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Geothermal systems on the island of Java, Indonesia

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ABSTRACT

This paper presents an overview of all known geothermal systems on the island of Java by presenting physico-chemical data for associated hot springs, cold springs and acid crater lakes. A total of 69 locations were sampled and classified based on their position in either a volcanic complex (volcano-hosted) or a fault zone (fault-hosted). In particular the potential of a magmatic heat source for fault-hosted geothermal systems was investigated. Volcano-hosted geothermal systems had higher HCO_3^- concentrations and higher Mg/Na ratios than fault-hosted geothermal systems. This geochemical difference is likely due to degassing and subsequent CO_2-water reaction in the volcano-hosted systems, which is absent in the fault-hosted geothermal systems. The HCO_3 vs. Cl and Mg/Na vs. SO_4/Cl systematics indicated that fault-hosted geothermal systems located in the active Quaternary volcanic belt received shallow magmatic fluids, hence should be classified as volcano-hosted geothermal systems. The heat source of fault-hosted geothermal systems located in the old (Tertiary) volcanic belt was investigated by a combination of Li enrichment and calculated reservoir temperatures. There a shallow magmatic heat source was indicated only for the Cilayu and Cisolok geothermal systems. Thus, a deep seated magma was considered to be the heat source for the fault-hosted geothermal systems of Cikundul, Pakenjeng, Parangtritis and Pacitan.

In ten of the volcano-hosted geothermal systems, ^{2}H and ^{18}O isotope enrichments were found, but not in any of the fault-hosted geothermal systems. Stable isotope enrichment due to evaporation was recognized in the Kawah Candradimuka and Kawah Sileri, Kawah Hujan and Candi Gedong Songo geothermal systems. A combination of intensive evaporation and magmatic gases input produced very heavy stable isotopes in the hot acid crater lakes of the Kawah Kamojang, Kawah Sikidang and Kawah Putih geothermal systems. The addition of substantial amounts of andesitic water to the geothermal fluid was observed in the Candi Songgoriti, Banyuasin and Pablengan geothermal systems.

Contrary to established belief fault-hosted geothermal systems on Java could be considered a potential source for geothermal energy.

1. Introduction

At least 62 geothermal fields with the potential for exploitation are present on the island of Java (Setijadji, 2010). Following Alam et al. (2010) geothermal fields can be divided into volcano-hosted and fault-hosted geothermal systems based on their geologic association. The former is a geothermal system related to a volcanic complex and the latter is a geothermal system located in a fault zone. To date, seven volcano-hosted geothermal fields were developed and five of them produce electricity. Fault-hosted geothermal fields were not developed and are rarely explored, due to the assumption of insufficient energy. However, considering the geology of Java, a volcanic (magmatic) influence on the fault-hosted geothermal systems is likely.

In other volcanic arcs around the world, fault-hosted geothermal fields which are located close to volcanic areas indicate a heating of deep circulated meteoric water, e.g., in the Liquiñe-Ofqui fault zone of Chile and in the Southern Apennines of Italy (Alam et al., 2010; Italiano et al., 2010). Using a trend of B enrichment, Alam et al. (2010) suggested for the Liquiñe-Ofqui fault zone (a) heating of meteoric water in fault-zone hosted geothermal systems and (b) condensation of volcanic steam in volcano-hosted geothermal systems. However, the authors did not indicate the heat source of the fault-hosted geothermal system. Arehart et al. (2003) identified a magmatic heat source for the Steamboat geothermal system (Nevada, USA), based on trace metal and gas data. Historically this geothermal system was considered as an extensional geothermal type with anomalous heat flow as the heat source (Wisian et al., 1999). Anomalous heat flow in the Alpine fault, New Zealand, for example, is considered to be caused by uplift and erosion (Allis and Shi, 1995; Shi et al., 1996).

Here physicochemical processes, fluid sources and reservoir temperature of volcano and fault-hosted geothermal systems on Java were

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examined, using chemical and isotope (^2H and ^{18}O) data. The data indicated a magmatic influence on the fault-hosted geothermal systems, and thus a hidden energy potential for some of the fault-hosted geothermal systems on Java.

2. Geological setting

Java, an island in the Indonesian archipelago is a part of a long volcanic arc that extends from Sumatera to Nusa Tenggara (Fig. 1). The volcanic arc is due to subduction of the Indo-Australian plate beneath the Eurasian plate, with a rate of about 6 to 7 cm/a (Hamilton, 1979; Simandjuntak and Barber, 1996). The subduction started in the middle Paleogene (Hall, 2002) and produced the east–west trending Southern Mountain volcanic arc (Soeria-Atmadja et al., 1994). Later, in the magmatic periods of the Neogene and the Quaternary, additional volcanic arcs were formed to the north, also trending from east to west (Van Bemellen, 1949; Hamilton, 1979). The older rocks (Tertiary) are andesitic, while the younger (Quarternary) rocks are more alkaline (Soeria-Atmadja et al., 1994). Clements et al. (2009) noted that subduction caused lifting and erosion in the southern part of the island, as indicated by the exposure of Cretaceous basement.

The tectonic setting of Java is dominated by four main faults, namely the E–W backarc-thrust of Barabis–Kendeng, the NE–SW strike-slip fault of Cimandiri, the SE–NW Citandui fault in West Java and the NE–SW Central Java Fault (Hoffmann-Rothe et al., 2001). These faults were generated since the Neogene by compressional forces (Simandjuntak and Barber, 1996; Hall, 2002). The Cimandiri fault is an active fault with a slip rate of about 6 to 10 mm/a (Setijadji, 2010; Sarsito et al., 2011). The Citandui and the Central Java faults are a pair of major strike-slip faults (wrench faults) that formed the geological features of Central Java and caused a northward shift of the Quaternary volcanic arc in this area (Bahar and Girod, 1983; Satyana, 2007). Besides those four faults, there are several smaller faults, which include the E–W Lembang fault in West Java, the NE–SW Opak fault in Central Java and the NE–SW Grindulu fault in East Java (Fig. 2).

The volcanoes and faults on Java are host to at least 62 geothermal fields (Setijadji, 2010), most of which are located in the Quaternary volcanic arc, including 7 developed geothermal fields, i.e. Dieng, Darajat, Kamojang, Wayang-Windu, Gunung Salak, Patuha and Karaha-Bodas.

3. Sampling and analysis

Water samples were collected from July to September 2012, the end of the dry season in Java. In total 69 samples were collected, 61 from hot springs, 4 from cold springs, and 4 from hot crater lakes (Table 1). The locations of the 4 cold spring samples were chosen based on their proximity to those hot springs which were sampled during this investigation.

Temperature, pH, conductivity, ORP and alkalinity, were measured in the field, either by probe or acid titration (HACH, 2007). The samples were filtered through a 0.45 μm nylon membrane. Part of the filtered sample was used for alkalinity measurement and two splits for the determination of anion, cation and isotopic compositions were stored in polyethylene bottles and transported to the University of Bremen for further analyses. The cation split was acidified to 1% concentrated HNO_3 to avoid precipitation of metals. The anions, Cl^-, SO_4^{2-}, NO_3^- and Br^-, were analyzed by ion chromatography using an IC Plus Chromatograph (Metrohm). The cations, Ca^{2+}, Mg^{2+}, Na^+ and K^+, and Si were determined by inductively coupled plasma-optical emission spectrometry (ICP-OES) using an Optima 7300 instrument (Perkin Elmer). Trace elements of B and As were measured by using inductively coupled plasma-mass spectrometry (ICP-MS) using an iCAP-Q instrument (Thermo Fisher). Stable isotopes (^{18}O and ^2H) were determined on a LGR DLT-100 laser spectrometer (Los Gatos Research). The isotope results were reported in δ per mil (‰) relative to VSMOW with an analytical uncertainty of approximately ± 1‰ for δ^2H and ± 0.2‰ for $\delta^{18}O$.

4. Results

The results of the field and laboratory measurements are presented in Table 1. Cold water springs in Java were slightly acid to slightly alkaline (pH = 6.2 to 7.8) and conductivity ranged from 86 to 324 μS/cm. Compared to the hot spring samples, the concentrations of Ca^{2+}, Mg^{2+}, Na^+, K^+ and Cl^- of the cold spring waters were low (≤31 mg/L). These cold spring waters had HCO_3^- and SO_4^{2-} contents of 19.5 to 115.9 mg/L and 2.7 to 40.6 mg/L, respectively.

The volcano-hosted hot springs had a larger variety of temperature, pH, conductivity, major anions (HCO_3^-, SO_4^{2-}, and Cl^-) and two major cations (Na^+ and Mg^{2+}), but relatively a similar range of K^+ and a

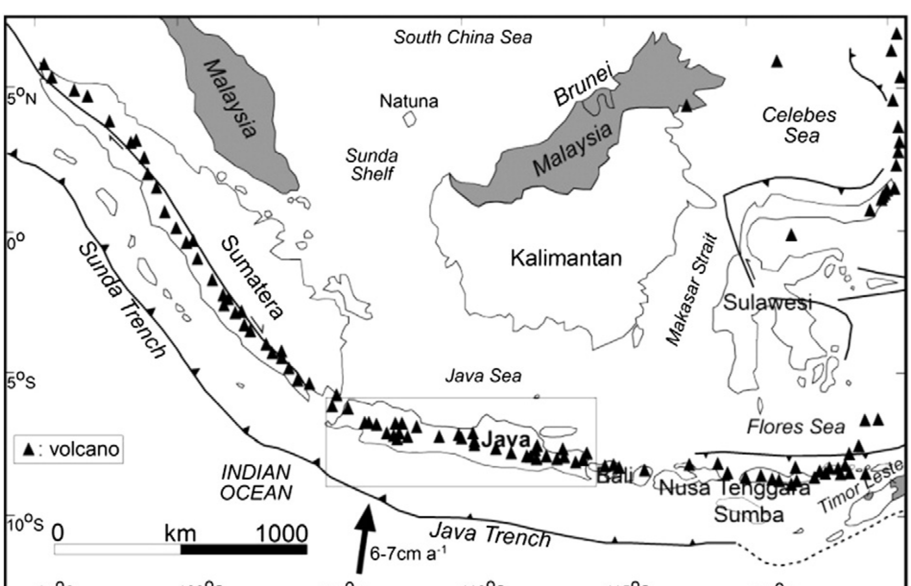

Fig. 1. Geographic and tectonic map of the Indonesian archipelago with Java in the center and the Sumatera-Nusa Tenggara volcanic arc (after Hamilton, 1979; Simandjuntak and Barber, 1996).