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Volcano-hosted vapor-dominated geothermal systems in permeability space

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ABSTRACT

Although volcano-hosted vapor-dominated geothermal systems are rare, West Java, Indonesia, has five such systems: Kamojang, Darajat, Patuha, Telagabodas, and Wayang Windu. This paper seeks an explanation for such vapor-dominated geothermal systems through heat and mass transfer numerical modeling based on the characteristics of these five systems. Specifically, the 3D model TOUGH2 is used to explore heat input and permeability conditions that lead to vapor-dominated systems. Our generic model consists of a reservoir, a host rock, and a caprock. The size of the reservoir is 16 km^2 and 2.8 km thick, with 10% porosity and a permeability of 10^{-13} m^2. The initial condition of the model is fully liquid saturated at a normal geotherm with hydrostatic pressure. An intrusive heatpulse of 8 MW/km^2 for 9 kyr is applied to the base to the reservoir and the resulting geothermal system characteristics are mapped out in permeability space. A vapor-dominated system is produced when the hostrock permeability is 5×10^{-17} m^2 or less accompanied by the caprock permeability varying from 10^{-17} to 4×10^{-16} m^2. The caprock permeability assures that the escaping steam exceeds the incoming liquids; the hostrock permeability prevents flooding until the heat source is turned off. Increasing the basal heat input to 12 MW/km^2 shifts the maximum host-rock permeability for vapor systems to 10^{-16} m^2, but there is minimal change in the maximum caprock permeability. In all models the maximum duration of the vapor reservoirs is 1.5 kyr, at which point the reservoir either dries out or floods. The timescale for vapor reservoir stability is an order of magnitude less than that for the formation or cooling of liquid-dominated geothermal reservoirs. The factors contributing to the occurrence of the five vapor-dominated reservoirs in West Java are intense heating due to prolonged active volcanism, an absence of shear faulting, and the restrictive range of low permeability in the host and caprocks surrounding a relatively permeable reservoir.

1. Introduction

Vapor-dominated geothermal reservoirs are rare, their pressures at depth being much less than the surroundings. In their classic paper describing vapor-dominated reservoirs, White et al. (1971) surmised that the reservoir boundaries had to be of uniformly low permeability to prevent flooding from adjacent or overlying groundwater. These authors also recognized that the heat input to the reservoir had to be sufficient so that any inflowing liquid was boiled to steam. At that time, The Geysers, California, Larderello, Italy, and Matsukawa, Japan were recognized as the only examples of such reservoirs. Subsequently, Hanano and Matsuo (1990) reviewed the original pressure and temperature data at Matsukawa and concluded that it was initially liquid-dominated and became vapor-dominated due to a production-induced pressure decline. Both The Geysers and Larderello have become recognized as very large vapor-dominated reservoirs (200–400 km^2) overlying equally large cooling intrusions in the upper crust (Moore et al., 2000; Barelli et al., 2010). However, apart from a cluster of volcano-hosted vapor-dominated reservoirs in West Java, Indonesia, which is the subject of this paper, no other vapor-dominated reservoirs have been found despite hundreds of geothermal systems having been drilled in young volcanic provinces around the world.

The distinguishing feature of vapor-dominated reservoirs (Fig. 1) is the near-static column of steam with the only discharge features being associated with steam. In particular, there are no chloride springs associated with the reservoir at lower elevations (Ingebritsen and Sorey, 1988). There may be a liquid reservoir underlying a vapor-dominated zone, but because of the vertical extent of the vapor zone, that liquid zone has pressures significantly below adjacent groundwater systems (cold hydrostatic—Fig. 1), so if there is any lateral flow at depth it has to be inwards towards

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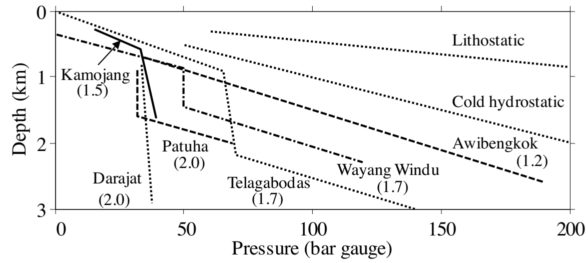

Fig. 1. Characteristic pressure regimes of the five known volcanic-hosted, vapor-dominated reservoirs in West Java: Kamojang, Darajat, Patuha, Telagabodas, and Wayang Windu. Awibengkok, a liquid-dominated reservoir about 100 km west of the vapor systems is shown for comparison. Numbers in brackets are the typical elevations in km above sea level. (Modified from Allis and Shook (1999), Layman and Soemarinda (2003), and Bogie et al. (2008)).

the reservoir. Many geothermal systems in mountainous topography have shallow vapor zones (sometimes called "parasitic" steam) overlying a liquid reservoir, but they all have either liquid outflow systems at lower elevations flanking the vapor system, or have a deep liquid pressure regime that appears to be in equilibrium with the surrounding ground water system. Examples are Palinpinon (Philippines), Los Azufres (Mexico), Olkaria (Kenya), and Awibengkok (Indonesia) (Grant and Bixley, 2011). There may also be superficial steam-heated waters overlying the vapor zone, so a sealed upper boundary may not be essential (Ingebritsen and Sorey, 1988; Hochstein and Sudarman 2008). The vapor zone is stable if its pressure is balanced by or exceeds that at the base of the overlying groundwater zone. Vapor-dominated reservoirs are distinct from magma chimneys associated with volcanic degassing. As the name implies, these are relatively narrow columns of corrosive, high temperatures fluids and most likely are ephemeral, closely related to the cycles of rising magma within volcanoes. Two drilled and studied examples of magma chimneys are Alto Peak in the Philippines (Reyes et al., 1993) and the Galunggung–Telagabodas system in Indonesia (Moore et al., 2008).

There have been many suggestions since the conceptual model of White et al. (1971) about how vapor systems may have formed. Ingebritsen and Sorey (1988) extensively simulated the stability of vapor-dominated reservoirs, showing they could evolve from liquid-dominated reservoirs on a time scale of 10^4 years. Their models included a low permeability shell of less than about 10^{-16} m^2 that surrounded a reservoir with a permeability of more than about 10^{-15} m^2 and a basal heat input of 1.5 MW/km^2 (similar to that at The Geysers). The vapor pressure near the top of the reservoir was influenced by the thickness of the overlying cap assuming hydrostatic conditions above the reservoir. Allis and Shook (1999) showed that reservoir dilation was capable of forming vapor-dominated reservoirs from liquid conditions as long as the reservoir boundaries remained intact, and pointed to the seismic evidence at The Geysers for uniaxial extension below 1 km depth. Allis (2000) also contrasted the surface heat flow at The Geysers and Larderello (~1 MW/km^2) with that at Kamojang and Darajat (West Java, Indonesia) which is an order of magnitude higher. There have been several models that invoke a sudden mass loss (over ~100 years) and subsequent sealing to trigger the formation of a vapor zone (Pruess, 1985; Shook, 1995). Moore et al. (2008) speculated based on petrologic evidence that catastrophic pressure reduction related to volcanic flank failure may have triggered the formation of the vapor zone at the Karaha-Telagabodas system. These authors proposed a general model, which involves an early-stage magmatic vapor chimney evolving into an expanding steam reservoir surrounding the chimney. The vapor reservoir would eventually be flooded once the heat input at depth is insufficient to boil all inflowing water.

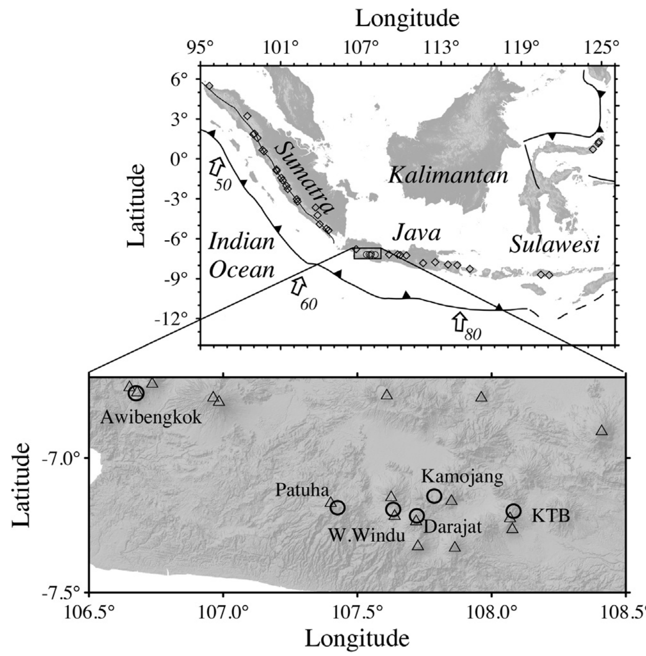

Fig. 2. Maps showing geothermal fields in Indonesia. Top. Geothermal fields (diamond symbol) in Sumatra, Java, and Sulawesi that have been studied, drilled, or developed. Plate motion arrows show the direction of convergence between the India–Australia plate and the Eurasian plate and convergence rates in mm/yr. Bottom. Five vapor-dominated geothermal systems (Kamojang, Darajat, WayangWindu, Patuha, Kahara-Telagabodas KTB) and one liquid-dominated system (Awibengkok) in West Java (open circles). Triangles show volcanoes with recent activity.

The purpose of this paper is to review the latest evidence for the occurrence of vapor-dominated reservoirs, and to investigate in more detail the thermal and permeability conditions that allow them to form. The modeling assumptions are based on the five volcano-hosted vapor-dominated reservoirs that have been discovered in West Java. We conclude with suggestions why this is apparently the only area in the world where these volcano-hosted reservoirs exist. In contrast to West Java, many geothermal systems in Sumatra also have been drilled, but so far no vapor-dominated system has been found. All these geothermal systems are close to the Sumatra Fault, a major dextral shear zone that extends the length of Sumatra.

2. Evidence from vapor-dominated reservoirs in West Java

The five known vapor-dominated geothermal reservoirs in West Java all occur in a 100 × 50 km^2 area (Figs. 1 and 2). All are associated with young volcanoes, and have been extensively drilled for geothermal power generation. The following are brief descriptions of reservoir characteristics with only a few recent relevant references cited.

The Kamojang reservoir is nearly equidimensional and situated in a depression high on Gunter volcano that last erupted in 1840. It is about 15 km^2 in area with a slight northeast orientation (Suryadarma et al., 2005). The most productive zones have transmissivities of over 100 Darcy-meters, but zones of lower productivity (<10 Darcy-meters) occur in an apparently non-uniform pattern in the middle of the reservoir, as well as surrounding the reservoir. The initial temperature in the vapor zone was 235–247 °C, pressures were 33–35 bar gauge (bar g), the gas content in the discharge steam was < 1% (mostly CO_2), and the initial liquid saturation has been calculated at 25–30%. No liquid zone has been found beneath the vapor zone, with productive wells extending to 2 km depth. A condensate layer extending to about