Journal of Volcanology and Geothermal Research 304 (2015) 349–358

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

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

Geothermal systems on the island of Bali, Indonesia

Budi Joko Purnomo, Thomas Pichler *

Geochemistry & Hydrogeology, Department of Geosciences, University of Bremen, Germany

ARTICLE INFO

Article history:
Received 27 February 2015
Accepted 7 September 2015
Available online 12 September 2015

Keywords:
Bali
Carbonate host-hock
Seawater input
Geothermometer
Volcanic host-rock
^{2}H and ^{18}O isotope

ABSTRACT

This paper presents an overview of the geothermal systems on the island of Bali, Indonesia. Physicochemical data of hot springs and shallow geothermal wells were collected from four geothermal locations: Penebel, Batur, Banjar and Banyuwedang. The concentrations for the three main anions varied significantly indicating a different geothermal history. The values for Cl^- ranged from 0.1 to 1000 mg/L, for HCO_3^- from 20 to 2200 mg/L and for SO_4^{2-} from 0.1 to 500 mg/L. Although the island of Bali is underlain by carbonate rocks, a carbonate host rock for the geothermal reservoirs could not be confirmed, because the $(Ca^{2+} + Mg^{2+})/HCO_3^-$ molar ratios were approximately 0.4, well below 1.0 and the K/Mg ratios were approaching those of a calc-alkaline rock reservoir. The HCO_3^- of the thermal waters correlated with Ca^{2+}, Mg^{2+}, Sr^{2+} and K^+ indicating water–rock interaction in the presence of carbonic acid. Phase separation was inferred for the Bedugul and Banjar geothermal systems, because of relatively high B/Cl ratios. Boron isotopes were determined for selected samples with values ranging from $\delta^{11}B$ of 1.3 to 22.5‰ (NBS 951). The heavy $\delta^{11}B$ of +22.5‰ together with a low B/Cl ratio indicated seawater input in the Banyuwedang geothermal system. The hydrogen and oxygen isotopic composition of the thermal water plotted along the global meteoric water line (GMWL) and close to the mean annual value for precipitation in Jakarta indicating a meteoric origin of the geothermal water. Comparison of the Si, Na/K, Na/K/Ca and Na/Li geothermometers with actual reservoir temperature measurements and physicochemical considerations led to the conclusion that the Na/Li thermometer provided most reliable results for the determination of geothermal reservoir temperatures on Bali. Using this thermometer, the following reservoir temperatures were calculated: (1) Penebel (Bedugul) from 235 to 254 °C, (2) Batur 240 °C and (3) Banjar 255 °C. Due to seawater input this thermometer could not be applied to the Banyuwedang geothermal system. There application of a SiO_2 thermometer indicated a reservoir temperature below 100 °C.

1. Introduction

The island of Bali (Indonesia) hosts several geothermal systems and some are of interest to geothermal exploitation. The Bedugul geothermal field, located near Lake Bratan, covers an area of approximately 8 km^2 with an estimated annual electric energy potential of 80 MWe for 30 years (e.g., Hochstein et al., 2005; Mulyadi et al., 2005; Hochstein and Sudarman, 2008). However, the development was suspended due to environmental and cultural concerns. In addition to Bedugul, other geothermal prospects on Bali are the Batur, Banyuwedang and Banjar geothermal systems. To estimate the geothermal potential of a given geothermal system its reservoir temperature needs to be known. Ultimately this temperature is measured directly in a geothermal well, but prior to drilling, solute geothermometers are used to aid in geothermal exploration (e.g., Giggenbach, 1991). However, one of the prerequisites for their application is information about the composition and type of the geothermal host rock (e.g., Giggenbach, 1991).

Bali is dominantly covered by volcanic rocks, overlying the Tertiary carbonate rocks that outcrop in the southern and western part of the island (Hadiwidjojo et al., 1998). The Bedugul geothermal field was reported producing brines where the gas phase was dominated by CO_2 of approximately 97 wt.% and thus it was thought that reservoir was in carbonate rocks (Mulyadi et al., 2005). To the contrary a thermobarometric study indicated that the reservoir could be in volcanic rocks and that the carbonate basement reacted with shallow magmatic intrusions in the Batur and Agung volcanoes (Geiger, 2014). The assimilation (thermal decomposition) of carbonate rocks by magma releases large amounts of CO_2 gas due to the breakdown of $CaCO_3$ into CO_2 and CaO (Allard, 1983; Gertisser and Keller, 2003; Chadwick et al., 2007; Marziano et al., 2007; Marziano et al., 2009; Deegan et al., 2010). The CO_2-rich volatile magma subsequently ascends and promotes phase separation in the geothermal reservoir, which in turn produces a CO_2-rich vapor phase (Lowenstern, 2001).

It is possible that geothermal systems on Bali could be hosted by carbonate rocks, but CO_2 content alone is not sufficient to allow that conclusion. Carbonate rocks, such as limestone and dolomite, for example,

* Corresponding author at: Geochemistry & Hydrogeology, Department of Geosciences, University of Bremen, PO Box 33 04 40, 28334 Bremen, Germany. Tel.: +49 421 218 65100.
E-mail address: pichler@uni-bremen.de (T. Pichler).

http://dx.doi.org/10.1016/j.jvolgeores.2015.09.016
0377-0273/

were identified as the reservoir rock in some volcanic areas in Italy, e.g., Vicano-Cimino and Sabatini- Tolfa (Cinti et al., 2011; Cinti et al., 2014). There the thermal water is characterized by a $(Ca^{2+} + Mg^{2+})/HCO_3^-$ molar ratio of ~1 as a result of calcite and/or dolomite dissolution (Gemici and Filiz, 2001; Levet et al., 2002; Grassa et al., 2006; Capaccioni et al., 2011; Cinti et al., 2011; Cinti et al., 2014). Another characteristic of thermal waters hosted by carbonate rocks can be a pronounced positive ^{18}O-shift due to the heavier $\delta^{18}O$ composition of carbonate rocks compared to magmatic rocks (Craig, 1966; Arana and Panichi, 1974; Gemici and Filiz, 2001). Although a depletion of $\delta^{18}O$ is also possible if there is isotope exchange between hydrothermal water and CO_2, as demonstrated for some geothermal systems in Italy (Grassa et al., 2006; Cinti et al., 2011; Cinti et al., 2014).

This paper presents new physicochemical and isotope (^{18}O, ^{2}H and ^{11}B) data for hot springs and shallow thermal wells on Bali with the objective to investigate the host rock of the geothermal systems and to determine the most applicable geothermometer for geothermal exploration. Additionally, boron isotopes were applied to identify seawater input and solute geothermometers to predict the reservoir temperatures.

2. Geological setting

Bali is a part of the Sunda-Banda volcanic islands arc, which extends for approximately 4700 km east to west, from the island of Damar to the island of Sumatera. The arc is caused by the convergence of the Indo-Australian and Eurasia plates, with a rate of 6 to 7 cm/a (Hamilton, 1979; Simandjuntak and Barber, 1996). This process drives volcanism on Bali since the late Tertiary (Van Bemellen, 1949; Hamilton, 1979; Hadiwidjojo et al., 1998) and produced a vast distribution of volcanic

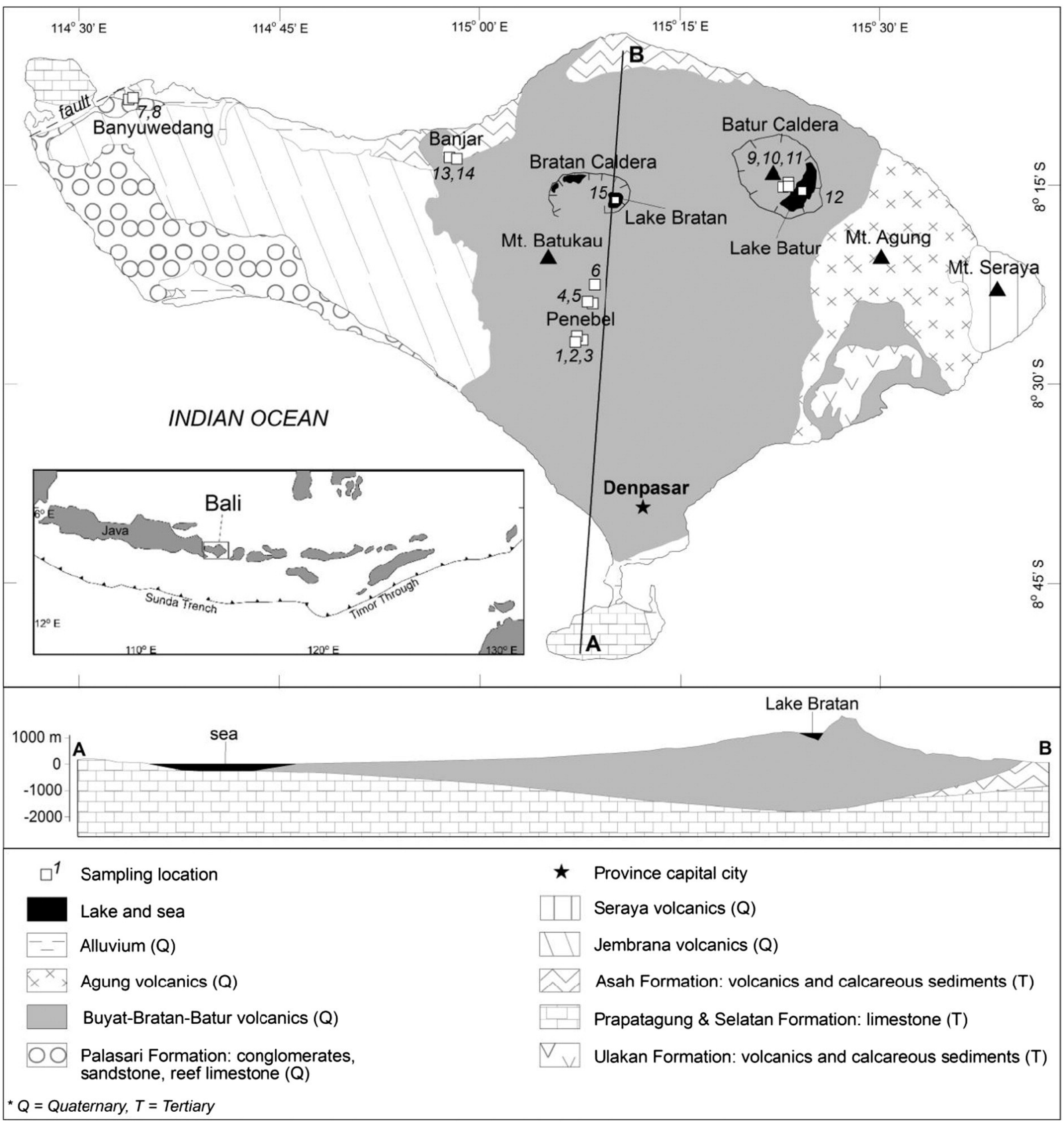

Fig. 1. Geological map of and cross section across (modified from Hadiwidjojo et al. (1998)). The sampling locations are indicated. Volcanic roots for the Batur and Bratan volcanic complexes were not indicated, due to a lack of geophysical mapping data. For scale: the distance between points A and B of the cross section is 80 km.