Geological Society of America
Special Paper 353
2002

Chemical characteristics of thermal water beneath the eastern Snake River Plain

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ABSTRACT

The eastern Snake River Plain aquifer is among the largest and most productive aquifers in the United States. Protection of this resource requires an understanding of the dominant mechanisms that control groundwater chemistry in the eastern Snake River Plain aquifer. To assess the chemistry of the deeper waters of the aquifer, two deep thermal wells and numerous thermal springs were evaluated. The results of this study indicate that the eastern Snake River Plain aquifer is composed of two systems, the upper aquifer, from which most water is produced, and a deep thermal aquifer. The chemistry of the upper aquifer is dominated by Ca-Mg-HCO_3, typical of groundwater in the arid west. The deep thermal system consists of Na-K-HCO_3 water. The difference in water chemistry between the upper and lower aquifers is the result of longer residence times and more water-rock interaction within the deep system. Differences in composition of the deep thermal waters may reflect the variety of types of aquifer host rock.

INTRODUCTION

The eastern Snake River Plain aquifer in eastern Idaho is among the largest and most productive aquifers in the United Sates. The aquifer is used as a groundwater resource and also provides significant recharge to the Snake River. Past and current activities at the Idaho National Engineering and Environmental Laboratory (INEEL), including reactor research, nuclear fuel reprocessing, nuclear waste storage, and other nuclear research, represent real or perceived risks to the eastern Snake River Plain aquifer. Quantification of these risks requires improved understanding of local (e.g., waste disposal practices) and regional (e.g., groundwater recharge and mixing) processes that influence the quality of groundwater in the aquifer. Enhanced characterization of large-scale rapid groundwater flow paths and the improved quantification of the role of water mixing and geochemical reactions in the evolution of water quality are of particular interest.

The eastern Snake River Plain is an arcuate structural depression 50–100 km wide by 300 km long and encompasses ~12 700 km^2 in southeastern Idaho (Fig. 1). The eastern Snake River Plain aquifer is composed of a sequence of basalt flows interlayered with fluvial sediments and loess. Individual basalt flows of relatively small volume were extruded primarily from northwest-trending fracture systems or from numerous small shields. At depths greater than ~1 km, welded rhyolite tuff and tuffaceous sediments dominate the eastern Snake River Plain (Pierce and Morgan, 1992). Recent volcanic activity on the

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McLing, T.L., Smith, R.W., and Johnson, T.M., 2002, Chemical characteristics of thermal water beneath the eastern Snake River Plain, *in* Link, P.K., and Mink, L.L., eds., Geology, Hydrogeology, and Environmental Remediation: Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho: Boulder, Colorado, Geological Society of America Special Paper 353, p. 205–211.

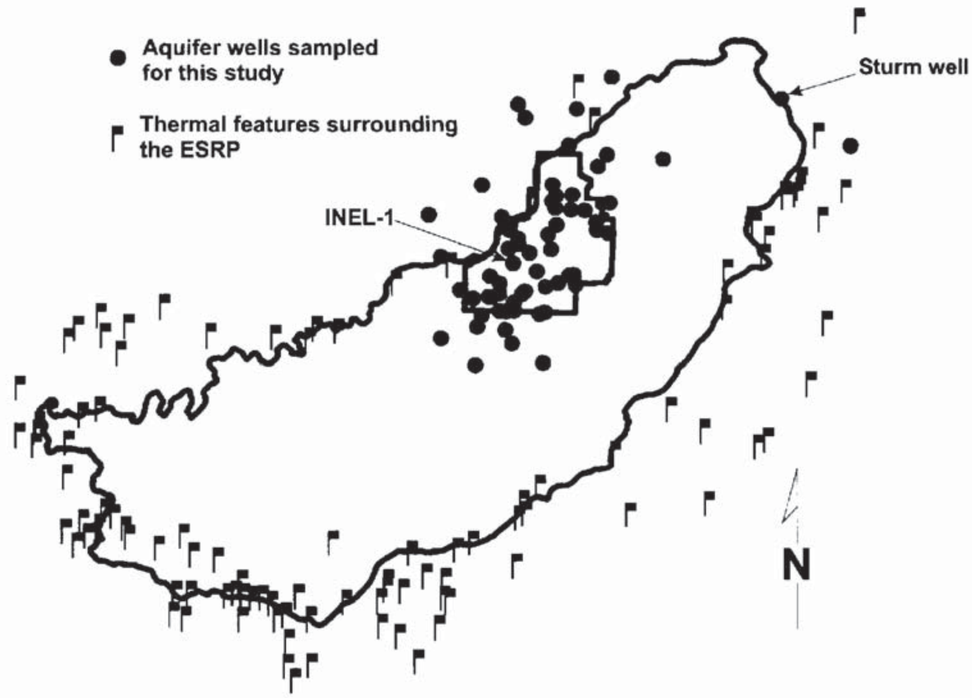

Figure 1. Location map showing eastern Snake River Plain (ESRP) and location of aquifer wells sampled for this study and thermal features located proximal to boundary of plain.

eastern Snake River Plain has resulted in a very high geothermal gradient of 40–50 °C/km (Blackwell, 1992), manifested by numerous thermal springs around the periphery of the eastern Snake River Plain.

Recharge to the aquifer is primarily from the drainage of highlands north of the plain (McLing, 1994). Groundwater is discharged to the Snake River through a series of springs near Hagerman, Idaho, ~260 km southwest of the INEEL (Wood and Low, 1988).

The aquifer is composed of two systems. The shallow, or effective, portion of the aquifer occurs from the water table (60–200 m below land surface [bls]), to a depth of 300–500 m bls. Fast-moving, (1.52–10.51 m/day), cold (9–15 °C), Ca- and Mg-rich waters characterize this part of the aquifer (Mann, 1986). The deeper portion of the aquifer is characterized by slower moving (0.006–0.091 m/day), warm (>30 °C) water (Mann, 1986). Although a sharp contact between these two systems is not always observed, changes in geothermal gradients can be used to delineate the two systems, as shown in Figure 2. The composition and extent of the lower system and the extent of its interactions with the upper system are the subjects of this chapter.

Thermal water derived from beneath the effective portion of the eastern Snake River Plain aquifer (the upper 100–400 m) has long been suspected of being a source of dissolved groundwater constituents (Robertson et al., 1974). Early investigators focused on numerous thermal springs that occur along the margins of the eastern Snake River Plain and the lack of such features on the plain to infer deep groundwater composition (Robertson et al., 1974; McLing, 1994). As part of INEEL efforts

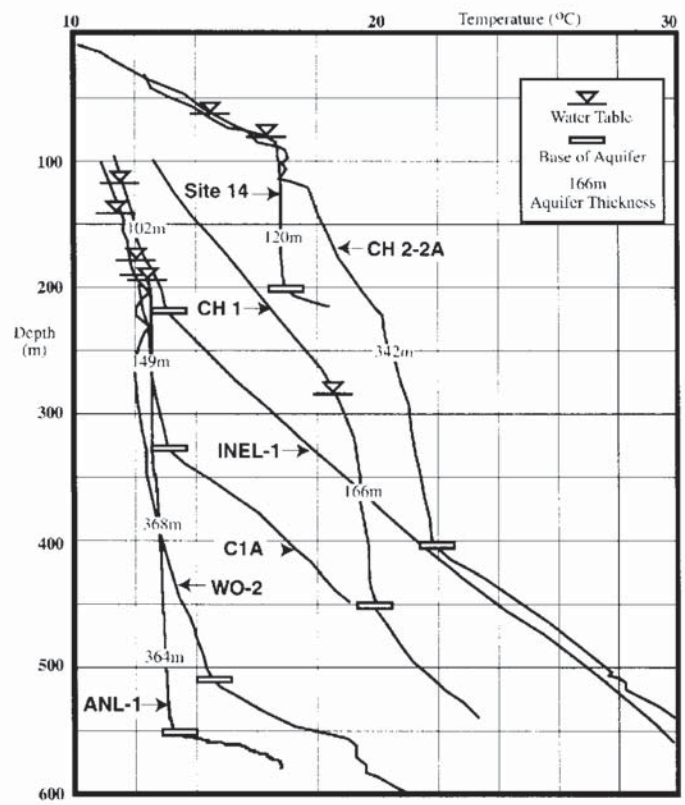

Figure 2. Temperature logs of wells and exploration drill holes that penetrate base of aquifer (from Blackwell, 1992).

in the early 1980s to assess the geothermal potential of the eastern Snake River Plain, the 3400 m INEL-1 well (Fig. 1) was drilled, and groundwater samples were collected at several depths (Mann, 1986). These groundwater samples show a progression from deep, warm, Na-HCO_3 waters to cooler Ca-Mg-HCO_3 waters at shallower depths (Table 1). Furthermore, the range in composition with depth in INEL-1 is similar to the range of compositions seen in thermal springs (Fig. 3) (Mariner et al., 1995). Although Mann's work (1986) provides significant insight into the nature of deep thermal water at a single location, samples of deep groundwater from additional wells and springs are needed to access spatial variability of deep groundwater composition. One such well and a subject of this paper is the 1000-m-deep Sturm well located near Ashton, Idaho (Fig. 1). Water samples collected from this well were analyzed for major and minor chemical species and for strontium isotopes. In addition, archived water samples from INEL-1 were analyzed for strontium isotopes. The results reported here are part of an ongoing study to delineate regional aquifer flow paths through the use of natural chemical tracers and isotopic ratios (Smith and McLing, 1998; Lou et al., 2000).

METHODS

Filtered (0.45 μm) groundwater samples were collected from the wells listed in Table 1, after purging three well-bore volumes. Because the Sturm well continually produces water under natural flow, purging was not required. Field measurements of pH, temperature, conductivity, and alkalinity were conducted by standard methods. Water samples were preserved using ultrapure HNO_3 and were shipped on ice for laboratory analyses of strontium isotopic ratios, cations, trace metals, and anions.

Selected thermal springs were also sampled using a peristaltic pump and 0.45 μm filter. The pH, temperature, and alkalinity were measured in the field, and samples were preserved and handled as described here. In addition, archived groundwater samples from INEL-1, collected by the U.S. Geological Survey in 1986, were used for strontium isotope and trace metal analyses.

Determination of 14 cations and trace metals (Li, B, Na, Mg, Al, Si, P, K, Ca, Mn, Fe, Sr, Ba, and U) was conducted by inductively coupled plasma mass spectroscopy (ICP-MS) with standard operating procedures using Ge and In as internal standards. Nominal uncertainty for the ICP-MS measurements is 5%, although duplicate measurements suggest that the reproducibility is generally much better than this. Anions were determined by ion chromatography. Strontium for isotope ratio analysis was concentrated from the water samples using Sr-specific cation exchange resin and determined by thermal ionization mass spectroscopy.

RESULTS

The strontium isotopic ratios, cation, and anion concentrations of selected aquifer and thermal water collected in this study are presented in Table 1, as are anion concentrations for INEL-1 reported in Mann (1986). These results, along with the results of Mariner et al. (1995) for thermal springs, are presented in Figure 3.

DISCUSSION

Although there are few thermal springs on the Snake River Plain, the high heat flow (Blackwell, 1992) and recent volcanic activity suggest the presence of geothermal potential beneath the eastern Snake River Plain. However, it is difficult to quantify the chemical contribution of geothermal waters to the upper portion of the aquifer, because there are a limited number of wells that sample the lower portion of the aquifer. These wells include INEL-1 and the rhyolite-hosted Sturm well. In addition, the chemistry of deep water may be inferred from the thermal springs on the margins of the eastern Snake River Plain. The new chemical data for thermal springs that are reported here complement previously reported compositions for thermal springs reported by Mariner et al. (1995).

Figure 4 is a Piper diagram showing the composition of eastern Snake River Plain groundwater collected from wells (including INEL-1 and Sturm). Most of these wells are completed in the upper portion of the aquifer, and specific sampling

TABLE 1. CHEMISTRY OF SELECTED AQUIFER WATERS AND THERMAL WATERS NEAR THE INEEL MG/L

Location	Ca	Mg	K	Na	SO_4	Cl	HCO_3	$^{87}Sr/^{86}Sr$
Condie HS	61.3	11.5	18	58.1	26.6	13.6	361.5	0.71440
Liddy HS	88	16	15	27	200	6.7	174	0.71082
Warm Spring	60.2	23.1	3.66	11.11	175	8.9	158.6	0.71434
Sturm	3.8	0.02	0.84	32.13	4.56	3.0	74	0.70871
INEL-1 > 1460 m (Anion data from Mann, 1986)	7.0	0.5	7.3	385	99	12	740	0.70980
INEL-1 1066–1460 m (Anion data from Mann, 1986)	8.9	1.1	8.1	370	97	13	670	Not analyzed
INEL-1 460–670 ft (Anion data from Mann, 1986)	8.2	2.0	10	92	32	17	210	0.70935
Big Lost River	37.5	9.9	1.4	5.80	18	4.8	200	0.71056
Little Lost River	31.1	12.6	1.2	6.51	16	8.8	177	0.71256
Birch Creek	41.2	14.3	1.5	6.07	4.5	25	164	0.71198
Yellowstone Plateau	10.1	6.2	9.06	4.52	3.5	3.7	63	0.70930
Site 17	54	17	1.3	10	16	11	228	0.710912

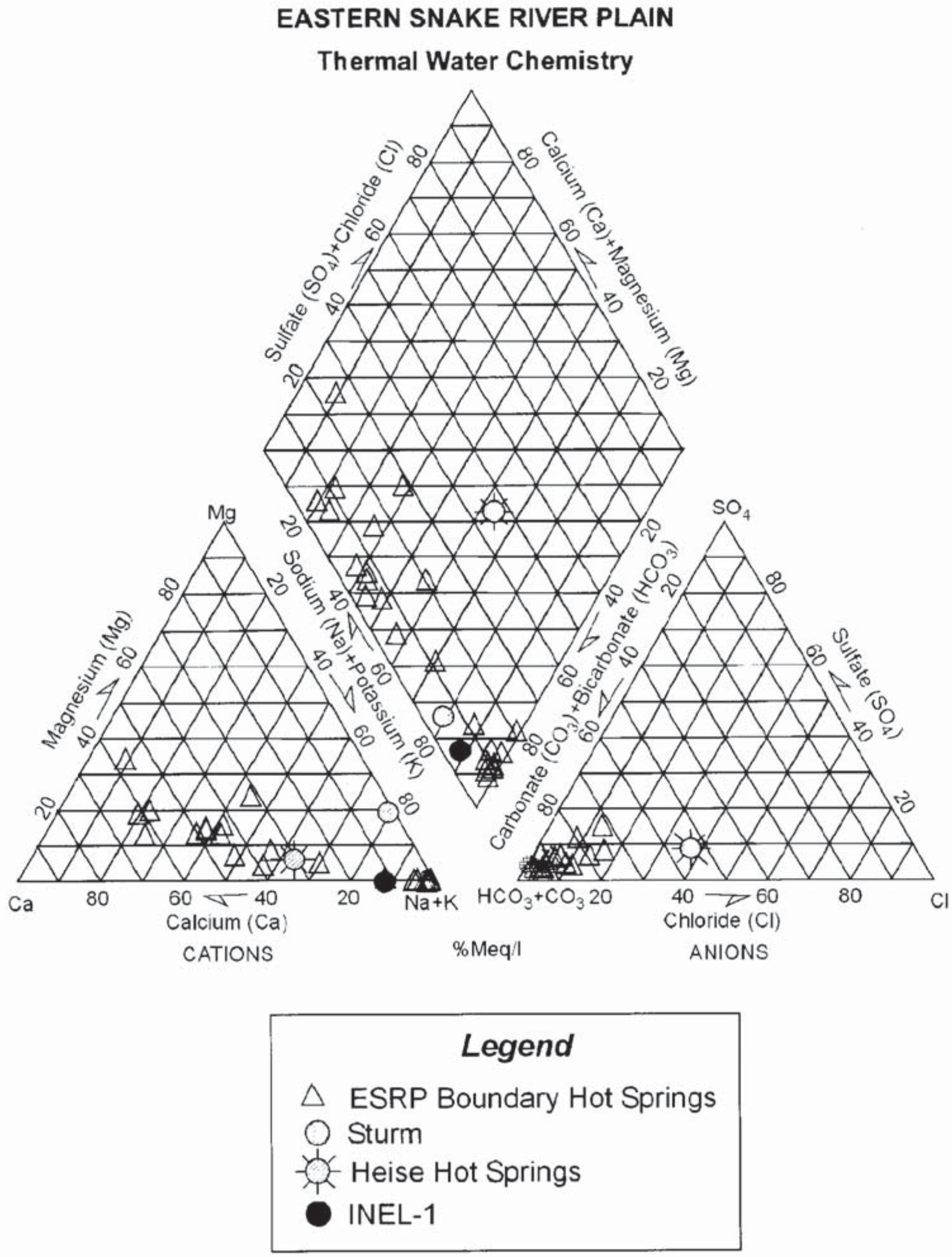

Figure 3. Water chemistries for monitoring wells and thermal springs located on eastern Snake River Plain (ESRP).

horizons are unknown. The Ca-Mg-HCO_3 waters characteristic of the upper portion of the aquifer are distinct from the two deep wells that are Na-K-HCO_3 waters. In addition, some data are intermediate between the deep wells and the upper aquifer, suggesting some mixing of water from these two sources. The lack of significant data between these two end-members may reflect a lack of water samples from intermediate depths, small amounts of mixing, or both.

Although the Sturm and INEL-1 water chemistries plot within the same region on a Piper diagram (Fig. 3), reflecting the dominance of Na and K in the cation balance, there are significant concentration differences between the two wells (Table 1). The INEL-1 water has a much higher total concentration than does the Sturm well water. The higher solute concentrations in INEL-1 water may indicate more extensive rock-water interactions than for Sturm well waters and also may indicate that the INEL-1 water has interacted with a greater diversity of host rock types. This conjecture is supported by the measured 35 ka age for INEL-1 water (Mann, 1986) and the fact that shallow aquifer water from wells near INEL-1 contains lower concentrations of dissolved minerals than deeper water. Although age dating for Sturm well water is not available, its location near the Yellowstone Plateau recharge region argues for a younger age.

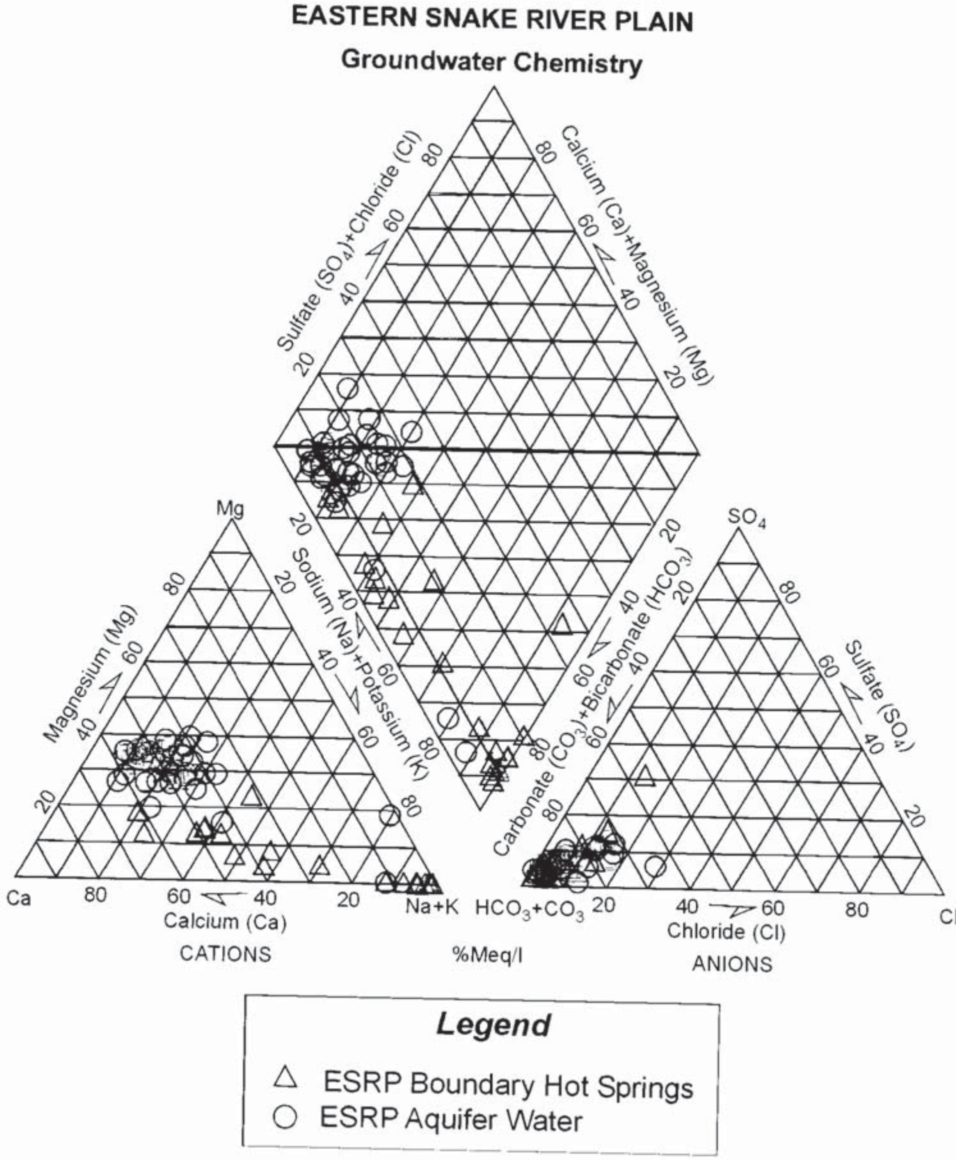

Figure 4. Piper diagram showing water chemistries from eastern Snake River Plain (ESRP) aquifer wells and thermal waters sampled for this study.

Speciation calculations using MINTEQA2 indicate that water from INEL-1 is supersaturated with calcite, while water from Sturm well is undersaturated with calcite. Supersaturation with calcite is characteristic of the upper aquifer and may reflect interactions with Paleozoic and Mesozoic carbonates within the recharge areas located to the north of the eastern Snake River Plain (Robertson, 1974). Calcite undersaturation is consistent with water recharged in the silicic rocks of the Yellowstone Plateau. Other potential explanations for the observed differences in saturation states include cation exchange and/or the dissolution of plagioclase and other minerals in the basalt host rock. Although ion exchange is a process that is likely occurring in the eastern Snake River Plain aquifer, it cannot be the dominant process controlling water chemistry because anions such as chloride that are expected to be conserved during cation exchange show significant variation. In addition, previous investigators (Wood and Low, 1988; McLing, 1994) concluded that the weathering of mineral phases in basalt is of minimal importance in the aquifer.

The $^{87}Sr/^{86}Sr$ isotope ratios for Sturm well water and INEL-1 water are 0.70871 and 0.70980, respectively. The value of 0.70980 for deep INEL-1 water is much lower than the value of 0.71091 that is characteristic of the upper aquifer in the vicinity of the well (see following section). The $^{87}Sr/^{86}Sr$ isotopic ratio for INEL-1 water is intermediate between the values of the upper aquifer and the values measured for deep silicic rock on the eastern Snake River Plain (0.7067–0.7072; M. McCurry, 1998, written commun.), suggesting that significant water-rock interactions have occurred. In addition, physical observation and previous studies of deep INEL-1 core show that significant diagenesis has occurred in the deep aquifer (Mann, 1986; Morse and McCurry, this volume).

The isotopic ratio of 0.70871 for Sturm well water is lower than for INEL-1 water (0.70980) and lower than surface water derived from the Yellowstone Plateau (0.70931), suggesting that Sturm well water may have equilibrated with the silicic volcanics. In addition, the low value, coupled with low total solute concentrations, suggests that water from the Sturm well had its source entirely within silicic volcanics of the Yellowstone Plateau.

Deep water from INEL-1 and the Sturm well are Na-K-HCO_3 type and reflect a chemistry significantly different than the Ca-Mg-HCO_3 waters of the upper portion of the aquifer. Although the deep waters share some compositional similarities, their individual chemistries reflect their differences in residence time and recharge and host rock geology (see Table 1). If the hypothesis is true that the water from the Sturm well has only reacted with silicic volcanics, then by comparison INEL-1 waters have probably undergone significant interaction with aquifer rocks, including volcanic and carbonate sequences.

GEOCHEMISTRY OF THERMAL WATERS

Examination of Figure 3 shows that most of the thermal springs bordering the eastern Snake River Plain aquifer (Fig. 1) have major ion compositions intermediate between the lower aquifer system and the upper effective portion of the aquifer. This observation suggests that these springs may be mixtures of groundwater derived from the lower and the upper aquifer systems. However, the high $^{87}Sr/^{86}Sr$ isotope ratios for many of the springs cannot be explained by simple mixing, and require Sr contributions from a source such as Paleozoic carbonate and siliciclastic rocks. We propose that the most likely explanation for the data presented in Figure 4 is that upwelling of deep thermal water is important, at least locally. The contribution of deep thermal water to the upper aquifer was first hypothesized ~30 yr ago, based on geological arguments (Robertson et al., 1974). Mann (1986) inferred from INEL-1 that as much as 19×10^6 m^3 of thermal water might be upwelling into the effective aquifer beneath the INEEL site. Wood and Low (1988) determined that, on the basis of ^{14}C and δ^2H values, water in the deep thermal system may be older than 17 ka and may have been recharged during a colder climatic time. Doherty et al. (1979) postulated that the thick sequence of unbroken volcanics in INEL-1 indicate the presence of a caldera complex and the associated ring fractures that would provide vertical conduits for upwelling thermal water. McLing (1994) assessed the relative importance of mixing and water-rock interactions in the evolution of groundwater composition along flow paths crossing the INEEL. He concluded that with the exception of the precipitation of small amounts of calcite, there were only limited water-rock interactions, and that mixing of waters from different sources accounts for the observed changes in water composition along flow paths. One of the sources McLing (1994) proposed was deep thermal water similar to that observed at Heise Hot Springs (Fig. 3). He found that only a small (<1.0%) amount of the chloride-rich Heise water was required to obtain mass balance for chloride. However, the Heise water is atypical (Fig. 2) of the thermal springs along the margin of the eastern Snake River Plain because its dominant anion is chloride rather than bicarbonate. Larger amounts of thermal waters would have been required if McLing (1994) had used waters with compositions consistent with the main trend shown in Figure 3. These lines of evidence suggest that a significant flux of thermal water impinges on the upper aquifer.

CONCLUSION

Several lines of indirect evidence support the possibility of thermal upwelling in the eastern Snake River Plain aquifer. These include diagenetic phases in well cores and high heat flows. In addition, the complete absence of geothermal springs on the recently volcanically active Snake River Plain and the large number of hot springs located on the periphery of the plain support this conclusion. While there is little doubt concerning the existence of thermal water deep in the eastern Snake River Plain aquifer, little is known about its chemistry. Examination of water compositions from two deep wells provides some information about the chemical composition of groundwater in the lower aquifer system. This study suggests that the deep Na-K-HCO_3 waters are distinct from the water of the upper aquifer system and that the deep Na-K-HCO_3 waters are widespread (based on two wells 80 km apart). However, the composition of deep waters, similar to the shallower aquifer, reflects differences in source area recharge and aquifer host rock. Water from INEL-1 has apparently undergone significant interactions with aquifer host rocks, including basalt, Paleozoic carbonates, and siliciclastic sequences. Although the areal extent of this water is unknown, it is likely that the composition is typical of deep waters that are proximal to edges of the eastern Snake River Plain. In contrast, Sturm well water has undergone only very limited interactions with rhyolitic aquifer host rocks. The chemical composition of Sturm well water is consistent with infiltrating rain or snow through the rhyolitic terrain of the Yellowstone Plateau.

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Manuscript Accepted by the Society November 2, 2000

Printed in the U.S.A.