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Noble and reactive gases of Palinpinon geothermal field (Philippines): Origin, reservoir processes and geodynamic implications

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ABSTRACT

Palinpinon is a high-temperature, liquid-dominated volcano-geothermal system located on southern Negros Island, Philippines, associated with subduction of Negros-Sulu arc (Early Pliocene to Recent). In 2001, eleven (11) producing wells of the Palinpinon geothermal field were analyzed for major gas components and for noble gases isotopic composition. Geothermal gases are dominated by H_2O, with CO_2 and H_2S being the most abundant species of the dry fraction. Chemical and isotope data indicate that two main components feed the geothermal system: (i) a deep component, enriched in CO_2, H_2S, H_2 and He, related to volcano-hydrothermal interactions occurring in the roots of the geothermal system, and (ii) a surficial component, enriched in N_2, Ar, Ne, related to natural meteoric recharge of the reservoir. The noble gas fraction is dominated by argon of atmospheric origin, as denoted by $^{40}Ar/^{36}Ar$ ratios between 295 and 310. Helium, in excess above the reference concentrations in air and air-saturated water (ASW), has an isotopic signature ($^3He/^4He$ ratios between 6.96 to 7.94 R_A) in the range of values normally observed for subduction-related volcanism. $^3He/^4He$ and $CO_2/^3He$ (between 12.1×10^9 to 28.7×10^9) ratios support the hypothesis that most of the deep gases are directly derived from a magmatic source and/or from the scavenging of an organic-depleted, basalt-rich crust. Water–rock interactions cause some geothermal overprinting of the deep magmatic component, allowing redox conditions in the reservoir to be controlled by the Fe(II)–Fe(III) buffer. Based on CO_2/CH_4 and H_2/Ar ratios, maximum equilibrium temperatures between 300 and 350 °C have been estimated in the geothermal reservoir. Chemical data indicate that the geothermal reservoir is largely flushed by steam derived from the boiling of waters of meteoric recharge and reinjected brines.

1. Introduction

Located in southern part of the Negros Island, Philippines, the Palinpinon high-enthalpy geothermal resource consists of two main producing sectors, Palinpinon I and Palinpinon II. The Negros Island is dominated by two andesitic complexes, the Mt. Silay–Mt. Mandalagan volcanic complex to the north, and the Cuernos de Negros volcanic complex to the south. The Palinpinon geothermal field is located on the northern slopes of the Cuernos de Negros volcanic complex (Fig. 1).

The geothermal area has been exploited for production of electricity since 1983 (Palinpinon I; current installed capacity 112.5 MWe), and successive improvements during the early 1990s led to the development of new modular plants in the Palinpinon II sector (total installed capacity 80 MWe). To date, a total of 73 wells, 48 producers and 25 reinjectors, have been drilled in the geothermal area (Pamatian et al., 2003).

The field is divided in three geographical areas: the Puhagan sector on the east, hosting the Palinpinon I producing area, the Nasuji and Sogongon sectors on the west, hosting the Palinpinon II (Fig. 2).

Reservoir temperatures are generally between about 200 and 300 °C, but locally exceed 325 °C. Geothermal brines are neutral-pH, and moderately saline (reservoir chloride between 4000 to 5000 ppm), with low gas content (generally below 0.1 mol%). The main upflow area of the deep parent geothermal fluid is located close to Lagunao, southwest and east of Puhagan and Nasuji sectors, respectively. The main outflow is along the fault-controlled Okoy Valley, northeastward from the upflow. Some secondary outflow occurs towards Nasuji and Sogongon sectors, on the northwest of Lagunao (Fig. 2). Along both outflow sectors, fluid temperatures and Cl concentrations decline due to dilution with groundwater (D'Amore et al., 1993).

Surface exploration and early development of the geothermal field have been summarized by Maunder et al. (1982) and Bromley and Española (1982). Fluid reinjection at Palinpinon started in parallel with production, and Harper and Jordan (1985) assessed geochemical changes induced by early exploitation of the field. Fluid circulation paths in the reservoir were reconstructed on the basis of tracer tests

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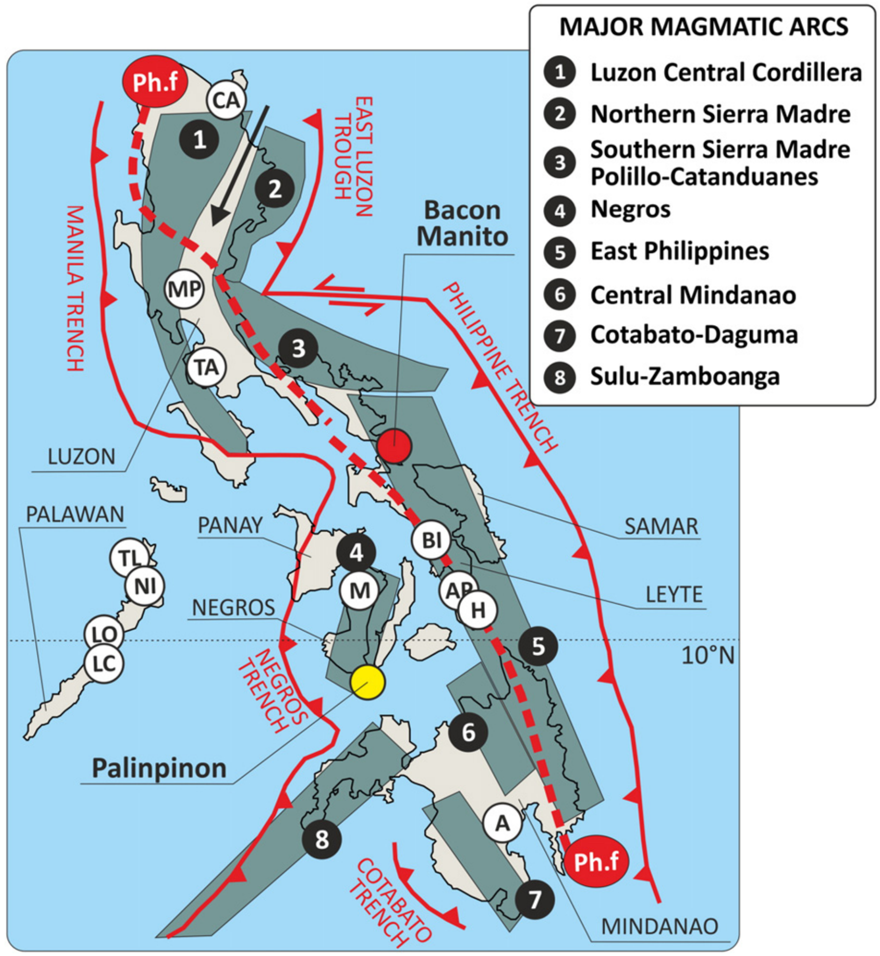

Fig. 1. Map of Philippines showing the tectonic setting, the Philippine fault zone (Ph.f), and the locations of Palinpinon (yellow circle) and Bacon–Manito (red circle) geothermal fields. Also shown are the locations of other geothermal and volcano-hydrothermal systems (white circles) investigated by Giggenbach and Poreda (1993), and of major magmatic arcs. Modified after Yumul et al. (2008). CA = Cagua; MP = Mount Pinatubo; TA = Taal; BI = Biliran; M = Mambucal; AP = AltoPeak; H = Mahagnao; A = Mount Apo; TL = Matinloc; NI = Mount Nido; LO = Lourdes; LC = Santa Lucia.

(Urbino et al., 1986) and preliminary numerical modeling studies (Sta. Ana and O'Sullivan, 1988).

Based on stable isotope evidence, the geothermal reservoir is fed by a deep parent water originating from a mixture of local meteoric (80%) and magmatic (20%) water, with meteoric recharge derived from ~1000 m (Gerardo et al., 1993). Stable isotope studies also provide evidence of injection return in the reservoir. Due to exploitation and depressurization, boiling has developed within the reservoir, and currently most of the producing wells are discharging high-enthalpy fluids, i.e. fluids with measured enthalpy in excess compared to that of steam saturated water at aquifer temperature.

D'Amore et al. (1993) used gas geochemistry to investigate physical processes due to exploitation from 1985 to 1991: (i) pressure drawdown in the southern part of the field, with local increase in reservoir vapor fraction; (ii) vapor loss from an original liquid phase during the fluid ascent through fractures; (iii) mixing and cooling due to injection returns located in the northeastern part of the field.

The pressure differential between production and injection sectors caused injected brine to enter the production zones. The Lagunao, Ticala, Puhagan and Nasuwa faults (Fig. 2) have been identified as preferential paths for brine returns (e.g. Rae et al., 2004). The return of reinjected brines has been documented since the beginning of the exploitation both in Palinpinon I (Seastres et al., 1995), and in Palinpinon II (Ramos-Candelaria et al., 1997). In order to attain and maintain stable reservoir pressures (approximately steadily decreased from 7 to 5 MPa, depending on the sectors of the field, during the 1992–2010 period), the reinjection strategy has been changed over time in terms of both location of the reinjection wells and rates of reinjection (Malate and Aqui, 2010; and references therein). Production and brine injection rates ranged between ~450 and ~700 kg s^{-1} and between 0 and 150 kg s^{-1}, respectively, during the 1992–2010 period, with a minimum of less than 200 and of 0 kg s^{-1}, respectively, between June 1997 and June 1998 (Malate and Aqui, 2010).

In the framework of a technical co-operation project funded by the International Atomic Energy Agency (IAEA), in 2001 eleven (11) production wells of the Palinpinon geothermal field have been analyzed for major gas components and for chemical and isotopic composition of noble gases. At the time of this sampling campaign, most of the injection load (about 80 kg s^{-1}) was concentrated in the peripheral sectors of Ticala and Malaunay, away from the central production sector of Puhagan (Fig. 2). Steam production (about 600 kg s^{-1}) was occurring from an expanded two-phase region extending over most of the geothermal field, although wells discharging single-phase gaseous fluid were also present.

This study is aimed at combining reactive and inert gas data for the evaluation of fluid origin and the assessment of main physical and chemical processes governing the geochemical evolution of the Palinpinon geothermal field. By comparing noble gas data from Palinpinon with data from other geothermal and volcano-hydrothermal features along the Philippines arc (Giggenbach and Poreda, 1993; Bayon et al., 2008), the geodynamical setting of the geothermal systems is also discussed.