terraces occur at each spring, but sinter is not actively depositing. Sinter deposition occurred at each spring at different times relative to the Holocene geomorphic evolution of the Alvord basin.

Borax Lake and associated springs discharge from an intra-basinal fault within Pueblo Valley. Borax Lake is a 0.04 km^2, shallow lake (less than 1 m) whose bottom and shore are lined by silica sinter. Hot water enters the lake from seeps located at the base of a funnel-shaped vent that is greater than 30 m deep. The lake surface is 8 m above the surrounding valley floor and occurs at the crest of a shield-shaped mound. This mound is an erosional feature protected by the silica sinter deposits that rim the lake. The silica sinter directly overlies diatomite that was deposited in Pleistocene Lake Alvord. North of Borax Lake are hot springs that discharge along a N10°E fault over a distance of 0.9

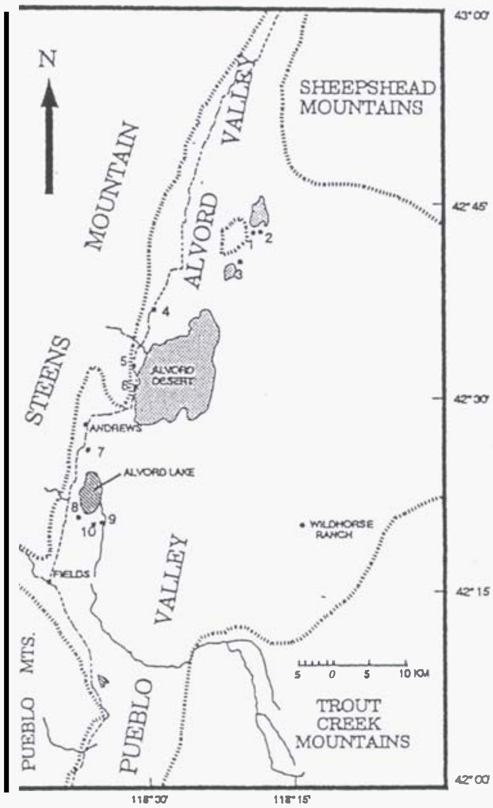

Figure 1-Location map for the Alvord basin, southeastern Oregon. 1-2. cold springs; 3. Mickey Springs; 4. Alvord Ranch; 5. Alvord Hot Springs; 6. Thomas place; 7. Kueny Ranch; 8. Kurtz well; 9. artesian well; 10. Borax Lake and springs to the north. Depressions are shown by a dot pattern.

km. An artesian well is located 0.8 km northeast of Borax Lake.

Mickey Springs and Alvord Hot Springs discharge from the range-front faults of Mickey Butte and Steens Mountain, respectively. Mud pots, an intermittently active geyser, steam vents, boiling and warm pools and silica sinter fossil vents and mounds occur at Mickey Springs. At Alvord Hot Springs small springs occur along a NE-striking fault.

At each hot-spring area, temperature and pH were measured and fluid samples were collected from the springs with the highest temperature and flow rate. Discharge temperatures at Mickey Springs and springs north of Borax Lake are 94 to 95° C and over 100° C in the bottom of Borax Lake (30 m). At Alvord Hot Springs, discharge temperatures are between 72 and 79° C (Table 1).

4. HYDROGEOCHEMISTRY

The fluids are dilute Na-HCO, with significant amounts of SO_4^{2-} and Cl^- (Table 1). The highest concentra

Table 1 – Chemistry of selected thermal and non-thermal waters from the Alvord basin.

	pH	T°C	Na	K	Ca	Mg	Cl	B	Li	F	SO_4	HCO_3	SiO_2
A	7.0	*	385	22	13	0.2	245	13	0.42	5.5	284	450	207
B	7.0	95	359	22	14	0.3	236	13	0.45	5.8	280	476	185
C	6.9	77	904	58	10	2.0	789	27	1.90	7.6	189	1205	144
D	8.4	94	487	27	1	0.1	216	9	0.79	12	193	780	233

A. Borax Lake at a depth of 30+ m. Temperature fluctuates widely near vents with maximum temperature at 110C. B. Highest temperature spring located north of Borax Lakm. C. Selected spring at Alvord Hot Springs. D. Highest temperature spring at Mickey Springs.
A: Borax Lakm, B: Springs north of Borax Lakm, C: Alvord Hot Springs, and D: Mickey Springs

tion of total dissolved solids (TDS) occur at Alvord Hot Springs. Constant ratios and relatively constant concentrations of Li, Cl, B, and F are noted among springs within each area. The B/Cl ratio ranged from 0.03 to 0.07 (n=31). Sorey et al (1991) note that ratios near 0.05 are indicative of interaction with metasedimentary rocks, while Goff et al (1987) note that ratios between 0.01 and 0.1 commonly indicate interaction with volcanic rocks. The variation in Cl^- concentrations between quarterly sampling during 1.5 years was less than 8% (an exception occurred at springs' north of Borax Lake between March and September, 1992 when variations were less than 15%).

The δD values for cold springs, wells, and streams located in the basin (-107 to -131, n=15) overlap those of thermal waters (Table 2). The $\delta^{18}O$ values for thermal fluids, are 2‰ heavier than the world meteoric water line.

Alvord basin.

Date	Site	δD	$\delta^{18}O$
12/91 6/92 9/92 11/91 6/92 9/92 6/92 9/92	Borax Lakm Spring. north of Borax Lakm Flowing well	-117 -118 -120 -124 -119 -121 -121 -12s	-13.7 -14.7, -14.0 -13.9 -14.9 -15.4, -15.3 -14.3 -16.2 -15.1
12/91 6/92 9/92	Alvord Hot Spring	-119 -118 -119	-13.6 -14.1 -13.2, -13.1
12/91 6/92 9/92	Mickey spring.	-124 -120 -121	-14.6 -15.4 -14.0

Chemical and isotopic geothermometers were used to calculate reservoir temperatures (Table 3). Results for both the Na/K and Na/K/Ca geothermometers indicate minimum reservoir temperatures between 170 and 200°C. silica geothermometers yield lower temperature estimates than the alkali geothermometers. The sulfate-water geothermometer yields minimum temperature estimates of 198 to 207 C for Borax Lake and Alvord Hot Springs, but a lower value (150°C) for Mickey Springs. The minimum reservoir temperature is inferred to be near 200°C at all three hot-spring areas.

To define the location of the reservoir, strontium isotopic

Table 3 – Chemical and isotopic geothermometers (°C) for the Alvord basin.

Site	Qtz_1	Qtz_2	Na/K	Na-K-Ca	K/Na	K/Mg	Iso
A	182	170	177	171	194	142	207
B	177	166	180	164	198	135	203
C	196	181	181	174	200	115	168
D	157	149	182	194	199	137	198
E	190	176	172	197	190	173	150

A. Borax Lake at a depth of 30+ m. B. Hottest spring north of Borax Lakm. C. Artesian well 0.8 km north-east of Borax Lake. D. Alvord Hot Springs. E. Hottest spring at Mickey Springs. Qtz_1 quartz geothermometer assuming no steam loss. Qtz_2 quartz geothermometer assuming maximum steam loss. Iso = $^{18}O/^{16}O$ in SO_4^{2-}-H_2O geothermometer.

compositions of thermal waters and a suite of volcanic rocks were determined. The Steens Basalt and age-equivalent Pueblo Basalt are the most voluminous volcanic units in the vicinity of the Alvord basin. Strontium isotope ratios ($^{87}Sr/^{86}Sr$) range from 0.70346 to 0.70392 (Hart et al, 1989; Carlson and Hart, 1987). Volcanic units below these basalts have $^{87}Sr/^{86}Sr$ ratios between 0.70398 and 0.70430. A rhyolite ash-flow tuff stratigraphically above the Steens Basalt has an isotopic value of 0.70723. The strontium isotopic compositions of metavolcanic and metasedimentary rocks was not determined. Thermal waters at the three hot-spring areas have $^{87}Sr/^{86}Sr$ ratios between 0.70424 and 0.70478 (Table 4). The strontium isotope ratios of the thermal waters are consistent with those of volcanic rocks below the Steens Basalt.

Table 4 – Strontium isotope concentrations and $^{87}Sr/^{86}Sr$ ratlos for stratigraphic units collected Cron the mast face of Steens Mountain. The number of localities is indicated in parentheses.

Stratigraphic Unit	Lithology	Sr (mg/kg)	$^{87}Sr/^{86}Sr$
Welded tuffs	Peralkaline ash flow tuff (1)	18.0	0.70723 (±11)
Steens Basalt Pueblo Basalt	High alumina olivine tholeiite (6) Qtz thollites to olivine basalts (12)	471-848 302-700	0.70370-0.70386 0.70346-0.70392
Steens Mountain Volcanics	Platy andesite (2)	655 476	0.70398 (±13) 0.70430 (±13)
Pike Creek Formation	Welded ash flow tuff (1)	254	0.70426 (±11)
Alvord Creek Formation	Fine grained basalt (1)	163	0.70423(±11)
Springs N of Borax Lake Alvord Hot Springs Mickey Springs		0.448 0.723 0.162	0.70424(±5) 0.70478(±8) 0.70439(±6)

5. DISCUSSION

In this discussion, we examine the chemical characteristics that were imposed during recharge, residency in the reservoir and upflow.

5.1 Recharge

Recharge of the geothermal system in the Alvord basin occurs primarily by infiltration of meteoric water from the Steens Mountain-Pueblo Mountains fault block. The δD values of thermal water, cold ground water, and surface runoff are similar. A single analysis for snow collected at 2,408 m on the western flank of Steens Mountain is isotopically lighter (δD=-134) while a precipitation sample collected from the basin floor is isotopically heavier ($\delta D=-62$). The isotopic composition of precipitation on Steens Mountain is expected to show considerable elevation-related isotopic variation. Evaporation during descent contributed to the heavier value for rain from the valley floor and suggests that rain falling on the valley floor does not contribute to the recharge of the geothermal system.

5.2 Reservoir

Tritium concentrations for thermal fluids (Table 5) are consistent with residence times from at least 57 years to greater than 10,000 years, depending upon the circulation model selected for evaluation of the data (Shevenell, 1990). Deep ground water and thermal water have little or no tritium indicating little or no interaction with the shallow cold ground water system.

Tabla 5 - Tritium concentrations In thermal and non-thermal waters from the Alvord basin.

	Date sampled	Tritium (T.U.)	Error (eTU)
Thermal			
Borax Lake	8/26/92	0.25	0.09
Spr N BL	8/26/92	0.15	0.05
Wall NE BL	8/26/92	-0.01	[illegible]
Alvord HS	9/1/92	0.14	
Mickey Spr	9/1/92	0.10	0.09
Non-thermal			
Xurt Well	8/26/92	0.04	0.09
Thomas Place	9/3/32	-0.03	0.10
Alvord Ranch	9/3/92	10.10	0.30
Pike Creek	11/2/02	7.50	0.27

Tritium concentrations for Portland, Oregon (Shevenell, 1990) and Pike Creek were used In modeling residence time.

Geothermometers indicate that the fluids equilibrated with reservoir rocks at temperatures near 200° C. The coincidence of temperatures calculated using the sulfate-water, and alkali and silica geothermometers indicates sulfate equilibration with the thermal water also occurred at these temperatures. A lack of detectable H_2S in gas discharged from the system (Cummings and St. John, 1993) suggests relatively oxidized conditions occur within the reservoir.

Strontium isotope data are consistent with a reservoir within rhyolite to basalt volcanic and volcaniclastic rocks beneath the Steens Basalt. Assuming that the volcanic units exposed on the face of Steens Mountain occur in the subsurface beneath the Alvord basin, the following estimates of the depth of circulation were made based on stratigraphic reconstructions and a regional geothermal gradient of 40-60°C/km (Blackwell et al., 1978): at least 2 to 2.5 km at Borax Lake, 2 to 3 km at Alvord Hot Springs, and 1.2 to 2.0 km at Mickey Springs.

Structural considerations and drilling data suggest that reservoirs occur at two levels in the Borax Lake area. During exploration drilling, Anadarko Petroleum Corporation flow tested a reservoir at a depth of 450 m. Potential hydrologic connection between this shallow reservoir and critical habitat for the Borax Lake Chub is at the center of environmental controversy. The deeper reservoir inferred herein is potentially more isolated from Borax Lake.

5.3 Upflow

Less than 8% seasonal variation in chloride concentration during 1.5 years suggest neither mixing of the thermal water with non-thermal waters nor thermal waters of different salinity occurs in the Alvord basin. However, the springs north of Borax Lake may experience occasional mixing in the shallow environment as suggested by variable salinities between March and September, 1992. White (1970) ascribed variations of less than 10% to evaporative concentration of a solution of constant chloride concentration by boiling in central spring channels. The consistently higher concentration of chloride in the thermal water at Alvord Hot Springs suggests a possible contribution from a chloride-rich source.

Fournier (1979) illustrated possible pathways and processes. that may influence the composition of thermal water during upflow from a geothermal reservoir. For the springs that boil at the surface (springs north of Borax Lake, Borax Lake at 30 m, and Mickey Springs) boiling at shallow depths (less than 180 m) and variable residence time in shallow reservoirs account for chemical variability of discharges.

Alvord Hot Springs is not boiling, but calculated reservoir temperatures based on Na/K and Na/K/Ca geothermometers are similar to those for the boiling springs. Silica geothermometers are 30 to 50°C lower than the alkali-based geothermometers. The chemical composition of these fluids suggest slow rise and/or low volume of fluid and conductive heat loss to surrounding rocks.

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