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Chloride in hot springs of the Cascade volcanic arc – the source puzzle

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ABSTRACT: Relationships between Cl and ^3He concentrations, $^3\text{He}/^4\text{He}$ ratios and Br in Oregon Cascade volcanic arc hot and cold springs provide new evidence for the origin of the Cl in these springs. The relationship of Cl with ^3He indicates that a significant part of the Cl in the hot and cold springs can be derived from a magmatic source located beneath the crest of the volcanic arc. Evidence for a second Cl component in the hot springs is clearly present, but hard to distinguish given the resolution that the data provide. The most likely source for this component is Tertiary marine sediments that the thermal fluids encounter as they travel along long flow paths in deep aquifers to their discharge points away from the volcanic crest.

1 INTRODUCTION

Many geothermal systems in volcanic areas are characterized by high-chloride fluids, but the source of the chloride is often uncertain. Possible sources include i) the magma (source) itself, ii) Cl-rich crustal rocks (marine sediments) interacting with the magma, and iii) Cl-rich aquifer rocks interacting with geothermal fluids. A further complication in the case of arc volcanoes is that the magmas can contain components derived from subducted (sedimentary) materials. Chloride isotopes do not provide a unique solution to this source question due to the very limited variation in chloride isotope ratios for the different sources. Therefore the problem of identifying chloride sources in volcanic areas has been addressed by (systematic) relationships with other (volatile) geochemical parameters (e.g., Giggenbach, 1995).

2 OREGON CASCADE HOT SPRINGS

The Cl-rich hot springs in the Oregon Cascades clearly illustrate this problem. These springs discharge 10 – 40 km west of the arc crest, but are linked to recharge areas near the crest by stable isotopes and heat flow models (Ingebritsen et al., 1994). The hot springs all have temperatures $>40^\circ\text{C}$ and contain magmatic helium, which indicates the presence of a magma-derived volatile component, but the discharge areas are likely underlain by Tertiary marine sediments that could supply part if not all of the chloride observed in these springs.

The hot springs are rich in N_2 and have total dissolved N_2/Ar ratios in excess of air saturated water (ASW – Mariner et al., 2003). Based on i) $\delta^{15}\text{N}$ values up to +5.3‰, ii) the presence of CH_4 with $\delta^{13}\text{C}$ values near -37‰, and iii) the fact that the highest excess N_2 concentrations correlate with calculated aquifer temperatures near 120°C (the optimal temperature for N_2 release from sedimentary formations), Mariner et al. (2003) concluded that the most likely origin for the nitrogen was the Tertiary marine sediments. A correlation between Cl and N_2/Ar ratios in these springs (Fig. 1, Mariner et al., 2003)

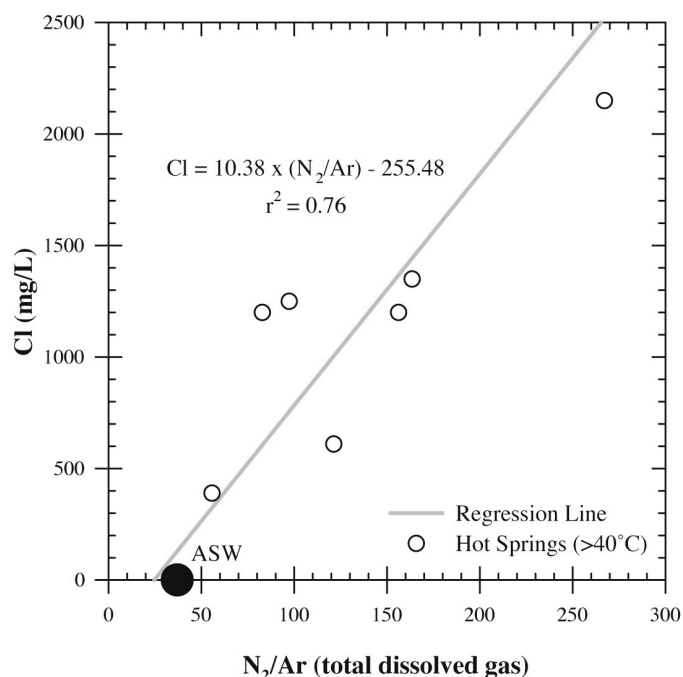


Figure 1. Cl vs. N_2/Ar for Oregon Cascade hot springs after Mariner et al. (2003).

suggests that the source of the Cl may also be the Tertiary marine sediments that form or more likely underlie the aquifer.

However, our recent work on low-temperature springs near the crest of the arc in the Three Sisters area in the central Oregon Cascades provides some additional information on potential Cl sources.

3 THREE SISTERS AREA COLD SPRINGS

An episode of uplift, attributed to magmatic intrusion, began near the Three Sisters volcanoes in 1998 (Wicks et al., 2002). To determine if this ongoing uplift has had any effects on the chemistry of local groundwater, water and gas samples have been collected from hot and cold springs in the Three Sisters area. The detailed results of this monitoring study can be found elsewhere (Evans et al. in press). The locations of these springs and their relation to the center of uplift and the Three Sisters are shown in Figure 2. As is characteristic for the Oregon Cascades the closest hot spring is over 25 km away from the volcanic edifice at the Cascade crest that forms the surface expression of the apparent heat source.

The cold springs that discharge in the area of the uplift all have temperatures $<15^{\circ}\text{C}$ but show slight and correlated anomalies in Cl concentration and temperature. Several have the highest $^3\text{He}/^4\text{He}$ ratios found anywhere in the Cascades (van Soest et al., 2002). These two observations suggest that there is a geothermal component in these springs and indicate that the source of the chloride could be magmatic.

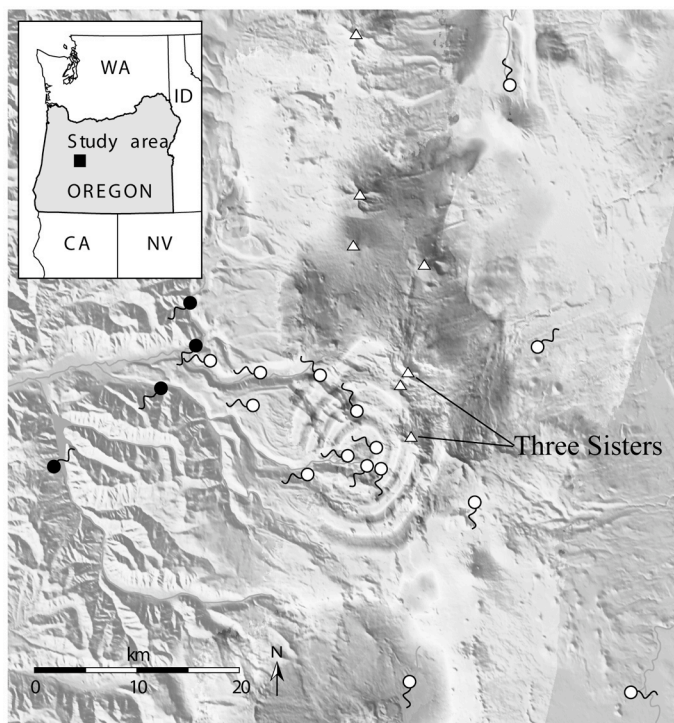


Figure 2. Map of the Three Sisters area with sample locations of cold springs (white symbols) and hot springs (black symbols). The area of uplift is indicated by the bulls-eye pattern. Several hot springs are located outside the area of this map. Their locations are given in Mariner et al. (2003).

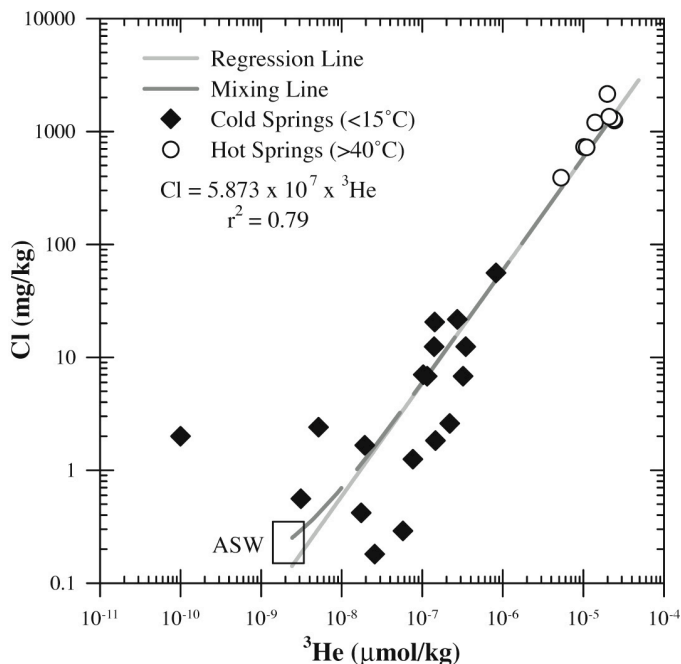


Figure 3. Cl vs. ^3He for Oregon Cascade hot springs and Three Sisters area cold springs.

This notion is further reinforced by the fact that, in contrast to the hot springs to the west, these springs are located in a wide, arc-centered rift, where the presence of underlying marine sediments as an alternative source for the chloride is uncertain. In addition, Ingebritsen et al. (2002) have pointed out that the total discharge of Cl by these springs is compatible with the amount of Cl that could be supplied by magma at the long-term Cascade intrusion rate assuming a magmatic Cl concentration of 0.1 wt-%, implying that a sedimentary source is not necessary to explain the anomalous Cl discharge.

4 DIFFERENT CHLORIDE SOURCES?

The hot- and cold-spring characteristics each suggest a different chloride source, while the water, recharge derived from local precipitation (marked ASW in all figures), derives from the same source area in the high Cascades. To study this in more detail we combine our measurements of helium concentrations and isotopes in the cold springs with the hot-spring data from Mariner et al. (2003). Figure 3 shows that Cl concentrations in the cold springs correlate with ^3He concentration. Since the source of the ^3He is definitely magmatic, this supports the possibility of magma-derived chloride in the cold springs. The regression line was calculated for the cold-spring data and passes through the cluster of hot-spring data. If a magmatic Cl-source is invoked for the cold springs near the crest, which we think is most likely, the correlation line in Figure 3 indicates a magmatic Cl-source for at least part of the Cl budget at the hot springs. It is worth noting that both axes of Figure 3 are log scale, and therefore significant variations can be easily obscured. However, based on the regres-

sion line and the fact that all ^3He is magmatic, we can calculate that 54 to 114% of the Cl in the hot springs is magma-derived, with all but two samples falling in the range $100 \pm 20\%$. Given the large scatter in the data and the significant uncertainties associated with the ^3He calculations these values should not be taken as absolute, but indicative that most hot springs carry a significant magma derived Cl component.

5 A SINGLE CHLORIDE SOURCE?

To better assess the implications derived from the observations made in Figure 3, we looked at Cl- $^3\text{He}/^4\text{He}$ and Br-Cl relations. The Br-Cl correlation for the cold springs is very tight ($R^2 > 0.99$ – Fig. 4 inset) and, when extrapolated to higher Cl and Br, passes through the hot-spring data (Fig. 4). This suggests that the halides in both fluid groups are derived from the same source and is consistent with the observations made from Figure 3. Although the slope of the regression line is not much different from the seawater ratio, the consistent offset of the data from the seawater trend would require some form of systematic elemental fractionation to occur between the time of their incorporation into the sediments and their discharge in the thermal fluids. Mariner et al. (1989) pointed out that Br is not as conservative as Cl in the thermal waters, so some form of fractionation process is possible. Similarly magmatic heating of marine sediments could result in differential halogen release, but this would require that the sediments occur in close proximity to the

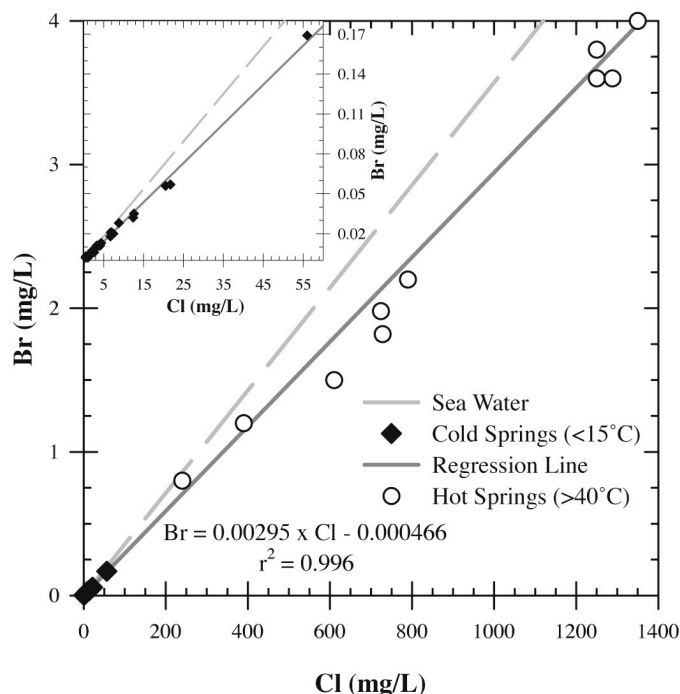


Figure 4. Br vs. Cl. The regression line is calculated through the cold-spring data. Details for the cold-spring data are shown in the inset. Both in this figure and Figure 5 there was more data available for the hot-spring group compared to Figure 3.

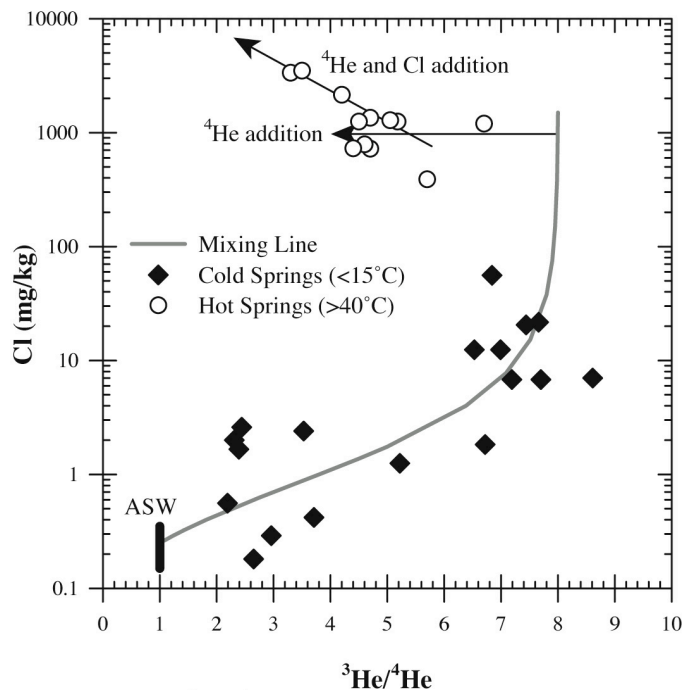


Figure 5. Cl vs. $^3\text{He}/^4\text{He}$, showing the mixing relationship for the cold springs and scenarios for the hot springs to evolve by interaction with aquifer rocks.

magma chamber. The presence of such sediments under the volcanic crest is uncertain, but the trend observed in our data could be indicative that they are there.

The Cl- $^3\text{He}/^4\text{He}$ plot shows an altogether different picture (Fig. 5). The cold-spring data trend is consistent with mixing a magmatic geothermal source with ASW and, therefore, also consistent with the Cl- ^3He systematics, shown in Figure 3. The main difference in Figure 5 is that the hot-spring data no longer plot along a common mixing trend with the cold spring data. In Figure 3 the magmatic end-member has been chosen arbitrarily at the high end of the hot spring cluster for the Cl and ^3He concentrations. In Figure 5, however, the end-member is well defined by the upper mantle $^3\text{He}/^4\text{He}$ ratio of $8R_A$, consistent with the Cascades, in general. Differences in the hydrologic setting for the cold and hot springs are probably the main reason why the hot springs do not fall on the mixing line. The cold springs mainly reflect fairly shallow, local circulation of young groundwater that retains a clear but dilute magmatic signal in both chemistry and temperature. The hot springs are fed by ground water from the same recharge area that has infiltrated deeper and attained a stronger magmatic signal in both chemistry and temperature. The deep flow paths from recharge to discharge area probably shielded the fluids from interacting with large amounts of shallow ground waters of ASW composition and temperature.

The long and deep flow paths at high temperatures enhanced fluid interaction with the aquifer rocks, adding significant amounts of radiogenic ^4He to the fluids and lowering the $^3\text{He}/^4\text{He}$ ratio. Addi-

tion of ^4He along the flow path is consistent with a systematic decline of $^3\text{He}/^4\text{He}$ with distance from the volcanic crest (Mariner et al., 2002; Evans et al., in press) and is observed at many other volcanic systems in the world (e.g. Marty et al., 1989; van Soest et al. 1998). This is indicated in Figure 5 by the horizontal arrow extending from the mixing line towards lower $^3\text{He}/^4\text{He}$ ratios. The diagonal arrow shown in Figure 5 suggests that the water-rock interaction process that provides the radiogenic ^4He may also provide a significant amount of Cl. This may reflect leaching of the Tertiary marine sedimentary source (Mariner et al., 2003) and would be in concordance with the Cl- N_2/Ar correlation (Fig. 1).

The source for the magmatic Cl could be a combination of upper mantle and subduction derived components or crustal materials that interact with the magma as it moves through the crust. The high mantle like $^3\text{He}/^4\text{He}$ ratios suggests little or no addition of radiogenic ^4He as would be expected with the addition of crustal material. In combination with the uncertainty about the presence of sediments in the crust near the volcanic crest, a mantle/subduction origin for the Cl in the magma and the cold springs seems most likely.

6 IN CONCLUSION

Our work raises the strong possibility of a common magmatic Cl component as a significant source of elevated Cl in the hot and cold springs along the west side of the Cascade Range. However, we also show that the geothermal fluids that feed the hot springs interact with aquifer rocks along their deep flow paths from recharge to discharge and acquire radiogenic ^4He released from the rocks. There is good evidence that Cl is added to the thermal fluids in a similar manner. Given the resolution of our data and uncertainties about the Cl and He composition of each end-member it is difficult to establish the relative importance of each Cl source.

The most likely source for the Cl and radiogenic ^4He in the aquifers is Tertiary marine sediments that are estimated to both be a significant source for halides and radiogenic ^4He . Any variability in Cl source among the hot springs could be due to the distribution of Cl-bearing sediments along the flow paths of the fluids. On the other hand the source of Cl associated with the magma and cold springs is unclear, but based on the occurrence of mantle like helium ratios and uncertainty regarding the presence of marine sediments in the rift zone underlying the volcanic crest an upper mantle/subduction origin seems likely.

Our data also provide strong additional evidence for the hypothesis that the hot springs are sourced near the Cascade crest.

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