

**EXTENT AND LOCATION OF THE GEOTHERMAL AQUIFER IN THE
ALVORD BASIN, HARNEY COUNTY, OREGON: A STUDY BASED ON
STRONTIUM ISOTOPE GEOCHEMISTRY OF ROCKS AND FLUIDS**

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U.S.D.I/Bureau of Land Management
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EXECUTIVE SUMMARY

Strontium isotopic ratios ($^{87}\text{Sr}/^{86}\text{Sr}$), Sr and Rb concentrations and major and trace element compositions of fluids and rocks were determined for stratigraphic units that are exposed in the ranges surrounding the Alvord basin, three hot spring areas (Borax Lake, Mickey Springs, and Alvord Hot Springs), and cold ground water (Kurtz well). These analyses were conducted to better constrain the location and possible extent of the geothermal aquifer in the Alvord basin.

Strontium isotopic ratios are distinctly different for stratigraphic units likely to be host for the thermal aquifers in the Alvord basin. The highest ratios occur in welded-ash flow tuffs in the Trout Creek Mountains, rhyolites exposed in the vicinity of Red Mountain north of Fields, Oregon and the Mickey Ignimbrite exposed in the Sheepshead Mountains east of Mickey Springs. These ratios are distinct from those for the Steens Basalt, Steens Mountain Volcanics, Pike Creek Formation, Alvord Creek Formation, and metamorphic rocks exposed at the base of the Pueblo Mountains.

The isotopic ratios for thermal waters are similar to those for the Steens Mountain Volcanics, rhyolite flows and ash-flow tuffs in the upper part of the Pike Creek Formation, and the Alvord Creek Formation. The isotopic ratios in thermal waters are higher than those for the Steens Basalt and lower than those for the metamorphic rocks of the Pueblo Mountains. Strontium isotopic ratios for thermal waters indicate that the thermal aquifer does not reside in the welded ash-flow tuffs of the Trout Creek Mountains, the rhyolites in the vicinity of Fields, or the Mickey ignimbrite.

Rb/Sr ratios separate the thermal waters from Mickey Springs from those at Borax Lake. However, this may be the result of higher Rb/Sr ratios produced by precipitation of carbonate minerals in the zone of upflow at Mickey Springs. If this process is occurring, the Rb/Sr and strontium isotopic ratios for the two areas are similar. Slightly higher strontium isotopic and Rb/Sr ratios for Alvord Hot Springs suggests that these waters have mixed with waters that have interacted with a higher radiogenic source than encountered in the Steens Mountain Volcanics, upper rhyolites of the Pike Creek Formation, or Alvord Creek Formation. The differences may indicate that rocks with isotopic ratios similar to those of metamorphic rocks exposed in the Pueblo Mountains occur in the deep subsurface beneath Steens Mountain.

Similarity in strontium isotopic ratios for all thermal fluids suggest that deep seated rocks in the Alvord basin with isotopic signatures similar to those of the Steens Mountain Volcanics, Pike Creek Formation, and Alvord Creek Formation are widespread. Data from this study do not preclude a single widespread thermal aquifer in the basin hosted in rocks below the Steens Basalt.

Distinctly different Rb/Sr ratios for cold groundwaters, but similar isotopic ratios suggest that the cold groundwaters are immature waters that have not interacted long enough or at high enough temperatures with the basin-fill sediments to attain a clear signature of host aquifers.

The assertion by Anadarko Petroleum Corporation (1995) that thermal fluids encountered in section 22 (T.37 S., R.33 E.) are hosted in ash-flow tuffs similar to those of the tuff of Trout Creek Mountains (Rytuba and others, 1984) should be testable by examining the strontium isotopic and Rb/Sr ratios of fluids in the exploratory wells. If the strontium isotopic ratios are higher than those for Borax Lake, a case for isolation of the shallow thermal aquifers is supported.

INTRODUCTION

The hydrogeochemical and physical characteristics of thermal aquifers provide information pertinent to the energy production potential, engineering design, and environmental impacts of geothermal development. During exploration and early development of a thermal aquifer system, these characteristics may be only partially known, but as a system responds to development and production these characteristics become constrained. Exploratory drilling of the geothermal system in the Alvord basin in southeastern Oregon has encountered thermal fluids at temperatures consistent with electrical generation. However, Borax Lake, a small thermal lake in the southern Alvord basin (Pueblo Valley) and within 1.2 km of drill hole sites is defined as critical habitat for the Borax Lake Chub, a species listed under the Rare and Endangered Species Act of 1973, as amended. Thus, the extent and location of thermal aquifers and the connection between these aquifers and surface thermal features, such as Borax Lake, are of interest.

The study reported herein utilizes strontium isotopes (^{87}Sr and ^{86}Sr) for rocks that may host the thermal aquifer, thermal waters, and cold ground water to provide additional constraints on host formation(s) and aerial extent. This study builds from data and interpretations contained in Cummings and St. John (1993), a report prepared for the Bonneville Power Administration on the hydrogeochemistry of the Alvord Valley Known Geothermal Resources Area.

Summary of previous work

Findings selected from Cummings and St. John (1993) are pertinent to this study and are summarized here.

Thermal waters originate in a hot-water system rather than a vapor-dominated system. The occurrence of high concentrations of boron, silica, arsenic and chloride support this conclusion. Fairly high ratios of Cl/Mg (Borax Lake = 1000-1289; Alvord Hot Springs = 379-471; Mickey Springs = 1294-10,450), Ca/Mg (Borax Lake = 50-62; Alvord Hot Springs = 3-6; Mickey Springs = 6-35) and low ratios of Ca/Na (Borax Lake = 0.01-0.04; Alvord Hot Springs = 0.01; Mickey Springs <0.01) are typical of hydrothermal systems having moderately high temperatures.

Calculated aquifer temperatures based on chemical and isotope geothermometers are similar for the three hot spring areas. The reservoir temperatures are estimated to be between 170° and 200°C. Oxygen isotope geothermometers for coexisting water and dissolved sulfate indicate reservoir temperatures between 198° and 207°C at Alvord Hot Springs and Borax Lake. Mickey Springs and a flowing well at Borax Lake yield temperatures of 150° and 168°C, respectively. These values may indicate partial reequilibration of the isotopic system by near-surface mixing with a different sulfate-bearing water.

Tritium concentrations indicate long residence times for the thermal water discharging from all three springs. The two end-member models used for the calculation of residence times generate a minimum of 57 years and a maximum of greater than 10,000 years.

The δD values indicate the source of recharge to the geothermal system is meteoric water, primarily from the Steens Mountain-Pueblo Mountains. Thermal fluids have the same δD composition as cold ground water and surface water. The $\delta^{18}O$ enrichment of 2-3 ‰ to the right of the meteoric water line is consistent with fluid-rock interactions in the aquifer.

Conservative element ratios (B/Cl: Borax Lake = 0.05-0.06; Alvord Hot Springs = 1.03-1.61; Mickey Springs = 0.04-0.05) suggest the geothermal aquifer is hosted in either volcanic rocks or metasedimentary rocks. The Li/Cs ratios for the Borax Lake thermal area (2.5-6.5) are consistent with a reservoir located in rhyolitic rocks. Radium isotope ratio analysis of thermal fluids indicates interactions with volcanic rocks at Borax Lake. These ratios for thermal fluids from Alvord Hot Springs and Mickey Springs are lower than those expected for volcanic rocks and may indicate local uranium accumulation in the aquifer or zones of upflow. Strontium isotope ratios for thermal waters are similar to those of volcanic rocks stratigraphically below the Steens Basalt. These formations include the Steens Mountain Volcanics, Pike Creek Formation, and Alvord Creek Formation.

Data obtained in this study (Cummings and St. John, 1993) do not preclude a single large reservoir system discharging at the three thermal areas in the Alvord basin. Differences in the chemical composition of discharge from the three springs is produced during upflow from the aquifer. During upflow, thermal waters follow a complex pathway of fractures and reside in shallow reservoirs before reaching the surface. Boiling, mixing with condensate, oxidation, mixing with 1-3% tritium-bearing, near-surface water, relative differences in flow rate and volume, and conductive heat loss are

processes that modify fluid composition during upflow from the deep geothermal aquifer.

Sample collection and analysis

Eighteen rock samples were collected from outcrops in the vicinity of the Alvord basin. Since this study was directed toward determining the present $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of potential aquifer rocks, samples that were distinctly hydrothermally altered as well as rock samples showing little hydrothermal alteration were collected for analysis. Water samples were collected from four hot springs including Borax Lake, boiling spring north of Borax Lake (SNBL), Alvord Hot Springs, and Mickey Springs, and from the Kurtz artesian well located northwest of Borax Lake on October 30, 1994 by Anna M. St. John.

Geochemical and isotopic analyses were performed at the Geochemical Laboratories in the Geology Department at Miami University, Oxford, Ohio under the direction of Dr. William K. Hart. Analysis for major and trace elements was determined by direct-current argon plasma (DCP) spectrometry. Replicate and duplicate analyses of up to four samples were completed. Strontium concentrations were determined by isotope dilution methods using two different ^{84}Sr spikes and by direct-current argon plasma (DCP) spectrometry. $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios were determined on a 12-inch, 90-degree sector Nuclide solid source (thermal ionization) mass spectrometer controlled by a microcomputer.

STRONTIUM CONCENTRATIONS AND ISOTOPIC RATIOS

To assess the source and input of strontium to Alvord basin geothermal waters, a suite of volcanic and metamorphic rocks (Table 1) were analyzed for $^{87}\text{Sr}/^{86}\text{Sr}$

isotopic ratios and geochemical composition. The suite includes Tertiary volcanic rocks exposed on the east-facing flank of the High Steens Mountain including the Alvord Creek and Pike Creek Formations, and lower flows of the Steens Mountain Volcanics; rhyolite flows and domes exposed near Red Mountain on the east-facing flank of the South Steens Mountain; rhyolite welded ash-flow tuffs from the Trout Creek Mountains east of the Pueblo Valley and the Mickey ignimbrite from the west-facing flank of the Sheephead Mountains. Two samples from the pre-Tertiary rocks of the Pueblo Mountains, one a muscovite schist and the other a chlorite schist, were selected to represent the older lithologies that underlie part of the area and which occur as lithic fragments in conglomerates that infill the southern Pueblo Valley.

Strontium isotopic data for the Steens Basalt and Pueblo Basalt reported by Carlson and Hart (1987) and Hart et al.(1989) are included in Tables 3 and 5. Including these published data, the sample suite examined in this study represents the major lithologic groups that are exposed in the mountain ranges that surround the Alvord basin and are likely to occur beneath the sedimentary fill of the basin. The samples are representative of the main units which may act as thermal aquifers in the Alvord Valley Known Geothermal Resources Area.

Strontium isotopic ratios, strontium concentrations, and error limits for water and rocks are recorded in Tables 2 to 5. Data contained in Tables 2 to 5 are distinguished by citation if obtained from published papers, by an * if obtained during this study, and a ^ if reported in Cummings and St. John (1993). Major and trace element geochemistry of samples collected for this study are reported in Table 6.

Table 1: Lithology and location of samples collected for Sr isotope and geochemical analysis reported in this study.

Sample number	Quadrangle	Location	Lithology
TC-1	Trout Creek Canyon	4668500N 381330E	Gray/green, porphyritic, flow laminated, moderately welded ash-flow tuff .
TC-2	Trout Creek Canyon	4668100N 380110E	Glassy, porphyritic, gray-black basal vitrophyre of welded ash-flow tuff
TC-3	Trout Creek Canyon	4668400N 380050E	Pumice-rich, vapor phase alteration of pumice is common. Gray/green porphyritic moderately welded ash-flow tuff.
TC-4	Trout Creek Canyon	4667860N 379590E	Gray/green, moderately welded, porphyritic ash-flow tuff with vapor phase alteration of flattened pumice.
PM-1	Colony Ranch	4658630N 366500E	Silver/gray muscovite schist with possible relict feldspar phenocrysts.
PM-2	Colony Ranch	4658630N 366500E	Gray/green chlorite schist.
SSM-1	Fields	7687250N 360165E	Flow banded, altered porphyritic rhyolite.
SSM-2	Fields	4685260N 361080E	Relatively low density, hydrothermally altered porphyritic rhyolite from the crest of Red Mountain.
SSM-3	Fields	4685520N 360780E	Porphyritic rhyolite, dense, light gray.
SSM-4	Fields	4685260N 361080E	Porphyritic rhyolite with argillic alteration of feldspar phenocrysts.
SSM-5	Fields	4683860N 362410E	Weakly altered porphyritic rhyolite.
SM-1	Alvord Hot Springs	4716430N 372610E	Pyroxene bearing basaltic andesite, unit Tspa of Minor et al. (1987) (6260 ft elevation).
SM-2	Alvord Hot Springs	4716380N 372820E	Hornblende-bearing light gray andesite (?), unit Tspa of Minor et al. (1987)(6300 ft elevation).
SM-3	Alvord Hot Springs	4716210N 372770E	Flow banded rhyolite partially altered, unit Tpdu of Minor et al. (1987) (6100 ft elevation).
SM-4	Alvord Hot Springs	4715770N 372650E	Flow banded weakly altered rhyolite, unit Tpdm of Minor et al. (1987) (5400 ft elevation).
SM-5	Alvord Hot Springs	4715090N 373430E	Flow banded rhyolite, unit Tprl of Minor et al. (1987) (4750 ft elevation).
SM-6	Alvord Hot Springs	4715125N 373640E	Green, lithic-rich tuff, well indurated, unit Tac of Minor et al. (1987)(4600 ft elevation).
SH-1	Mickey Springs	4724225N 390930E	Welded ash-flow tuff, Mickey ignimbrite

Strontium isotopic ratios were determined for water samples collected from four hot springs in the Alvord basin (Borax Lake, hot spring north of Borax Lake-SNBL, Alvord Hot Springs, and Mickey Springs) in May, 1992 (Cummings and St. John, 1993) and October, 1994 (this study). At Mickey Springs and spring north of Borax Lake, samples were collected from the same boiling springs sampled by Cummings and St. John (1993). Discharges from all three thermal areas issue from basinal sediments. Strontium concentrations and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for hot spring waters are recorded in Table 2.

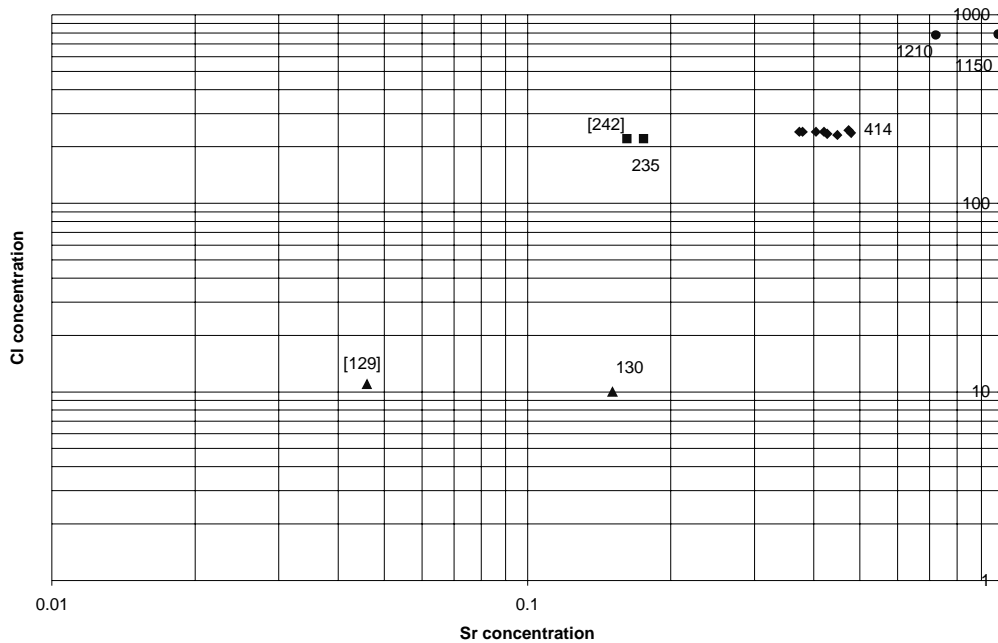
Strontium-chloride concentrations are plotted in Figure 1 for thermal and non-thermal waters from the Alvord basin. For each site, the range of HCO_3 concentrations determined by Cummings and St. John (1993) are indicated in this figure. The highest concentrations of Sr and Cl occur in thermal waters at Alvord Hot Springs, consistent with higher concentrations for other dissolved constituents relative to Borax Lake and Mickey Springs (Cummings and St. John, 1993). Sr and Cl concentrations for Borax Lake and spring north of Borax Lake are the same. Mickey Springs thermal water contains the lowest concentration of Sr, a value similar to that for cold ground water from the Kurtz well located 3.2 km northeast of Borax Lake. However, the Cl concentration at Mickey Springs is much higher than at the Kurtz well and similar to that for Borax Lake.

Strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) for thermal waters are similar to those for cold ground water represented by the Kurtz well located in the Pueblo Valley. Among the waters from hot springs, the highest ratios are reported for Alvord Hot Springs. However, all ratios fall within a narrow range between 0.7042 and 0.7048.

Table 2: Strontium concentrations and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for thermal and cold groundwaters.

Sample site	Sr (ppm)	uncertainty	$^{87}\text{Sr}/^{86}\text{Sr}$	+/-
Borax Lake	0.4738	0.014%	0.704393	0.000020*
Springs north of Borax Lake	0.4787 0.448	0.004%	0.704218 0.70424	0.000040* 0.00005^
Alvord Hot Srpings	0.9761 0.723	0.033%	0.704838 0.70478	0.000020* 0.00008^
Mickey Hot Springs	0.1753 0.162	0.025%	0.704388 0.70439	0.000053* 0.00006^
Kurtz Well (cold)	0.1510	0.014%	0.704335	0.000043*

Figure 1: Strontium versus Chloride concentrations in thermal and non-thermal waters from Alvord basin.



Strontium isotopic data and geochemistry for formations exposed in the mountain ranges surrounding the Alvord basin are compiled in Tables 3, 4 and 5 and Table 6, respectively. The oldest units are metamorphic rocks exposed in the lower slopes of the Pueblo Mountains west of Tumtum Lake in the southern Pueblo Valley. Two samples were collected to represent the extremes in bulk compositions in the vicinity of the sampling locality: a muscovite schist (PM-1) and a chlorite schist (PM-2). In both samples, the degree of metamorphism and strain-induced recrystallization is great enough that primary textures indicative of protolith have been destroyed. The protolith may be estimated from the composition of these samples as presented in Table 6. The composition of PM-1 suggests that the protolith is a rhyolitic rock, possibly a rhyolite tuff. The high loss on ignition (LOI) and total alkali (K₂O and Na₂O) concentrations in PM-2 suggest extensive alteration of what may have been an andesitic protolith. Strontium isotopic ratios (⁸⁷Sr/⁸⁶Sr) for both samples are approximately 0.705 (Table 5).

The Alvord Creek Formation was sampled from outcrops of a lithic fragmental unit exposed along Pike Creek at the base of the High Steens Mountain. The composition is consistent with that of a dacite (Table 6). The strontium isotopic ratio determined in this study, 0.704041 (Table 3), is similar to that reported in Cummings and St. John (1993) (0.70423) for a sample collected at Scoubes Creek at the base of the South Steens Mountain by Langer (1991).

The Pike Creek Formation was sampled at three localities along Pike Creek at the base of the High Steens Mountain. Three different rhyolitic flow units were sampled at the elevations indicated in Table 1. Sample SM-5 was collected from a flow banded rhyolite at the base of the section near the contact between the Pike Creek and Alvord

Creek Formations (Minor et al., 1987). Sample SM-3 is a porphyritic flow-layered rhyolite that occurs stratigraphically near the top of the Pike Creek Formation. There are significant geochemical and isotopic differences among the three rhyolites that are apparently related to their stratigraphic position. This is most clearly illustrated in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios which range from 0.708155 for the stratigraphically lowest sample to 0.704131 for the sample collected from the top of the formation. Likewise, Sr concentrations increase dramatically from 27.5 ppm for the stratigraphically lowest to 237.7 ppm for the stratigraphically highest sample. A sample collected from an ash flow exposed along Carlson Creek (20 km south) by Langer (1991) and analyzed in Cummings and St. John (1993) has a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.70426 (Sr concentration 254 ppm) suggesting that it is from near the top of the formation.

Strontium isotopic and concentration data are available for four samples from the Steens Mountain Volcanics. In this study, the lowest flow exposed along Pike Creek and a light gray plagioclase-rich flow approximately 20 m above the base were analyzed. In Cummings and St. John (1993) data for two samples collected by Langer (1991) from near the base and middle of the formation are reported. The samples collected near the base have low strontium isotopic ratios (0.703536, this study; 0.70398, Cummings and St. John, 1993). The ratio increases in samples collected higher in the unit. Of the two samples collected for this study, sample SM-1, stratigraphically lowest, is a relatively low aluminum basalt (Table 6) while sample SM-2 is a dacite. These data suggest that the Steens Mountain Volcanics are more heterogeneous in lithology and composition than has been previously reported (Minor et al., 1987).

The isotope geochemistry of the Steens Basalt and the stratigraphically equivalent Pueblo Basalt are reported by Carlson and Hart (1987) and Hart et al. (1989). These data are presented in Table 3 and 5. No additional data were obtained in this study. The strontium concentration varies from 302 to 731 ppm and the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio from 0.7035 to 0.7039.

Table 3: Strontium concentrations and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for formations from the High Steens Mountain.

Sample number	Sr (ppm)	uncertainty	$^{87}\text{Sr}/^{86}\text{Sr}$ ratio	+/-
Steens Basalt	471		0.70372	
(Carlson and Hart, 1987)	553		0.7037	
	453		0.70384	
	731		0.70386	
	476		0.7037	
	471		0.70375	
Steens Mountain	655		0.70398	
Volcanics	476		0.70430	
	297.4	0.021%	0.703536	0.000024*
	548.6	0.022%	0.704008	0.000046*
Pike Creek	254		0.70426	0.00011^
Formation	237.7	0.007%	0.704131	0.000034*
	119.2	0.044%	0.705122	0.000020*
	27.47	0.008%	0.708155	0.000032*
Alvord Creek	163		0.70423	0.00011^
Formation	485.2	0.054%	0.704041	0.000020*

The age relations of rhyolites that crop out north of Fields in the vicinity of Red Mountain are not well established. One interpretation is that these units are domes and low-volume flows extruded along the ring fractures of the Pueblo caldera as defined by Rytuba and McKee (1984). If this is the case, these units are similar in age (15.8 Ma) to the welded ash-flow tuffs sampled in the Trout Creek Mountains east of the Alvord basin. The rhyolites near Red Mountain show strong hydrothermal alteration visible in hand samples and indicated by geochemistry (Table 6). Sample SSM-3 is the least altered of these samples while silica veining and silicification occur in the other SSM samples.

Strontium concentrations for the TC and SSM samples are relatively low (1 to 19 ppm). Strontium isotopic compositions for SSM samples vary from 0.706546 to 0.716944 whereas those for the TC samples vary from 0.718910 to 0.730120. Also recorded in Table 5 is the isotopic ratio and Sr concentration for a sample collected by Langer (1991) and reported in Cummings and St. John (1993). The Sr concentration (18 ppm) is similar to values for the SSM samples as is the strontium isotopic ratio (0.70723). Sample SH-1, the Mickey ignimbrite (Table 5) has Sr concentration and strontium isotopic ratio similar to the TC samples. This ignimbrite overlies the Steens Basalt near Mickey Springs.

Table 4: Strontium concentrations and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for rhyolite exposures near Red Mountain, southern Steens Mountain (north of Fields, Oregon).

Sample number	Sr (ppm)	uncertainty	$^{87}\text{Sr}/^{86}\text{Sr}$ ratio	+/-
TCT-1 (Langer, 1991)	18		0.70723	0.00011 [^]
SSM-1	7.2	0.056%	0.716944	0.000028*
SSM-2	16.5	0.009%	0.711245	0.000020*
SSM-3	16.4	0.007%	0.708560	0.000039*
SSM-4	16.7	0.006%	0.706546	0.000053*
SSM-5	11.0	0.005%	0.708130	0.000020*

Strontium concentrations are plotted against $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for all stratigraphic units except the Steens Basalt-Pueblo Basalt in Figure 2. The range of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for geothermal fluids and cold groundwater plots along the left margin of the diagram. These values are within the range of strontium isotopic ratios for the metamorphic rocks of the Pueblo Mountains, Alvord Creek and Pike Creek Formations, and Steens Mountain Volcanics. The strontium isotopic ratios for thermal and ground waters are distinctly different than isotopic ratios for welded ash-flow tuffs of the Sheepshead (SH) and Trout Creek (TC) Mountains and the rhyolites near Red Mountain

Table 5: Strontium concentrations and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for samples from the Trout Creek (TC), Pueblo Mountains, and Sheepshead Mountains.

Sample number	Sr (ppm)	uncertainty	$^{87}\text{Sr}/^{86}\text{Sr}$	+/-
Trout Creek Mountains				
TC-1	4.5	0.005%	0.718910	0.000073*
TC-2	4.6	0.018%	0.730210	0.000043*
TC-3	4.9	0.007%	0.723207	0.000063*
TC-4	6.6	0.003%	0.724793	0.000047*
Pueblo Mountains				
	457		0.70379	
Pueblo Basalt	489		0.70361	
(Hart et al., 1989)	499		0.70346	
	457		0.70359	
	497		0.7036	
	616		0.70367	
	526		0.70391	
	485		0.70373	
Pre-Tertiary				
PM-1	322.6	0.020%	0.705067	0.000029*
PM-2	226.3	0.052%	0.705382	0.000027*
Sheepshead Mountains				
SH-1	9.0	0.014%	0.716642	0.000032*

(SSM) in the South Steens Mountain. In Figure 3, the strontium concentrations and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the metamorphic rocks, Alvord Creek and Pike Creek Formations, Steens Mountain Volcanics and the Steens-Pueblo Basalt are plotted. The field in which these data for the Steens-Pueblo Basalt (diamond) fall is more narrowly defined than for any other stratigraphic unit. The greatest variability is illustrated by the rhyolite flows of the Pike Creek Formation (square). The range of thermal and non-thermal waters plot (larger squares) along the left margin of the diagram. The formations that most closely

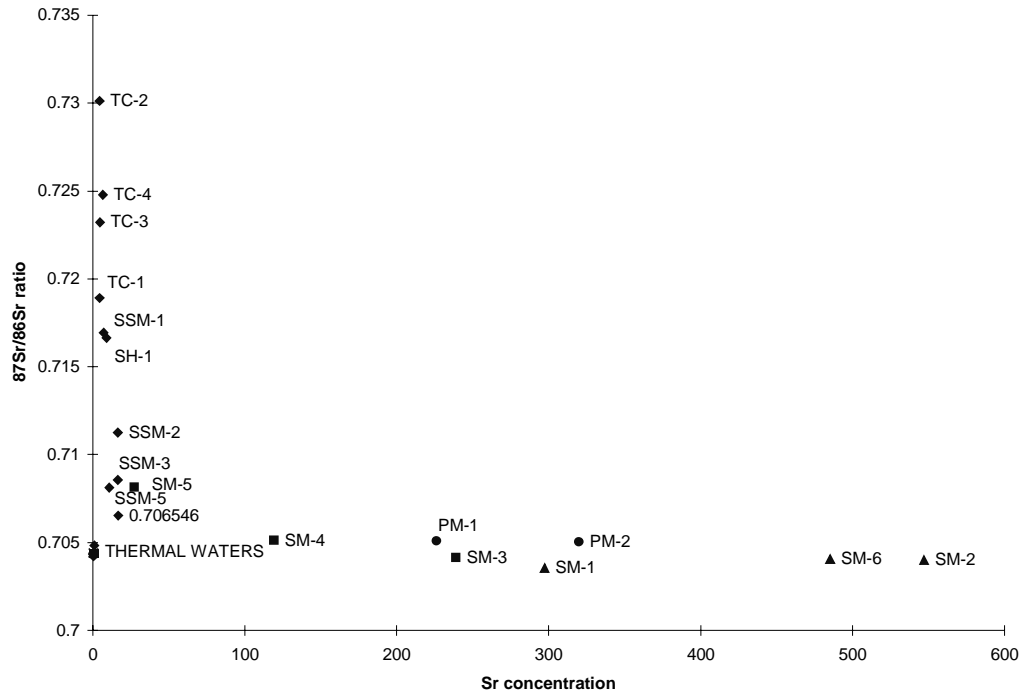


Figure 2: Sr concentration versus $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for fluids and rocks (excluding Steens-Pueblo Basalt)

fall within this range are the upper rhyolite flows of the Pike Creek Formation, Alvord Creek Formation, and Steens Mountain Volcanics. The metamorphic rocks of the Pueblo Mountains have higher and the Steens-Pueblo Basalts lower isotopic ratios than the waters.

In Figure 4, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is plotted against the Rb/Sr ratio for rock samples and water samples. This diagram again demonstrates the differences between the composition of rhyolitic rocks from near Red Mountain (circles) and the Trout Creek Mountains (squares) and the formations exposed on the east-facing flank of the High Steens Mountain in the vicinity of Pike Creek (Steens Basalt, Steens Mountain Volcanics,

Pike Creek Formation, and Alvord Creek Formation (triangles)). Since the isotopic ratios and concentration ratios for the rhyolites are so different from those of the formations sampled along Pike Creek, the ratios for the latter units are plotted in Figure 5a and 5b at

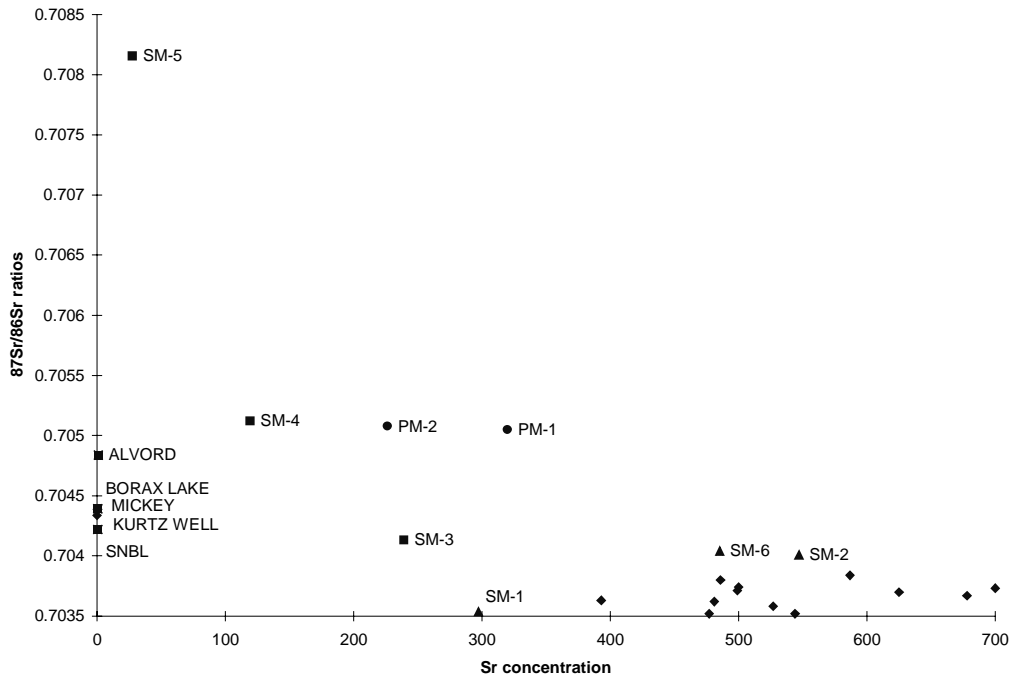


Figure 3: Strontium concentrations versus $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for fluids and lithologic units other than TC, SSM, and SH samples.

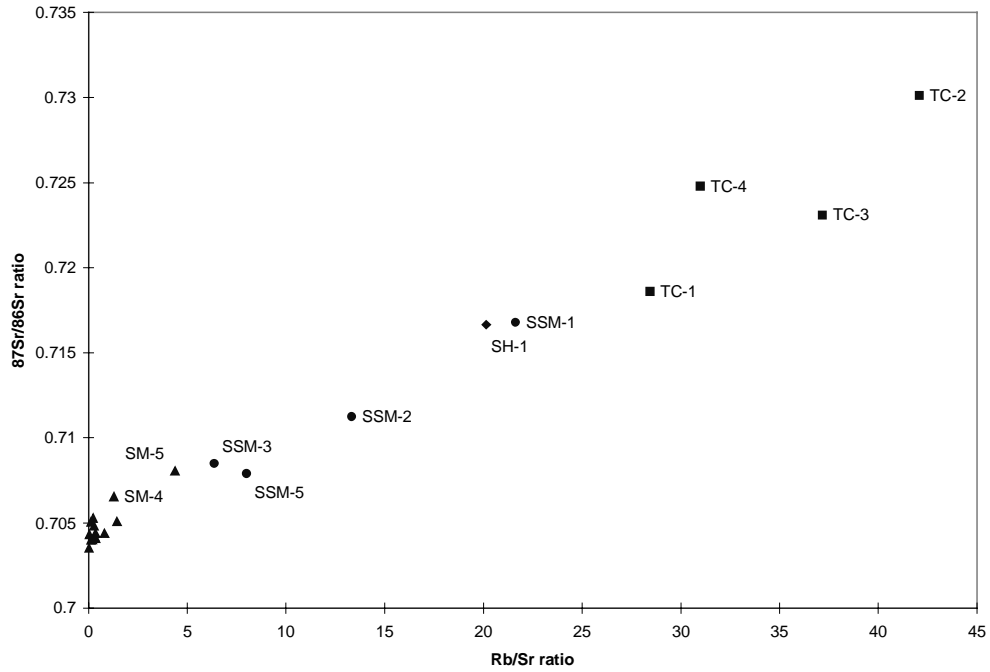


Figure 4: Strontium isotope data versus Rb/Sr ratios for rocks (excluding Steens Basalt) and fluids

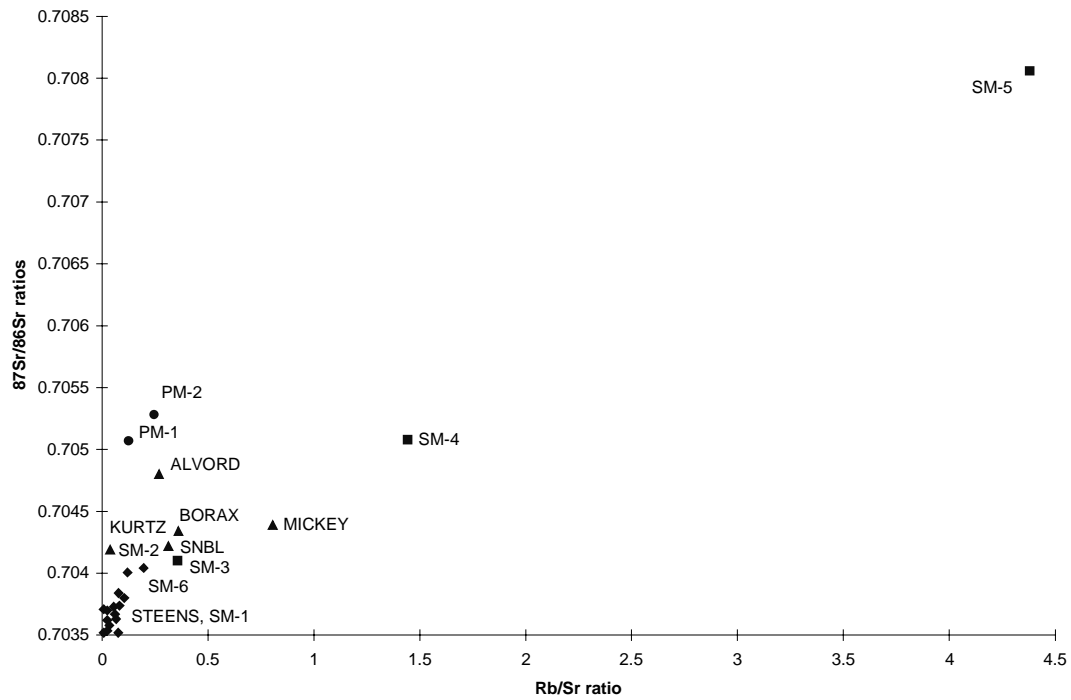


Figure 5a: Strontium isotopic ratios versus Rb/Sr ratios for fluids and rocks samples (excluding TC, SH, and SSM samples)

expanded scales. In these diagrams, the points for the hot spring fluids and cold ground water (triangles) are distinctly separated. Water from Mickey Springs has the highest Rb/Sr ratio and plots near the trend in isotopic and Rb/Sr variations (squares in Figure 5a) in the rhyolite flows of the Pike Creek Formation. Borax Lake and spring north of Borax Lake waters also plot near this trend, but at a lower Rb/Sr ratio. Water from Alvord Hot Springs has a higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and slightly lower Rb/Sr ratio. These values plot in a part of the diagram surrounded by data points representing the formations exposed at the High Steens Mountain and the metamorphic rocks of the Pueblo Mountains. The point for the Kurtz well is distinct: the Rb/Sr ratio is considerably lower while the strontium isotopic ratio is similar to the thermal waters.

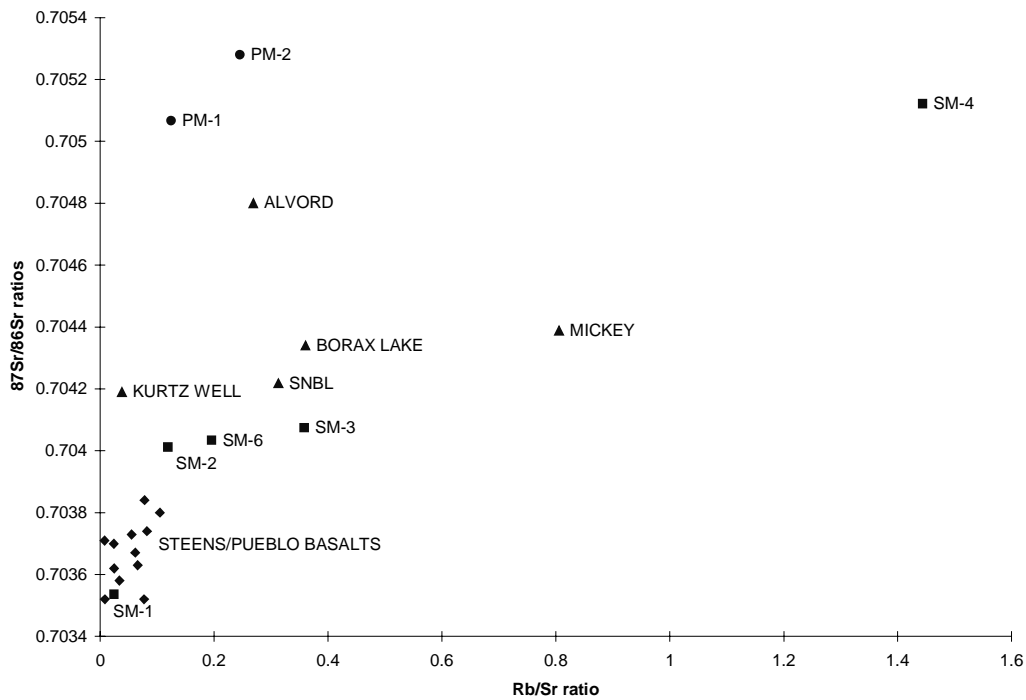


Figure 5b: Strontium isotopic ratios versus Rb/Sr ratios for fluids and rocks (excluding TC, SH, SSM, and sample SM=5)

Table 6: Major and trace element geochemistry of rocks.

Oxide	SH-1	TC-1	TC-2	TC-3	TC-4	SSM-1	SSM-2	SSM-3	SSM-4	SSM-5	PM-1	PM-2	SM-1	SM-2	SM-3	SM-4	SM-5
SiO2	73.72	76.18	74.21	76.03	76.38	80.77	82.03	76.88	83.50	81.87	70.78	54.57	49.09	65.06	71.97	70.53	75.06
TiO2	0.23	0.27	0.24	0.25	0.25	0.20	0.16	0.54	0.29	0.27	0.26	0.91	1.72	0.62	0.46	0.38	0.19
Al2O3	11.20	10.40	9.75	10.02	9.94	9.81	9.17	12.44	9.47	9.85	15.69	17.71	14.37	16.54	14.67	14.90	13.78
Fe2O3	3.28	4.07	4.48	4.59	4.57	1.83	1.07	0.63	2.06	0.92	1.93	7.10	12.24	4.54	2.19	2.12	1.46
MnO	0.07	0.10	0.09	0.07	0.07	0.04	0.02	0.01	0.03	0.01	0.06	0.07	0.18	0.05	0.02	0.02	0.01
MgO	0.08	0.04	0.02	0.05	0.05	0.05	0.02	0.01	0.05	0.01	1.56	6.49	8.97	1.03	0.19	0.23	0.04
CaO	0.35	0.22	0.16	0.18	0.20	0.07	0.13	0.16	0.75	0.02	0.68	1.32	10.42	3.93	1.36	0.53	0.22
Na2O	3.74	4.31	4.25	4.45	4.46	3.51	1.57	4.19	0.06	3.11	6.49	4.61	2.41	3.95	4.01	2.49	4.02
K2O	5.29	4.60	4.99	4.54	4.49	4.17	5.69	5.14	0.62	4.46	2.08	2.73	0.42	2.93	4.04	7.43	5.32
P2O5	0.07	0.08	0.08	0.13	0.11	0.17	0.12	0.12	0.13	0.10	0.23	0.35	0.29	0.23	0.13	0.03	0.06
LOI	1.89	0.13	2.25	0.15	0.10	0.32	0.61	0.20	3.90	0.31	0.95	2.98	0.17	0.71	0.81	1.36	0.60
TOTAL	99.93	100.39	100.51	100.46	100.61	100.94	100.60	100.32	100.86	100.92	100.71	98.64	99.94	99.60	99.86	100.01	100.76
ELEMENT																	
Ni	14	5	<5	9	8	<5	<5	<5	<5	<5	10	26	188	21	8	<5	<5
Zn	185	167	246	233	229	66	46	26	52	36	42	32	94	60	44	25	21
Cu	5	<5	7	5	6	<5	<5	<5	<5	<5	13	6	140	40	10	6	<5
Cr	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	6	16	386	15	<5	<5	<5
Zr	604	482	775	750	789	480	501	352	328	178	100	130	108	142	209	262	246
V	<10	<10	<10	<10	<10	<10	<10	<10	11	<10	25	151	247	109	31	17	<10
Sc	0.9	<0.5	<0.5	<0.5	<0.5	1.5	1.1	15	1.6	1.2	2.4	15.5	30.4	10	3.9	2.7	1.6
Nb	28	17	33	24	27	27	23	16	16	10	4	6	23	12	20	16	31
Ba	44	55	36	31	33	44	66	487	94	101	914	802	121	1444	1398	1009	377
Sr	4	3	1	3	2	6	19	17	16	15	312	223	245	528	248	110	28
Rb	185	126	178	177	207	113	176	107	3	71	41	44	2	67	95	152	120
Y	92	72	140	119	60	56	27	56	41	14	8	23	26	13	17	18	31

SH-1 Mickey ignimbrite; TC-1, TC-2, TC-3, TC-4 tuff of Trout Creek Mountains; SSM1, SSM-2, SSM-3, SSM-4, SSM-5 rhyolite and ash-flow tuffs north of Fields; PM-1, PM-2, metamorphic rocks of the Puget Sound; SM-1, SM-2 Steens Mountain Volcanics; SM-3, SM-4, SM-5 rhyolites of Pike Creek Formation; SM-6 Alvord Creek Formation.

DISCUSSION

Isotopic ratios are standard tools to ascertain the evolution of fluids in complex geologic environments. Light stable isotopes (H, S, O, C) provide insight into geologic processes because they are widely occurring and participate in a wide range of interactions between fluids, rocks, and organisms. Ratios among radiogenic isotopes are similar to ratios among conservative ions such as chloride and bromide, once established in a material by a geologic process they tend to remain constant. In this discussion, the behavior of strontium isotopes in fluids is briefly reviewed, the strontium geochemistry of rocks and fluids of the Alvord basin discussed, and the findings of Cummings and St. John (1993) reviewed in light of the data presented in this study.

Strontium isotope hydrogeochemistry in thermal aquifers

The chemical behavior of strontium in water is linked to the temperature of the aquifer, type of reservoir rock, water/rock mass ratios, residence time in the aquifer, Sr availability from various rock phases, and precipitation of secondary minerals, particularly carbonate minerals. The exchange of strontium between water and rock is mainly determined by chemical reaction (dissolution, precipitation, or ion exchange) or possibly by equilibrium isotope exchange. During the process of chemical reaction, rocks may lose variable amounts of strontium to the circulating waters and, in this way, the waters gradually reflect the strontium isotopic composition of their host rocks (Pampura et al., 1980). Since the high atomic weight of the two isotopes (^{87}Sr , ^{86}Sr) avoids isotopic fractionation, the Sr isotopic ratio can be considered to represent the ratio of the source (Stettler and Allegre, 1978).

The strontium isotopic evolution of fluids in geothermal aquifers is similar to that of sea water interacting with rocks of the ocean floor. Gillis and Thompson (1993) present the basic concepts for the process by which the strontium isotopic composition of seawater evolves to that of ocean floor basalt as it migrates through the oceanic crust. Whether the hydrothermal solution attains the isotopic ratio of the rock is dependent upon the flow path of the fluid. Short flow paths produce “immature” signatures in the fluid while long flow paths or residency allows the isotopic ratio of the rock to be imposed (Elderfield and Greaves, 1981). Once the solution chemistry becomes rock dominated with respect to Sr-isotopes, little or no detectable effect is produced on the isotopic composition of rocks or fluids with continued interaction. Because of these characteristics, strontium isotope ratios can be used to identify the country rocks with which fluid interacted. Strontium isotope ratios have been used to determine thermal aquifers in several geothermal systems (Stettler and Allegre, 1978; Plyusnin et al., 1978; Elderfield and Greaves, 1981; Vuataz et al., 1988; Kharaka et al., 1990; Goff et al., 1991; Graham, 1992).

Strontium of thermal waters and rocks in the Alvord basin

Interpretation of strontium isotopic ratios for the thermal aquifer requires distinct isotopic ratios in stratigraphic units that are potential aquifers and confinement of water-rock interactions to the aquifer (Vuataz et al., 1988). The stratigraphic units likely to serve as aquifers as determined from structural interpretation of the Alvord basin and the rocks exposed in the range fronts of surrounding mountains have been sampled in this study. The stratigraphic relations in the range fronts and thus their projection into the subsurface beneath the Alvord basin requires some discussion. The common practice is to

project stratigraphic units as though they were bounded by simple normal faults. As a consequence, the stratigraphic sequences observed in the mountain fronts should occur in a relatively simple layered pattern beneath the basin floors. This assumption is probably not valid.

Stratigraphic units in the High Steens Mountain, Mickey Butte, and the southern Sheepshead Mountains, the ranges surrounding the Alvord Valley in the northern Alvord basin include, from oldest to youngest, the Alvord Creek and Pike Creek Formations, Steens Mountain Volcanics, Steens Basalt (Minor et al., 1987), and Mickey ignimbrite (Hook, 1981). These same formations are likely to occur beneath the Alvord Valley and, at least some, have been reported in drill holes described by Hook (1981).

The lateral continuity of these formations southward along the range front into the vicinity of the South Steens Mountain and the Pueblo Valley is less clear. Tuffs and rhyolites exposed along the base of the South Steens Mountain and Pueblo Mountains were assigned by Rytuba and McKee (1984) to the Pueblo caldera and outflow facies of the tuff of Trout Creek Mountains (15.8 Ma). Of the two members exposed in the Trout Creek Mountains, the lower member of the tuff of Trout Creek Mountains is densely welded, alkali-element-enriched (7.40 to 8.76 weight percent $K_2O + Na_2O$) rhyolite with phenocrysts of quartz (1%), ferrohedenbergite (1%), anorthoclase (26%), aenigmatite (1-5%), Fe-Ti oxide (0.5%), and hypersthene (1%). The basal vitrophyre is 1- to 2-m thick and the tuff is blue green and columnar jointed (Rytuba and McKee, 1984). This tuff was sampled in the Trout Creek Mountains in this study (samples TC-1, TC-2 (basal vitrophyre), TC-3, and TC-4). The upper member is exposed only in the Tule Springs Rims east of the Alvord basin.

The rhyolitic rocks sampled north of Fields in the vicinity of Red Mountain may form part of the Pueblo caldera and are genetically related to the tuff of Trout Creek Mountains. These rhyolites are strongly altered with the possible exception of sample SSM-3. Hydrothermal alteration precludes using most geochemical approaches to establish genetic ties between these units. However, certain trace elements such as Y and Zr are particularly immobile during hydrothermal alteration and may provide a basis for correlation of units. The concentrations of these elements may increase or decrease in rocks depending upon mass/volume changes during alteration. However, the ratio between the elements should not change or changes that reflect patterns produced by primary igneous fractionation among these elements should be noted. The concentrations of these elements and ratios are recorded in Table 7 for the samples collected during this study and those reported in Rytuba and McKee (1984). From these data, the ratio of Zr/Y ranges from 5.5 to 8.6 for six of the nine samples. The other three samples have higher ratios (12.7 to 18.6). Overall, these ratios are higher than those reported for samples of the tuff of Trout Creek Mountains reported by Rytuba and McKee (1984) (3.6 to 4.3). These differences may reflect igneous fractionation between these elements.

The stratigraphic relations of the thick conglomerate sequences (at least 240 m thick along Cottonwood Creek) described by Ross (1942) and Williams and Compton (1953) between Fields and Tumtum Point to other stratigraphic units is not clear. Although the conglomerates locally are flat lying, they may have dips up to 35° to the

Table 7: Concentration of Y and Zr and Zr/Y ratios for rhyolites and ash flow tuffs possibly related to the Pueblo caldera.

Sample Number	Concentration of Y	Concentration of Zr	Zr/Y
Trout Creek Mtns			
TC-1	72	482	6.7
TC-2	140	775	5.5
TC-3	119	750	6.3
TC-4	60	789	13.2
Rhyolite N of Fields			
SSM-1	56	480	8.6
SSM-2	27	501	18.5
SSM-3	56	352	6.3
SSM-4	41	328	8.0
SSM-5	14	178	12.7
tuff of Trout Creek Mountains (Rytuba and McKee, 1984)			
Base		588	
Base	150	647	4.3
Middle	100	419	4.2
Top	100	357	3.6

west. Volcanic rocks which protrude through these conglomerates have dips that are contrary to those in the Pueblo and Steens Basalts and the conglomerates. Locally, these volcanic rocks dip up to 45° east, toward the Pueblo Valley (Williams and Compton, 1953). In general, the foothills volcanic rocks for the Steens and Pueblo Mountains dip eastward between Tumtum Point and Wildhorse Valley. At least part of these east-dipping rocks may be included in the Pueblo caldera by Rytuba and McKee (1984).

Cummings and St. John (1993) examined silica-cemented conglomeratic sandstone deposits exposed southwest of Borax Lake. Paleocurrent indicators indicate transport from south and southwest to north and northeast. In addition, rhyolitic clasts were abundant and metamorphic rock fragments minor. On the basis of these characteristics, Cummings and St. John (1993) interpreted these sediments to be co-

extensive with the conglomeratic rocks exposed in the vicinity of Fields. In a plan of development for geothermal energy in the Pueblo Valley by Anadarko Petroleum Corporation (1995), the continuity of these units is disputed on the basis of proprietary data obtained from exploration wells. Proprietary data cited in this report indicate the conglomeratic sandstone “is much more localized, and exists only where unconsolidated sand and gravel have been cemented by minerals deposited by hot water.”

Anadarko Petroleum Corporation (1995, p. 23) reports that “the geothermal reservoir..... in Section 22 occurs in highly fractured volcanic formations and interstratified sediments underlying 1,087 feet or more of post-volcanic sediments.” The thermal aquifer host rocks consist of unwelded and welded crystal, lithic, and ash tuffs. “Thick basalt” was intersected “in only one observation well, 25-22A, at a depth of 2,400 ft.” Anadarko Petroleum Corporation (1995) suggests that the welded and unwelded tuffs of the thermal aquifer correlate with the tuffs exposed in the Tule Springs Rims mapped by Rytuba et al. (1982).

The strontium isotopic ratios of the formations surrounding the Alvord basin have distinct values as illustrated in Figures 2 and 3, meeting one of the requirements for establishing the thermal aquifer on the basis of these ratios (Vuataz et al., 1988). In these figures, the strontium isotopic ratios for thermal fluids from the three hot spring areas, Borax Lake, Alvord Hot Springs, and Mickey Springs, fall within a narrow range (0.70421-0.70483), a range similar to those for the Steens Mountain Volcanics (0.7035-0.7043), upper rhyolite flows and ash-flow tuffs of the Pike Creek Formation (0.7041), and the Alvord Creek Formation (0.7040-0.7042). The similarity between the strontium isotopic composition of thermal waters and these formations indicate they are the likely

hosts of the thermal aquifer. The strontium isotopic ratios for the Steens Basalt-Pueblo Basalt (0.7035-0.7039) are lower than the values for the thermal waters.

The location of the thermal aquifer may also be inferred from plots of the strontium isotope ratio versus the Rb/Sr ratio as illustrated in Figures 4 and 5. From these plots it appears the isotopic composition of thermal waters at Mickey Springs is strongly influenced by interaction with rhyolites of the Pike Creek Formation. Thermal waters from Borax Lake and spring north of Borax Lake also appear to be influenced by interactions with rocks of similar isotopic composition to the upper rhyolites of the Pike Creek Formation and the Alvord Creek Formation.

The waters discharging at Alvord Hot Springs, however, may result from mixing of waters with different isotopic compositions. Cummings and St. John (1993) indicate that the hydrogeochemistry of thermal fluids at Alvord Hot Springs suggest a potential contribution of waters from a deep source. If so, this deep fluid may be interacting with rocks of isotopic composition similar to that of the metamorphic rocks exposed in the Pueblo Mountains. As it rises toward the surface, this water mixes with water that has interacted with a less radiogenic source rock.

Although the strontium isotopic ratios for thermal fluids at Mickey Springs are similar to those for other hot springs areas, the Rb/Sr ratios for thermal fluid at Mickey Springs are higher. This may reflect mineral precipitation prior to surface discharge. The concentration of Sr in waters discharged at Mickey Spring (0.1753 ppm) is lower than that at Borax Lake (0.4738 ppm) and Alvord Hot Springs (0.9761 ppm). Cummings and St. John (1993) interpreted the low calcium (0.7 to 1.0 ppm; 11-14 at Borax Lake) concentrations and relatively high pH (8.0-8.5; 6.6-7.4 at Borax Lake) at

Mickey Springs as indicating mineral precipitation, particularly carbonate minerals, from the thermal fluid in the subsurface. Strontium substitutes for calcium in the lattice of carbonate minerals. Subsurface precipitation of carbonate minerals at Mickey Springs could preferentially remove Sr from the thermal fluid, increasing the Rb/Sr ratio, but not influencing the strontium isotopic ratio (Elderfield and Greaves, 1981).

The strontium isotopic ratio for the Kurtz well, a cold ground water source in the Pueblo Valley, falls within the range of isotopic values for thermal waters (Table 1, Figures 2 and 3). However, the Rb/Sr ratio is distinctly lower (0.03) (Figure 5a,b). The cold ground water interacts with basin-fill sediments composed of detritus derived from the formations surrounding the Alvord basin. Cummings and St. John (1993) present modal data for sandstones collected southwest of Borax Lake. Lithic clasts of basalt (15-25%), rhyolite (24-32%), and metamorphic (2%) rocks and metamorphic/plutonic minerals (40-42%) are present in this unit. Given the transport directions indicated by paleocurrent indicators, these lithic fragments are most likely sourced in the metamorphic rocks of the Pueblo Mountains, the rhyolites near Red Mountain, and the Steens Basalt. The extremely low Rb/Sr ratio, far lower than in any stratigraphic unit (except lowest flows in the Steens Mountain Volcanics; Rb/Sr=0.02), suggests that these cold basin waters are immature waters that have not interacted with host lithologies adequately to attain their isotopic or concentration ratios.

Integration with previous work

Cummings and St. John (1993) presented findings that were listed at the beginning of this report. On the basis of the new data provided in this report, some of these findings can be modified. However, several remain unchanged and provide important constraints on findings in this report. Among these are the temperature of the thermal aquifer (near 200°C), residence time (model dependent, but expected to be greater than 10,000 years), and physical state of water in the aquifer (hot-water system).

Cummings and St. John (1993) concluded that the geothermal aquifer was in the Steens Mountain Volcanics, Pike Creek Formation, and/or Alvord Creek Formation and calculated minimum depths to aquifers hypothesized to be in these units. The strontium isotopic data reported in this study support the conclusions in Cummings and St. John (1993) that the geothermal aquifer is potentially within three formations, Steens Mountain Volcanics, Pike Creek and Alvord Creek Formations. The narrow range in isotopic ratios for thermal waters suggest that these formations or rocks of similar lithology and isotopic characteristics occur extensively beneath the Alvord basin. The data presented in this study favor the Steens Mountain Volcanics and upper rhyolite flows of the Pike Creek Formation as the site of the main thermal aquifer.

As discussed in Cummings and St. John (1993) the aquifer near Borax Lake tested by Anadarko Petroleum Corporation (press releases of November 7, 1989;) is likely within the Steens Basalt. This interpretation is refuted by Anadarko Petroleum Corporation (1995) and welded ash-flow tuffs similar to the upper member of the tuff of Trout Creek Mountains is indicated as the thermal aquifer. In either case, measured aquifer temperatures are only 152 °C at 451 m while calculated chemical and isotopic

geothermometers indicate aquifer temperatures near 200°C. Cummings and St. John (1993) proposed a deeper seated aquifer as the major source of thermal fluids. This is supported by Anadarko Petroleum Corporation (1995, p. 27) in the following statement. “The zone or zones of upwelling hot water which recharge the geothermal reservoir in Section 22 have not been encountered in the wells drilled to date.” Cummings and St. John suggested that this deep-seated thermal aquifer was located beneath the Steens Basalt-Pueblo Basalt section. Strontium isotopic ratios and Rb/Sr ratios presented in this study are consistent with this interpretation. In addition, strontium isotopic data for the rhyolitic rocks that crop out in the Trout Creek Mountains (0.718-0.730; 28-42) and Red Mountain (0.706-0.716; 6-21, (SSM-4 has a ratio of 0.22)) in the South Steens Mountain area indicate these rocks clearly do not host the thermal aquifer. Likewise, the metamorphic rocks of the Pueblo Mountains (0.705; 0.12-0.24) are unlikely hosts.

Conservative-element ratios in thermal fluids have been used to determine the host rocks for thermal aquifers; however, disputes arise over such interpretations (e.g. Goff et al, 1987; Sorey et al., 1991). Conservative element ratios for Borax Lake and spring north of Borax Lake reported by Cummings and St. John (1993) and unpublished data indicate B/Cl ratios are consistent with volcanic or metasedimentary host rocks. In the Alvord basin, the B/Cl ratios most likely reflect a volcanic host; however, Rb/Sr ratios and strontium isotopic ratios for Alvord Hot Springs allow for mixing with fluids interacted with rocks similar to metamorphic rocks exposed in the Pueblo Mountains. The Li/Cs ratios (2.5 to 6.5) reported in Cummings and St. John (1993) and unpublished data are consistent with a rhyolite host rock (Taylor, 1974). Strontium isotopic ratios and Rb/Sr ratios of thermal waters at Borax Lake and spring north of Borax Lake are

consistent with an aquifer host of the upper rhyolite flows of the Pike Creek Formation or rhyolites of similar isotopic composition.

The similarity in strontium isotopic data for thermal waters from Borax Lake, Mickey Springs, and Alvord Hot Springs suggest that rocks of similar isotopic composition occur widely in the subsurface of the Alvord basin beneath the Steens-Pueblo Basalts. Cummings and St. John (1993) indicate that isotopic and hydrogeochemical data do not preclude a single large reservoir system discharging at the three thermal areas in the Alvord basin. Differences in hydrogeochemistry among the three hot spring areas is explained by differences in conditions in the upflow zone and not the reservoir. A similar conclusion is suggested by data from the present study. Loss of Sr by subsurface precipitation of carbonates at Mickey Springs and contribution of waters with somewhat higher strontium isotopic ratio at Alvord Hot Springs accounts for the relatively minor differences in Rb/Sr and strontium isotopic ratios among the three hot spring areas.

Anadarko Petroleum Corporation (1995) indicates that the thermal reservoir is hosted in welded and non-welded rhyolite ash-flow tuffs and interbedded sediments that may correlate with the ash-flow tuffs mapped by Rytuba and others (1982) in the Tule Springs Rims. If this correlation is correct, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for thermal fluids in the exploration wells drilled to date should be distinctly different from that for the thermal fluids discharged at Borax Lake. If the stratigraphic correlation by Anadarko Petroleum Corporation is accepted, thermal fluids should have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios between about 0.718 and 0.730, the isotopic range for the tuff of Trout Creek Mountains. If the rhyolites exposed north of Fields are the host lithology, the isotopic ratio of the thermal

fluids should be between 0.706 and 0.716. If so, a case for isolation of this thermal aquifer from the thermal aquifer that discharges at Borax Lake is supported. However, if the strontium isotopic ratio for these waters is approximately 0.704, similar to that at Borax Lake, the stratigraphic correlation suggested by Anadarko Petroleum Corporation and isolation of the thermal aquifer from that discharging at Borax Lake needs to be reevaluated. If the strontium isotopic ratios indicate that the thermal aquifers at the exploration site and Borax Lake are isolated, extremely complex structures characterized by substantial displacements must lie buried beneath the basin fill in the Pueblo Valley.

It is possible that thermal water rising from a deep aquifer has a strontium isotopic signature similar to that for Borax Lake fluids, but that in a near-surface aquifer composed of the tuff of Trout Creek Mountains, it resides long enough to change isotopic composition. Relatively short residence in a shallow aquifer is consistent with the model proposed by Cummings and St. John (1993) to explain differences in calculated reservoir temperatures using various geothermometers. A strontium isotopic signature in fluid with this history could be higher than that at Borax Lake. Although this situation would confirm that the two systems are isolated in the shallow aquifer, it does not preclude sharing of a common deep aquifer.

CONCLUSIONS

1) Strontium isotopic ratios for thermal fluids discharging at Borax Lake, Alvord Hot Springs, and Mickey Springs fall within a narrow range between 0.70438 and 0.70483. The narrow range in isotopic values suggests fluids have interacted with rocks of similar isotopic composition in the thermal aquifer and that such rocks are widespread beneath the Alvord basin.

2) Strontium isotopic ratios for formations exposed in the mountain fronts surrounding the Alvord basin (Alvord Valley and Pueblo Valley) are isotopically distinct. Thermal fluids that have interacted with these formations for sufficient time are isotopically distinct and can be matched to the host formation(s).

3) Strontium isotopic ratios and Rb/Sr ratios suggest that the thermal aquifer is located in the Alvord Creek Formation, upper rhyolite flows and ash-flow tuffs of the Pike Creek Formation, or the Steens Mountain Volcanics. The Steens Basalt has isotopic ratios that are too low and metamorphic rocks exposed in the Pueblo Mountains have isotopic ratios too high to match the thermal fluids.

4) Strontium isotopic ratios and Rb/Sr ratios indicate that the tuff of Trout Creek Mountains (TC samples), rhyolites and ash-flows exposed north of Fields and presumed to be part of the Pueblo caldera (SSM samples), rhyolite flows and ash-flow tuffs (?) of the lower Pike Creek Formation, and the Mickey Ignimbrite are not host lithologies for the thermal aquifer.

5) Strontium isotopes, Rb/Sr, and Li/Cs suggest that rhyolites and ash-flow tuffs similar to those in the upper part of the Pike Creek Formation are the likely host for the thermal aquifer at Borax Lake.

6) Strontium isotope ratios provide a method to test the stratigraphic location of the thermal aquifer discharging at Borax Lake and the thermal aquifer discovered by Anadarko Petroleum Corporation. If the strontium isotopic ratio for thermal fluids at the exploration site fall within a range of values between approximately 0.706 and 0.730, a case for shallow aquifer isolation is favored.

REFERENCES CITED

- Blackwell, D. D., Kelley, S. A., and Edmiston, R. C., 1986, Analysis and interpretation of thermal data from Borax Lake geothermal prospect, Oregon: Geothermal Resources Council Transactions, v. 10, p. 169-174.
- Cummings, M. L. and St. John, A. M., 1993, Hydrogeochemical characterization of the Alvord Valley know Geothermal Resources Area, Harney County, Oregon: Report to the Bonneville Power Administration prepared under procurement number De-PR79-91BP19408, 272 p.
- Carlson, R. W., and Hart, W. K., 1987, Crustal genesis on the Oregon Plateau: Journal of Geophysical Research, v. 92, p. 6191-6206.
- Elderfield, H. and Greaves, M. J., 1981, Strontium isotope geochemistry of Icelandic geothermal systems and implications for sea water chemistry: *Geochimica et Cosmochimica Acta*, v. 45, p. 2201-2212.
- Gillis, K. M., and Thompson, G., 1993, Metabasalts from the Mid-Atlantic Ridge: new insights into hydrothermal systems in slow-spreading crust: *Contributions to Mineralogy and Petrology*, v. 113, p. 502-523.
- Goff, F., Truesdell, A. H., Grigsby, C. O., Janik, C. J., Shevenell, L. A. Paredes, J. R., Guitierrez, J. W., Trujillo, P. E. Jr., and Counce, D. A., 1987, Hydrogeochemical investigation of six geothermal sites in Honduras, Central America: Los Alamos, New Mexico: Los Alamos National Laboratory, Publication no. LA-10785-MS, 170 pp.
- Goff, F., Wollenberg, H. A., Brookins, D. G., and Kistler, R. W., 1991, A Sr-isotope comparison between thermal wters, rocks and hydrothermal calcites, Long Valley caldera, California: *Journal of Volcanology and Geothermal Research*, v. 48, p. 265-281.
- Graham, I. J., 1992, Strontium isotope compositon of Rotorua geothermal waters: *Geothermics*, v. 21, p. 165-180.
- Hart, W. K., Carlson, R. W., and Mosher, S. A., 1989, Petrogenesis of the Pueblo Mountains basalt, southeastern Oregon and northern Nevada: *Geological Society of America Special paper 239*, p. 367-378.
- Hook, R., 1981, The volcanic stratigraphy of the Mickey Hot Springs area, Harney County, Oregon: Corvallis: Oregon: Oregon State University, unpublished M.S. thesis, 66 p.

- Kharaka, Y. K., Mariner, R. H., Ambats, G., Evans, W. C., White, L. D., Bullen, T. D., and Kennedy, B. M., 1990, Origins of water and solutes in the north of the Norris-Mammoth corridor, Yellowstone National Park: *Geothermal Resources Transactions*, v. 14, p. 705-714.
- Langer, V. W., 1991, *Geology and petrologic evolution of silicic and intermediate volcanic rocks underneath Steens Mountain Basalt, SE Oregon*: Corvallis, Oregon: Oregon State University, unpublished M.S. thesis, 109 p.
- Minor, S. A., Rytuba, J. J., Goeldner, C. A., and Tegtmeier, H. J., 1987, *Geologic map of the Alvord Hot Springs quadrangle, Harney County, Oregon*: U.S. Geological Survey Miscellaneous Field Studies Map MF-1915, scale 1:24,000.
- Pampura, V. D., Plyusnin, G. S., and Sandimirova, G. P., 1980, Geochemical and isotopic composition of strontium in mineral forming solutions of the Pauzhetka hydrothermal system (Southern Kamchatka): *Geokhimiya*, v. 1, p. 122-135.
- Plyusnin, G. S., Sandimirova, G. P., Pakhol'chenko, Yu. A., Lomonosov, I. S. and Rzhechitskiy, Yu. P., 1978, Origin of recent hydrothermal solutions of the Baykal Rift zone according to isotope ratios: *Geochemistry International*, v. 15 no.5, p. 83-89.
- Ross, C. P., 1942, Quicksilver deposits in the Steens and Pueblo Mountains southern Oregon: U.S. Geological Survey Bulletin 931-J, p. 227-258.
- Rytuba, J. J., and McKee, E. H., 1984, Peralkaline ash flow tuffs and calderas of the McDermitt volcanic field, southeast Oregon and north central Nevada: *Journal of Geophysical Research*, v. 89, p. 8616-8628.
- Rytuba, J. J., Vander Meulen, D. B., Vercoutere, T. L., and Minor, S. A., 1982, *Reconnaissance geologic map of the Borax Lake Quadrangle, Harney County, Oregon*: U.S. Geological Survey Open-File Report 82-1126.
- Sorey, M. L., Suemnicht, G. A., Sturchio, N. C., and Nordquist, G. A., 1991, New evidence on the hydrothermal system in Long Valley caldera, California, from wells, fluid sampling, electrical geophysics, and age determinations of hot-spring deposits: *Journal of Volcanology and Geothermal Research*, v. 48, p. 229-263.
- Stettler, A. and Allegre, C. J., 1978, ^{87}Rb - ^{87}Sr studies of waters in a geothermal area: The Cantal, France: *Earth and Planetary Science Letters*, v. 38, p. 364-372.
- Taylor, H. P., 1974, The application of hydrogen and oxygen isotopes to problems of hydrothermal alteration and ore deposition: *Economic Geology*, v. 68, p. 843-883.

Vuataz, F-D., Goff, F., Fouillac, C., Calvez, J-Y., 1988, A strontium isotope study of the VC-1 core hole and associated hydrothermal fluids and rocks from Valles caldera, Jemez Mountains, New Mexico: *Journal of Geophysical Research*, v. 93, p. 6059-6067.

Williams, H., and Compton, R. R., 1953, Quicksilver deposits of the Steens Mountain and Pueblo Mountains, southeast Oregon: *U.S. Geological Survey Bulletin* 995-B, p. 19-77.