

Water Rock Interaction [WRI 14]

Helium sources to groundwater in active volcanic terrain, and implications for tritium-helium dating at Mount St. Helens

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Abstract

Groundwater helium sources and residence times were investigated using groundwater discharging from springs surrounding Mount St. Helens in the Cascades region of the United States. Significant contributions of mantle helium were found in all samples and are attributable to interaction between groundwater and magmatic gases. Bounding calculations for residence times were made on the basis of helium isotope mixing plots and historical tritium data.

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1. Introduction

Environmental tracer studies of spring water have yielded insights about groundwater provenance, residence times, and hydrogeochemical processes in a wide range of hydrogeologic settings, including volcanic and geothermal systems. However, investigations in volcanic areas have highlighted several challenges to gas-based residence time indicators of “young” groundwater because of groundwater interaction with magmatic gases and high-temperature water/rock interactions. In the context of tritium-helium dating, contributions of mantle-derived helium to total dissolved helium in shallow groundwater may be significant in volcanic settings, and must be taken into account in helium source partitioning. The objectives of this work were to examine helium sources to spring water near Mount St. Helens and to examine the implications of magmatic helium inputs for tritium-helium dating of spring discharge.

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2. Study Area

Mount St. Helens is an active stratovolcano within the Cascades mountain range in southern Washington State, USA. Recent volcanic activity included a major explosive eruption in 1980, and a period of dome building in 2004-2008. The volcanic edifice is a dacitic composite dome comprised of late-Holocene lava flows, lahars, pyroclastics and rockfall deposits. Drainage features have developed on the crater floor (Loowit and Step Creeks) and are fed by a combination of seasonal glacier melt water and thermal springs (up to ~70 °C). Spring-fed creeks also emerge from the volcano flanks, and primarily have low temperature, although some have a slight thermal signature. Following the 1980 eruption, thermal and chemical signatures of mantle outgassing in spring water have rapidly declined in response to progressive cooling of the near-surface geothermal system.

3. Methodology

Groundwater residence time estimation using the tritium-helium method in groundwater is based on the accumulation of tritiogenic ^3He from tritium decay with increasing residence time:

$$\tau = \frac{T_{1/2}}{\ln 2} \ln \left(1 + \frac{{}^3\text{He}_{\text{trit}}}{{}^3\text{H}} \right) \quad (1)$$

where τ is mean residence time (years), $T_{1/2}$ is the half-life of tritium, and $^3\text{He}_{\text{trit}}$ is tritiogenic helium. Evaluation of $^3\text{He}_{\text{trit}}$ requires partitioning of measured ^3He ($^3\text{He}_{\text{meas}}$) into source components:

$$^3\text{He}_{\text{meas}} = {}^3\text{He}_{\text{eq}} + {}^3\text{He}_{\text{ea}} + {}^3\text{He}_{\text{terr}} + {}^3\text{He}_{\text{trit}} \quad (2)$$

where $^3\text{He}_{\text{eq}}$ is from equilibration with the atmosphere, $^3\text{He}_{\text{ea}}$ is from dissolution of excess air, and $^3\text{He}_{\text{terr}}$ is from terrigenic sources. Substituting $^3\text{He}/^4\text{He}$ ratios into Eq. 2 and solving for $^3\text{He}_{\text{trit}}$:

$$^3\text{He}_{\text{trit}} = ({}^4\text{He}_{\text{meas}} R_{\text{meas}}) - ({}^4\text{He}_{\text{eq}} R_{\text{eq}}) - ({}^4\text{He}_{\text{ea}} R_{\text{ea}}) - ({}^4\text{He}_{\text{terr}} R_{\text{terr}}) \quad (3)$$

$^4\text{He}_{\text{ea}}$ was estimated from statistical best fit to a closed-system equilibration model (CE model; [1]), where independent variables were Ne, Ar, Kr, Xe, N_2 , and recharge elevations; dependent variables were excess air amount, excess air fractionation factor, and recharge temperature. $^4\text{He}_{\text{eq}}$ was calculated from Henry's Law using sample elevation and CE model-based recharge temperature. $^4\text{He}_{\text{terr}}$ is assumed to include crustal ($^4\text{He}_{\text{c}}$) and mantle ($^4\text{He}_{\text{m}}$) components and can be estimated as the difference between measured and atmospheric components:

$$^4\text{He}_{\text{terr}} = {}^4\text{He}_{\text{c}} + {}^4\text{He}_{\text{m}} = {}^4\text{He}_{\text{meas}} - {}^4\text{He}_{\text{eq}} - {}^4\text{He}_{\text{ea}} \quad (4)$$

Estimation of R_{terr} is the main challenge in evaluating Eq. 3 because i) it represents an unknown mixing ratio of He_{c} and He_{m} and ii) R_{m} (mantle source $^3\text{He}/^4\text{He}$ ratio) is not well-constrained and can be spatially variable. In this study, two bounding approaches were used to constrain $^3\text{He}_{\text{trit}}$. First, a helium source mixing plot was used to bound R_{terr} from sample trends. Second, the historical tritium input function was used to bound $^3\text{He}_{\text{trit}}$ directly.

Water and gas samples were collected from 6 springs within 10 km of the Mount St. Helens crater in July 2010. Dissolved noble gases and N_2 were collected with passive diffusion samplers [2]. Two

samplers per site (for analytical replication) were deployed together inside the spring cavities, including at least one advanced sampler that is sealable prior to retrieval in order to provide the total dissolved gas pressure measurement needed for gas partial pressure determinations. All other diffusion samplers were sealed by cold welding copper samplers within 1 minute of retrieval after 24 hours of equilibration. Noble gases and tritium (helium ingrowth method) were measured at the Dissolved and Noble Gas Laboratory at the University of Utah using noble gas mass spectrometry.

4. Results and Discussion

The terrigenous helium contribution to spring samples was made with a plot of R_{meas} corrected for excess air ($0.0 - 0.1$ ccSTP/g) and normalized to the helium isotope ratio in air (R_a) versus the fraction of total ^4He attributable to atmospheric equilibria (Fig. 1a; [3]). Samples generally conform to a trend of increasing excess air-corrected R/R_a with increasing fraction of $^4\text{He}_{\text{terr}}$ ($r^2 = 0.96$). Because the crustal $^3\text{He}/^4\text{He}$ ratio R_c is less than R_a (R/R_a typically > 0.05), and R_m is likely to be much greater than R_a (for example, mid-ocean ridge basalts have R/R_a of 8 ± 2), the trend suggests that $^4\text{He}_m$ represents the majority of $^4\text{He}_{\text{terr}}$ in this dataset. Moreover, the point of intersection between the regression line and the y-intercept (100% terrigenous helium) suggests that $R_{\text{terr}}/R_a = 8.1$, which is close to the average value of R/R_a for the Cascades Range.

Uncertainty in the trend line prediction of R_{terr} was evaluated by calculating statistical confidence intervals for the y-intercept value. Confidence intervals of 80% and 95% are shown in Fig 1a. Substituting the resulting lower and upper bound estimates for R_{terr} into Eq. 3 allows for bounding calculations of residence time using Eq. 1. Sensitivity of residence times estimates to uncertainty in the R_{terr} parameter is illustrated in Fig 1b. Overall, residence time ranges are not well constrained for most samples, even at the 80% confidence level. The high range of the calculated confidence intervals exceeds maximum theoretical values in some cases (the value above which $^3\text{He}_{\text{trit}} < 0$).

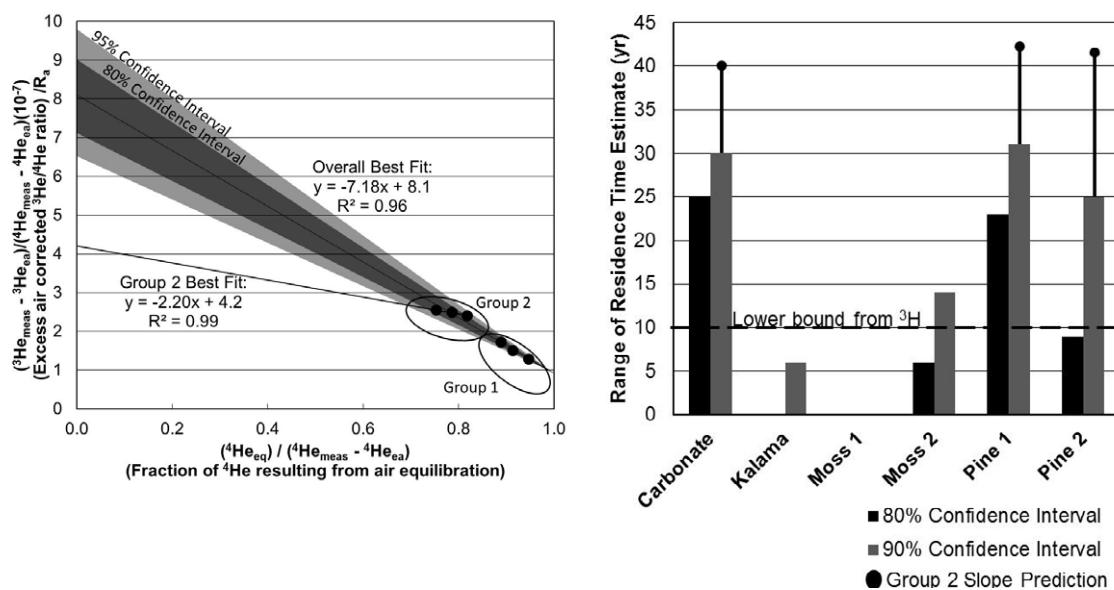


Fig. 1. (a) Helium source plot; (b) summary of resulting uncertainty range for piston-flow mean residence times.

Although the best fit line for the six samples has a high correlation coefficient ($r^2 = 0.96$), visually it appears that the six samples cluster into two groups with differing slopes. Dividing the dataset accordingly results in two regression lines with differing slopes and slightly higher correlation coefficients. The y-intercept for the group with lower slope (Group 2) falls below the 95% confidence interval lower bound. Hence, results using this value ($R_{\text{terr}}/R_a = 4.2$) are included in Fig 1b for Group 2 samples.

One additional constraint on minimum ages can be provided by the historical tritium input function. Based on monitoring data from Portland OR (~ 80 km south of the study area; GNIP Database, International Atomic Energy Agency, accessed Sept 2010), tritium activities in rainfall in the few years prior to the 2010 sampling campaign were ~ 4 TU and these are the lowest of the past 50 years. Tritium activities in spring samples were all >2 TU. Therefore, the difference (2 TU) may be considered as a minimum lower bound for $^3\text{He}_{\text{trit}}$, assuming that mixing with pre-bomb groundwater (low-tritium water that recharged prior to the thermonuclear testing era) was negligible. The resulting minimum residence time is ~10 years for all samples.

5. Conclusions

- Contributions of terrigenous helium sources to total dissolved helium in spring water ranged from 5 to 23%. The majority of terrigenous helium was derived from magmatic sources.
- Trend extrapolations using helium source mixing plots can be used to make preliminary estimates of R_{terr} . Although resulting estimates were consistent with regional data, remaining uncertainty in R_{terr} estimates nevertheless led to large estimate ranges of groundwater mean residence times (up to 30 years in some cases). In situations where R_{terr} or other mixing end members are poorly constrained, input uncertainties can far exceed analytical error ranges when propagated to groundwater residence time. However, uncertainties in input parameters are rarely included in reported uncertainties of age estimates in the literature.
- Groundwater residence times of spring discharge at Mount St. Helens are < 50 yrs based on tritium and tritium-helium methods. However, because of the significant uncertainty with helium isotope ratios, additional tracers are necessary to further refine these estimates.

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