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EFFECTS OF VOLCANISM, CRUSTAL THICKNESS, AND LARGE SCALE FAULTING ON THE HE ISOTOPE SIGNATURES OF GEOTHERMAL SYSTEMS IN CHILE

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ABSTRACT

The Chilean cordillera provides a unique geologic setting to evaluate the influence of volcanism, crustal thickness, and large scale faulting on fluid geochemistry in geothermal systems. In the Central Volcanic Zone (CVZ) of the Andes in the northern part of Chile, the continental crust is quite thick (50-70 km) and old (Mesozoic to Paleozoic), whereas the Southern Volcanic Zone (SVZ) in central Chile has thinner (60-40 km) and younger (Cenozoic to Mesozoic) crust. In the SVZ, the Liquiñe-Ofqui Fault System, a major intra-arc transpressional dextral strike-slip fault system which controls the magmatic activity from 38°S to 47°S, provides the opportunity to evaluate the effects of regional faulting on geothermal fluid chemistry. Measurements of $^{3}He/^{4}He$ and $^{4}He/^{36}Ar$ ratios in Chilean geothermal water and gas samples have been used to guide exploration efforts. He gas samples were collected from the El Tatio geothermal system in the CVZ and the Tinguirgirica, Chillán, and Tolhuaca geothermal systems in the SVZ. The Rc/Ra values for gas samples collected from hot springs and fumaroles at El Tatio range from 1.39 to 2.44. This range of values supports the model that magmatic fluids in the CVZ mix with crustally derived ^{4}He, which would be more abundant in the thicker, older silicic crust that is present in northern Chile, resulting in lower $^{3}He/^{4}He$ values for this region. Higher $^{3}He/^{4}He$ values were observed for most of the thermal features sampled in the SVZ. Gas sampled from a distal chloride hot spring at Tinguiririca yielded an Rc/Ra value of 1.4, and a sample collected from a fumarole at Chillán had a value of 3.21. Three fumaroles and two steam-heated bicarbonate hot springs were sampled at the Tolhuaca geothermal system, which is located near the Liquiñe-Ofqui Fault System. The Tolhuaca samples had He Rc/Ra values ranging from 6.16 to 6.71, suggesting that the geothermal fluids from this system have a significant mantle noble gas component, similar to that observed in fluids from active volcanic arc complexes. These new values agree with previously published results for the Chilean Andes.

INTRODUCTION

Measurement of $^{3}He/^{4}He$ in geothermal water and gas samples has been used to guide geothermal exploration efforts (e.g., Torgersen and Jenkins, 1982; Welhan et al., 1988) Elevated $^{3}He/^{4}He$ ratios (R/Ra values greater than ~0.1) have been interpreted to indicate a mantle influence on the He isotopic composition, and may indicate that igneous intrusions provide the primary heat source for the associated geothermal fluids. Studies of helium isotope compositions of geothermal fluids collected from wells, hot springs and fumaroles within the Basin and Range province of the western US (Kennedy and van Soest, 2007) have provided key insights into deformation-enhanced permeability, suggesting that mantle fluids, as indicated by elevated R/Ra values, can penetrate the ductile lithosphere, even in regions where there is no substantial magmatism.

A number of investigators (Hilton et al., 1993; Hoke et al., 1994; Ray et al., 2009) have previously conducted regional scale He isotope measurements of geothermal manifestations in the Central and Southern Volcanic Zones of Chile. These studies indicated that while there was a wide range in He isotopic values (with R/Ra ranging from 0.1 to 6.65 for hot spring and fumarole samples), nearly all of the features contained a significant mantle helium gas component. This variation was interpreted to represent the effects of magmatic degassing and different amounts of mixing with crustal and/or atmospheric helium. Hilton et al. (1993) noted that lower ratios were generally observed in the CVZ and interpreted this to reflect increased amounts of crustal contamination because of the thicker, older crust in the northern portion of the Chilean Andes. Hilton et al. (1993) and Hoke et al. (1994) did not find a correlation between proximity of the sampled features to the nearest volcanic summit and elevated $^{3}He/^{4}He$ values.

A series of geothermal and volcanic thermal manifestations for active volcanic centers and geothermal systems in the CVZ were studied by Tassi et al. (2009; 2010; 2011) and Aguilera et al. (2012). Gas samples collected from six hydrothermal systems in the CVZ (Tassi et al., 2010) had $^{3}He/^{4}He$ values very similar to those reported by Hilton et al. (1993), with Rc/Ra values ranging from 1.09 to 3.07. However, gas samples collected from fumaroles associated with active volcanoes in the CVZ had elevated $^{3}He/^{4}He$ values consistent with a MORB-like mantle helium source associated with arc volcanism (e.g., Poreda and Craig, 1989). Fumaroles sampled from the summit crater of Lascar volcano yielded R/Ra values ranging from 6.41 to 7.29, (Tassi et al., 2009). Nine gas samples collected from four different groups of fumaroles at Lastarria volcano had He R/Ra values ranging from 4.55 to 6.23 (Aguilera et al., 2012). Three gas samples collected from fumaroles at Tacora volano had He R/Ra values ranging from 4.32 to 5.87 (Capaccioni et al., 2011). Gases collected from fumaroles at the Putana, Olca, Irruputuncu, and Alitar volcanoes (Tassi et al., 2011) had He R/Ra values of 6.15-7.14, 6.11, 7.27, and 4.8, respectively. The volcanic fumaroles in the CVZ have significantly higher R/Ra values than gas samples associated with hydrothermal systems from this region.

FIELD AND LABORATORY METHODS

A total of ten gas samples were collected in March 2012 from thermal features from four different geothermal systems in the Chilean Andes: El Tatio (in the CVZ), and Tinguiririca, Chillán, and Tolhuaca (in the SVZ). An additional six thermal features at El Tatio were sampled in November 2012, along with a repeat sampling of the fumarole at Chillán. A type-K thermocouple was used to measure the temperature of the thermal features. Gas samples for noble gas analyses were collected from fumaroles and bubbling hot springs using either a titanium tube or an inverted plastic funnel. These were connected with Tygon tubing to a copper tube. Gas was bubbled through the system to purge any atmospheric contamination, and the gas samples were then trapped in the copper tube using cold seal weld clamps, resulting in a gas sample volume of 9.8 cm^3. The samples were then analyzed with a noble gas mass spectrometer at the Center for Isotope Geochemistry at LBNL using the methods described in Kennedy and van Soest (2006).

Noble gas results are presented in Table 1. The samples have $F(^{4}He)$ and $F(^{22}Ne)$ values (which reflect the $^{4}He/^{36}Ar$ and $^{22}Ne/^{36}Ar$ sample ratios relative to those of air) between 4.6 and 224, and 0.25 and 0.80, respectively.

Table 1: Noble gas results.

Sample ID	Feature type	Temp (C)	R/Ra	Rc/Ra	F (^{4}He)	F(^{22}Ne)
El Tatio						
ET12-1b	hot spring	84	2.10	2.16	9.69	0.4364
ET12-2b	fumarole	87	1.32	1.39	4.59	0.8070
ET12-3	fumarole	86.6	2.41	2.44	68.13	0.3975
Tinguiririca						
TIN12-2b	hot spring	90	1.39	1.40	14.39	0.2450
Chillán						
NDCH12-1b	fumarole	94.5	3.11	3.21	6.85	0.3321
Tolhuaca						
TOL12-1b	fumarole	94.6	6.36	6.40	46.79	0.3553
TOL12-2b	fumarole	95	6.13	6.16	75.48	0.4335
TOL12-3b	fumarole	93.4	6.23	6.24	223.6	0.5430
TOL12-4b	hot spring	54.5	6.58	6.64	22.15	0.2524
TOL12-5b	hot spring	57.7	6.63	6.71	24.06	0.3140

RESULTS

El Tatio

The El Tatio geothermal field is located in the CVZ, and contains abundant fumaroles, geysers, mudpots and hot springs (Lahsen and Trujillo, 1976). The geothermal field is located in a fault-bounded graben filled with ignimbrites, tuffs, and lavas. The hot springs consist of sodium chloride brines (the dominant water type) and steam-heated bicarbonate and sulfate waters. Exploratory drilling conducted between 1969 and 1974 confirmed the presence of a 260°C geothermal reservoir, and additional drilling has been conducted more recently by Geotérmica del Norte. Significant variations in the fluid geochemistry of boiling hot springs and geysers were reported by Cusicanqui et al. (1976), Giggenbach (1978), and Cortecci et al. (2005); these were interpreted to represent the effects of processes such as mixing of geothermal brine with dilute meteoric fluids, boiling, and water-rock interaction.

Two fumaroles and one hot spring were sampled during a field visit in March 2012 (Figure 1). The Rc/Ra values from the three features sampled in March 2012 ranged from 1.39 to 2.44. These values are consistent with earlier results reported by Hilton et al. (1993), Hoke et al. (1994), and Tassi et al. (2010), which range from 1.73 to 2.94. Because of the observed variation in $^3He/^4He$ ratios, an additional six features (four hot springs, one geyser, and one fumarole) were sampled in November 2012 – the analytical results from this sampling visit are not yet available. These analyses will be used to evaluate whether local variations in He isotopic compositions can be used to identify zones of upflow and outflow.

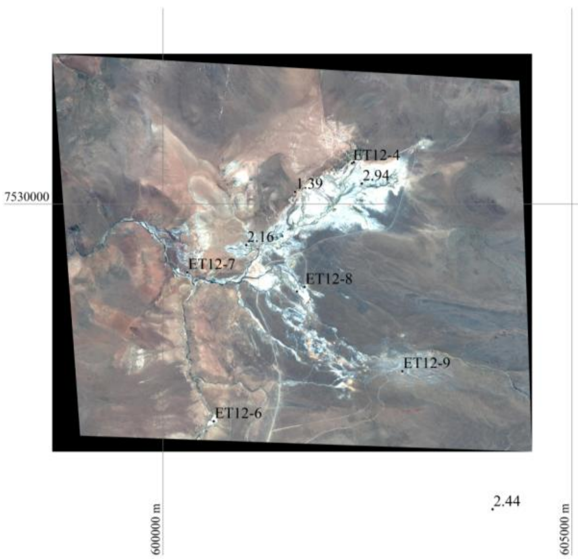

Figure 1: Image of El Tatio geothermal field with Rc/Ra values of He samples (this study and Tassi et al., 2010) and locations of additional samples collected in Nov. 2012.

Tinguiririca

The Tinguiririca geothermal system is located in the SVZ, approximately 150 km SW of Santiago (Clavero et al., 2011). It is situated on the western flank of the Tinguiririca Volcanic Complex. Fumaroles and associated acid-sulfate springs are located high on the flank of the volcano, and a distal chloride hot spring (Termas del Flaco) is situated along the southern margin of the complex. A gas sample collected from the Termas del Flaco spring yielded an Rc/Ra value of 1.40. This value is lower than the He compositions (2.7-2.9) reported by Clavero et al. (2011) for this system. The lower values observed at the distal hot spring may reflect mixing and fluid-rock interaction occurring during lateral flow from the main upflow zone.

Chillán

The Chillán geothermal system is located within the southern portion of the Nevados de Chillán volcano, a large active composite stratovolcano complex located in the SVZ (Dixon et al., 1999). Most of the hot springs and fumaroles are located in two thermal areas, one comprised of the Termas de Chillán, Termas Superior, and Olla de Mote (all near the ski resort), and the other being the Valle de Aguas Calientes. Two intermediate depth (< 1000 m) exploration wells have been drilled; however, neither appears to have reached the geothermal reservoir. Samples were collected from the same fumarole in the Termas Superior thermal area during the March and November 2012 field visits. The sample from the March 2012 sampling had an Rc/Ra value of 3.21, similar to those reported for thermal features at Chillán by Hilton et al. (1993) (3.63), Ray et al. (2009) (2.6 and 2.49), and Dobson and Mella (2000) (3.69).

Tolhuaca

The Tolhuaca geothermal system is located on the NW flanks of the Tolhuaca stratovolcano, which is situated in the SVZ to the E of Temuco (Melosh et al., 2012). This volcanic edifice is located just west of the Liquiñe-Ofqui Fault System, a major intra-arc transpressional dextral strike-slip fault system. Three fumaroles and two steam-heated bicarbonate hot springs were sampled in March 2012 (Figure 2), close to the youngest (post glacial Pemehue volcanic rocks of this volcanic complex (Melosh et al, 2012). Tolhuaca has been the site of exploratory drilling by GeoGlobal Energy, LLC, which recently reported a discovery well of 12 MWe (GRC Bulletin, Nov./Dec. 2012, pp. 16-17). The four wells at this system have identified a shallow (100-300 m deep) geothermal reservoir that is underlain by a much deeper, higher temperature resource. The three fumaroles have Rc/Ra values ranging from 6.16 up to 6.40, and the two hot spring gas samples have even higher values of 6.64 and 6.71. These values are significantly higher than the Rc/Ra values reported by Hilton et al. (1993) (4.64 and 5.07) and Ray et al. (2009) (3.20) for samples from the more distal Termas de Tolhuaca bicarbonate spring, located several km to the NW. The elevated $^3He/^4He$ values for the Tolhuaca thermal features suggest that there is a significant mantle component to the gases. The highest He Rc/Ra values were observed for the two high elevation bicarbonate hot springs, which lie directly above the shallow steam reservoir, and nearer to the upflow zone based on the conceptual model of Melosh et al. (2012).

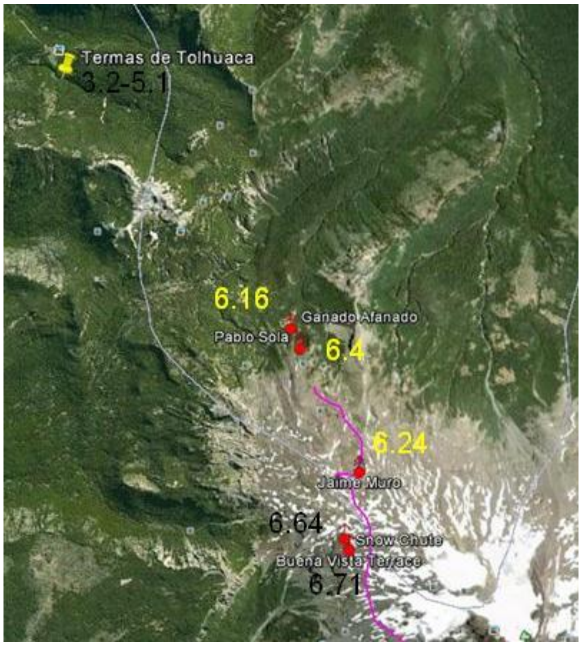

Figure 2: Image of Tolhuaca geothermal field with Rc/Ra values of He samples for fumaroles (yellow) and hot springs (black).

DISCUSSION

Effect of Crustal Thickness

One of the hypotheses to be tested in this study was the potential impact that variations in the thickness, composition, and age of the crust might have on regional trends in $^{3}He/^{4}He$ values for geothermal fluids. A number of published studies (e.g., Introcaso et al., 1992; Martinez et al., 1994; Beck and Zandt, 2002; Yuan et al., 2002; Fromm et al., 2004; Ramos et al., 2004; Gilbert et al., 2006; Hackney et al., 2006; McGlashan et al., 2008) have used gravity and seismic techniques to estimate crustal thicknesses across different sections of the Andes (Figure 3). In general, crustal thicknesses are greater in the CVZ (49-70 km) than in the SVZ (38-70 km, with values ≤ 50 km at latitudes below 36°S), and in both sections, decrease to the south.

Published He isotope data (Hilton et al., 1993; Hoke et al., 1994; Urzua et al., 2002; Sepulveda et al., 2007, Ray et al., 2009; Tassi et al., 2009, 2010, 2011; Aguilera et al., 2012) and the results of this study to date have been plotted as a function of latitude along the volcanic arc to examine if there is a marked difference in He Rc/Ra values between the CVZ and SVZ (Figure 4). For samples collected from features that have been identified as hydrothermal in origin, those located in the CVZ generally have Rc/Ra values less than 3.5. There is a much wider range of He isotopic compositions observed for gas samples obtained from hydrothermal surface manifestations in the SVZ, with higher values observed at latitudes below 38°S, where most samples have Rc/Ra values greater than 3.5. However, because of the wide range of values observed throughout the SVZ, any effect relating to crustal thickness appears to be secondary in nature with respect to determining the magnitude of the He mantle component.

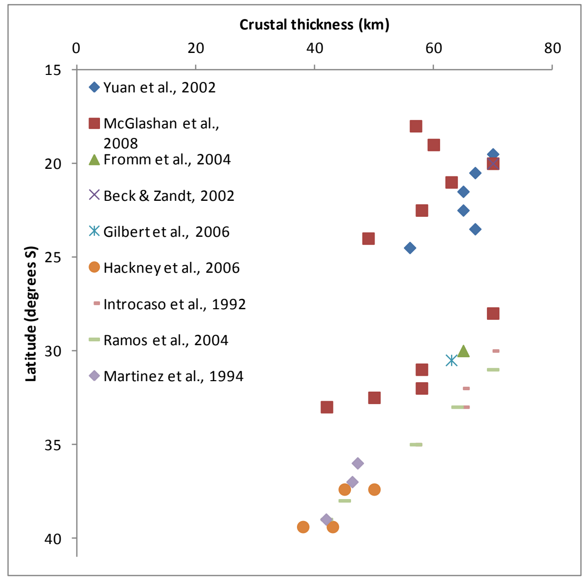

Figure 3: Estimates of crustal thickness beneath the Chilean Andean cordillera based on gravity and seismic models.

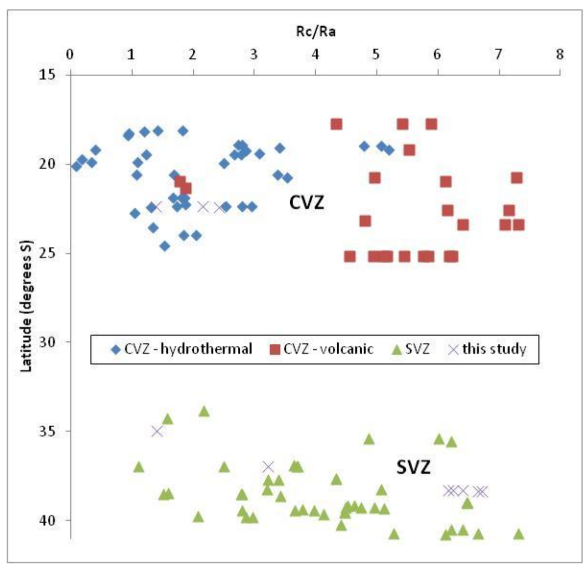

Figure 4: He isotope compositions for hydrothermal and volcanic features within the Chilean cordillera.

Effect of Volcanism

There are two distinct types of features that have been sampled in the CVZ: hot springs and fumaroles associated with hydrothermal systems, and fumaroles and solfataras near the summits of active volcanoes.

Many of the volcanic features are superheated, with measured vent temperatures up to 400°C. In contrast to the hydrothermal features of the CVZ, which generally have Rc/Ra values between 0.1 and 3.5 Rc/Ra (Figure 4), the volcanic features of the CVZ have (with two reported exceptions) significantly higher He Rc/Ra values between 4.3 and 7.3. This pronounced difference is likely reflective of a dominant mantle source for the volcanic features (e.g., Poreda and Craig, 1989).

The hydrothermal systems in the Chilean Andes have heat sources associated with magmatic activity, and this is clearly reflected in the measured He isotopic signatures. However, the fraction of mantle-derived He would be expected to be much higher in summit fumaroles at an active volcano, where the primary source of He would be derived from degassing of very young (months to years) magmas. In contrast, gases from hot springs and fumaroles associated with hydrothermal systems would have had a much more protracted history of interaction with shallow crust and meteoric fluids, and the older intrusive bodies that provide the heat for these systems have had a more prolonged degassing history. Local variations in He isotopic ratios within a geothermal system may provide insights as to the role that these processes have in modifying the magmatic He signature.

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