Available online at www.sciencedirect.com

ScienceDirect

Geochimica et Cosmochimica Acta 184 (2016) 193–211

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

Exploring the structural controls on helium, nitrogen and carbon isotope signatures in hydrothermal fluids along an intra-arc fault system

Daniele Tardani [a,b,*], Martin Reich [a,b], Emilie Roulleau [a,b], Naoto Takahata [c], Yuji Sano [c], Pamela Pérez-Flores [b,d], Pablo Sánchez-Alfaro [a,b], José Cembrano [b,d], Gloria Arancibia [b,d]

[a] *Department of Geology, FCFM, Universidad de Chile, 8370450 Santiago, Chile*

[b] *Andean Geothermal Center of Excellence (CEGA), FCFM, Universidad de Chile, 8370450 Santiago, Chile*

[c] *AORI, Atmosphere and Ocean Research Institute, University of Tokyo, Kashiwa, Chiba 277-8564, Japan*

[d] *Department of Structural and Geotechnical Engineering, Pontificia Universidad Católica de Chile, 7820436 Santiago, Chile*

Received 30 November 2015; accepted in revised form 18 April 2016; available online 26 April 2016

Abstract

There is a general agreement that fault-fracture meshes exert a primary control on fluid flow in both volcanic/magmatic and geothermal/hydrothermal systems. For example, in geothermal systems and epithermal gold deposits, optimally oriented faults and fractures play a key role in promoting fluid flow through high vertical permeability pathways. In the Southern Volcanic Zone (SVZ) of the Chilean Andes, both volcanism and hydrothermal activity are strongly controlled by the Liquiñe-Ofqui Fault System (LOFS), an intra-arc, strike-slip fault, and by the Arc-oblique Long-lived Basement Fault System (ALFS), a set of transpressive NW-striking faults. However, the role that principal and subsidiary fault systems exert on magma degassing, hydrothermal fluid flow and fluid compositions remains poorly constrained. In this study we report new helium, carbon and nitrogen isotope data ($^3He/^4He$, $\delta^{13}C–CO_2$ and $\delta^{15}N$) of a suite of fumarole and hot spring gas samples from 23 volcanic/geothermal localities that are spatially associated with either the LOFS or the ALFS in the central part of the SVZ. The dataset is characterized by a wide range of $^3He/^4He$ ratios (3.39 Ra to 7.53 Ra, where $Ra = (^3He/^4He)_{air}$), $\delta^{13}C–CO_2$ values (−7.44‰ to −49.41‰) and $\delta^{15}N$ values (0.02‰ to 4.93‰). The regional variations in $^3He/^4He$, $\delta^{13}C–CO_2$ and $\delta^{15}N$ values are remarkably consistent with those reported for $^{87}Sr/^{86}Sr$ in lavas along the studied segment, which are strongly controlled by the regional spatial distribution of faults. Two fumaroles gas samples associated with the northern "horsetail" transtensional termination of the LOFS are the only datapoints showing uncontaminated MORB-like $^3He/^4He$ signatures. In contrast, the dominant mechanism controlling helium isotope ratios of hydrothermal systems towards the south appears to be the mixing between mantle-derived helium and a radiogenic component derived from, e.g., magmatic assimilation of ^4He-rich country rocks or contamination during the passage of the fluids through the upper crust. The degree of ^4He contamination is strictly related with the faults controlling the occurrence of volcanic and geothermal systems, with the most contaminated values associated with NW-striking structures. This is confirmed by $\delta^{15}N$ values that show increased mixing with crustal sediments and meteoric waters along NW faults (AFLS), while $\delta^{13}C–CO_2$ data are indicative of cooling and mixing driving calcite precipitation due to increased residence times along such structures. Our results show that the structural setting of the region exerts a fist-order control on hydrothermal fluid composition by conditioning residence times of magmas

* Corresponding author at: Department of Geology, FCFM, Universidad de Chile, 8370450 Santiago, Chile.
E-mail address: daniele.tardani@ing.uchile.cl (D. Tardani).

http://dx.doi.org/10.1016/j.gca.2016.04.031

and thus promoting cooling/mixing of magmatic vapor, and therefore, must be taken into consideration for further geochemical interpretations.

Keywords: Helium isotopes; Nitrogen and carbon isotopes; Southern Volcanic Zone; Hydrothermal systems; Liquiñe-Ofqui Fault System

1. INTRODUCTION

In arc settings, helium isotopes have been successfully used, coupled with stable isotopes of carbon and nitrogen data, to constrain mantle heterogeneities and mechanisms of volatile recycling (Sano and Marty, 1995; Sano and Williams, 1996; Fischer et al., 1998, 2002; Sano et al., 2001). Subduction zones represent one of the preferential escape routes for primordial ^{3}He from the mantle, and previous studies have emphasized the role of the mantle wedge in dominating the helium budget in the great majority of cases (Hilton et al., 2002). Furthermore, it has been shown that participation of other contributors to the arc volatile inventory – i.e., the subducting slab and/or arc crust – can be traced using the isotopic composition of noble gases such as $^{3}He/^{4}He$ ratios and stable isotopes of carbon and nitrogen (Sano and Marty, 1995; Sano and Williams, 1996; Fischer et al., 1998, 2002; Sano et al., 2001). Such studies have proved critical to constrain the relative mantle vs. subducted sediment contributions on the isotopic signature of hydrothermal fluids, as well as the degree of contamination by upper crustal rocks. Despite these significant advances, very few studies have focused on deconvolving the regional scale structural and tectonic controls affecting the composition of deep-seated fluids during the separation from the magmatic source and the passage through the crust (Kennedy et al., 1997; Kennedy and van Soest, 2005; Karlstrom et al., 2013). In particular, the local scale control of interconnected faults and associated fractures (fault-fracture meshes; Sibson, 1996) on fluid flow in geothermal and hydrothermal systems has been largely studied over the past twenty years (Sibson, 1994, 1996; Manning and Ingebritsen, 1999; Sibson and Rowland, 2003; Fairley and Hinds, 2004; Micklethwaite and Cox, 2004; Rowland and Sibson, 2004; Blenkinsop, 2008; Graf and Therrien, 2009; Cox, 2010; Faulkner et al., 2010; Gudmundsson et al., 2010; Micklethwaite et al., 2010; Rowland and Simmons, 2012). These studies have improved our understanding about the structural factors controlling fluid flow, and have provided crucial information to refine conceptual models of the local fault-fracture hydraulic architecture in geothermal and hydrothermal systems.

The goal of this study is to unravel the regional scale structural controls on the isotopic composition of subduction-related magmatic gas, from its source to their pathway toward the surface. Our aim is to assess the nature of the link among fault-fracture meshes, magmatic degassing, crustal assimilation and fluid mixing processes taking place in the upper crust, that affect the composition of hydrothermal fluids discharged along principal and subsidiary structures of a regional scale, intra-arc strike slip fault. Considering the fact that tectonic activity defines the nature, geometry and kinematics of fault-fracture networks, a better understanding of the structural pattern and its link with the chemical evolution of fluids may give significant insights into the processes governing the dynamics of hydrothermal systems associated with such large-scale crustal structures.

The Andean Cordillera of Central-Southern Chile is a perfect natural laboratory to test this hypothesis. In this region, the relationship between tectonics and volcanism is the result of interaction between the crustal structures of the basement and the ongoing regional stress field (Pritchard et al., 2013). As pointed out by several studies, magmatism and volcanism, as well as geothermal activity in the region are spatially associated with tectonic features (Hildreth and Moorbath, 1988; López-Escobar et al., 1995; Hauser, 1997; Pérez, 1999; Sepúlveda et al., 2004; Lara et al., 2006; Cembrano and Lara, 2009; Alam et al., 2010; Lahsen et al., 2010; Sánchez et al., 2013). In particular, in the Southern Volcanic Zone (SVZ) between 37° and 46°S, the volcanic and geothermal activity is partially controlled by the ~1000 km long, NNE-striking intra-arc dextral strike-slip Liquiñe-Ofqui Fault System (LOFS), and by the NW-SE Arc-oblique Long-lived Basement Fault System (ALFS). Many geothermal surface manifestations and shallow fumarolic emissions are spatially related to stratovolcanoes and fault segments associated with both fault systems (Fig. 1).

Previous geochemical surveys conducted in this region have recognized a wide range of $^{3}He/^{4}He$ ratios in volcanic/geothermal fluids, suggesting mixing between mantle helium and the radiogenic helium sourced from country rocks (Hilton et al., 1993; Ray et al., 2009; Dobson et al., 2013). However, these studies have focused either on orogen-scale controls on noble gas compositions, or have addressed the local structural controls in individual geothermal systems (Sepúlveda et al., 2007; Agusto et al., 2013). In this study we present a comprehensive dataset of helium, nitrogen and carbon isotope analyses from a suite of about 20 volcanic fumaroles and thermal springs between the 37° and 41°S. The gas samples were collected from fumaroles in active volcanic systems and thermal springs that are closely spatially associated with both the LOFS and the ALFS. Based on new and unpublished mapped structures and as a up-to-date structural background in the region (Potent, 2003; Melnick et al., 2006; Lara et al., 2006; Cembrano and Lara, 2009; Pérez-Flores et al., 2014), we highlight the role of LOFS and ALFS on fluid circulation and provide a new interpretation that explains the spatial variations of helium, nitrogen and carbon isotopes in thermal fluids in the Central Southern Volcanic Zone of Chile.