

FLUID GEOCHEMISTRY AT THE RAFT RIVER GEOTHERMAL FIELD, IDAHO: NEW DATA AND HYDROGEOLOGICAL IMPLICATIONS

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ABSTRACT

Following a period of exploration and development in the mid-late 1970's, there was little activity at the Raft River geothermal field for the next ~20 years. US Geothermal Inc. acquired the project in 2002, and began commercial power generation in January 2008. From mid-2004 to present, US Geothermal Inc. has collected geochemical data from geothermal and monitoring wells in the field, as well as other shallow wells in the area. An additional sampling program was completed in July 2010 to measure a wider range of trace elements and key water isotopes ($\delta^{18}\text{O}$, δD , and ^3H (Tritium)) in the field. The data indicate that the fluid geochemistry in the field is spatially variable and complex, with two distinct deep geothermal fluid types (high vs. low K, Na, Cl, Ca, Li, F concentrations) and two groundwater fluid types. These differences have been interpreted to reflect deep structural controls on fluid pathways in the field, which has compartmentalized the fluids and limited the degree of mixing between them.

1. INTRODUCTION

The Raft River area was designated a Known Geothermal Resource Area (KGRA) in 1971, and in 1973 the United States Geological Survey (USGS) and Energy Research and Development Administration (ERDA, now the Department of Energy (DoE)) began a geothermal exploration program in southern Idaho. Between 1974 and 1980, 84 wells were drilled at Raft River, including 7 deep wells that formed the basis for a geothermal demonstration plant (Covington, 1980). This plant operated from late 1981 until June 1982, generating 4 MWe net from geothermal fluids that ranged in temperature between 135-145°C. Following a change in government priorities, the DoE declared the project a success and sold off the plant equipment. The Raft River site remained untouched for the next 20 years. US Geothermal Inc. acquired the site in mid-2002, and after upgrading existing wells and

drilling additional wells, a binary plant was installed. The field began generating ~10 MWe in January 2008. The field contains 9 deep geothermal wells (> 1500 m depth), 4 are currently used for production (RRG-1, RRG-2, RRG-4, RRG-7) and 3 for reinjection (RRG-3, RRG-6, RRG-11). Production temperatures are approximately 140 °C, with a total production rate of ~400 kg/s. The production wells generally produce from the Precambrian basement, which is intersected at approximately 1400 m depth on the northwest side of the field, and approximately 1750 m depth on the southeast side of the field. Well RRG-9 is currently the focus of a DoE-funded EGS project that will stimulate the well to increase near-well-bore permeability. If successful, this well will be used for production or injection.

2. GEOLOGIC SETTING

The Raft River valley is located in Cassia County, south-western Idaho, on the north-eastern edge of the Basin and Range province and on the southern side of the Snake River Plain (which demarcates the Yellowstone hotspot trace)(Figure 1a). The valley is approximately 60 km long and 20 km wide, and the valley floor lies at an average elevation of 1400 m above MSL (mean sea level). The geology in the valley is complex, and reflects the combined influences of these two geologic terrains. Precambrian metamorphic rocks are found to the west and south in the Albion and Raft River Mountains, and also underlie the Raft River basin where they form the primary reservoir of the geothermal system: lithologies include quartzite, schist and quartz monzonite (Covington, 1980; Williams *et al.*, 1982; Blackett & Kolesar, 1983). To the immediate west lie the Jim Sage Mountains and the Cotterel Mountains, consisting of Late Tertiary rhyolites and tuffs that erupted when the Yellowstone thermal pulse was situated to the north of the Raft River basin (Christiansen and Lipman, 1972). To the east lie the Black Pine and Sublett Mountains that expose allochthonous Paleozoic limestone, siltstone and shale. The Raft River basin consists of ~1800 m

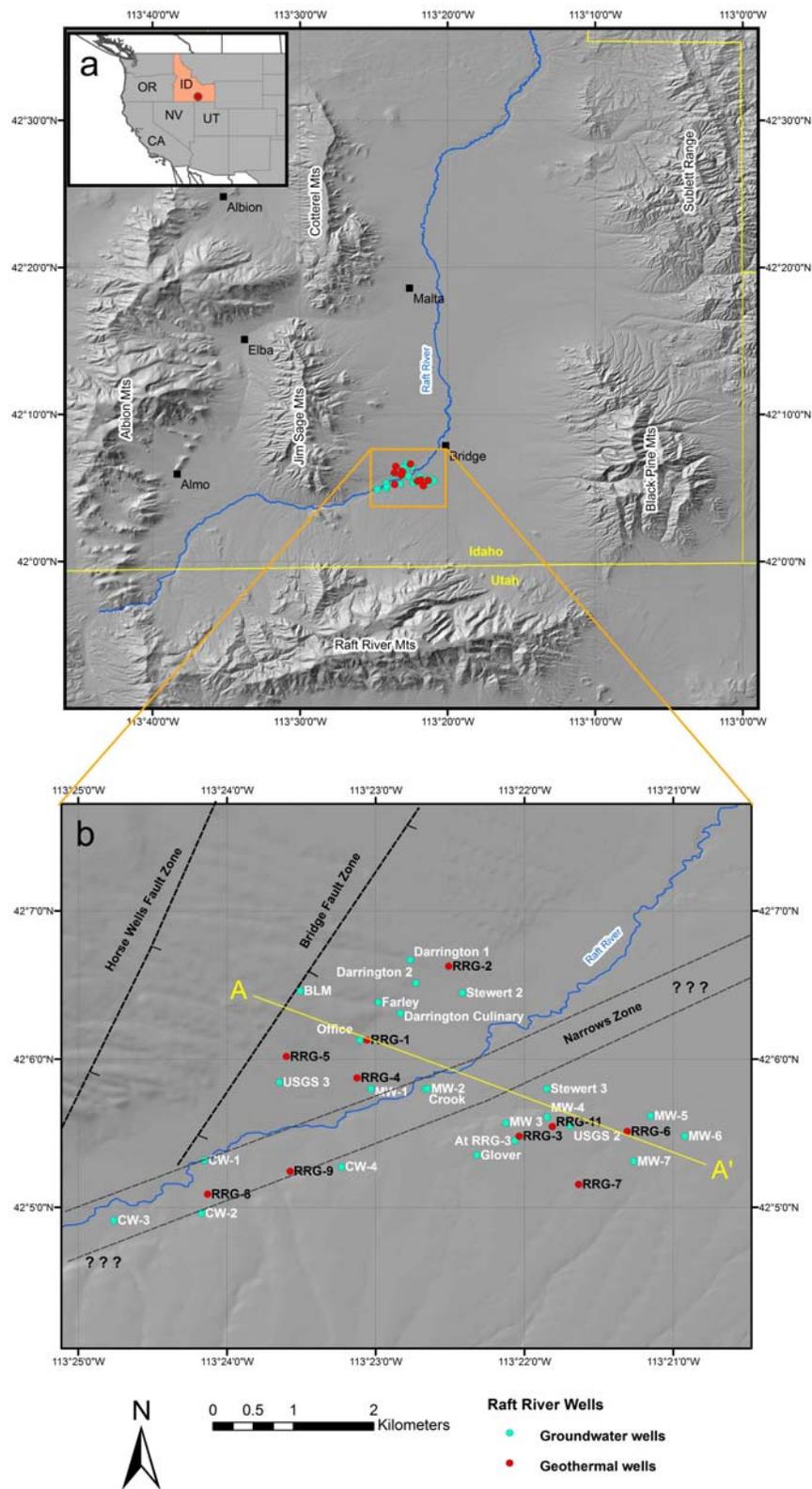


Figure 1 (a): Physiographic setting of the Raft River geothermal field (inset- location within the western USA)
 (b) Locations of the geothermal and groundwater wells, inferred structural features and cross section location.

of Tertiary and Quaternary infill sediments and volcanic rock overlying the Precambrian basement. The top 300 m of basin fill defines the Raft River Formation, composed of fluvial, alluvial and loess sediments that are lenticular and gradational in nature. The underlying Salt Lake Formation consists of Miocene-Pliocene lacustrine deposits and volcanic tuffs and flows. The basement contact gently dips to the east and is inferred to be a detachment surface (Williams et al., 1982).

Two major fault zones have been identified on the west side of the valley: the Bridge Fault Zone and the Horse Wells Fault Zone (Figure 1b). Both zones strike approximately north-south; the faults are inferred to be listric in nature, flattening at the basement-sediment contact (Dolenc et al., 1981). The NW production wells are believed to intersect permeable zones associated with the Bridge Fault (or adjacent parallel fault(s)). From geophysical data, another major structure has been inferred to exist beneath the Tertiary deposits - the Narrows Zone, which trends northeast-southwest and has been interpreted as a basement shear (Mabey et al., 1978). The morphology of this zone is not well characterized, however it appears the Bridge and Horse Wells Faults terminate at their southern ends against the proposed Narrows Structure (Mabey et al., 1978; Dolenc et al., 1981). The intersection of the assumed Narrows Zone and Bridge Fault Zone plays an integral role in controlling the location of the upflow zone in the geothermal system.

3. DATA SOURCES

The geochemical data includes analyses collected as part of the early DoE studies as well as recently acquired monitoring data collected by U.S. Geothermal after 2004. Additional samples were collected in July 2010 for tritium, stable isotopes (^2H , ^{18}O) and a wider range of dissolved species. The complete dataset includes samples analyzed from the geothermal wells (RRG-1, RRG-2, RRG-3, RRG-4, RRG-6, RRG-7, RRG-11, RRG-9), monitoring wells (MW-2, -3, -4, -5, -6, -7), shallow geothermal wells (BLM, USGS-1,-2,-3) and groundwater wells in the vicinity of the producing field (CW-1, -2, -3, -4, Darrington Culinary, Stewart-2, -3, Crook, Farley, Glover) (see Figure 1b for map view of the well locations). In this study, only the chemical data from the production wells are used for interpretation: geothermal wells RRG-3, RRG-6 and RRG-11 produced fluids for a short time before they were converted to injection in September-October 2007 and analyses of these production fluids are used to characterize the fluid geochemistry from these wells. However additional complexity lies in the nature of the well completions: RRG-3,-6 and -11 were completed as injection wells and were not cased to

the same depths as the production wells. Thus these wells have long open-hole sections in the Tertiary sediments overlying the basement. Consequently, past production intervals for these wells are not well constrained, and the fluid chemistry may represent a mixture of waters from the sedimentary section and basement.

4. RESULTS

4.1 Aqueous chemistry

The geothermal reservoir fluids at Raft River are neutral-pH, alkali chloride waters with low sulfate and bicarbonate contents. The fluids from the shallower monitoring wells are typically also 'mature'. The shallowest groundwater shows the greatest range in chemical composition and trends towards increased HCO_3 concentrations.

Although all geothermal waters are alkali chloride type, there are some distinct differences in the water geochemistry between the southeastern (SE) and northwestern (NW) parts of the currently-exploited field. Waters sampled from the SE geothermal wells (closest to the center of the Raft River Basin; RRG-3, RRG-6, RRG-7, RRG-11) are generally enriched in K, Li, Ca, Cl, Na and depleted in F compared to waters sampled from the NW wells (RRG-1, RRG-2, RRG-5) (Figure 2). In addition, there is greater geochemical variability in the waters collected from the SE wells. Dissolved SO_4 , Mn, Mg and SiO_2 appear similar across the valley. We infer from these data that there are two deep fluid types with distinctive chemical signatures, and that these do not appear to reflect mixing between deep and shallow fluids. Variation in chloride concentration does not correspond to a difference in measured or inferred fluid temperatures: production fluid temperature from both sides of the field is approximately 140 °C, and silica and cation geothermometry results are also in agreement.

Additional complexity lies in the chemistry of the shallow groundwater (<320 m depth). Again there are two distinct fluid types. One is very low in dissolved salts and typically has Mg concentrations above 10 mg/l. Wells that fall into this group include CW-1, CW-2, CW-3, MW-5 and MW-7, Glover, Stewart-2, Darrington-1 and -2, RRG-3 Culinary and Office Domestic and these are collectively referred to as Groundwater Group 1. These fluids represent a shallow, low-salinity groundwater end-member for the Raft River field. The other groundwater group is characterized by higher dissolved salt concentrations, and lower Mg (<10 mg/l). This group includes CW-4, monitoring wells MW-1, -2, -3, 4, -6, Crook and USGS-3 and is referred to as Groundwater Group 2 hereafter (Figure 3). Groundwater Group 1 wells have a broad spatial extent, spanning most of

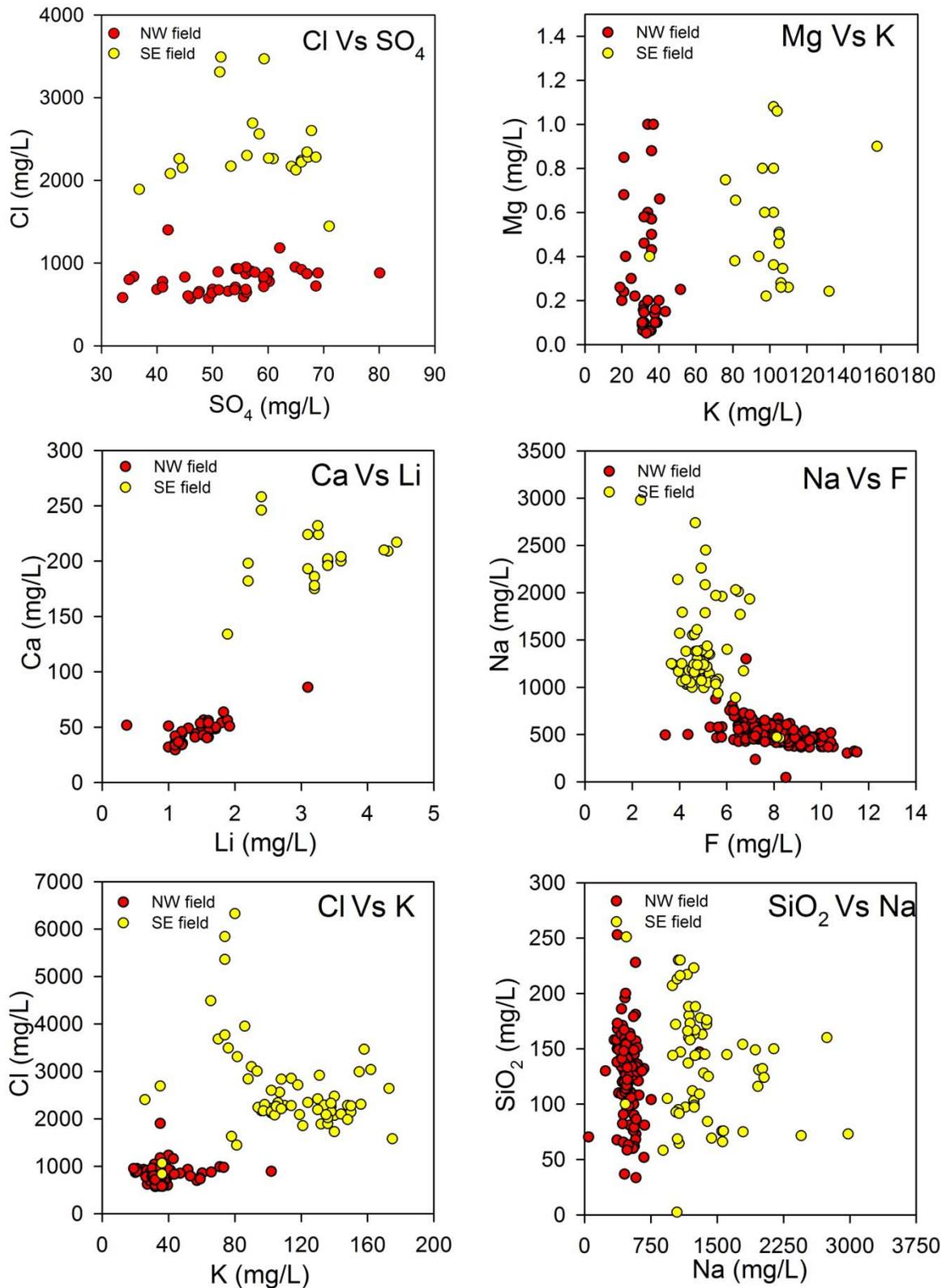


Figure 2: Scatter plots illustrating chemical signatures of the two deep geothermal fluids at Raft River.

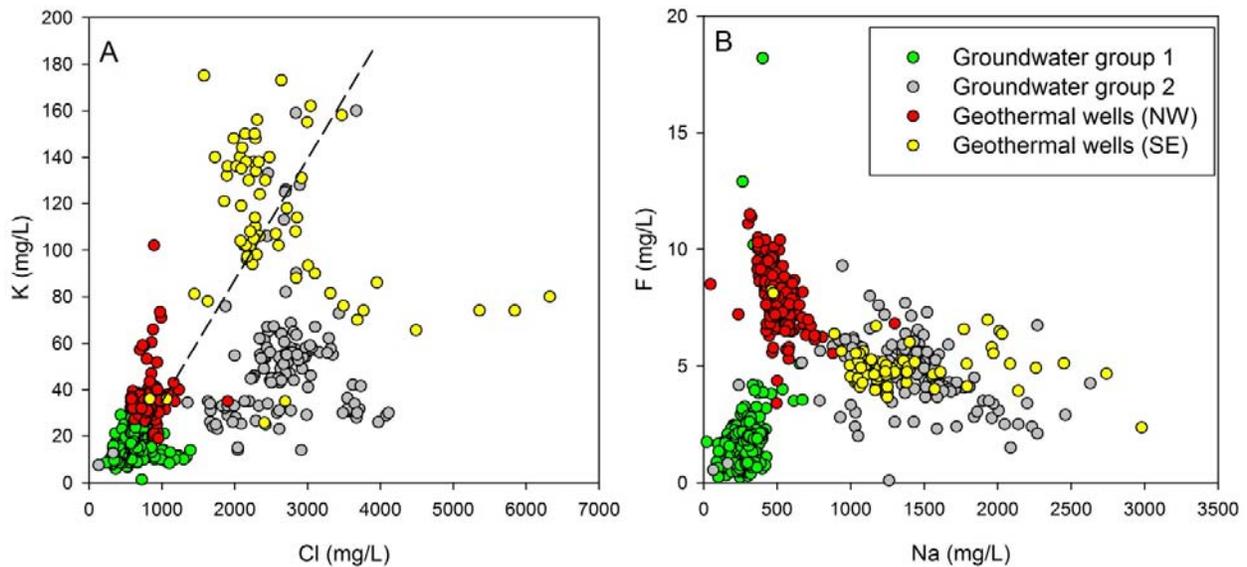


Figure 3: Cross plots illustrating the four fluid types at Raft River (a) Cl Vs. K (b) Na Vs. F.

the field (refer to Figure 1b), whereas Groundwater Group 2 wells are more tightly-clustered around the center of the field. The two groups do not appear to be separated on the basis of well depth, however on average, Group 2 fluids correspond to greater depths.

The chemical signature of both groundwater groups is distinct from the two deep geothermal fluid types. Groundwater Group 2 fluids and the deep SE geothermal fluids share many characteristics (high Cl, Na and F) but are differentiated on the basis of K and Mg: Groundwater Group 2 fluids have much lower K and slightly higher Mg. Given these similarities and differences, it appears that the deep SE geothermal fluid and Groundwater Group 2 may have similar parent fluids, which have since re-equilibrated at different temperatures. It does not appear that the source of Groundwater Group 2 fluid is due to mixing between the SE geothermal fluids and either the shallow groundwater or NW geothermal fluid: the data do not fall on mixing lines between the two (Figure 3).

4.2 Geothermometry

Of the four defined fluid types (SE deep geothermal, NW deep geothermal, Groundwater Group 1 and Groundwater Group 2), all but the Groundwater Group 1 fluids appear to have equilibrated with the reservoir rocks as indicated by their positions on a Giggenbach plot (Figure 4). The geothermal fluids from both the SE and NW parts of the field plot in a linear array with a full equilibration temperature of 200-220 °C. The USGS well fluids suggest the highest equilibration temperatures at ~260 °C. Groundwater Group 2 fluids appear to be

equilibrating at temperatures between 120-180 °C. In addition, the deep geothermal fluid array is clearly separated from the Groundwater Group 2 fluids.

A few samples from the deep geothermal wells plot in the Groundwater Group 2 array (Figure 4). As mentioned earlier, RRG-6, RRG-3 and RRG-11 were all not fully cased to basement; thus the produced fluids may have represented a mixture of the intermediate-depth high-salinity fluid and the deep geothermal fluid, but the degree of mixing with the intermediate fluids is difficult to determine because they are geochemically very similar. Also, the relatively high production temperatures (>110°C) suggests the contribution is not too large. A few samples from RRG-6 are interpreted to be mixed with Groundwater Group 2 fluids as they plot well within the groundwater array (refer to Figure 4). Similarly, two samples from RRG-4 plot in this array these waters are inferred to reflect mixing with the shallow groundwater prior to deepening of this well in 1978. One sample from RRG-7 is also inferred to reflect mixing with the shallow groundwater as a result of a liner collapse.

Average silica geothermometer temperatures (conductive; Fournier (1973)) for the Raft River geothermal fluids range between 143 and 162 °C, whereas the chalcedony (conductive) geothermometer suggests average temperatures between 117 – 140 °C. As the maximum measured temperatures in each geothermal well are 140 °C to 148 °C, the quartz geothermometer appears to give better results. Cation geothermometer temperatures (Na/K, Na/K/Ca, K²/Mg, Li/ \sqrt{Mg} , and

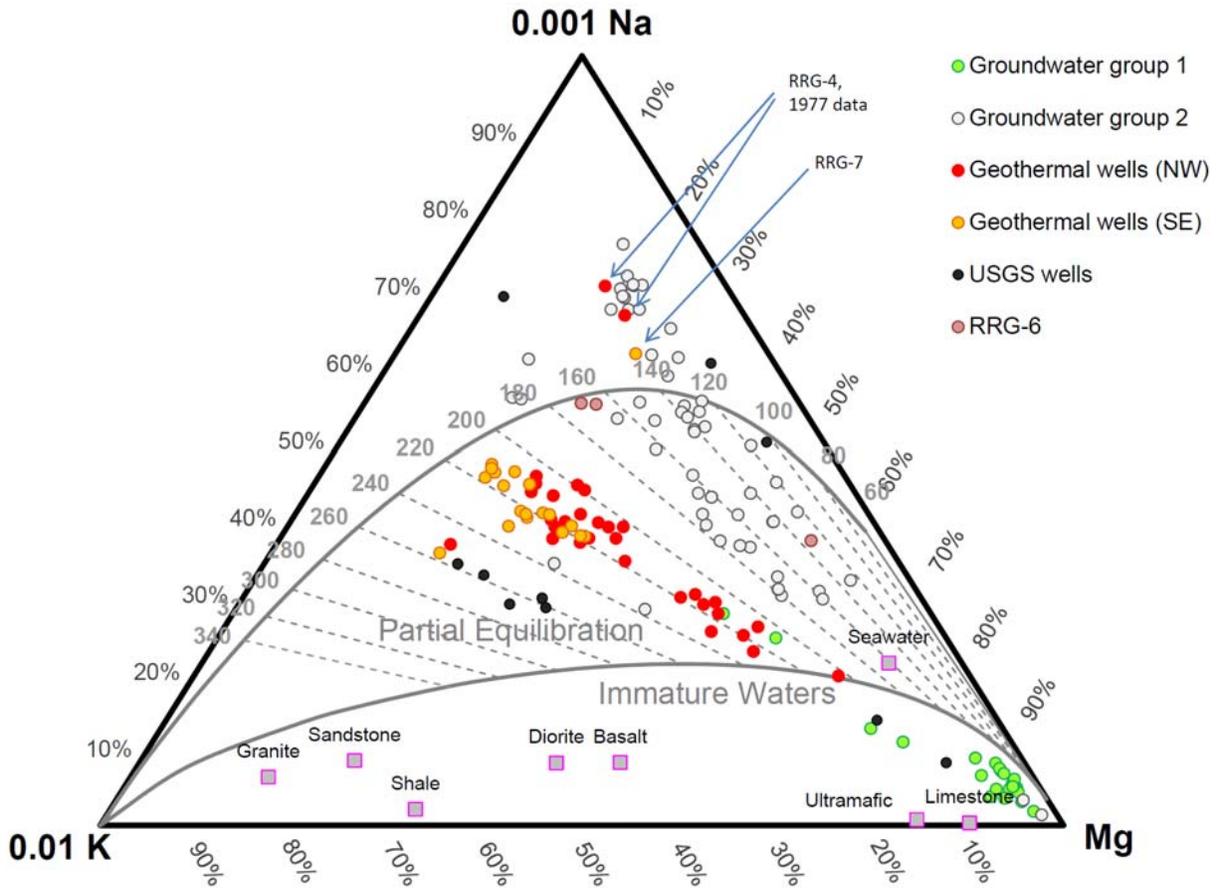


Figure 4: Giggenbach plot evaluating Na-K-Mg temperatures. Equilibration line is derived from the Giggenbach (1988) Na/K and K/Mg equations.

Table 1: Average geothermometer temperatures for the Raft River deep geothermal fluids. Temperatures in °C.

Well avg	Fournier & Potter (1982)	Fouillac & Michard (1981)	Kharaka et al. (1982)	Kharaka & Marina, (1989)	Giggenbach (1988)	Fournier (1979)	Arnorsson et al (1983) (25-250°C)	Giggenbach (1983)	Fournier & Truesdell (1973) b = 1/3
	Quartz-cond	Na/Li	Na/Li	Li/Mg	K/Mg	Na/K	Na/K	Na/K	Na-K-Ca
RRG-1	150.1	155.3	215.7	174.1	161.0	192.2	166.1	209.1	177.0
RRG-2	152.8	140.8	203.7	162.2	157.3	208.0	186.5	223.4	181.5
RRG-3	163.8	130.7	195.1	183.1	183.9	198.8	173.6	215.3	184.7
RRG-4	149.6	145.8	207.6	187.9	154.7	182.9	155.5	200.3	149.2
RRG-5	161.6	154.8	215.2	173.7	156.2	186.6	159.4	203.8	171.5
RRG-6	143.3	123.5	189.1	188.9	144.8	142.1	109.3	161.5	146.6
RRG-7	147.9	127.4	192.3	181.2	209.2	225.3	205.3	239.9	212.8
RRG-11	149.0					136.5	103.0	156.1	

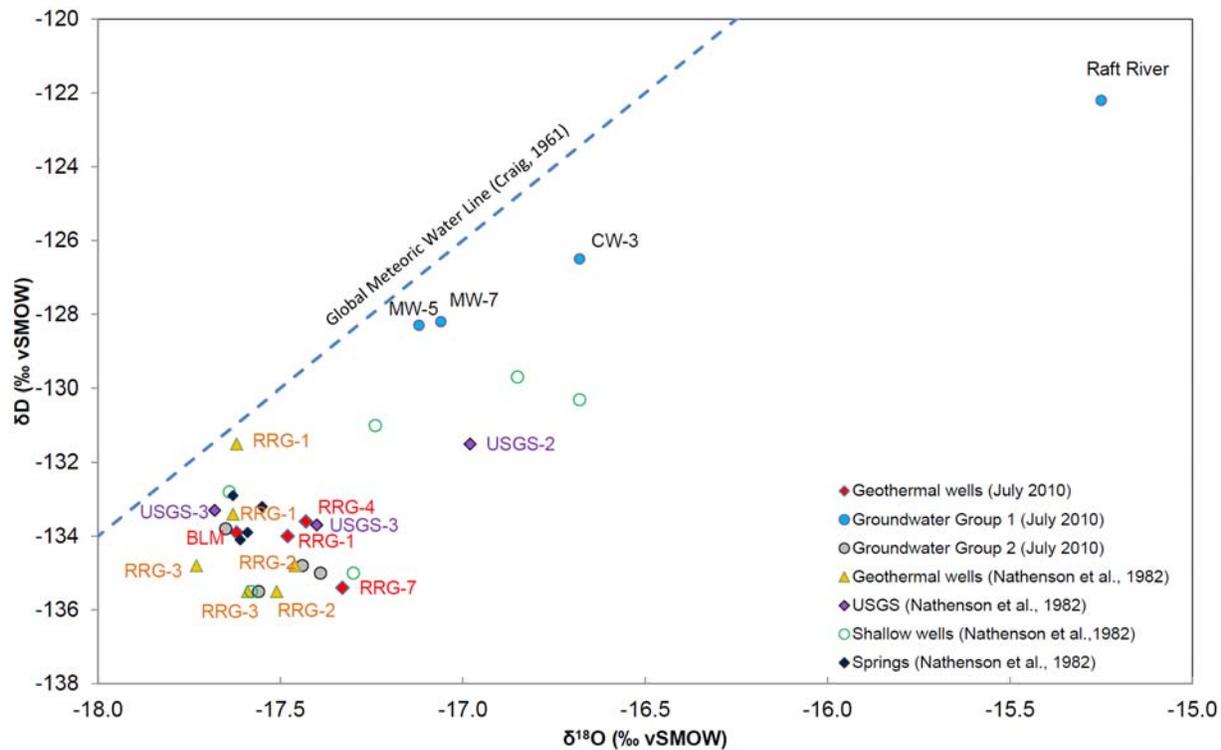


Figure 5: New stable isotope data for samples collected in the Raft River geothermal system in July 2010, plotted against the global meteoric water line from Craig (1961) and existing data collected by Nathenson et al. (1982). Data reported relative to Standard Mean Ocean Water.

Na/Li) vary between 103 and 240 °C, with typical averages in the range 150-200 °C (Table 1).

4.3 Stable Isotopes

The stable isotope data ($\delta^{18}\text{O}$ and δD) for the 12 samples collected in July 2010 are presented in Figure 5. The data are consistent with a meteoric fluid source and vary only slightly from the global meteoric water line (MWL). The majority of the measurements form a cluster of relatively-depleted ^{18}O and ^2H , with a few groundwater and surface water measurements that are more enriched in ^{18}O and ^2H trending sub-parallel to the meteoric water line (wells MW-5, MW-7 and CW-3 (= Groundwater Group 1), and the surface water measured from Raft River). The data suggest that Groundwater Group 1 fluids in the Raft River valley are not contributing to the deep geothermal system at present because the deeper geothermal fluids are all significantly more depleted in ^{18}O and ^2H . The Raft River surface sample is offset from the MWL, suggesting that the sample was affected by evaporation, which results in non-equilibration fractionation of both isotopes (Craig, 1961). Given that the sample was collected in mid-summer and the Raft River is a low-flow stream, evaporation seems likely.

Prior to the recent data collection, no stable isotope data had been collected from the Raft River area

since the early 1980's. Data that was collected from the same wells in the 1980's are also presented in Figure 5 for comparison. Although the geothermal well samples (RRG-1, RRG-2, RRG-3, RRG-4 and RRG-7) appear to have similar δD compositions, their $\delta^{18}\text{O}$ values are more scattered. The recent data are more enriched in ^{18}O compared to the earlier measurements compiled by Nathenson et al. (1982). It is not clear if this is a real feature of the data or reflects analytical differences. Regardless, the two sets of data are broadly consistent in that they define a geothermal system that has a likely source fluid with $\delta^{18}\text{O}$ and δD values around -17.7 ‰ and -136 ‰ respectively. Groundwater Group 2 fluids have similar isotopic composition to the deep geothermal fluid types, suggesting that these three fluids share a common source. The depleted values of -17.7 ‰ ($\delta^{18}\text{O}$) and -136 ‰ (δD) suggest the source fluid is either precipitation that fell at higher elevation relative to the Raft River valley or is precipitation that fell during a period of cooler climate. A few spring-water samples from Nathenson et al. (1982) are also plotted for comparison: these were sampled from the southern Albion Mountains and western Raft River Mountains (refer to Figure 1a).

4.4 Tritium

Three samples were collected for tritium from the deep geothermal wells RRG-1, RRG-4 and RRG-7,

and three were from shallower wells; the results are summarized in Table 2. These data indicate that recent (post-1950's) surface waters have not contributed to the geothermal production fluids in the Raft River field, given that they all have measured TU less than 0.11 (Clark and Fritz, 1997).

The CW-3 well is a shallow (142 m) cold well, and the relatively elevated TU value of 1.00 suggests that surface waters have contributed to this fluid. This is also consistent with the stable isotope and aqueous chemistry for CW-3 water: of the 11 groundwater and geothermal samples analyzed, CW-3 is most enriched in ^{18}O and ^2H and thus the closest to the surface water composition measured from the Raft River creek, and also has the highest magnesium and lowest chloride contents.

Measured tritium results for USGS-3 and MW-6 are the lowest of the 6 samples, suggesting that the intermediate-depth source fluids (300-450 m below surface) are also not recent and predate the 1950's.

Table 2: Tritium results

Sample I.D.	Collection date	TU \pm 0.1
RRG-1	07/12/10	0.11
RRG-4	07/12/10	0.07
RRG-7	07/12/10	0.05
CW-3	07/13/10	1.00
USGS-3	07/14/10	0.02
MW-6	07/14/10	0.03

5. INTERPRETATION

5.1 Fluid types

To summarise the characteristics of the Raft River geothermal fluids:

Groundwater Group 1: water samples from these wells have the highest Mg concentrations (~20-30 mg/l), lowest Cl, Na and K concentrations, and are isotopically-enriched (^{18}O and ^2H) compared to the rest of the field. In addition, the Tritium data for CW-3 indicates this water is the youngest of the 6 tritium samples analyzed. The Groundwater Group 1 fluid is therefore inferred to be the shallow groundwater end-member for the Raft River field.

Groundwater Group 2: characterized by the highest Ca (up to 350 mg/l), high Cl (1500-4000 mg/l), high Na, moderate K (20-70 mg/l), relatively low Mg, tritium-dead water (TU<0.8) and depleted stable isotopes (^{18}O and ^2H).

Deep Geothermal SE: characterized by the highest K (80-160 mg/l), high Cl (2000-4000 mg/l), high Na and Ca, and low Mg (<1 mg/l). Isotopically, the fluid is depleted in ^{18}O and ^2H , and is tritium dead.

Deep geothermal NW: characterized by the lowest Ca (<75 mg/l), low Cl (~1000 mg/l), Na, Ca, and Mg, moderate K, and highest F (~6-10 mg/l) compared to the other fluid types. Isotopically, the fluid is depleted in ^{18}O and ^2H , and is tritium dead.

5.2 Fluid recharge areas and implications

Groundwater Group 1 fluids are likely sourced from modern precipitation and recharge along the valley margins and through percolation through the surficial sediments. Groundwater Group 2 and the deep SE geothermal fluid types are very similar. The key differences between these two fluids are their measured temperatures, K concentrations and inferred equilibration temperatures. As such, it is interpreted that these two fluids have a common origin but have taken different pathways to the Raft River field where they have equilibrated at their respective temperatures. Given the long equilibration times required for the Na/K geothermometer, and the observed discrete nature of the two arrays on the Giggenbach plot (Figure 4), it is inferred Groundwater Group 2 fluids are not a cooled version of the deep SE geothermal fluids (i.e. the SE geothermal fluid is the parent). It is more likely the two fluids had a common parent in their past, and subsequently took different paths to the Raft River. We concur with earlier studies that attributed the high dissolved salt concentrations at intermediate depths in the field to evaporitic sediments in the Tertiary basin fill at Raft River (Molling, 2006). Given what we know about Basin and Range systems and sedimentary deposits, this is a reasonable assumption. In addition, the deep SE geothermal fluid also has high TDS, and likely had contact with evaporitic sediments in its past as well. Since well RRG-7 is producing from the Precambrian basement and these are high salinity, low Mg fluids that are fully equilibrated, accumulating Na, Cl, K etc from evaporites would had to have happened before the fluids percolated into the basement.

Despite marked differences in dissolved solutes (Cl, Na, K etc), the Groundwater Group 2 fluids and both deep geothermal fluids share similar isotopic characteristics (^{18}O , ^2H , ^3H), suggesting that the three fluids have the same parent. If the fluids are modern (but pre-1950), an area where isotopically-depleted waters are found at present is to the south of the Albion Mountains and west of the Raft River Mountains, which are up to 1500 m higher than the Raft River valley floor (Nathenson et al., 1982). This hypothesis restricts the source area for all three fluid types to one geographic area, and their subsequent

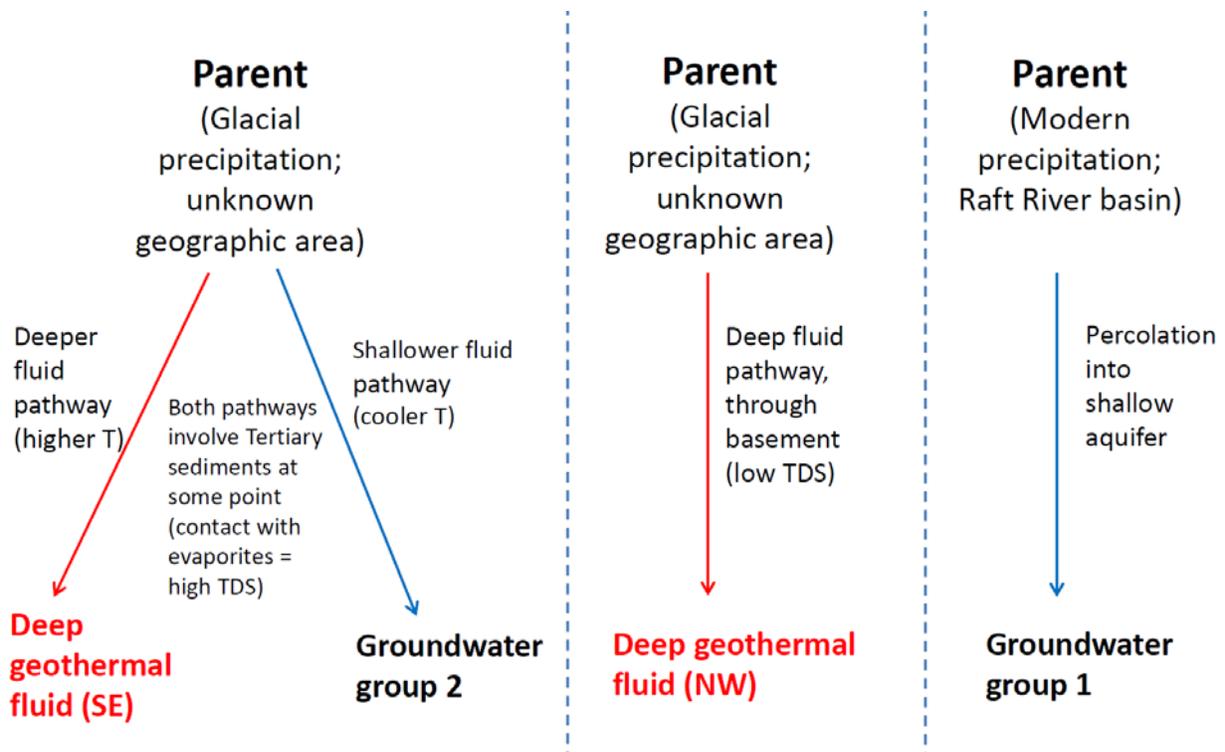


Figure 6: Schematic diagram representing sources and possible fluid pathways that are consistent with the observed water chemistry at Raft River.

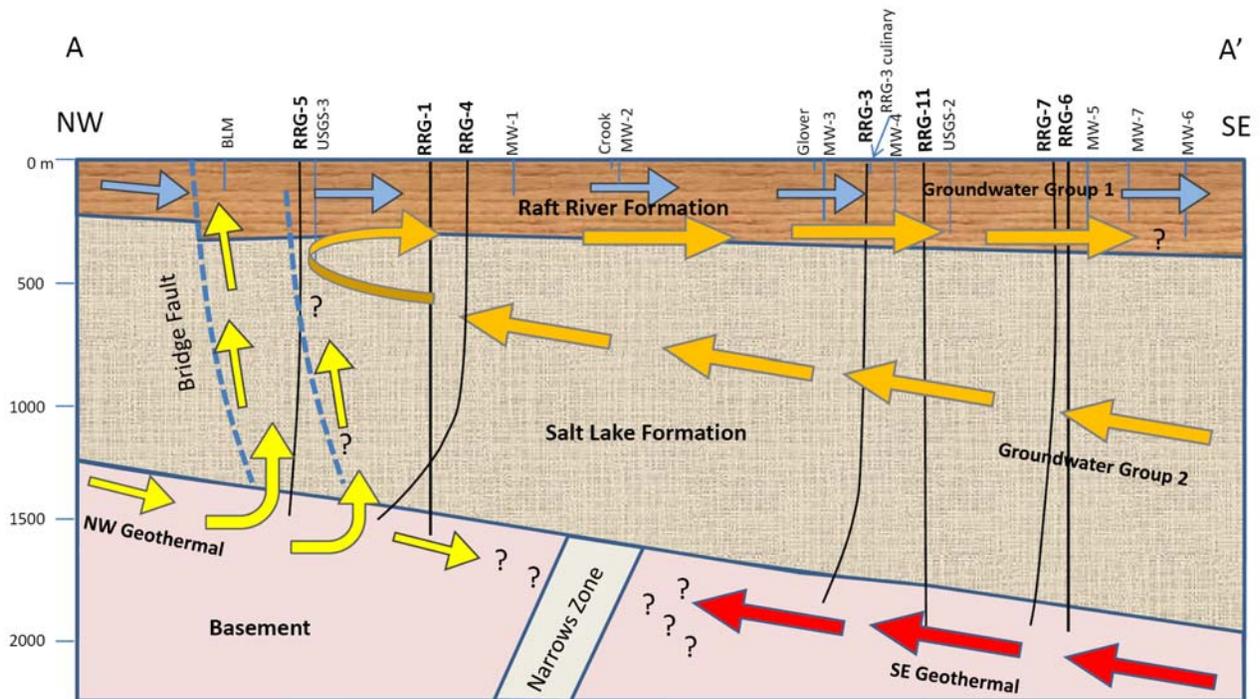


Figure 7. Speculative fluid pathways for the four fluid types at Raft River indicated on a simplified NW-SE cross section through the field (refer to Figure 1b for cross section location). Approximate trajectories of the geothermal wells are indicated by the black lines, shallow groundwater and monitoring wells are indicated by blue lines.

chemical signatures would have to be explained by different flow paths. An alternative hypothesis is that the geothermal fluids are glacial in age: the cooler temperatures associated with this climate could have produced isotopically-light meteoric fluids in many areas surrounding the Raft River basin. Paleotemperatures in the Boise area during the Last Glacial Maximum were 4-5°C cooler than present day (Schlegel et al., 2009), and assuming that similar temperatures were experienced in the Raft River region, this is a plausible mechanism for generating ¹⁸O and ²H-depleted water (temperature fractionation for oxygen is approximately 0.5‰/°C). This hypothesis does not restrict the source area to one geographic location, and thus does not necessitate three different fluid pathways in between shared start and end points. If these fluids are glacial, it suggests the fluids are moving very slowly from the recharge area, and/or have long circulation paths. The geographic source regions may be quite distant to the field.

Figure 6 is a schematic diagram that summarizes these ideas and how they relate to the observed fluid geochemistry at Raft River. Given the considerable uncertainty in the location, nature and character of the inferred structures in the Raft River valley (particularly the Narrows Zone), linking these ideas to specific fluid pathways in the basin is difficult. However it is clear that structural controls are very important in compartmentalizing the deep geothermal fluid chemistry (possibly separated by the Narrows Zone), because there is limited mixing between the three mature fluid types. Speculative fluid pathways for the four fluid types are illustrated on a cross section through the field in Figure 7.

6. CONCLUSIONS

Review of historical and recent geochemical data indicates that there are four fluid types at Raft River geothermal field. One is a shallow, modern groundwater, which forms the freshwater end-member for the field. The other 3 fluids appear to be older, and on the basis of their isotopic (¹⁸O, ²H, ³H) signatures they are inferred to be of glacial age. Although the fluids have this common history, they have since developed unique chemical signatures as defined by their dissolved solute compositions. It is inferred that there are two source regions, neither of which has been geographically constrained. The basin is structurally complex and mapped and inferred structures (the Bridge Fault and Narrows Zone respectively) appear to influence the fluid pathways and compartmentalize the fluids. Improved structural data would assist in refining the conceptual model.

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