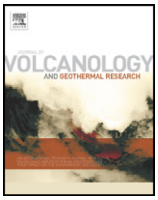
Journal of Volcanology and Geothermal Research 345 (2017) 172–183

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores



Stable isotopes evidence of recycled subduction fluids in the hydrothermal/volcanic activity across Nicaragua and Costa Rica

Ramírez-Leiva A. [a], Sánchez-Murillo R. [a,*], Martínez-Cruz M. [b], Calderón H. [c], Esquivel-Hernández G. [a], Delgado V. [d], Birkel C. [e,f], Gazel E. [g], Alvarado G.E. [h], Soulsby C. [f]

[a] *Stable Isotope Research Group, Chemistry School, Universidad Nacional, P.O. Box: 86-3000, Heredia, Costa Rica*
[b] *Observatorio Sismológico y Vulcanológico de Costa Rica, Universidad Nacional, P.O. Box: 2346-3000, Heredia, Costa Rica*
[c] *Institute of Geology and Geophysics, IGG-CIGEO, UNAN-Managua, P.O. Box: 4598, Nicaragua*
[d] *Centro para la Investigación en Recursos Acuáticos de Nicaragua, CIRA, UNAN-Managua, P.O. Box: 4598, Nicaragua*
[e] *Department of Geography, University of Costa Rica, P.O. Box 11501-2060, San José, Costa Rica*
[f] *Northern Rivers Institute, University of Aberdeen, P.O. Box: AB24 3UF, Aberdeen, Scotland*
[g] *Earth and Atmospheric Science Department, Cornell University, P.O. Box: 14853-1504, Ithaca, NY, USA*
[h] *Instituto Costarricense de Electricidad, P.O. Box: 10032-1000, San José, Costa Rica*

ARTICLE INFO

Article history:
Received 10 July 2017
Received in revised form 27 August 2017
Accepted 28 August 2017
Available online 1 September 2017

Keywords:
Central America volcanic front
Hydrothermal systems
Isotopic fractionation
Recycled subduction fluids
Groundwater mixing

ABSTRACT

The Central America volcanic front provides a unique opportunity to study hydrothermal inputs and their interaction and mixing with modern meteoric waters. The objectives of this study were to: a) characterize the isotopic composition ($\delta^{18}O$, $\delta^{2}H$, *d*-excess, and lc-excess) of hydrothermal/volcanic systems, b) analyze the influence of kinetic fractionation and meteoric water inputs in the isotopic composition of hydrothermal waters, and c) estimate the 'andesitic water' contribution (recycled subduction fluids) within the volcanic front of Nicaragua and Costa Rica. Hydrothermal evaporation lines are described as: $\delta^{2}H = 4.7 \cdot \delta^{18}O - 13.0$ (Costa Rica) and $\delta^{2}H = 2.7 \cdot \delta^{18}O - 31.6$ (Nicaragua). These regressions are significantly ($p < 0.001$) deviated from their respective meteoric water lines: $\delta^{2}H = 7.6 \cdot \delta^{18}O + 7.4$ (Costa Rica) and $\delta^{2}H = 7.4 \cdot \delta^{18}O + 5.2$ (Nicaragua). The greater rainfall inputs in Costa Rica with respect to Nicaragua, resulted in the attenuation of the evaporative effect as observed in the strong bimodal distribution of the hydrothermal waters, which can be divided in fluids: a) isotopically-close to meteoric conditions and b) isotopically-altered by the interaction with recycled subduction fluids and kinetic fractionation. The latter is clearly depicted in the significantly ($p < 0.001$) low *d*-excess and lc-excess median values between Costa Rica (+5.10‰, −5.25‰) and Nicaragua (−2.42‰, −10.65‰), respectively. Poor correlations between $\delta^{18}O/\delta^{2}H$ and the elevation gradient emphasize that the contribution of recycled subduction fluids and subsequent surface kinetic fractionation are the main drivers of the isotopic departure from the orographic distillation trend captured in the rainfall isoscapes. End-member mixing calculations resulted in a significant difference ($p < 0.001$) between the mean 'andesitic water' contribution to the hydrothermal systems of 15.3 ± 10.8 (%, $\pm 1\sigma$) (Nicaragua) and 19.7 ± 10.3 (%, $\pm 1\sigma$) (Costa Rica). The spectrum of 'andesitic water' contribution largely reflects the degree of mixing with isotopically 'pre-shifted' recycled subduction fluids. The latter is supported by previous strong evidence of mantle-derived N_2/He contributions across the volcanic front of Nicaragua and Costa Rica.

1. Introduction

The Central America subduction zone is a complex deformation region characterized by a rapid (70–90 mm/year) convergence rate of young (15–25 Ma) oceanic lithosphere (DeMets, 2001; Peacock et al., 2005; Hoernle et al., 2008), whereby the convergence rate and age of the incoming lithosphere vary slightly along-strike (Protti et al., 1995; DeMets, 2001), and mainly responds to the interaction of four plates: Caribbean, Cocos, Nazca, and South American (Sak et al., 2009). Between the Cocos and Caribbean plates, convergence rate increases from 60 mm/year (NW) to −90 mm/year (SE) (DeMets, 2001; Peacock et al., 2005; Hoernle et al., 2008; Protti et al., 2012). Through this margin, deep earthquakes record the rupture at the interface of the Cocos-Caribbean plates, defining a zone that marks the subducting Cocos plate up to 250 km beneath Nicaragua and about 80 km beneath the Costa Rican Volcanic front (Protti et al., 1995; Husen et al., 2003; Hoernle et al., 2008; Arroyo et al., 2009).

Currently, the Costa Rica-Nicaragua subduction zone is a non-accreting margin, which is described by subduction erosion (von Huene and Scholl, 1991; Ranero and von Huene, 2000; von Huene et al., 2000).

---

[*] Corresponding author at: Stable Isotope Research Group, Chemistry School, Universidad Nacional, Campus Omar Dengo, P.O. Box: 86-3000, Heredia, Costa Rica.
E-mail address: ricardo.sanchez.murillo@una.cr (R. Sánchez-Murillo).

http://dx.doi.org/10.1016/j.jvolgeores.2017.08.013
0377-0273/

The modern arc develops on a base of volcanic strata, which is related to arc magmatism in Nicaragua and the Caribbean Oceanic Plateau in Costa Rica (Denyer and Gazel, 2009 and references therein) The maximum elevation of volcanoes along Central America decreases from Guatemala (Tajamulco volcano: 4220 m a.s.l.) to Nicaragua (San Cristóbal volcano: 1745 m a.s.l.) with a decrease in crustal thickness (50 km to <35 km) and variations in the basement geology from continental to oceanic dominated characteristics, whereas in Costa Rica, volcanoes elevation increases (Irazú volcano: 3432 m a.s.l.) (45 km) near the amagmatic gap, then decreases (25 km) beneath central Panamá (La Yeguada volcano: 1297 m a.s.l.) (Leeman et al., 1994). The composition of the lavas in Nicaragua are typical of arc volcanoes (Feigenson and Carr, 1993; Saginor et al., 2011; Saginor et al., 2013; Gazel et al., 2015), but the volcanic front lavas in Costa Rica are well-known for their enriched ocean island basalt - like (OIB-like) signature (e.g., Reagan and Gill, 1989; Feigenson et al., 2004; Gazel et al., 2009). Recent studies have provided convincing geochemical (i.e. rare trace elements) evidence that this anomalous OIB-like signature in the volcanic front is derived from the interaction of the mantle wedge with the Galapagos Hotspot tracks subducting beneath Costa Rica and Panama (Hoernle et al., 2008; Gazel et al., 2011, 2015).

This geochemical scenario in Nicaragua and Costa Rica offers the necessary heat and decompression cooling for storing fluids (i.e., meteoric water, sea water, magmatic water or mixed fluids including gas vents; Molina and Martí, 2016) within fractured volcanic aquifers, which ultimately constitute the main energy transport mechanism for surface hydrothermal manifestations. This hydrothermal upwelling provides heat, dissolved gases, and minerals to maintain a broad spectrum of ecosystems across the Pacific and Caribbean slopes of Costa Rica and Nicaragua, but also sustain a large set of hot-spring tourist activities and moderate hydrothermal energy production (Martínez-Tiffer et al., 1988; Balcazar et al., 1993; Fridleifsson, 2001; Manzo, 2005). Although, stable isotope studies have been used to investigate hydrothermal manifestations in Central America over three decades ago (Fournier et al., 1982; Goff et al., 1987; Giggenbach and Corrales, 1992; IAEA, 1992; Rowe et al., 1995; Nieva et al., 1997; Tassi et al., 2005; López et al., 2006; Birkle and Bundschuh, 2007; Rouwet et al., 2009; Molina and Martí, 2016), these efforts were mainly focused on a specific hydrothermal field or volcano edifice. To our knowledge, no spatial analysis has been undertaken to compare the contribution of recycled subduction fluids within the volcanic front of Central America using water stable isotopes and second order variables in hydrothermal system discharges.

In this study, stable isotope archives in hydrothermal waters of Costa Rica and Nicaragua were combined with new stable isotope data to a) characterize the isotopic composition ($\delta^{18}O$, δ^2H, *d*-excess, and lc-excess), b) analyze the influence of secondary kinetic fractionation and meteoric water inputs in the isotopic composition of hydrothermal waters, and c) estimate the ‘andesitic water’ contribution (i.e. recycled subduction fluids) (Taran et al., 1989; Giggenbach, 1992) within the volcanic front of Nicaragua and Costa Rica. This information provides new insights regarding the use of stable isotopes and second-order variables as indicators of hydrothermal/volcanic activity, as well as offering spatially-oriented and quantitative evidence of subduction recycled fluid dynamics within the volcanic front of Central America.

2. Study area description

2.1. Hydrothermal/volcanic activity across Costa Rica and Nicaragua

Costa Rica (52,100 km^2) is located in the southern extreme of Central America to the west of the Caribbean plate, between the eastern Pacific Ocean and the Caribbean Sea. There is a convergent boundary, where the Cocos plate is subducted beneath the Caribbean plate, which generated the volcanic front of Costa Rica (Fig. 1). In Costa Rica, there are about fifteen dormant and five historically active volcanoes since 1700 to present, most of them are considered of a composite origin (Alvarado, 2009), extending from NW with Orosí volcano (OR) to SE with Turrialba volcano (TU) (Fig. 1). The volcanic front of Costa Rica is divided into two main cordilleras (i.e. mountain ranges): Guanacaste Volcanic Cordillera (GVC), which is a NW-trending chain of volcanoes (Orosí, OR; Rincón de la Vieja, RV; Miravalles, MV; and Tenorio, TE; Alvarado, 2009) and the Central Volcanic Cordillera (CVC) (Platanar, PA; Poás, PO; Barva, BA; Irazú, IR; and Turrialba, TU). Between GVC and CVC, two twin isolated volcanoes exist: Arenal (AR) and Chato (not shown in Fig. 1, it is located next to AR) (Carr and Stoiber, 1990; Herrstrom et al., 1995; Husen et al., 2003; Alvarado, 2009) (Fig. 1).

The GVC is considered a geothermal province with particular geochemical signatures (Giggenbach and Corrales, 1992; Molina and Martí, 2016), which are transitional between an isotopically depleted mantle source and a high subduction signal characteristic of the Nicaraguan volcanoes as well as the enriched mantle source and limited subduction signal characteristic of the central Costa Rican volcanoes (Carr and Stoiber, 1990; Herrstrom et al., 1995; Gazel et al., 2015). Multiple hydrothermal systems have been identified at the slopes (mainly Pacific facing slopes) of AR, RV, and MV volcanoes. In addition, PO, IR, and TU volcanoes have hydrothermal systems with fluid discharge temperature close to 90 °C (Giggenbach and Corrales, 1992; Fehn et al., 2002; Marini et al., 2003; Zimmer et al., 2004; Moya et al., 2005; López et al., 2006; Phillips-Lander et al., 2014).

Nicaragua (130,700 km^2) is located between the Caribbean plate to the east, and the Cocos plate to the west (Arengi and Hodgson, 2000). The active volcanic front (developed 350 ka ago; Carr et al., 2007; Brasse et al., 2015) is located in western Nicaragua (within the Cordillera Los Marrabios), and it is represented by a great variety of volcanic formations (i.e., active volcanoes, explosion craters, and scoria cones), along which most of the areas of geothermal priority are also located (Martínez-Tiffer et al., 1988). The volcanism in Nicaragua is located mainly in the Pacific slope of the country (Carr et al., 2004) (Cosigüina, CS; San Cristóbal, SC; Telica, TE; El Hoyo, EH; Momotombo, MT; Apoyeque, AP; Masaya, MA; Mombacho, MO; Zapatera, ZP; Ciguatepe, CI; Las Lajas, LA; Concepción, CO; and Maderas, MD; Fig. 1), and it is divided into segments that are between 100 km and 300 km long (Carr et al., 2007; Saginor et al., 2011). Nicaragua has a region of active subsidence, which is located roughly parallel to and within the Nicaraguan Depression (i.e., Lake Nicaragua) (Fig. 1), where sediments cover the bases of the active volcanoes (Saginor, 2008).

The Nicaraguan territory includes at least ten stratovolcanoes (including nine active volcanoes, calderas, and pyroclastic cones; Simkin et al., 2011). Conduction to the surrounding ground and the condensation of the gas are examples of losing heat mechanisms within hydrothermal fluid manifestations, an example of the thermal structure is the Masaya volcano, where diurnal temperature variations are <5 °C, mainly due to the influence of rain events or variations about 10 °C related to volcanic events (Pearson et al., 2008).

2.2. Governing climatic features across Costa Rica and Nicaragua

Four regional air circulation patterns predominantly control the climate of Costa Rica: NE trade winds, the latitudinal migration of the Intertropical Convergence Zone (ITCZ), cold continental outbreaks, and sporadic influence of Caribbean cyclones (Waylen et al., 1996; Sáenz and Durán, 2015). These circulation processes produce two predominant rainfall maxima, one in May and June and the second in September–October, which are interrupted by a relative minimum in July–August known as the Mid-Summer Drought (MSD) (Magaña et al., 1999; Maldonado et al., 2013). In addition to these circulation processes, the continental divide of Costa Rica (i.e. a mountainous range that extends from NW to SE with a maximum elevation at the Chirripó peak: 3820 m a.s.l.) also influences rainfall patterns across the country, dividing the territory into the Caribbean and Pacific slopes. In general, annual rainfall in Costa Rica varies from < 1500 mm in the drier northwestern region, 2500 mm in the Central Valley, and up to 7000 mm on the