Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

INSIGHTS ON THE FORMATION OF VAPOR-DOMINATED GEOTHERMAL SYSTEMS

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Keywords: vapor-dominated systems, reservoir pressure, The Geysers, Larderello, Kamojang, Darajat

ABSTRACT

Although many reservoirs have shallow vapor-dominated zones, only four fields are known to have low pressure (< 7 MPa) vapor-dominated zones extending to below sea level (The Geysers, Larderello, Kamojang, and Darajat). Under-pressured gas reservoirs in petroleum-bearing basins at such depths are even rarer. A review of the physical characteristics of these four fields indicates that The Geysers and Larderello have probably evolved differently to Kamojang and Darajat. The former two fields have very large reservoir areas (~100 km^2), low heat flow intensities (< 1 MW/km^2), and long lifespans (> 10^5 years for the vapor-dominated conditions; >10^6 y for the hydrothermal-magmatic system). The order of magnitude greater heat flow intensity at Kamojang and Darajat implies a much great infiltration rate of water (> 30 kg/s) and a shorter life for the vapor system as we presently know it (< 10^4 y). At The Geysers and Larderello, naturally low permeability metamorphic rocks surrounding the much of the reservoir limits water infiltration rates, and factors such as reservoir dilation and steam loss to the surface can cause and/or sustain low pressures in the system. Volcanic-hosted Kamojang and Darajat may have evolved from a magmatic-hydrothermal system analogous to Alto Peak (Philippines; Reyes et al., 1993), where a vapor chimney is surrounded by a liquid-dominated geothermal system. After multiple cycles of magmatic-hydrothermal activity, the permeability of the host volcano may become sufficiently small that the high pressure vapor chimney decays into an under-pressured vapor-dominated system. Because of a requirement for prolonged seal integrity, such systems may only evolve in volcanic arcs where the adjacent subduction is perpendicular to the trench/fore-arc region.

1. INTRODUCTION

Naturally occurring vapor-dominated geothermal systems are rare. Many reservoirs may contain vapor-dominated zones, particularly at shallow depth or if they are located in high relief areas, but very few undisturbed reservoirs do not have liquid reservoirs below sea level elevation. The Geysers (northern California, USA), Larderello (Italy), and Kamojang, Darajat (both in central Java, Indonesia) are the four fields with published pressure data confirming vapor-dominated pressures profiles at substantial depth in their reservoirs (White et al., 1971; Barelli et al., 1995; O'Sullivan et al., 1990; Whittome and Salveson, 1990). The original pressure-depth trends in these four systems are shown in Fig. 1. Pressures typically range between 3 and 7 MPa, depending on the temperature trend at depth, and once partial gas pressure is considered, the pressure typically follows the saturation trend, implying the presence of immobile water trapped in the micro-fractures and pores of the reservoir. Very high temperatures (>300°C) and low pressures such as those in the northwest part of The Geysers and at depth in Larderello field could be consistent with either super-heated conditions (Truesdell et al., 1993) or a residual, immobile brine in a two-phase, vapor-dominated reservoir (Shook, 1995). A conductive temperature gradient in hot, ductile and impermeable rock (>400°C) below the reservoir may contain isolated fluid pockets with pressure inferred to be approaching the lithostatic gradient (Fournier, 1991, 1999; Capetti et al., 1985; Nielson, 1996). There is evidence of mobile water overlying or around the edges of some parts of all four fields (Truesdell et al., 1993; Calore et al., 1980; Sulaiman et al., 1995; Whittome and Salveson, 1990).

Matsukawa (northern Japan) was at one time also considered to be vapor-dominated, but a review of the original pressure data has shown that reservoir pressures were controlled by a liquid column extending up to near the ground surface (Hanano and Matsuo, 1990). This highlights a potential difficulty in identifying vapor-dominated conditions just from discharge enthalpy. If permeability around the wellbore is not high, local pressure drawdown in the formation outside the wellbore can cause boiling of the mobile liquid and give the appearance of vapor-dominated conditions. Temperature and pressure logs, ideally before initial discharge, and during a recovery period after first discharge, are needed to identify the true initial fluid state of the reservoir. After extensive periods of discharge, the original pressures may never be recoverable (e.g. old Larderello borefield; Barelli et al., 1995). Deep feedzones (> 1 km) are likely to be more indicative of a vertically extensive vapor-dominated reservoir than shallow feedzones. In areas with moderate relief, a sequence of relatively narrow vapor-dominated zones (sometimes called parasitic) and intervening, perched liquid zones may overlie the deep liquid system. In such cases the head, or pressure regime of the deep liquid zone may be controlled by the elevation of an outflow zone down-slope, several kilometres from the high temperature upflow zone (Henley and Ellis, 1983; Ingebritsen and Sorey, 1988).

A hybrid type of geothermal system in which a saline, liquid-dominated system surrounds a chimney of high temperature vapor has been suggested as a common fluid state in dormant volcanoes (Reyes et al., 1993). These authors studied the fluid chemistry and petrology of the geothermal activity, including the results from several exploration wells, on Alto Peak, Leyte Island, The Philippines. The vapor chimney is hypothesized to have a vertical pressure profile close to, but probably exceeding, the pressure profile in the surrounding liquid zone. It is considered to have a vertical length of about 3 km and a diameter of 1 km, linking magmatic conditions at depth beneath the volcano, with shallow steam-heated waters high in the volcanic cone. This type of system is different from the classic vapor-dominated model with strong under-pressures at depth with respect to hydrostatic a local hydrostatic pressure gradient. It is not mentioned again here until the discussion section at the end of this paper where it is suggested that this could be the first stage in the development of volcanic-hosted vapor-dominated systems such as Kamojang and Darajat.

The requirements for the classic vapor-dominated system are usually considered to be a long-lived, potent heat source at depth, and long-lived, low permeability boundaries to seal the entire system and prevent flooding by adjacent groundwater (White et al., 1971; Ingebritsen and Sorey, 1988). Mineralogical evidence in all the vapor-dominated systems suggests that the vapor-dominated systems were initially liquid-dominated systems. A change in fluid state is assumed to have occurred during a period when mass discharge exceeded recharge. Some numerical models invoke rapid venting of reservoir fluids over a short time (< 100 years) and subsequent sealing of the vents to cause a relatively sudden transition to vapor-dominated conditions (Pruess, 1985; Shook, 1995). However Ingebritsen and Sorey (1988) showed that a slow transition is also possible. Recently, Allis and Shook (1999) showed that reservoir dilation at the Geysers could also cause and/or sustain vapor-dominated conditions. A period of venting of excess liquid from the system is not essential. This model will be reviewed in more detail below.

The purpose of this paper is to briefly review present knowledge and offer some new insights about the natural occurrence and stability of vapor-dominated systems. It is now over 10 years since the thorough analysis and review of the stability of vapor-dominated systems by Ingebritsen and Sorey (1988). In that time no new vapor-dominated systems have been reported despite extensive exploration and development (e.g. numerous papers in World Geothermal Congress volumes, 1995). Although parasitic vapor zones are common where geothermal fields are located in high local topography, the total number of naturally vapor-dominated systems has actually decreased from five to four. Two newly drilled fields in central Java within 50 km of Kamojang and Darajat, Karaha and Patuha, are interesting because they apparently do have thick vapor zones overlying liquid zones. These two cases could be transitional between the four examples with strongly under-pressured vapor reservoirs, and the numerous geothermal systems with a liquid upflow zone at depth. The last 10 years has also seen new research results from The Geysers and Larderello revealing remarkably simple, monotonic cooling histories with no evidence of periods of reheating or episodic invasion of the reservoir by liquid once the vapor reservoir had formed (e.g. Moore et al., 1998; Hulen et al., 1997). In 1998, the world's most powerful production well ever drilled occurred at Darajat (Whittome, 1999). The recent drilling here has confirmed the presence of deep, open, vapor-dominated fissures at Darajat extending to at least 900 m below sea level (E. Erb pers. comm), clearly indicating that the vapor zone is not just a shallow phenomena, and not an artifact of low permeability around the wellbore.

2. THERMAL REGIME

The Geysers and Larderello have similarities in their fluid state, geology and the genesis of the vapor-dominated reservoirs which have intrigued researchers for many years (e.g. White et al., 1973, D'Amore and Truesdell, 1979; Gianelli and Puxeddu, 1994). Both fields are hosted in metamorphic terrane invaded by batholithic scale intrusions (100 – 400 km^2 in area), and the evidence from age dating suggests slow cooling over a timescale 1 – 3 million years (Del Moro et al., 1982; Hulen et al., 1997; Moore and Gunderson, 1995). The thermal history inferred from Ar-Ar dating at The Geysers reservoirs implies a period of more rapid cooling around 0.25 Ma which has been interpreted as the change to vapor-dominated conditions in the reservoir (Hulen et al., 1997; Moore et al., 1998). Slow cooling from ~280 to ~250°C has occurred since that time. At the Geysers, the main felsite intrusion and related Cobb Mountain volcanics have been dated at ~1.2 Ma and the earliest adularia date (indicative of liquid-dominated conditions) obtained so far is at 0.6 Ma (Hulen et al., 1997).

The evidence for both the highest temperatures and for liquid-dominated conditions being early in the thermal history of the systems, and for vapor-dominated conditions to be relatively late in the history, suggests that a *potent* heat source is *not* critical for the formation of vapor-dominated conditions. This conclusion is consistent with qualitative observations of the heat flow from the four vapor-dominated systems. The pre-development, natural surface heat flows were not exceptionally large (e.g. ~90 MW_{th} for Kamojang, Hochstein, 1976; ~70 MW_{th} at Darajat, Whittome and Salveson, 1990; ~50 MW_{th} for The Geysers, Allis and Shook, 1999; Larderello is unlikely to have been significantly larger). In contrast, the heat flows from liquid-dominated systems can range up to 500 MW_{th} (Bibby et al., 1995).

However, there is a big difference in the heat flow/area between The Geysers (also probably Larderello) and Kamojang-Darajat fields. The Geysers heat flow is 0.5 – 1 MW/km^2 depending on assumptions of convective steam loss and reservoir area. At Kamojang and Darajat, the heat flow is an order of magnitude higher because of the smaller reservoir area (~ 10 km^2). This appears to imply an important difference in the longevity of Kamojang and Darajat fields. Simple stored heat considerations indicate a 20 km^3 volume of magma at solidus temperature cools in ~ 10^4 years with a heat loss rate of 10 MW/km^2. This volume is similar in magnitude to the present reservoir volume. Preserving a vapor-dominated system at Kamojang or Darajat for ~10^5 years with their present rate of heat loss seems unlikely. The requirement for ongoing magmatic and volcanic activity, (for which there is ample evidence) would surely mean that the reservoir, its fluid state, surface thermal activity have all changed considerably if the reservoir has been present for ~ 10^5 years. The simplest conclusion is that the vapor-dominated fluid state of Kamojang and Darajat is probably short-lived (< 10^4 years) in comparison to that at The Geysers and Larderello (> 10^5 years).

3. SEAL INTEGRITY

Self-sealing of fractures from heating of peripheral, deeply circulating meteoric waters or formation waters rich in bicarbonate and/or sulphate provides a mechanism for maintaining a permeability barrier (White et al., 1971). However the common occurrence for reservoirs and reservoir boundaries to be cut by active fault systems may the main reason for the scarcity of vapor-dominated systems. Perhaps it is no coincidence that Kamojang and Darajat are adjacent to a subduction zone where there is *not* oblique subduction. This contrasts with the geothermal systems in Sumatra, the Philippines, part of Japan, and New Zealand which are all adjacent to major shear zones as a result of oblique subduction. The role of local uniaxial extension in the four vapor-dominated systems, rather than the more common trans-tensional stress regime is discussed below.

In the case of The Geysers, the mass inflow from infiltration across the boundaries and downward draining condensate has to have been very small to avoid flooding of the reservoir (Ingebritsen and Sorey, 1988; Allis and Shook, 1999). For an average Geysers heat flow of 0.5 W/m^2 (5 MW/10 km^2; conductive plus convective), 1 kg/s of water infiltration per 10

km^2 area of the reservoir requires half the available heat to convert the water to steam and retain the steam saturation in the reservoir. An excess of just 1 kg/s of water infiltration per 10 km^2 of reservoir area (0.04 porosity) is capable of saturating the reservoir in 30,000 years. The same sensitivity to mass flow applies to a net mass loss in the form of steam loss to the surface, or steam condensing into an overlying condensate layer and lateral outflow into the regional hydrology away from the reservoir. Despite its very large area, The Geysers reservoir is almost totally sealed, and has remained in this state for > 10^5 years.

The much higher heat flow intensity at Kamojang and Darajat allows a greater tolerance of water infiltration variations. The 70 - 90 MW natural heat loss implies a mass infiltration rate of 25 – 33 kg/s if the field is in mass flow equilibrium. The heat loss estimates exclude lateral outflows of condensate down the flanks of the volcanoes which may be manifest as steam-heated spring waters at lower elevations, or may be concealed. The total heat flux, and therefore the inferred infiltration mass flux, is a minimum.

Seal integrity requires a sealed caprock. The metamorphic assemblages capping The Geysers and Larderello clearly have the requisite properties, but why Darajat and Kamojang are sealed is less clear. Goff et al. (1977) suggested that the high heat flow area immediately northeast of The Geysers is liquid-dominated because the numerous volcanic vents allow excessive downward infiltration of meteoric water. There are no volcanics immediately overlying the Geysers reservoir. The role of volcanics as major conduits for downflowing water in a low permeability cap rock could also apply at Larderello. There are no volcanics directly overlying this reservoir, but the reservoirs adjacent to Mt Amiata volcano, 70 km from Larderello, is liquid-dominated (Bertini et al. 1995).

At Kamojang and Darajat we have to appeal to the extensive argillic alteration of near-surface volcanic rocks approximately 1 km in thickness preventing significant infiltration of meteoric water (Sudarman et al., 1995; Whittome and Salveson, 1990). Whether the alteration is more intense than at adjacent liquid-dominated fields is unclear. At the liquid-dominated Awibengkok field 100 km west of these two fields, it has been suggested that recent rhyolite extrusions (Perbakti rhyolite) on the northeast of the field are allowing downward infiltration of water to cool that portion of the reservoir (Allis, 1999). This may be providing pressure support to the liquid reservoir. Perhaps the key to Kamojang and Darajat is a lack of recent volcanic activity within the field to preserve low permeability boundaries, but a potent heat source at depth capable of sustaining the vapor-dominated conditions. The value of this as a predictive indicator is limited because the summit of Gunter volcano 5 km from Kamojang field has erupted historically, and there are rhyolite extrusives (Kiamis) just 4 km from Darajat field.

Similarly, the traditional indicator of a vapor-dominated reservoir being a lack of chloride hot water outflow may also unreliable in this steep topography. Wayang Windu geothermal field, just 10 km west of Darajat has hot spring characteristics similar to Kamojang and Darajat, with the maximum chloride concentration bring 20 mg/kg (Sudarman et al., 1986). This led the authors to surmise ahead of deep drilling that Wayang Windu would be vapor-dominated like its neighbors. Exploration drilling in the field has apparently shown it to be liquid dominated at depth. It appears that in volcanic-hosted geothermal systems, evidence of a chloride outflow downslope is a good indicator of a liquid system, but the converse is not necessarily true. Also, acid chloride waters high on a volcano may be due to magmatic steam condensate, and may say little about the fluid state of an adjacent geothermal system.

4. LOCALIZED RESERVOIR DILATION

It is possible for extensional tectonic fracturing to be localized, and not traverse low permeability boundary zones. The pull-apart basins and geothermal systems in dilational jogs along the Southern San Andreas fault zone are examples of localized areas of extension (Sibson, 1987). Magma intrusion beneath geothermal systems is also likely to cause dilation in overlying reservoirs, but may have less impact and therefore retain the integrity of sealed boundary zones. Localized reservoir dilation is capable of causing or sustaining vapor-dominated conditions (Allis and Shook, 1999).

The concept that faulting and rock dilation could cause reduced fluid pressure was proposed by Sibson (1987) as an explanation for much fault-hosted epithermal mineralization. Earthquake rupture termination at dilational jogs is believed to involve extensional fracturing, fluid pressure reduction, enhanced fluid flow, and local boiling with mineralization where temperatures are high enough. Allis and Shook (1999) reviewed the geological and geophysical evidence for extension at The Geysers, with probably the most compelling being fault plane solutions from > 1 km depth indicating uniaxial extension (Openheimer, 1986; Eberhart-Phillips, 1988). Subsurface geological evidence from within the reservoir is conflicting, with a variety of suggestions for randomly oriented fractures, north-northeast fractures, low angle fractures, and a domed structural relationship to the felsite (Beall and Box, 1992; Thompson and Gunderson, 1992; Thompson, 1992). A surprisingly large number of fractures in The Geysers reservoir have no alteration minerals on the fracture walls (Moore, pers. comm.). This could mean the fracturing post-dates the early, liquid-dominated phase of the reservoir and is an indication of reservoir dilation.

At Larderello, the reservoir has been undergoing extension for at least the last 1 Ma, although periods of compression may have affected the area during the last 5 Ma (Cameli et al., 1993; Boccaletti et al., 1997; Gianelli and Puxeddu, 1994). The entire Italian promontory is now under extension with the Adriatic Sea being a microplate rotating counterclockwise towards Yugoslavia at about 2 cm/y (Anderson and Jackson, 1987; based on earthquake focal mechanisms). These authors suggest the extensional tectonics are superimposed on compressional features which formed the Appenines and related structures, and this has confused many earlier researchers. The micro-seismic evidence at Larderello is also consistent with active extension (Batini et al., 1985). Tensile stress in the area is assumed to have caused, or allowed, the rise of magma from the mantle into the crust.

At Kamojang and Darajat, downhole logging with fracture detection tools has revealed a consistent direction for both fields. Prominent surface faults strike northeast at both fields, but at Kamojang cross-faults are also present and there has been doubt over the principal direction of permeability. FMS and dipmeter logs from these fields confirm open fractures predominantly striking northeast to north with a high dip angle

(Huntoro et al., 1996; Whittome and Salveson, 1990). The recent 40 MW well drilled at Darajat was deviated to the NW (Whittome, 1999) which would have maximized its chances for intersecting NE-trending open fractures. Interestingly, the same direction for open fractures has been found at liquid-dominated Awibengkok geothermal field, about 100 km NW of these two fields (Hulen and Allis, 1999), suggesting that this direction is a consequence of the regional stresses in central Java. The present day plate convergence vector in the Java trench is N 20°E (derived from Euler pole data in De Mets et al., 1994) which, if affecting central Java, could be consistent with pure extension on the major normal faults striking NNE across Kamojang and Darajat fields. This would result from the maximum horizontal stress being NNE, but the maximum principal stress being vertical in central Java.

Numerical modeling has shown that a low porosity, liquid-dominated reservoir with sealed boundaries apart from a leaky cap can become vapor-dominated with extension (Allis and Shook, 1999). The modeling was based on the geometry of The Geysers reservoir, with the model domain being a two dimensional vertical slice,10 km long, 4 km deep and 1 km wide. The uppermost and lowermost 1 km of the domain simulated caprock and impermeable bedrock with a permeability of 1 x 10^{-18} m^2, and zero porosity. The reservoir portion of the domain had a constant permeability of 1 x 10^{-14} m^2 and an initial porosity of 0.0125. The initial conditions assumed a conductive gradient of 230°C/km, and a lower boundary condition assumed a constant heat flux of 0.5 W/m^2. When this reservoir is dilated to a porosity of 0.04, either sequentially over time, or in one step, the upper portion of the reservoir becomes vapor-dominated and the lower portion superheated. Inclusion of a leaky cap with 0.5 - 1 kg/s of water inflow through one end of the caprock, and a central discharge vent to allow steam discharge, causes lateral variations in steam saturation after 30,000 years remarkably similar to the inferred initial state of The Geysers reservoir (Fig. 2). Further modeling including the effects of salinity and dual porosity is planned by these authors.

5. ANALOGIES IN SEDIMENTARY BASIN GAS ZONES

Are there any insights from under-pressured gas reservoirs in sedimentary basins that could help understand geothermal vapor-dominated systems? Where gas accumulations are sufficiently thick, their pressure in the upper portions of the "reservoir" structure are abormally high (Neuzil, 1995), and atypical of vapor-dominated geothermal reservoirs. Under-pressured gas reservoirs are generally restricted to uplifted and eroded basins, such as the Rock Mountain chain (Davis, 1984; Powley, 1990; Neuzil, 1995). Some under-pressuring is due to relative decompression of the reservoir fluid in sealed compartments due to erosion and basin unloading (Neuzil and Pollock, 1983). However, most of the under-pressured portions of basins can be explained by deep equilibration of pressures with the regional pressure regime distant from the high topography. These reservoirs are analogous to the parasitic vapor zones discussed by Ingebritsen and Sorey (1988).

Seal-bounded fluid compartments are now recognized as a common occurrence in oil and gas basins (Powley, 1990). Low permeability shales frequently form upper or lower boundaries to compartments in sedimentary basins, and may have analogous hydraulic properties to argillic-altered tuff layers in stratovolcanoes in a geothermal setting. Pressure gradients across these seals can range up to 0.3 – 0.6 MPa/m of thickness (Powley, 1990). Calcite and/or silica infilling of porosity on the low pressure side of seals is attributed to precipitation of dissolved minerals as water seeps through the seals. Lateral seals in sedimentary basins are generally less than 200 m thick, vertical, and straight, suggesting control by faults. Where these have been drilled they have generally found to be slightly fractured and infilled with calcite and/or silica (Powley, 1990). A geothermal analogy to reservoir compartments could be at Kamojang field. Sudarman et al., (1995) comment that the reservoir has at least three areas of high transmissivity separated by zones of low permeability with poor connections based on pressure differences (presumably under production). This could be a feature of vapor-dominated reservoirs because of the stringent requirement for self-sealing boundaries.

Despite many examples of abnormally pressured regimes in sedimentary basins in the above-mentioned papers, only one example has been found which approaches the strongly under-pressured regime found at depth in geothermal vapor-dominated systems. That is from the Elmworth Basin in the Canadian Rocky Mountains (Masters, 1984). Here water overlies gas within shallow-dipping, stacked, permeable formations at 1 – 2 km depth. The down-dip formations produce dry methane with up to 600 m (vertical) in the gas leg (Davis, 1984; Gies, 1984; Welte et al., 1984). The lower boundary is an impermeable, structural feature; the upper, gas/water interface is close to the regional hydrostatic trend. The average pressure of the gas reservoirs depends on the depth of the formation being considered, but typically it is in the range 10 and 20 MPa. Explanations for the stability of the water over gas reservoir are varied, but appear to be consistent with the stability requirements for vapor-dominated systems summarized by Ingebritsen and Sorey (1988). Water was initially expelled by gas generation and migration from organic material in adjacent shale, with gas continuing to slowly seep into the reservoir and sustain the pressure regime. At the top of the reservoir, permeability appears be sufficiently low for a continuing gas flux into the overlying sediments to prevent a downflow of water.

6. DISCUSSION

It has been noted that the stability of the pressure regime in an ideal vapor-dominated systems appear to be controlled by deep pressures (or mass inflow, temperature and saturation), whereas that of liquid-dominated systems is controlled by the near-surface pressure (McGuiness and Pruess, 1987; McGuinness, 1992). Some physical mechanism has to keep pressures low at depth in a vapor-dominated system to prevent flooding from much higher pressures outside the system. Ingebritsen and Sorey (1988) pointed out that the pressure in vapor-dominated reservoirs is also influenced by the depth of, and therefore fluid pressure at, the base of the reservoir cap. Vapor-pressures at the top of the reservoir have to exceed the overlying weight of water in the cap in order to sustain steam flow into the cap and impede downflowing water.

There are similarities in the flux requirements for both vapor- and liquid-dominated systems for a stable pressure regime. Both require an outflow threshold to be exceeded for "overflow" to occur, and both require an inflow condition at their base. With liquid systems it is a link to the regional basement fluid which allows adequate meteoric fluid circulation into the hot rock at depth to sustain the buoyant upflow and subsequent outflow. With vapor systems the permeability around the reservoir has to be sufficiently low so that the reservoir is isolated from basement permeability, liquid inflow is impeded, and the heat input is sufficient to vaporize all the inflow (as well as downflowing condensate) and sustain the steam outflow.

Despite the material reviewed in this paper, seal integrity over geologic time in tectonically and volcanically active environments remains an enigmatic issue, possibly explaining why so few vapor-dominated systems have been proven by drilling. The comparison here of all four known vapor-systems does suggest that volcanic-hosted Kamojang and Darajat are in a different class to The Geysers and Larderello. The latter two fields have very large reservoir areas (~100 km^2), low heat flow intensities (< 1 MW/km^2), and long lifespans (> 10^5 years for the vapor-dominated conditions; >10^6 y for the hydrothermal-magmatic system). The order of magnitude greater heat flow intensity at Kamojang and Darajat implies a much great infiltration rate of water (> 30 kg/s) and a shorter life for the vapor system as we presently know it (< 10^4 y). At The Geysers and Larderello, naturally low permeability metamorphic rocks surrounding the much of the reservoir limits water infiltration rates, and factors such as reservoir dilation and steam loss to the surface can sustain low pressures in the system. Naturally low permeability vertical boundaries are not necessarily present in volcanic-hosted systems, so a combination of factors are needed for an extensive vapor-dominated system to form

The suggestion of Reyes et al. (1993) that many dormant volcanoes with thermal activity on their upper flanks may have vertically extensive, but relatively narrow, vapor-dominated chimneys in pressure equilibrium with a surrounding liquid-dominated system may be an important starting point. Acidic alteration caused by neutralization of upflowing magmatic-hydrothermal vapor and downward flowing steam-heated water from the near-surface will cause intense alteration in the vicinity of the chimney. More pervasive propylitic alteration will accompany the liquid-dominated system surrounding the chimney (Giggenbach, 1997). If the magmatic-hydrothermal system goes through several cycles of activity due to intermittent volcanic activity, the central vapor chimney probably expands and contracts, possibly collapsing during prolonged intervals of inactivity. Eventually the core of the volcano may be reduced to pervasive low permeability due to the alternation of upward and downward fluxing of minerals into the core of the hydrothermal system. During magmatic pulses, deep pressures may then approach lithostatic stress causing hydrofracturing, and brecciation. The concept of a "chimney" may no longer be valid, with vapor filling whatever volume is present in the local fracture network.

In rare cases, the host rocks possibly become sufficiently sealed that surrounding liquid cannot inflow sufficiently rapidly to flood a waning magmatic-hydrothermal pulse. The vapor pressures at depth begin to decline, and the pressure profile becomes strongly underpressured as seen at Kamojang and Darajat. This mechanism for forming a vapor-dominated system in volcanic settings differs from the conventional "boil-down" of liquid systems frequently cited for The Geysers reservoir. Invasion from depth by a high temperature-high pressure vapor phase begins the process, and where the host rock is sufficiently impermeable, this decays into a low pressure vapor-dominated reservoir. Petrological, chemical, and hydrological evidence from the great variety of volcanic-hosted geothermal systems in recently drilled west Java, Indonesia should provide a rigorous test for this hypothesis.

ACKNOWLEDGEMENTS

I thank Bob Erhlich for introducing me to the unusual water-over-gas characteristics of the Elmworth Basin, many EGI colleagues for fascinating discussions about the evolution of The Geysers system. This work was carried out under DOE geothermal contracts #DE-AC07-95ID13274 and DE-FG07-00ID13892 to EGI, University of Utah.

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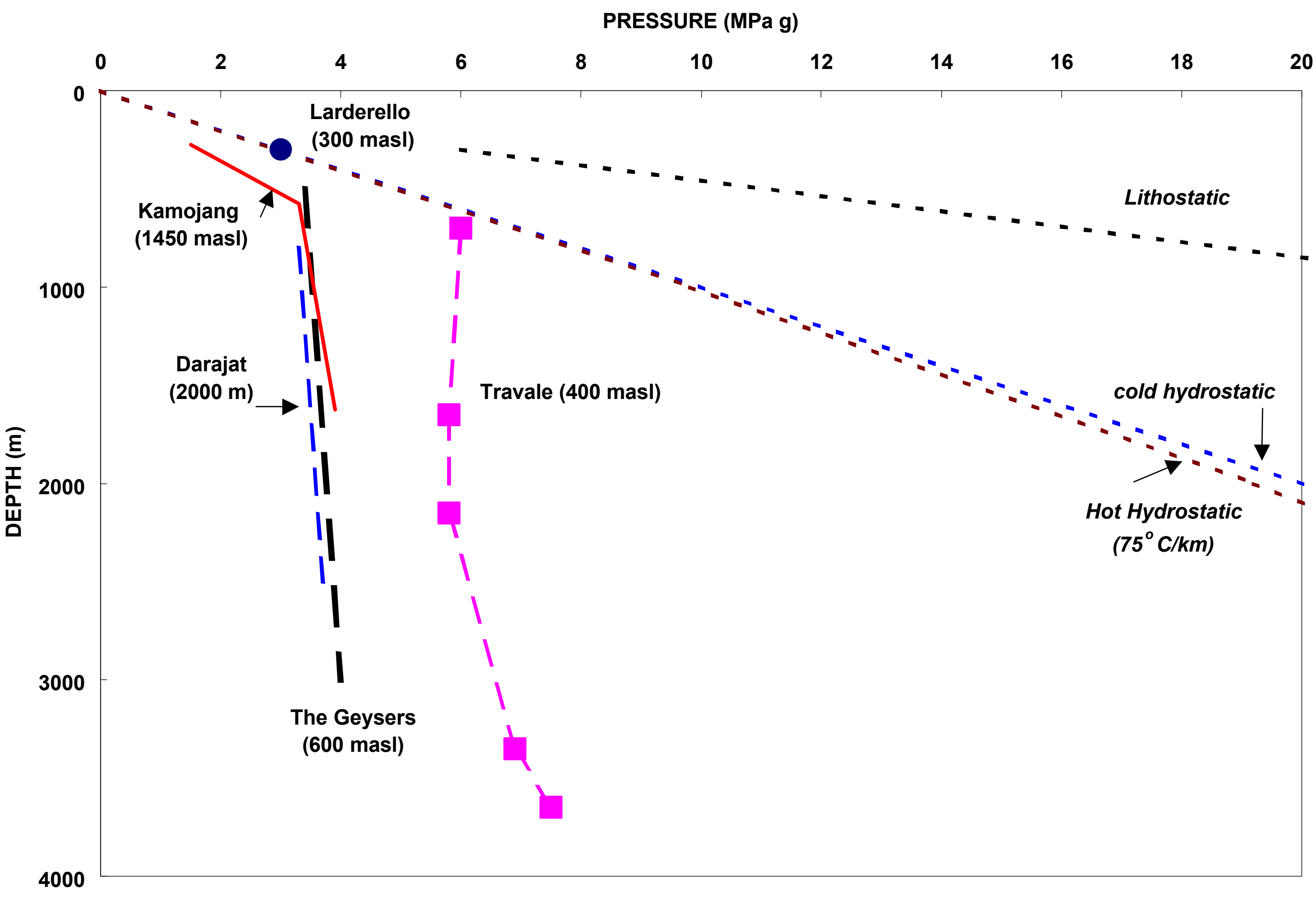

Figure 1. Pressure-depth trends in the four vapor-dominated systems discussed in the text. Trends are indicative, because of lateral pressure gradients in most reservoirs. Refer to text for source references. Number in brackets after each name is the ground elevation.

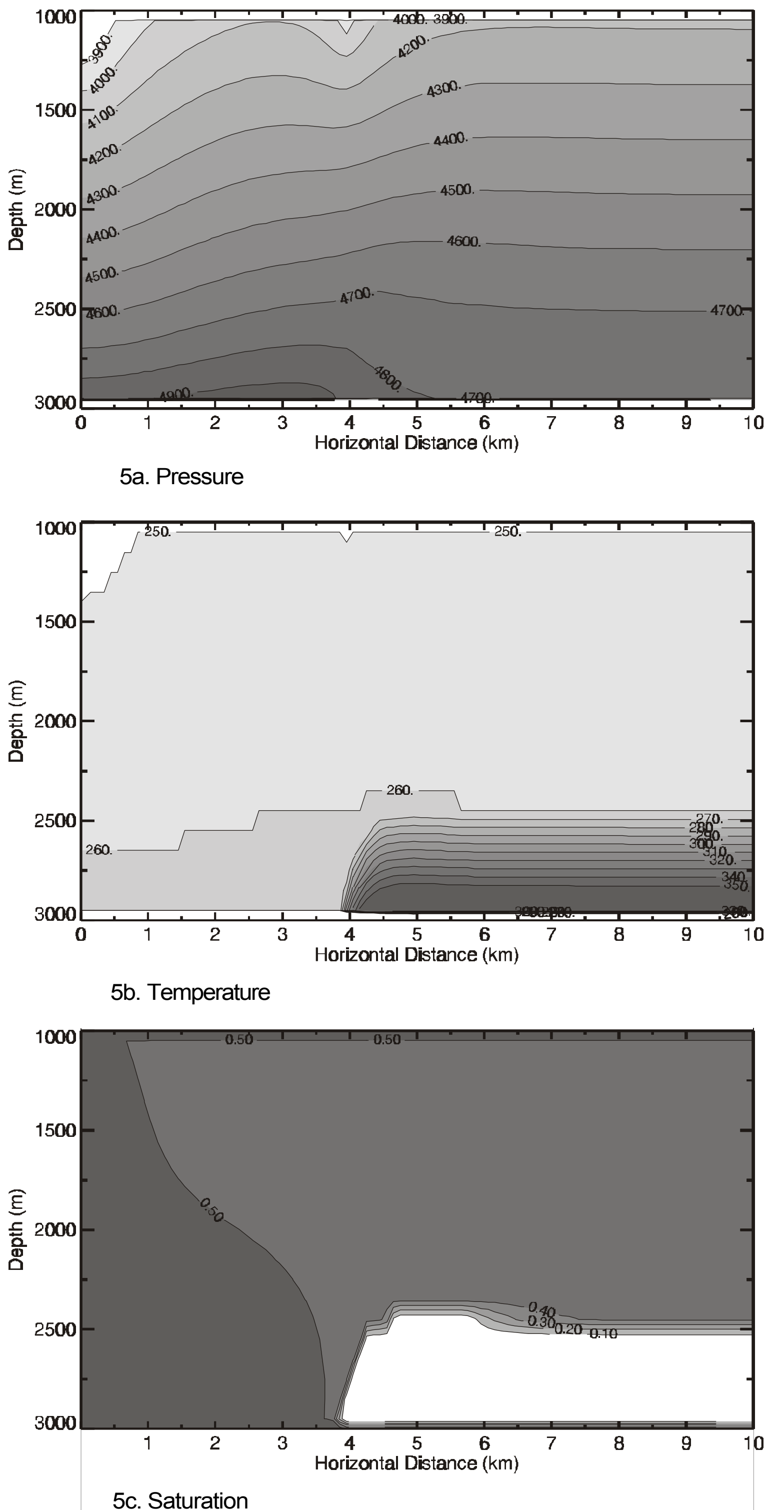

Figure 2. Results of 2-D numerical simulation of a slice through The Geysers reservoir, 30,000 years after increasing the porosity from 0.0125 to 0.04 in a liquid-dominated reservoir (Allis and Shook, 1999). There is an inflow "leak" of 0.5 kg/s into the top left corner, and a vent in the top center to simulate steam loss. The three graphs show that vapor-dominated conditions overlie a super-heated zone in the lower right portion of the reservoir