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ScienceDirect

Geochimica et Cosmochimica Acta 182 (2016) 173–196

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

Widespread distribution of ascending fluids transporting mantle helium in the fore-arc region and their upwelling processes: Noble gas and major element composition of deep groundwater in the Kii Peninsula, southwest Japan

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Received 15 August 2015; accepted in revised form 15 March 2016; available online 21 March 2016

Abstract

Chemical and isotopic studies including analyses of noble gases were comprehensively conducted on the groundwater of the entire Kii Peninsula, which is located in the fore-arc region of southwest Japan. Groundwater of Na–Cl–HCO_3, Na–HCO_3–Cl, and Na–Cl types was shown to be distributed across the whole area. Groundwater in the inland central part of the peninsula shows relatively low salinity, whereas groundwater from the area along the ENE-trending Median Tectonic Line (MTL), on the north side of the peninsula, shows high salinity (up to 18,800 mg/L of Cl^-) and the presence of unusual heavy oxygen isotopes. This trend is similar to that documented in saline waters from the Arima region (the so-called "Arima-type thermal water"). High $^3He/^4He$ ratios relative to the atmospheric value (up to 6.7 Ra) were recorded throughout the Kii Peninsula, covering a wider area than documented previously. The saline groundwater is also strongly depleted in ^{20}Ne and heavy noble gases.

From the wide distribution of high $^3He/^4He$ values and the associated ^{20}Ne and Cl^- concentrations, we infer that aqueous fluids derived from dehydration of the subducting slab are present at depth beneath almost the entire Kii Peninsula. These aqueous fluids may ascend along the major north-dipping boundary faults. The isotopic composition of groundwater from the southern part of the peninsula suggests that the contribution from these dehydration-derived fluids is relatively small in this region. However, volatile components (e.g., noble gases and CO_2) in the groundwater of this area may originate from the dehydration-derived fluids. Upwelling of Arima-type thermal water of the Na–Cl–HCO_3 type is expected to undergo a phase separation of volatile species due to decompression as the fluid ascends. The variety of water types documented may be due to this water–gas separation and the subsequent incorporation of gaseous species into shallow meteoric groundwater.

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http://dx.doi.org/10.1016/j.gca.2016.03.017

The observed high $^{3}He/^{4}He$ ratios in the absence of a mantle wedge below the southern part of the Kii Peninsula may reflect the oblique ascent of these fluids along north-dipping boundary faults.

1. INTRODUCTION

Sakai and Matsubaya (1974) classified the thermal waters of the Japanese islands into four distinct categories: volcanic, ''Green Tuff''-type, coastal, and Arima-type. Volcanic thermal waters with widely differing chemical compositions commonly co-exist within a single volcanic body (White, 1957). Several studies have revealed that the chemical compositions of volcanic waters reflect the mixing of meteoric water and magmatic volatiles (White, 1957; Giggenbach, 1988; Hedenquist and Lowenstern, 1994; Brusca et al., 2001; Hurwitz et al., 2003). The Green Tuff-type thermal water has the composition Na–(Ca)–Cl–SO_4, which has been explained as meteoric water containing ''fossil'' Miocene seawater sulfates leached from Green Tuff formations (Sakai and Matsubaya, 1974). The coastal thermal waters are a mixture of oceanic brine and meteoric water. Interaction between the hot water and the host rocks is responsible for the typical Na–Ca–Cl chemistry of this type of thermal water (Sakai and Matsubaya, 1974). The origins of these three types of thermal water are relatively easy to understand, as their chemistry and geology are closely connected.

The Arima hot springs, a representative of the Arima-type thermal water, have unusually high temperatures and chlorine concentrations, although they are located in the fore-arc region of southwest Japan where the Philippine Sea (PHS) Plate is subducting but there is no Quaternary volcanic activity (Fig. 1). Matsubaya et al. (1973) found several saline springs ($Cl^- = 0.7$–1.1 mol/L) with high temperatures (ca. 97 °C) in Arima that are significantly enriched in heavy oxygen isotopes, at levels up to +6.5‰. Similar mineral springs are also found in the Ishibotoke region (south of the Osaka Plain), 50 km southeast of the Arima region (Fig. 1). The hydrogen and oxygen isotopic compositions of these waters indicate mixing of local meteoric water and a unique thermal brine with high $\delta^{18}O$ and Cl^- concentrations. This high-δD and high-$\delta^{18}O$ Arima-type thermal water extends to the range of andesitic water, as defined by Giggenbach (1992) for island-arc magmatic water. Although several studies of water chemistry, isotopes, and mineralogy have been conducted in the Arima and Ishibotoke regions (Matsubaya et al., 1973; Sakai and Matsubaya, 1974; Masuda et al., 1985, 1986; Kazahaya et al., 2014; Tanaka et al., 2013), the origins of the water itself, and its dissolved constituents, remain poorly understood. Kusuda et al. (2014) suggested that the observed geochemical features originate from a dehydrated component derived from the subducted Philippine Sea (PHS) slab. Dehydration-derived water is thought to be highly saline and contain high amounts of CO_2 (Kerrick and Connolly, 2001; Jarrard, 2003; Kendrick et al., 2011; Kawamoto et al., 2013).

Nagao et al. (1981) and Sano and Wakita (1985) reported high $^{3}He/^{4}He$ ratios, up to 7.9 Ra (where Ra is the atmospheric ratio, 1.4×10^{-6}; Ozima and Podosek, 2002), comparable to values in the upper mantle (7.5–9.5 Ra; Graham, 2002), in gases from the Arima thermal water and the Ishibotoke mineral springs, although $^{3}He/^{4}He$ ratios of thermal waters in the fore-arc region are generally lower than the atmospheric value (Sano and Wakita, 1985). A number of investigations of He isotopes in adjacent regions have revealed that these unusually high $^{3}He/^{4}He$ ratios are widespread in the fore-arc region of southwest Japan, especially in the central and western parts of the Kii Peninsula (Matsumoto et al., 2003; Morikawa et al., 2005, 2008; Doğan et al., 2006; Umeda et al., 2006a,b; Sano et al., 2009). Sano et al. (2009) showed that many springs with He ratios higher than 4 Ra ocuur distributed in the central and western parts of the Kii Peninsula. Matsumoto et al. (2003) and Umeda et al. (2006b) suggested that the mantle-derived He component is carried to the Kii Peninsula by aqueous fluids generated by dehydration of the subducting slab. The presence of fluids generated by slab dehydration in the central and western parts of the Kii Peninsula has been inferred from a number of geophysical observations, such as non-volcanic seismic swarms (Mizoue et al., 1983; Kato et al., 2010, 2014; Yoshida et al., 2011), deep non-volcanic tremors (Obara, 2002; Obara et al., 2012), and seismic velocity structures (Salah and Zhao, 2003; Nakajima and Hasegawa, 2007a, b). Sano and Nakajima (2008) suggested that high-$^{3}He/^{4}He$ mantle material is upwelling beneath the PHS Plate and passing through a large fissure or slab tear in the plate. Clearly, the presence of this anomalous high-$^{3}He/^{4}He$ signature in a non-volcanic region indicates that a deep-seated fluid of some kind has been upwelling from the lower crust to the surface in this area.

The studies of noble gas chemistry cited above and studies of major element chemistry in the region were conducted separately, and their mutual relationship has not been sufficiently discussed. As noted above, the Arima-type thermal water, which may include slab-derived fluids, has unusual oxygen and hydrogen isotope compositions, accompanied by high chloride (Cl^-) and bicarbonate (HCO_3^-) concentrations. However, data of water chemistry and isotope compositions in the Kii Peninsula are scarce. Previous studies of noble gas chemistry focused on the central and western parts of the peninsula. In this study, we investigate both the water chemistry/isotopes and noble gas isotopes in groundwater from the entire Kii Peninsula, to comprehensively assess the distributions of the high-$^{3}He/^{4}He$ signatures and