Why Are the Only Volcano-Hosted Vapor-Dominated Geothermal Systems in West Java, Indonesia?

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ABSTRACT

Although volcano-hosted vapor-dominated geothermal systems are rare, West Java, Indonesia, has five such systems: Kamojang, Darajat, Patuha, Telaga Bodas, 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. Using a basal heat input of 12 MW/km^2 into a cube-shaped reservoir, vapor-dominated systems are produced when the host rock permeability is less than 3 x 10^{-16} m^2 and the caprock permeability varies between 10^{-17} and 10^{-15} m^2. The caprock permeability assures that the escaping steam exceeds the incoming liquids; the host rock permeability prevents flooding until the heat source is turned off. The maximum duration of the vapor reservoirs is 2000 years, 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 permeability range of the host and caprocks surrounding a relatively permeable reservoir.

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.

This paper reviews the main factors that allow the formation of volcano-hosted vapor-dominated geothermal systems. A more detailed analysis of these factors is contained in Raharjo et al., *in press*, and Raharjo, 2012.

Characteristics

The distinguishing features of vapor-dominated reservoirs (Fig. 1) are the near-static column of steam, only steam discharges are present, and 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 (Fig. 1), so if there is any lateral flow at depth it has to be inwards towards 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-temperature 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).

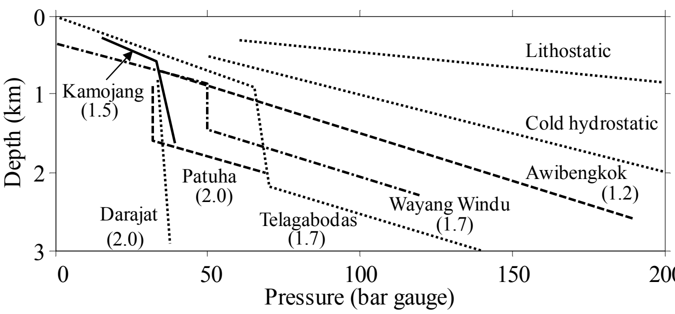

Figure 1. Characteristic pressure regimes of the five known volcanic-hosted, vapor-dominated reservoirs in West Java: Kamojang, Darajat, Patuha, Telagabodas, and Wayang Windu. Awibengkok, a liquid-dominated reservoir about 100 km west of the vapor systems is shown for comparison. Numbers in parentheses 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 five known vapor-dominated geothermal reservoirs in West Java all occur in a 100 x 50 km^2 area (Fig. 2). All are associated with young volcanoes, and have been extensively drilled for geothermal power generation. West of these five systems is the liquid-dominated Awibengkok field (Stimac et al., 2008; Acuna et al., 2008), and even farther west are the numerous geothermal systems in Sumatra. Many of these 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.

Fig. 1 shows that the simplified vapor pressure trends in the five vapor-dominated systems are variable, and within several of these systems the vapor pressure varies greatly (Patuha, 18 – 50 bars, Wayang Windu, 30 – 80 bars; Layman and Soemarinda, 2003; Bogie at al., 2008). Temperatures and partial gas pressures also vary widely. Kamojang and Darajat appear to have the greatest vertical extent of the vapor zone, with no base being detected to date (Suryadarma et al., 2005, Rejeki et al., 2010). The base of the reservoir at Darajat is inferred from microearthquakes to be at about 4 km depth. Wayang Windu, Patuha, and Telagabodas (Moore et al., 2008) have vapor zones ranging between about 500 m and 1000 m thick. The vapor zones may be roughly equidimensional (Kamojang, 10 km^2 in area, Darajat, 15 – 25 km^2), or may be elongate at about 10 km in length and 1 – 4 km in width. At Kamojang, 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. At Darajat, the most productive zones occur at 1 – 2 km depth, and tend to be associated with andesite lavas and intrusives rather than with pyroclastics. Some zones of enhanced permeability may have developed along the margins of dikes, sills, and stocks during their emplacement. There is some relationship between enhanced permeability and the northeast-trending faults although this relationship is not always clear (Rejeki et al., 2010).

A feature common to all five vapor-dominated reservoirs is the over-printing of current conditions on pre-existing liquid-dominated hydrothermal alteration signatures, confirming previous models for the formation these reservoirs. A history of hydrothermal alteration allows for more extensive clay formation and reduction in permeability of the host rocks. It is also clear that these five reservoirs have a strong heat source at depth, with surface heat losses due to fumaroles, steaming ground, and condensate outflows on the order of at least 100 MW. The presence of these systems on or near the crest of coalescing andesite volcanoes, their proximity to recently volcanic activity, and evidence in three of the reservoirs for magmatic fluids, all confirm the likelihood of a strong heat source at depth. The diverse orientations and geometries of the reservoirs (circular to elongate, and east-west to north-south) do not support a simple genetic relationship to the stress regime. However, the absence of permeable faults that cut through the reservoir boundaries and allow large inflows to flood the under-pressured vapor zones is an important factor.

Modeling Process

Our models use the TOUGH2 simulator with the Equation of State 1 module and a relative permeability function (Corey type) with a residual liquid saturation of 0.25 and a residual vapor saturation of 0.01. The model geometry and properties were finalized after considerable testing and comparison of some of the models discussed by Ingebritsen and Sorey (1988). Their models involved a reservoir surrounded by an impermeable shell, and similar results were obtained with our modeling (Raharjo, 2012). In this work we modify the model to be closer to the conditions found in the volcano-hosted systems discussed above. The reservoir, with a fixed permeability of 10^{-13} m^2, is assumed to be hosted in water-saturated rock with a uniform permeability that is varied in the modeling to investigate varying lateral inflows of water. The reservoir is 4 km x 4 km in area, and 2.8 km in height. The top of the reservoir, which is at 300 m depth, has 150 m of caprock with a permeability that is varied, and this is overlain with 150 m of surficial rock with a fixed permeability of 10^{-13} m^2. The entire model domain has a matrix density of 2600 kg/m^3, porosity of 10%, thermal conductivity of 2.5 W/mK, and a specific heat of 1 kJ/kg. The model comprises 1152 active cells with 3320 interfaces. The initial state of the simulations is a thermal gradient of 30 °C/km and a hydrostatic pressure gradient.

For the suite of simulations discussed here, a relatively high conductive heat flow of 12 MW/km^2 is applied to the 16 km^2 base of the reservoir for 6 kyr, followed by 1 MW/km^2 to 21 kyr, and then 0.075 MW/km^2 (75 mW/m^2) subsequently (Fig. 3). Raharjo et al. (in press) discuss other heating histories. This rapid heating history, which is followed by prolonged cooling, provides an opportunity to see both the formation and the subsequent flooding of the vapor reservoir.

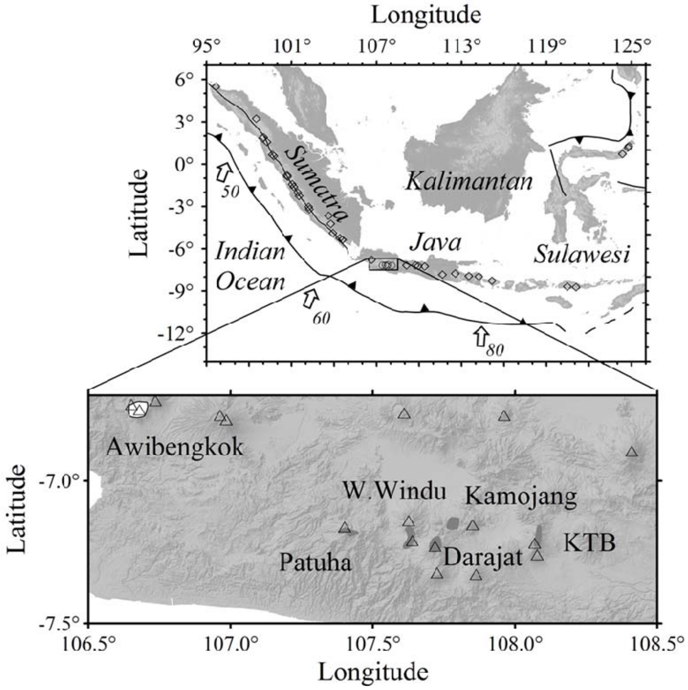

Figure 2. Maps showing geothermal fields in Indonesia. Top. Geothermal fields (diamond symbol) in Sumatra, Java, and Sulawesi that have been studied, drilled, or developed. Plate motion arrows show the direction of convergence between the India-Australia plate and the Eurasian plate and convergence rates in mm/yr. Bottom. Five vapor-dominated geothermal systems and one liquid-dominated system (Awibengkok) in West Java. Triangles show volcanoes with activity since 1800. KTB refers to the Karah-Telagabodas geothermal system.

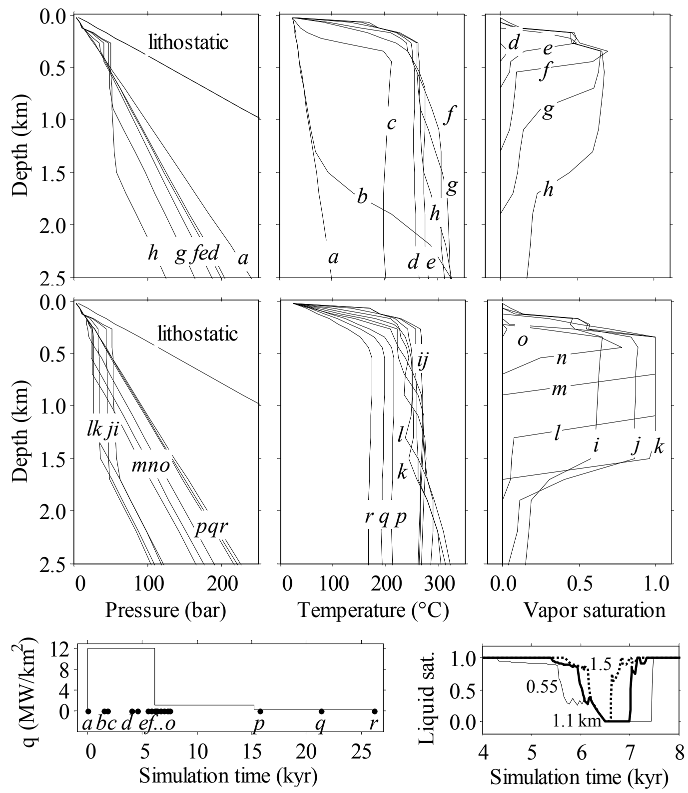

Figure 3. Evolution of a geothermal reservoir for basal heat input of 12 MW/km^2. Simulation results for pressure (top and middle left), temperature (top and middle center), and vapor saturation (top and middle right) conditions through time. The permeabilities of the caprock and the host rock are 10^{-16} and 3 x10^{-16} m^2 respectively. Basal heat input history (bottom left) with times shown for system snapshots. Liquid saturation (bottom right) showing the gradual downward development of a vapor-dominated reservoir with saturation trends at 0.55 (thin line), 1.1 (bold line), and 1.5 (dotted line) km depth. The vapor reservoir progressively floods after the basal heat inflow is reduced and the deep liquid reservoir increases in pressure.

The modeling shows the vapor-dominated reservoir evolving in two stages: development of a hot, liquid-dominated reservoir, and then liquid to steam conversion. The stage in which a hot, 240 ºC liquid-dominated reservoir is developed is shown by curves a to d, but takes only 4 kyr. Pressure-depth profiles for a and d (Fig. 3 top left) represent cold and hot hydrostatic profiles, respectively

The second stage of liquid to steam conversion starts at 4 kyr (Fig. 3, curve *d*) with a vapor zone forming immediately beneath the steam cap, and this lasts until 6 kyr (curve *k*). The development of a vapor-dominated zone in Fig. 3 is shown by curves *e* through *k*. The steam zone expands downwards at a nearly constant pressure of 50 - 60 bar as the underlying liquid pressure gradually declines, and the liquid zone heats to over about 300 °C. As before, the vapor saturation within the vapor-dominated reservoir is almost uniform. By 6 kyr the vapor-dominated zone extends to 1500 m depth, and by 6.6 kyr the deep liquid zone has boiled off and the reservoir is, in effect, dry.

When the magnitude of the basal heat flow is reduced to 1 MW/km^2 at 6 kyr the base of vapor zone continues to shift downwards from 1500 m to about 1700 m depth by 6.3 kyr. This means that even with optimal conditions for sustaining the vapor-dominated conditions with an under-pressured liquid reservoir beneath lasted for at most about 2 kyr. With the reduced basal heat flow of 1 MW/km^2, the entire reservoir floods (re-saturation trends in lower right graph) between 6.7 kyr and about 7.5 kyr. Curves l through o (Fig. 3) illustrate the decreasing thickness of the steam zone (middle right), evolution of the pressure profile towards the hot hydrostat (middle left), while still maintaining a uniform reservoir temperature of about 270 ºC (middle center). Conversion from a vapor-dominated to a liquid-dominated system takes less than a thousand years (bottom right). This is because the reduced basal heat input is unable to boil off the water flowing in from the host rock and caprock.

By running the simulation longer, to 25 kyr, we observe the process of the liquid reservoir gradually cooling after 7.5 kyr. Overall further cooling of the liquid system takes much longer; at a simulation time of 25 kyr the reservoir temperature is still 170 ºC (Fig. 3, middle center, curve r).

The consequences of different caprock and host rock permeabilities with the basal heat input of 12 MW/km^2 and a simulation time of 6.2 kyr are summarized in Fig. 4. Vapor-dominated reservoirs are produced with caprock permeabilities between 10^{-15} and 10^{-17} m^2. The upper limit of this range is over an order of magnitude higher than that inferred by Schubert and Straus (1980) for a stagnant water overlying a steam zone. It is also significantly higher than the 10^{-16} m^2 speculated by Ingebritsen and Sorey (1988) when assuming a lower heat input and a hot fluid flow into the base of the reservoir. Host rock permeabilities

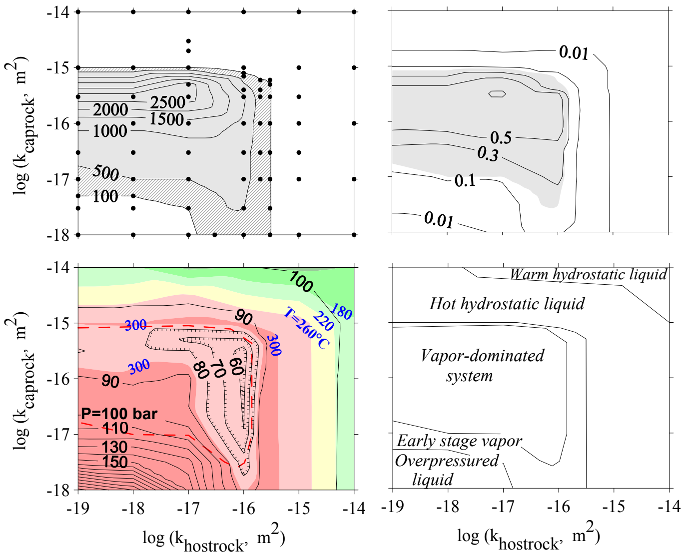

Figure 4. Geothermal reservoir characteristics for a basal heat input of 12 MW/km² and a simulation time at 6.2 kyr. Top left: thickness (in meters) of vapor-dominated reservoirs (shaded grey) and early stage vapor zones (hatchured) for combinations of the model caprock and host rock permeabilities. Top right: vapor saturation for a depth of 1.1 km. Bottom left: pressure and temperature fields for a depth of 1.1 km. Bottom right: types of geothermal systems in permeability space.

can range up to a maximum of 3 x 10^{-16} m² for early stage vapor formation (100 – 500 m of vapor zone thickness). The pressures and temperatures within the main vapor-dominated zone are in the range of 50 – 100 bar and 260 to 300 ºC) indicate over-pressured liquid-dominated conditions. At caprock permeabilities above about 10^{-15} m² and host rock permeabilities above about 3 x 10^{-16} m², hot, liquid-dominated, hydrostatic reservoirs occur. At caprock and host rock permeabilities above about 5 x 10^{-15} m², the liquid reservoirs are less than about 200 ºC.

The pressures and temperatures for vapor-dominated reservoirs are slightly higher than that found at Kamojang and Darajat, but this is attributed to the amplitude of the basal heat input. More extensive modeling discussed by Raharjo et al., (in press), using a heat input of 8 MW/km² produces a good match to those reservoirs.

Conclusions

The existence of five vapor-dominated, volcano-hosted geothermal systems in West Java, Indonesia, which appear to be unique in the world, provided a motivation to find the heat input and permeability configurations that produce such systems. A review of the key physical characteristics of these systems and subsequent numerical modeling of their heat and mass transfer using the code TOUGH2 lead to the following conclusions.

1. The natural surface heat output of these volcano-hosted systems is ~ 10 MW/km², significantly higher than the two large vapor-dominated systems at The Geysers and Larderello. The five reservoirs also have liquid-dominated geochemical alteration signatures which are now being overprinted by the vapor signatures. These vapor-dominated reservoirs therefore evolve in two stages: development of a hot, liquid-dominated reservoir, and then liquid to steam conversion. There can also be a cooling phase, when the underlying heat source is exhausted and the vapor-dominated reservoir is flooded by liquid from the surrounding host rock.

2. We have simulated a reservoir that has an area 4 km x 4 km, with a height of 2.8 km, and whose top is 300 m below the surface. Above the reservoir is a 150 m thick caprock and 150 m of overburden. In this paper we show that with a heat source of 12 MW/km², it takes roughly 2000 years to produce a hot, liquid reservoir with a temperature of 200 ºC and another 2000 years to raise the temperature to 260 ºC. For a certain range of caprock and host rock permeabilities, and continued heating, a vapor zone begins to develop at about 5500 years and by 6200 years the vapor zone is over 1000 m thick. If the basal heat input remains unchanged, residual water in the vapor zone has disappeared by 6,500 years. Depending on the permeability of the caprock and the surrounding host rock, the vapor zone has temperatures of 260 – 300 ºC and pressures of 50 – 100 bars. These conditions match the reservoirs at the several of the higher-temperature vapor-dominated reservoirs in West Java, and models with a lower heat input were able to match the conditions at all five vapor-dominated reservoirs (Raharjo et al., in press.)

3. By performing a large number of simulations in which the caprock and host rock permeabilities are systematically varied, we have been able to map, in permeability space, the permeability configurations that produce both liquid and vapor dominated systems. Five fields are produced, namely warm hydrostatic liquid-dominated, hot hydrostatic liquid-dominated, overpressured liquid-dominated, early stage vapor zones, and vapor-dominated systems. Each occupies a specific permeability space. Liquid-dominated systems take place when the caprock permeability is higher than 10^{-15} m², and the host rock permeability is about 3 x 10^{-16} m² or greater. When the caprock and the host rock are very impermeable, an overpressured liquid-dominated system is developed. The favorable permeability space for a vapor-dominated reservoir, when the heat source is 12 MW/km², is restricted to caprock permeability within the range from 10^{-17} to 10^{-15} m², accompanied with host rock permeability of 3 x 10^{-16} m² or less.

4. By running the simulations longer, to 25 kyr, we observe the process of system cooling and flooding of the vapor zone, resulting in a hot liquid-dominated reservoir. Even when the basal heat flow is reduced at the time the vapor zone starts to develop, we were unable to sustain the vapor reservoir for more than about 2000 years. The reservoir either dries out or floods depending on the timing of basal heat input changes. The duration of the vapor zone is short compared to the timescale for heating and cooling the liquid-dominated reservoir (~ 10^4 years) and may be one factor explaining why these systems are rare. Similarly, hot liquid-dominated systems are created for a wide range of permeability combinations, providing an explanation for the abundance of these systems.

5. The issue remains as to why the five volcano-hosted, vapor-dominated systems occur in this relatively small part of West Java, and apparently nowhere else in the world. One factor is clearly the stress regime. Immediately west of the five vapor systems is the liquid-dominated Awibengkok system (Figure 2), and farther west on Sumatra Island are numerous liquid-dominated systems adjacent to the Sumatra Fault, a dextral fault system extending the length of the island. This observation suggests that shear stress on faults that cross through the reservoir and associated enhanced permeability possibly play an important role in preventing a vapor-dominated system from developing.
6. In West Java, the plate convergence is normal to the volcanic arc, and it has been suggested that subduction zone rollback may be occurring (Bogie et al., 2008), perhaps explaining the unusually broad zone of volcanism in this section of the volcanic arc. Faults that were previously strike-slip have become normal faults. However normal faults are also often permeable. Our modeling requires that fracture and fault permeability characteristic of the productive reservoir ($\sim 10^{-13}$ m^2) does not penetrate the surrounding host rock. Vapor zones often also have elevated gas contents so as the vapor zone forms, it is possible the increased reactivity of the fluids, especially where condensation processes are occurring at the reservoir boundary, has created enhanced seal integrity at the boundaries.
7. It appears volcano-hosted vapor-dominated systems are rare because of several limiting factors – intense heat flow from depth, and a restricted permeability space for the entire reservoir boundary, which is several orders of magnitude lower than the permeability within the reservoir.

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