Geological Evaluation of the Waringin Formation as the host of a Vapor-Dominated Geothermal Reservoir at the Wayang Windu Geothermal Field

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ABSTRACT

The Waringin Formation is part of the Quaternary Volcanic rocks that host the upper parts of the Wayang Windu geothermal field. It is part of a medial facies of an andesitic stratovolcano with its eruptive centre in the south. Its importance is that it hosts the vapour dominated zone of the Wayang part of the field. It consists of andesitic lava flows and medium to coarse grained pyroclastics. The lava flows generally become less common with depth. The upper lava flows mark the formational break from the overlying Pangalengan Formation that consists of fine pyroclastics and epiclastics.

Hydothermal alteration in the Waringin Formation that formed during earlier liquid dominated conditions that spanned the transition from argillic to propylitic alteration with depth. Smectite-illite clay and chlorite predominate in the argillic zone with the top of the propylitic zone marked by the first occurrence of epidote. This lies well above the top of the vapor dominated reservoir, which is confined to the lower part of the formation where medium to coarse grained pyroclastics predominate. This is a similar situation to that in the Gambung part of the field where the separate vapour dominated zone there has its top at the formational break between the lava rich Malabar Formation and medium to coarse grained pyroclastics of the underlying Dogdog Formation.

The elucidation of similar geological controls over the top of the reservoir between the two separate vapor dominated zones is of major assistance for well design for further exploitation of the Wayang vapour dominated zone.

INTRODUCTION

Wayang Windu geothermal field is located in a southern volcanic area, 40 kilometers to the south of Bandung in West Java, Indonesia (figure 1). The geothermal system is situated in a rugged volcanic terrain and has been interpreted to be transitional between vapor-dominated and liquid-dominated systems (Bogie et al., 2008). Wayang Windu Geothermal field has been in production since 2000, with a total installed electricity generating capacity of 227 MWe.

The volcanoes in the study area are part of the Sunda Volcanic Arc, which resulted from the northward subduction of the Indo-Australian plate to the south of West Java. The subduction has a major control of the structure and volcanism in the area. The volcanism associated with the subduction started in the early Tertiary, resulting in volcanoes in the northern part of West Java, while the southern volcanoes are late Tertiary until early Quaternary (Susanto, 2011).

Stratigraphically, the Wayang Windu area is part of the regional Malabar and Wayang Windu Formations (Quaternary) Pangalengan Formation (Pleistocence), Waringin Formation (Pleistocene), and Loka Formation (Pleistocene), (Bronto et al., 2006).

GEOLOGY OF WAYANG WINDU FIELD

1. Stratigraphy

An interpretation of the stratigraphy of the Wayang Windu Geothermal Field developed through studies from surface and subsurface geology which consist of drill cuttings and cores, interpretation of image logs. Rock type and hydrothermal alteration were also studied by petrography, XRD, and fluid inclusion geothermometry.

In an early exploration phase Star Energy developed geology model using a volcanic facies model (figure 2) (Bogie, Mckenzie, 1998) to differentiate the geologic formations encountered at Wayang Windu. Five different formations were indentified, from oldest to youngest these are, Loka Formation (distal facies), Waringin Formation (medial facies), Pengalengan Formation (distal facies), and Wayang Windu Formation (proximal facies) (figure 3). But development in the northern area, identified the Dogdog Formation of similar age and interfingering with the Pengalengan Formation, and Malabar Formation (proximal facies) with similar age and interfingering with Wayang Windu Formation. This paper writer focuses on the Waringin Formation as host of the vapor dominated reservoir.

The Waringin Formation consists of andesitic lava and medium to coarse pyroclastics. The lava becomes thinner and less common with the depth. In The upper lava flow marks the formational break from the overlying Pengalengan Formation that consists of fine pyroclastic and epiclastic. As with the Pengalengan formation, the volcanic centre for this unit erupted to the south. In the lower part of the formation medium to coarse grained pyroclastics predominate.

The matrix porosity model shows declining porosity with depth in Wayang Windu, which is commonly observed at other andesitic stratovolcanoes hosting geothermal system (Stimac, 2001 op.cit UGI report, 2002). The decrease results from compaction and lithification of the tuffaceous rocks. The porosity data also shows a typical lithologic relationship. Porosity in tuffaceous rocks are widely varied compared to lava flows and brecciated lavas. The weighted average porosity from matrix and fractures is 7.1 %.

2. Structure

To acquire the permeability distribution in Wayang Windu there are two targets, the main target is secondary porosity from faults and fractures. The fault and fracture traces from the surface lineaments, then confirmed from subsurface data such as image log, spinner surveys and from cores. The loss zone depth in the Waringin Formation is variable; depending on the penetration the fault zone or facture. The other permeability target is fracture/ brecciated lava that created space for fluid flow but this is only limited, and the margin on igneous intrusive rock like microdiorite and dolerite of the Waringin and Loka Formation. It is difficult to recognize because of a combination of hydrothermal alteration and blind drilling. The primary porosity from lithology had little effect since the porosity distribution is 7.1%.

3. Volcanic eruption history

Surface geology mapping and air photo interpretation identify some eruptive centers and circular features in the area that were active in the past and are the likely source of the Wayang Windu reservoir rocks. Most of the eruptive centers are located on the north and east sides of the field (figure 4).

The north eruption center, with a distinct drainage pattern, represents the Malabar volcanic complex and appears to consist of several nested caldera. The eastern eruption centers are represented by the northeast-southwest trending Wayang, Windu and Bedil domes. Waringin possibly comes from the southern part, but it is not seen on the topography since it is covered by the younger eruption centre. Situated far to the south of the field, it may have contributed to the reservoir rocks at the southern end of Wayang Windu. No obvious eruption center can be located to the west.

4. Hydrothermal Alteration

Hydrothermal alteration mineralogy encountered in the Waringin Formation can be categorized into interlayered illite-smectite (argillic assemblage) until its transition to a prophylitic assemblage with a top marked by the presence of epidote. At greater depth, illite become the main sheet silicate. In the deep liquid reservoir, wairakite and phrenite, along with epidote are common alteration and vein minerals. (Bogie. et al, 2008).

In the Wayang Windu geothermal field, epidote minerals occur at range elevations from 1000 to 1300 m ASL.the epidote appears to fluctuate at depth in vapor dominate zone and lying above the deep liquid reservoir. This is probably because the water level in the system was previously higher, reminding the epidote generally forms at temperature above 240^{0}C under near neutral pH in a liquid reservoir (Browne, 1980). Most of the alteration in and above the vapor dominated zone is now above the water level and must be relict. This zone, which characterized by conductive temperature profile, constitutes the caprock of the geothermal reservoir.

RESERVOIR CHARACTERIZATION

1. Reservoir Boundary

There are four known Vapor Dominated Zones (VDZ) in Wayang Windu, from south to north are *Windu* VDZ, *Wayang* VDZ, *Gambung* VDZ, and *Puncak Besar* VDZ. The boundaries of these VDZ are partially defined from well data and further delineated laterally using MT base-of-conductor contour (figure 5).

Generally the *Windu*, *Wayang* and *Gambung VDZ*, western and southern boundaries are well defined from existing well data. However, the eastern boundaries of Wayang VDZ, where there are no existing wells, are delineated using an MT base-of-conductor contour pattern. So, the eastern boundary has a higher uncertainty than the western boundary. This reservoir boundary is a guide to the Waringin Formation hosted on the reservoir section especially in the vapor dominated zone at the northern in *Gambung* and *Puncak besar VDZ,* and the two phase zone in *Wayang* or *Windu VDZ.*

2. Top of Reservoir

Since the presence of epidote in the Waringin Formation shows a relict condition, the actual top of reservoir is represented from the downhole pressure and temperature (P-T) profiles from completion tests.

The downhole pressure and temperature (P-T) profile survey indicates that the top of the reservoir is marked by a change in temperature gradient and pressure withinthe reservoir. For most of the Wayang Windu production wells, the depth at which they penetrate the top of the reservoir is indicated by a distinct change at temperature gradient reflecting reservoir temperature of approximately 240^{0}C (Asrizal et al., 2006).

The Waringin Formation is hosted in a vapor dominated reservoir in the Wayang Windu Geothermal Field, shown by a changing temperature trend from conductive gradient to a convective gradient (figure 7). The productive reservoir section of Waringin Formation shows a shallow two-phase or vapor dominated reservoir at elevations are 600 to 1000 m asl, some overlying at deep liquid reservoir at the elevations are 400 – 600 m asl.

3. Temperature and Pressure

The fluid inclusion was study from Abrenica in 2007. The study shows the homogenization temperatures in primary and secondary fluids inclusions. The primary fluid inclusions from quartz shows between 230 and 240 ^{0}C while those contained in calcite homogenized at 260-300^{0}C. Since the data suggest these inclusions were trapped in a boiling environment, the measured homogenization temperatures represent the trapping temperature of the boiling fluid, therefore these inclusions result from an earlier liquid reservoir condition. Secondary fluid inclusions in the quartz are vapour rich, consistent with presence of increasing vapor dominated condition.

Homogenization temperatures from quartz ranging from 240-260^{0}C and secondary inclusions in calcite have homogenization temperature range from 260-300^{0}C (figure 6).

This condition is consistent with current conditions of the pressure and temperature profiles (figure 7). In the northern part the temperature in two-phase or vapor dominated reservoir range from 230-260^{0}C and in deep liquid reservoir up to 300^{0}C. The pressure indicated is based on the pressure and temperature profiles. The pressure in two-phase or vapor dominated reservoir ranges from 40-50 bar.a and pressure in the deep liquid reservoir is up to 100 bar.a.

CONCLUSIONS

The Waringin Formation lies in a vapor dominated reservoir with a temperature in the range from 240-260^{0}C, consisting of andesitic lava and medium to coarse pyroclastic. In the upper lava flows mark the formational break from overlying fine pyroclastic and epiclastic of the Pengalengan Formation. The Hydrothermal alteration in Waringin Formation formed during an earlier liquid dominated condition in is relict. The Pressure and Temperature Survey shows water level in the system was previously higher than the current conditions from the epidote occurrences. The permeability of the Waringin depends on the secondary porosity i.e the fault and fracture zone. The average primary porosity is less than 10% and declines with depth. The Waringin Formation provides major assistance for well design for further exploitation of the Wayang Windu Geothermal system, especialy of a vapor dominated reservoir.

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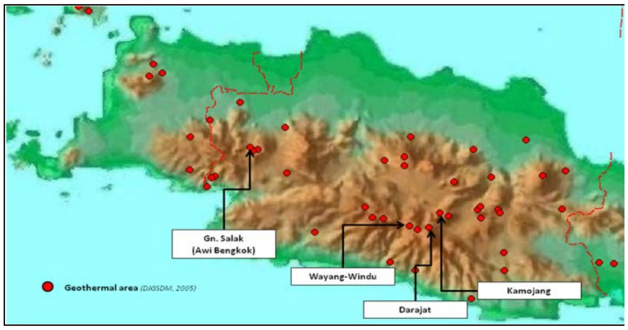

Figure 1. Geothermal concession area on west Java, Indonesia, Wayang Windu located in southern volcanic area

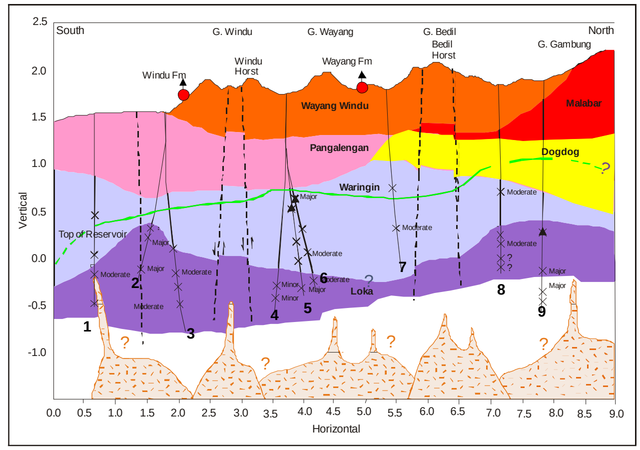

Figure 3. Schematic Wayang Windu Geological model from south to north. Modified from UGI report (2002).

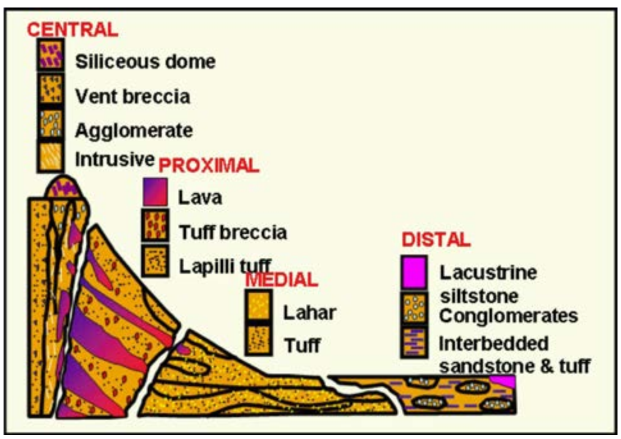

Figure 2. Schematic model of volcanic facies, Waringin Formation, including a medial-proximal facies. (Bogie and Mckenzie, 1998)

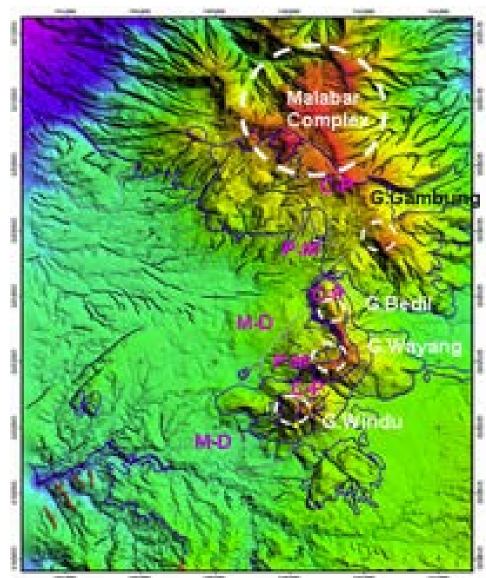

Figure 4. Eruption centre at Wayang Windu Geothermal Field. Shows volcanic eruption with volcanic facies (central-medial-proximal) (Arizal, 2006)

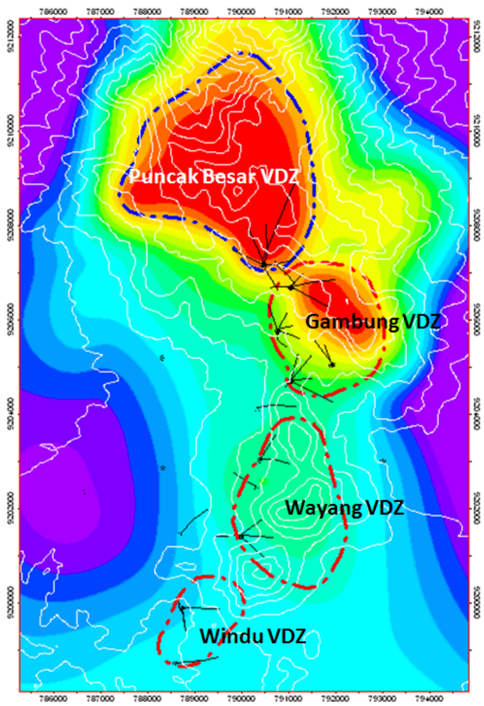

Figure 5. Estimated boundary of several vapor-dominated zones (VDZ) in Wayang Windu. The colored contour is MT base-of-conductor, white contour is topography, and black lines are existing well tracks (unpublished report).

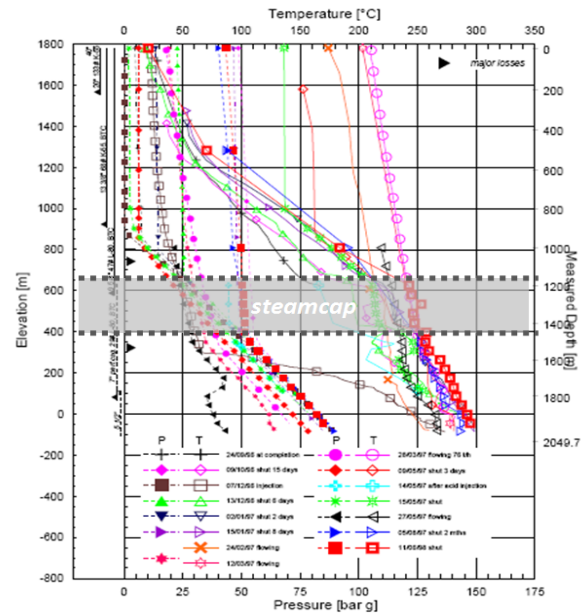

Figure 7. Temperature pressure profile at northern part of Wayang Windu Geothermal Field, show the steam cap over two-phase or vapor dominated zone (unpublished report).

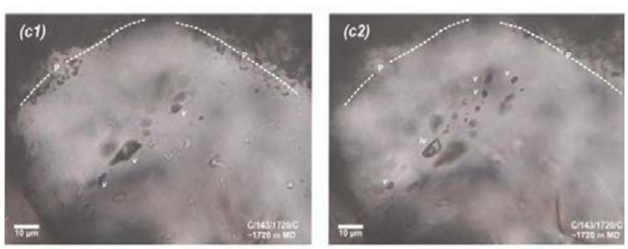

Figure 6.(c1) Primary fluid inclusions in Well C are parallel to the grain boundary of wairakite crystal; (c2) cluster of secondary fluid inclusion in wairakite containing two-phase *(lv)* and vapor-rich *(v)* inclusions (Abrenica, 2007).