Mantle Helium and Carbon Isotopes in Separation Creek Geothermal Springs, Three Sisters Area, Central Oregon: Evidence for Renewed Volcanic Activity or a Long Term Steady State System?

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Keywords

Helium isotopes, carbon isotopes, South Sister Volcano, Oregon Cascades, geothermal springs

ABSTRACT

Here we present the helium and carbon isotope results from the initial study of a fluid chemistry-monitoring program started in the summer of 2001 near the South Sister volcano in central Oregon. The Separation Creek area which is several miles due west of the volcano is the locus of strong crustal uplift currently occurring at a rate of 4-5 cm/yr (Wicks, *et. al.*, 2001).

Helium [R_C/R_A = 7.44 and 8.61 R_A ($R_C/R_A = (^3He/^4He)_{sample-air\ corrected}/(^3He/^4He)_{air}$))] and carbon ($\delta^{13}C$ = -11.59 to -9.03‰ vs PDB) isotope data and $CO_2/^3He$ (5 and 9 x 10^9) show that bubbling cold springs in the Separation Creek area near South Sister volcano carry a strong mantle signal, indicating the presence of fresh basaltic magma in the volcanic plumbing system. There is no evidence though, to directly relate this signal to the crustal uplift that is currently taking place in the area, which started in 1998. The geothermal system in the area is apparently much longer lived and shows no significant changes in chemistry compared to data from the early 1990s. Hot springs in the area, which are relatively far removed from the volcanic edifice, do not carry a strong mantle signal in helium isotope ratios (2.79 to 5.08 R_A), unlike the cold springs, and also do not show any significant changes in helium isotope ratios compared to literature data for the same springs of over two decades ago.

The cold springs of the Separation Creek area form a very diffuse but significant low temperature geothermal system, that should, due to its close vicinity to the center of up uplift, be more sensitive to changes in the deeper volcanic plumbing system than the far removed hot springs and therefore require much more study and consideration when dealing with volcano monitoring in the Cascade range or possibly with geothermal exploration in general.

Introduction

InSAR imagery data indicates that the Three Sisters volcanic area in Central Oregon has been the locus of strong crustal uplift since about 1998 (Wicks. *et. al.*, 2001, 2002). Uplift is occurring in a concentric area with its center several km west of South Sister volcano on the Cascades crest. Maximum uplift rates for the center of 'the bulge' are 4-5 cm/yr and modeling suggests this is consistent with intrusion of 0.006 km^3/yr magma at a depth of 6-7 km in the crust (Wicks, *et. al.* 2001, 2002).

The area of the uplift has no young (<1 ka) volcanic vents and so far there have been no clearly identifiable occurrences of ground deformation or increases in seismicity. A decade prior to the onset of the uplift a source of geothermal fluid was identified by means of a Cl^- anomaly in the Separate Creek drainage, which is the main drainage system for the area of the bulge (Ingebritsen, *et. al*,. 1994). This Cl^- anomaly is present at most (all) Cascades geothermal sites and is a clear indication of a thermal input to the fluids. Most of the Cl^- anomalies are associated with hot springs that occur at the bottom of major river valleys (between elevations of 460m to 760m – Figure 1, overleaf). Studies by Ingebritsen, *et. al.*, (1994) and Iverson (1999) traced the anomaly of the Separation Creek drainage to much higher elevations (1050 to 1850m) and a large but widespread number of springs that were just a few degrees centigrade above ambient temperature. The springs in the Separation Creek area show a strong correlation between Cl^- and temperature (Evans, *et. al.* 2002a) allowing the total advective heat transport to be calculated at the gaging site down stream from the confluence of the major streams in the drainage area. The estimated advective heat transport of ~16MW is larger than some of the major hot spring systems in the Cascades making this a significant, but diffuse geothermal area. The hydro-geochemical studies (Mariner, *et. al.* 1990; Ingebritsen, *et. al.*, 1994; Iverson, 1999) carried out before or just prior to onset of the uplift provide a good background chemical database for the ongoing monitoring project.

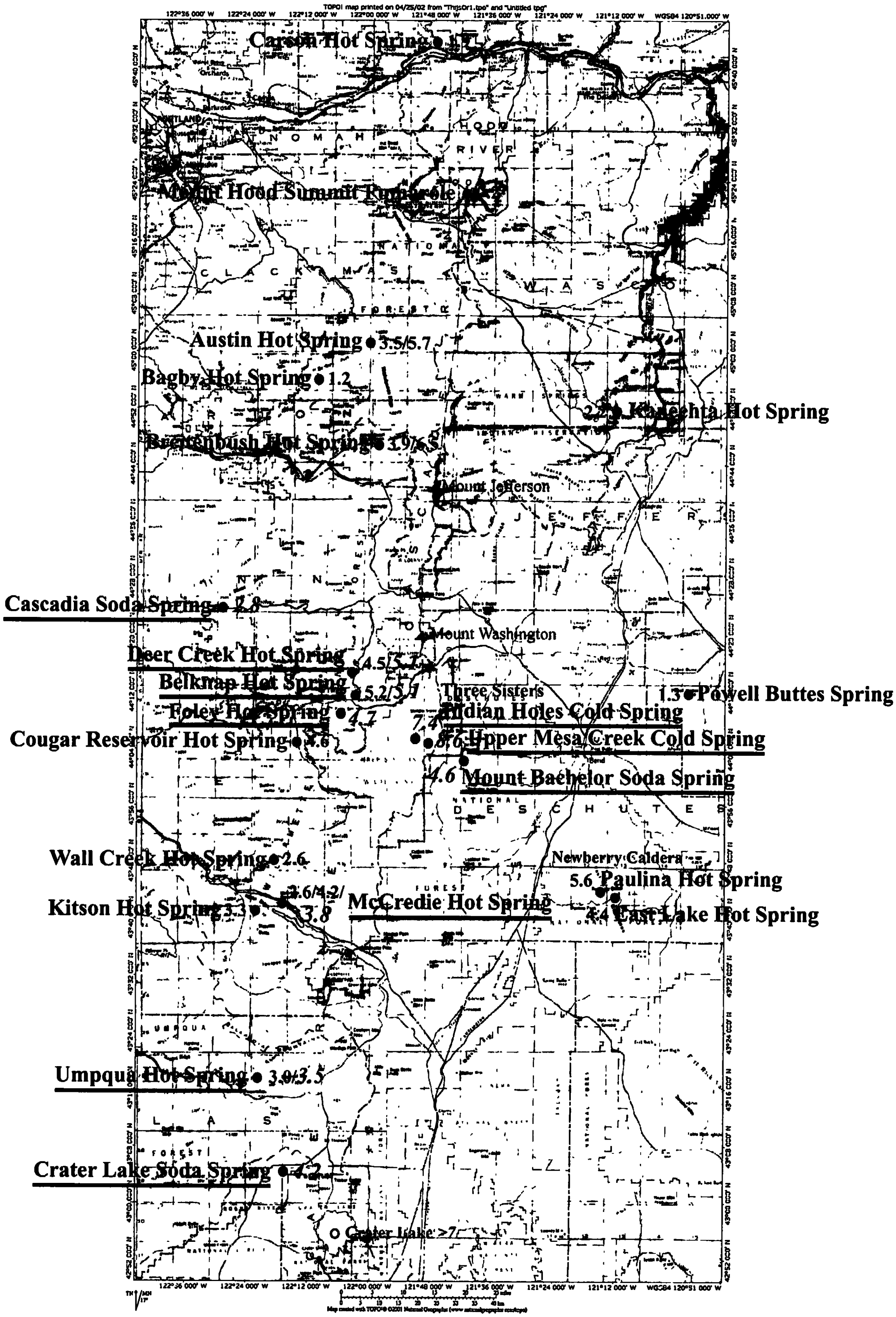

Figure 1. Location map of the Oregon Cascades. Hot springs with literature $^3He/^4He$ data are shown. The sites sampled for the current study are underlined and new data is given in bold italics and larger type. Several of the main topographic features are also emphasized. (The number for Crater Lake should reflect the influx of gas through the bottom and is unconfirmed from an unknown source).

There are no pre-existing noble gas/carbon isotope data for the Separation Creek area, but the other previously known geothermal sites (Figure 1) in Central Oregon have been subject of several studies (Ingebritsen, *et. al.*, 1994; Welhan, *et. al.*, 1988) and an exploration effort by UNOCAL (Powell & Gambill, 1982) that provides background data for the current study.

In the summer of 2001 a chemical monitoring effort of the springs in the Separation Creek area and surrounding geothermal localities was started with the aim to study any changes in the systems that could be related to the current uplift. Below we present and discuss the noble gas and carbon isotope results of this first field season and their implications for the origin of the bulge. We will also discuss plans for future (spring and summer 2002) field seasons.

Samples and Procedures

Within the Separation Creek area a large set of fluid samples was taken from springs and analyzed for fluid and carbon isotope chemistry at the USGS by WCE and RHM. Other measurements taken in the field at streams and springs were: conductivity, temperature, dissolved oxygen, pH, and alkalinity measurements and several soil CO_2 gas samples were taken. The results of these experiments and the gen-

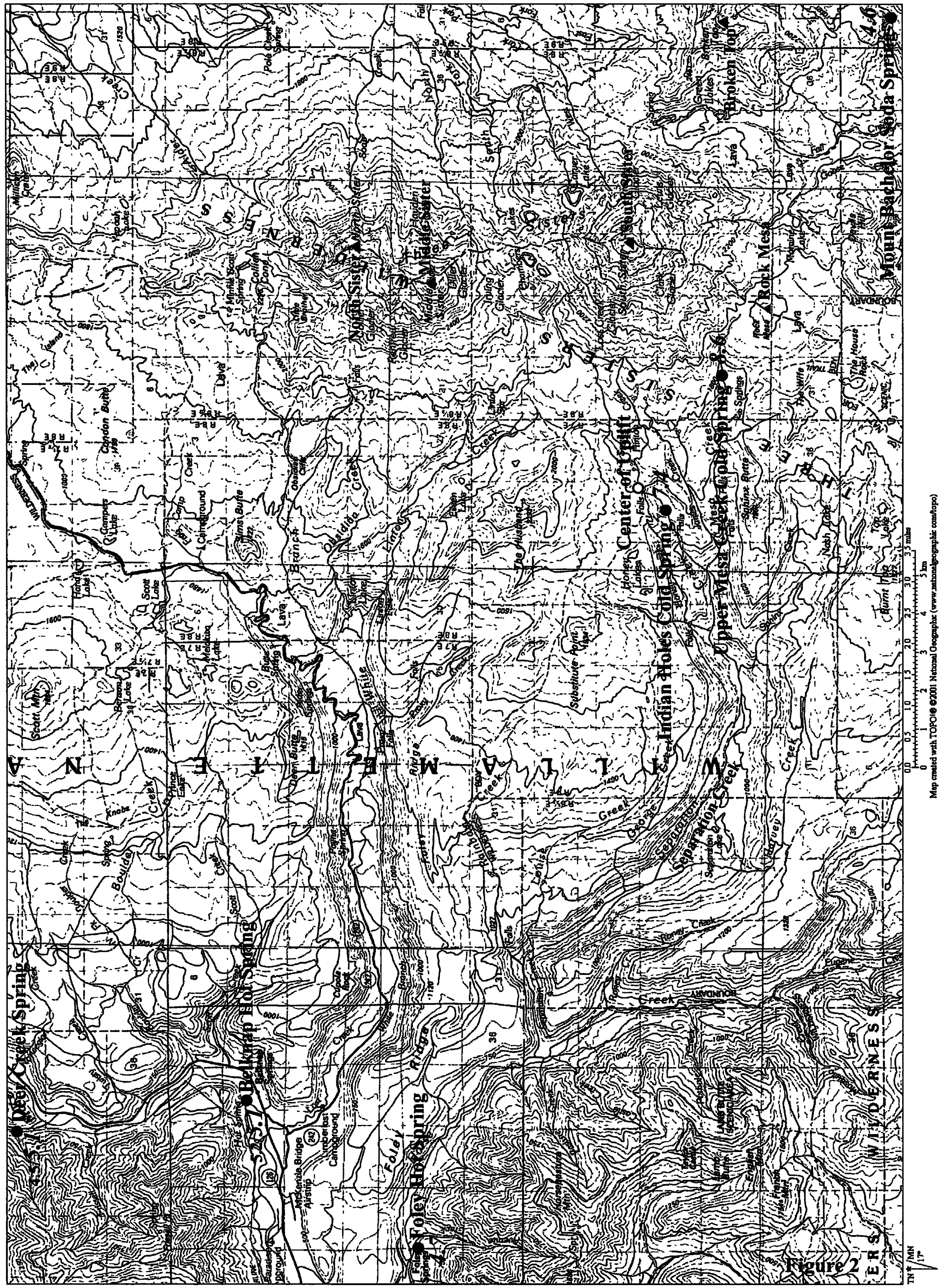

Figure 2. Detail of Separation Creek area. Showing the hot spring locations and $^3He/^4He$ data. Helium isotope data from the current study are again shown in bold italics and larger type.

eral water chemistry are presented and extensively discussed by Evans, *et. al.,* (2002a).

Two of the springs in the Separation Creek area, which are amongst the warmest, produced streams of gas bubbles, which were collected in pre-evacuated Pyrex tubes for gas chemistry analysis and Cu tubes for noble gas analysis. A further 8 samples were taken from selected hot and soda springs in the area, their locations are presented by the underlined spring names in Figure 1. Fluid chemistry data for these springs is available in Mariner, *et. al.,* (1980), Ingebritsen, *et. al.,* (1994) and Mariner (unpublished data).

Analyses for fluid and gas chemistry were carried out at the USGS in Menlo Park, CA with ICP-MS, ion chromatography, and GC-MS. ^{14}C analyses were carried out at LLNL using AMS. Noble gas analyses were carried at LBNL on the RARGA system following procedures described in Kennedy, *et. al.,* (1985) and Hiyagon & Kennedy (1992).

Results

Fluid chemistry and carbon isotope results for the Separation Creek area are presented in Evans, *et. al.,* (2002a) and in general do not show any significant changes compared to the data from Ingebritsen, *et. al.,* (1994) and Iverson (1999) except for an area near Rock Mesa which is the youngest volcanic product of South Sister volcano (~2 ka, Wozniak, 1982).

Noble gas abundances in the hot springs are consistent with an origin from air-saturated ground water or show a large air derived component. Except for helium, which is enriched in all samples showing enrichment factors of 3 to 198 times $^4He/^{36}Ar$ in air. Helium isotope ratios have been corrected for any air derived contributions and show a range of 2.79 to 8.61 R_A (Figure 1). This indicates that all hot springs have a significant component of mantle-derived helium. The two samples with the highest helium isotope ratios (7.44 and 8.61 R_A) are indistinguishable from mantle-derived helium (8 ± 1 R_A – e.g. Kurz & Jenkins, 1981) and are located in the area of the uplift. The Indian Holes sample (7.44 R_A) is right near the center of the uplift, while the Mesa Creek sample (8.61 R_A) is close to the latest volcanic product from South Sister volcano: Rock Mesa (Figure 2). Both these samples have helium isotope ratios that are among the highest in the Cascades. The other samples show a range of 2.79 to 5.08 R_A and are not significantly different compared to the literature data available for hot springs in the area (Figures 1 & 2) that were collected pre-1998. From Figures 1 & 2 it can be clearly seen that samples within the immediate area of the Bulge (up to 40 miles away) show a distinct decrease in $^3He/^4He$ with distance from the bulge. This is due to addition of crustal-derived helium with low $^3He/^4He$ (R/R_A ~ 0.02) as the gases travel away from the volcano in an aquifer. Samples that are much further away from the Three Sisters area do not follow this pattern and are probably related to geothermal systems associated with other volcanoes in the area.

$\delta^{13}C$ results from the springs in the Separation Creek drainage area span a small range (-11.59 to -9.03‰ vs. PDB – Evans, *et. al.,* 2002a) that is heavier than expected for ground water recharging through soils formed in the coniferous forest of the area (Reardon, *et. al.,* 1979; Fritz, *et. al.,* 1985; Evans, *et. al.,* 2002b) of the area ($\delta^{13}C$ ~ -20‰). This suggests the presence of a deep (mantle-derived?) component ($\delta^{13}C$ MORB = -6.5 ± 2.5‰ – Pineau & Javoy, 1983). In an effort to determine the fraction of deep vs. shallow carbon several ^{14}C analyses were carried out on several of the samples. Based on tritium values for these samples the residence time of the groundwater is very short (less than 50 years) and therefore most groundwater would be expected to have modern or close to modern ^{14}C values (see extensive discussion in Evans, *et. al.,* 2002a). Depletions in ^{14}C can only be the result of addition of abiogenic carbon from depth. As can be seen in Figure 3 most carbon in the samples is abiogenic. This results in a $\delta^{13}C$ value of -9‰ for the deep carbon component, which is right on the lighter limit of the mantle range and could therefore reflect some addition of a light carbon component deep in the crust. Alternatively, this could be a reflection of the $\delta^{13}C$ composition of the mantle wedge below the Cascades, since at most Cascade volcanoes $\delta^{13}C$ values in the range of -12 to -9‰ are found (Evans, *et. al.,* 1981, unpublished USGS data), which is supported by the $^3He/^4He$ of the springs that are indistinguishable from mantle values.

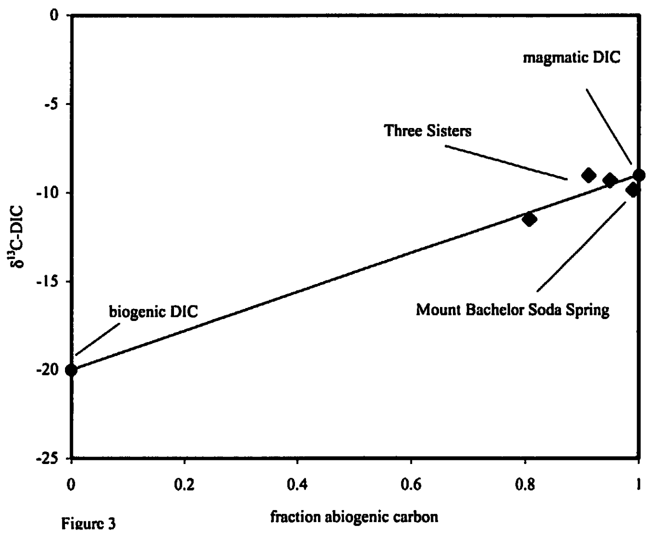

Figure 3. A plot of the fraction of abiogenic carbon vs. $\delta^{13}C$, figure reproduced from Evans et al. (2002a) with permission. See text for explanation.

From the gas chemistry of the Indian Holes and Mesa Creek samples and their helium isotope ratios $CO_2/^3He$ ratios can be calculated. The ratios are 5 x10^9 and 9 x 10^9 respectively, which is close to, but significantly greater than the $CO_2/^3He$ for the mantle 2 ± 1 x 10^9 (Marty & Jambon, 1987). However, these values fall in the lower end of the range for $CO_2/^3He$ at arcs worldwide (10^9 – 10^{11} – van Soest, *et. al.,* 1998 and references therein), combined with the mantle $^3He/^4He$ in these springs this suggests that the extra CO_2 is a slab-derived recycled component added to the mantle wedge from the subducting slab. This extra CO_2 from the subducting slab is probably also responsible for the slight deviation of $\delta^{13}C$ from mantle values and suggests that the subducting CO_2 in the Cascades is strongly influenced by organic derived carbon as opposed to carbonate-derived carbon (see e.g. van Soest, *et al.,* 1998).

Discussion

The main question to address is whether or not there have been any changes in the geothermal discharge from the Separation Creek area that can be related to the uplift that started in 1998. Of all the chemical indicators of a deep geothermal component only Cl^- and SO_4^{2-} were analyzed in the pre-1998 studies. The other tracers: helium isotopes, $\delta^{13}C$, and $CO_2/^3He$ were not analyzed for Separation Creek samples until this current study. Compared to pre-1998 studies Cl^- and SO_4^{2-} do not show any significant changes for the Separation Creek drainage except for the upper Mesa Creek area, which shows increases of about 100% in concentrations of both chemical species. For the general drainage area as determined at the downstream gaging area there were no significant changes suggesting that for the complete drainage the up-flow of deep fluid has remained more or less constant compared to pre-1998, despite the changes at upper Mesa Creek.

The origin of the changes at upper Mesa Creek is not clear: it could mean that there has been an increase in up-flow of deep fluid for that area or it could reflect some dilution-related effect due to the dry conditions in the summer of 2001. With respect to upper Mesa Creek, it is noteworthy that it is located away from the center of the uplift, which lies close to the Indian holes area (Figure 2), but that it does have the highest $^3He/^4He$ measured to date and it is next to most recent volcanic vent of the South Sister volcano – Rock Mesa. This could mean that if we are dealing here with an increase in up-flow of deep fluid that the existing vent provides an easy pathway for the fluid to reach the surface slightly less influenced by the upper crust and the shallow ground water system compared to the Indian Holes samples.

Evans, *et. al.,* (2002a) estimate a maximum magmatic CO_2 discharge of 21 tonnes/day, which is not insignificant for a diffuse geothermal system like the Separation Creek area. It is also not uncommon, though: James et al. (1999) found evidence for discharges of similar size in several large cold spring systems on the east side of the Cascades, related to several long-dormant central Oregon volcanoes, and postulated the presence of such systems on the west side of the Cascades. Thus the amount of carbon discharging from the system does not necessarily require magmatic activity that is linked to the current uplift, but the steady discharge of magmatic CO_2 and the mantle-like helium isotope ratios do require a source of continuously replenished basaltic magma to keep the values stable. Evans, *et. al.,* (2002a) estimate that the current magmatic CO_2 discharge from the Separation Creek system requires a volume of 0.0005 km^3 basalt to completely degas each year, which is significantly less than the volume of magma necessary to sustain the current rate of uplift (0.006 km^3 – Wicks, *et. al.,* 2002). The discrepancy between the two numbers may reflect the long term steady state situation which could be in effect at many dormant Cascades volcanoes: a continuous supply of small magma batches to keep the system 'alive', vs. the situation currently in effect at South Sister volcano: the short term 'awakening' of the system caused by an increase in magma supply.

If indeed the uplift in the Separation Creek area is caused by an increased supply of magma to the system we would expect to see some form of reaction in the chemistry of the fluids discharging from the system. At the moment there is no evidence to suggest that the system has changed compared to pre-uplift conditions, so it can simply be that the chemical pulse related to the uplift has not reached the surface yet in any of the systems: close by in the Separation Creek area or distant at the hot springs. For the latter that is not a surprise: ground water flow from the Separation Creek area to the locations of the hot springs is thought to take longer than the current time span since the onset of the uplift, but for the former this is surprising and this will require further study. With respect to this, the changes observed at upper Mesa Creek could herald the first indication of a change in the chemistry.

Future Research

From the data presented above and recent findings by James, *et. al.,* (1999) it is clear that cold springs can be carriers of strong magmatic signals and are therefore an important factor in volcano monitoring studies. A factor which so far has remained relatively unstudied, since the focus is usually on hot springs as the surface manifestation of volcanic or geothermal activity. The current model for geothermal systems in the Cascades (Iverson, 1999; Evans, *et. al.,* 2002a and references therein) suggest that outflows from a hydrothermal system under the Cascade crest feed the lower elevation hot springs, while a combination of fluid and vapor (from a vapor zone overlying the liquid reservoir) fluxes feed the high elevation ground water system, so forming a very diffuse geothermal system with a significant geothermal discharge. The high elevation system, although cold, is much closer to the hydrothermal reservoir itself and should therefore react much quicker to changes in chemistry caused by e.g. increase of magma supply at depth. With this in mind we will focus our study more on the cold springs system of the Separation Creek area and other such systems around the Cascade volcanoes to obtain a better understanding and possibly a more rapid indication of changes within the system.

For the spring and summer of 2002 the plans regarding the Separation Creek area are to resample a lot of the cold springs that were sampled before, extend our sampling to areas that were not visited before, so that we can monitor any changes in fluid and gas chemistry that have occurred/are occurring. Furthermore, we will try and map out the area where the strong mantle signal in helium and carbon is reaching the surface and so get a better idea of the size and make up of the hydrothermal feature that is feeding the system and possibly to see it changing over time. We will also monitor nearby hot springs sites. Since, if indeed the mantle helium signal is related to the current uplift and not the longer lived geothermal system, we would expect this signal to travel over time to the hot springs at lower elevations and to springs at elevations in between. The results of these field trips will also be presented at the GRC meeting.

Conclusions

Cold bubbling springs in the Separation Creek area, the locus of current uplift at South Sister volcano show strong mantle signatures in helium and carbon isotopes and $CO_2/^3He$. This suggests the presence of fresh basaltic magma in the volcanic plumbing system.

Currently there is no evidence to link this system directly to the uplift, which started in 1998. To the contrary, all geochemical evidence suggests that there is a long-lived geothermal system in the Separation Creek area, which has not significantly changed since the early 1990s. There was no archived helium and carbon data, so a definite conclusion regarding the strong mantle signature observed in these tracers cannot yet be drawn.

There is a distinct discrepancy between the yearly magma supply required to explain the current uplift (0.006 km^3/yr) and that required to explain the discharge of CO_2 from the system (0.0005 km^3/yr). This discrepancy may imply that the chemical signal associated with the increase in magma supply has not reached the surface yet. With respect to this the small changes observed at upper Mesa Creek require further attention, due to the recent volcanic vent in that area it may be the location were the chemical signal related to the uplift can most quickly reach the surface.

Occurrence of such strong mantle signals in cold/diffuse geothermal systems suggests that these systems should not be ignored during volcano monitoring or geothermal evaluation studies. Although the surface-expression of these springs in terms of heat is minimal, the chemistry carries important information concerning the size and nature of the underlying high-temperature system and any changes taking place in it.

Acknowledgements

We would like to acknowledge UNOCAL for granting us permission to use the helium isotope data contained in the report of their exploration effort in the Oregon Cascades. Pat Dobson is thanked for his assistance in obtaining access to the UNOCAL data.

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