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Porosity Study for Detail Reservoir Characterization in Darajat Geothermal Field, West Java, Indonesia

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ABSTRACT

Porosity is one of the critical factors in geothermal reserve estimation, as a majority of geothermal fluid reserves in a vapor system are stored in the reservoir rock matrix porosity. Volcanic rocks typically give a wide range of primary matrix porosity, which can be enhanced or reduced by alteration. Heterogeneity of rock distribution and alteration processes makes the evaluation of porosity in a geothermal reservoir difficult and can be misleading.

In order to realistically predict future field performance, porosity of Darajat reservoir rock has been studied in detail by combining core porosity measurements (total and effective porosity), petrography of blue-dye impregnated thin sections, X-Ray Diffraction (XRD) and Portable Infrared Mineral Analyzer (PIMA). Core data are mostly available from the wells located on the field's margin, and very limited from the field's center. A wireline porosity log estimate becomes critical where core data is not available. Integration of Schlumberger's Accelerator Porosity Sonde (APS) and Formation Micro Scanner (FMS) pseudo-resistivity were correlated with core data and provided porosity estimates for the field center. The core porosity data were used as primary data for reservoir simulation, while wireline log data were used to predict the range of porosity values.

The porosity distribution in the reservoir appears to be mainly related to rock type (texture, phenocryst size and abundance, etc.), fracture and hydrothermal alteration. Porosity of fresh lava is generally much lower compared to breccias, while porosity of breccias is lower than tuffs. A moderate to high alteration intensity generally leads to a wide range of porosity values. In lava, a higher intensity of alteration usually occurred along fracture zones and less altered in the rock matrix. In pyroclastics, alteration can occur anywhere.

1. INTRODUCTION

1.1 Background

The Darajat field began its production in October 1994, and presently supplies steam to two power plants, Darajat Unit I and Unit II, 55 and 95 MWe respectively. An additional power plant with a capacity of 110 MWe is being planned. To support the field development, a realistic reserve assessment, using reliable input parameters becomes an important issue. In a vapor dominated reservoir, the source of the produced steam is mainly liquid stored in the reservoir that boils to produce steam. Research has shown that the majority of the initial reserves at the Geysers were stored as liquid water in the matrix porosity of the reservoir rock (Williamson, 1990). Reservoir porosity is a basic input for pore volume calculations, and ultimately for the reserves assessment. This study was conducted to define factors controlling matrix porosity and provide the most reliable porosity values and porosity distributions throughout the reservoir.

1.2 Geology of the Darajat geothermal field

The Darajat Geothermal Field is located in the West Java Province, of Indonesia. It is about 35 km southeast of Bandung (capital city of West Java Province) and 25 km west-southwest of the nearest town, Garut. The field lies within the Kendang volcanic complex, one of many volcanoes in the volcanic arc that extends from the northern tip of Sumatra, through Java, and eastward through the Banda Arc. The Kendang volcanic complex is part of a Quaternary volcanic range, extending from Papandayan volcano in the southwest to the Guntur volcano in the northeast. Adjacent to the Darajat field, is Kamojang geothermal field to the northeast and Wayang Windu field to the west (Figure 1).

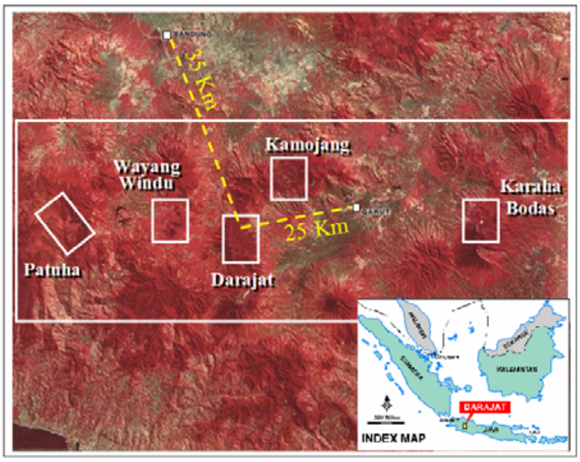

Figure 1: Location of the Darajat geothermal field relative to other volcanic activities and other geothermal fields.

Surface and subsurface volcanic facies studies indicated that Darajat is part of an old andesitic strato-volcano that has collapsed to the east and overlain by volcanic materials deposited from younger eruptions. A new geology model that was developed by comparing with a volcanic facies model of Bogie & MacKenzie (1998) suggested that Darajat consists of several volcanic units from several volcanic sources. Thirteen different volcanic units were identified, based on similar litho type compositions. In lower sections (Event I), thick lavas and intrusions from tholeiitic to calc alkaline magma type dominates the center of the field. This represents the central facies of a basaltic-andesitic strato-volcano. Thick pyroclastics dominates the margins, representing the proximal – medial facies. The Darajat reservoir is mainly composed of these two major sequences

(Figure 2). These sequences are overlaid by interbedded pyroclastics and andesitic lava, with thicker lava flows in the west compared to the center and eastern side (Event II) (Figure 2). There is intercalation of the relatively thick basaltic unit that deposited from the north. Obsidian flows at the northeastern side occurred as a late stage of volcanic activities in the field.

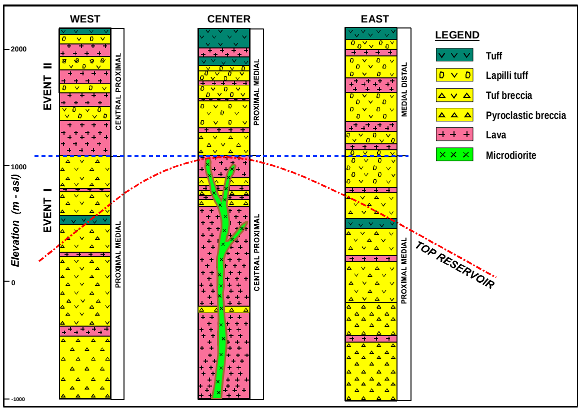

Figure 2: Typical subsurface rock unit and the main lithology composed the Darajat reservoir.

In general, structural features are of NE-SW and NW-SE orientations, with the most prominent features from air photography being the Kendang and Gagak faults. These faults have been proven to be the main productive zone in this region.

The alteration study indicates the occurrence of multiple geothermal events in the past showing acid and neutral pH alteration assemblages (Hadi, 1997; Harvey, 1998; Herdianita, 2001). These events resulted in replacement and dissolution alteration minerals in and out of the reservoir. Clay alteration study indicates the presence of a series of alteration zones which include a near surface supergene zone, a mixed layer Illite/Smecite, Illite-Wairakite zone, Garnet-Amphibole zone and a deep acid zone identified in the western area (Harvey, et.al, 1998). The reservoir zone is characterized by propylitic alteration with chlorite, pyrite, epidote and illite dominating the alteration mineral.

1.3 Previous work

Previous porosity studies of Darajat identified the relationship between porosity, rock type and fracture. Effects of alteration were not well defined yet. In the past, the Darajat porosity was classified into matrix and fracture porosity. However, due to the small contribution of fractures to porosity (Schlumberger, 2003 - pers. comm.; Hensel, 1987), the recent study was more focused on identifying the effect of alteration such as replacement type minerals and alteration intensity to porosity and other factors that may have a relationship to the development of the matrix porosity.

To validate the relationship between rock type and porosity and to provide reliable input for pore volume calculations, a consistent definition and classification of subsurface rock is a must. The first step before conducting the porosity study was reinterpretation and reclassification of the existing rock data. Darajat subsurface rocks were reinterpreted and reclassified by applying pyroclastic classification by Fisher (1984) and igneous rock classification by Thorpe & Brown (1985). All continuous cores and cuttings were re-described, supported by thin section examinations to verify the rock's name. In the zones with no drilling returns, the lithology interpretation from Formation Micro Scanner (FMS) logs was extensively used. A surface geology mapping and subsurface correlation by applying a volcanic facies approach was conducted to define the rock distribution and refine the geology model.

The mineralogical and textural controls to the porosity and its clay composition were observed mainly from petrographic examination of thin sections (with and without blue dye staining) and supported with X-Ray Diffraction (XRD) and Portable Infrared Mineral Analyzer (PIMA). PIMA analysis was applied on several samples due to the lower cost than XRD analysis.

2. POROSITY ANALYSIS

2.1 Porosity database

Porosity data and technology used for analysis have significantly increased since early field development, due to the increasing number of wells drilled and resolving problems that were identified and corrected during the study (Table 1).

DATA	PRE 1996	1998	2001/02	2003/04
Sport Core (sample amount)	6 Wells (35 – He)	24 Wells (227 – He)	24 Wells (227 – He)	24 Wells (227 – He) (70 – Hg)
APS Log			7 large bore wells 1 slim hole (outside reservoir)	7 large bore wells 1 slim hole (outside reservoir)
FMS Pseudo Resistivity			2 large bore wells 1 slim hole (outside reservoir)	4 large bore wells 1 slim hole (outside reservoir)

Table 1: Increasing porosity data set and technology applied for porosity analysis.

2.1.1. Core

Due to the heterogeneity of volcanic rocks and different degrees of alteration, a representative sampling strategy to proportionally cover lateral and vertical distribution and altered versus fresh rock is essential. To estimate the porosity values and porosity distributions in the reservoir, direct measurement from core and wireline log were integrated. Obtaining good, representative core data was difficult, because the reservoir is usually highly fractured and difficult to core in these fractured intervals. Seven slim-holes, mostly located on the field's margins, provided continuous core. However, only five of these wells penetrated the reservoir zone. Reservoir core porosity was mainly obtained from these slim-holes and spot cores from large-bore wells that are mostly located in the field's center (Figure 3). A totals of 297 samples of core porosity, including 132 samples (85 helium and 57 mercury porosimetry) taken within the reservoir were used for analysis (Table 1). Continuous porosity data from well S3 and S4, located in the west and northern side of the field, provided an opportunity to get a detailed picture of the relationship between porosity with alteration, depth of burial and to characterize the differences between reservoir and non reservoir zones. Core porosity data was used as the primary data for porosity determination, due to the higher level of confidence.

2.1.2. Wireline log

Due to limited core samples on the main production area, high temperature APS (Accelerator Porosity Sonde) logs were run in seven large-bore wells located in the center and northern part to acquire continues porosity data within the reservoir. APS was also run in one slim-hole that had continuous core (Figure 3). This allowed for a direct comparison between wireline and core data.

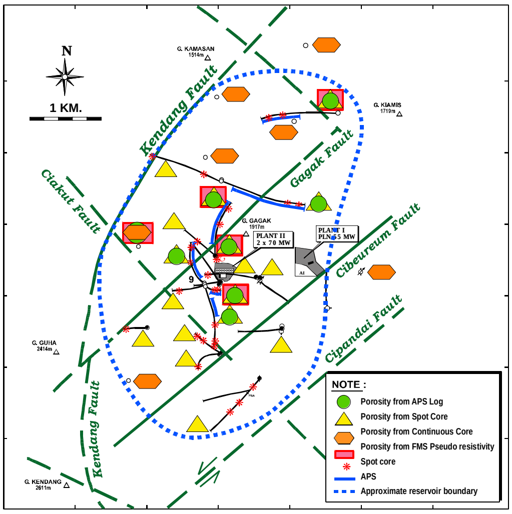

Figure 3: Porosity data source

APS is a wireline log that uses an electronic neutron source to measure hydrogen ions in the pore space to detect porosity. In general, APS response has good correlation with rock type and core porosity measurements, especially in lava (homogeneous) sections. However, APS tends to give unrealistic porosity value in rugose hole sections that commonly occurred in pyroclastic rocks. APS also has to be assessed carefully. Several factors, such as the presence of steam, gas (CO_2) and formation stand-off have a significant effect on the porosity measurement.

In order to obtain more realistic porosity values, especially in pyroclastics, an effort was made to maximize the use of the available FMS micro-resistivity. Based on this, a porosity transformation study was conducted in 2002-2003 for five pilot wells (Figure 3). FMS is a small pad resistivity device that has good contact with the formation. Basically, this pseudo-porosity was derived from FMS micro-resistivity by applying Archie's equation. Porosity obtained from wireline logs were compared with core data and has been used to define the porosity range for reservoir simulation (Figure 4).

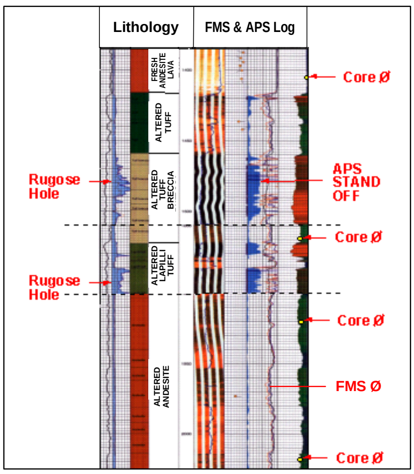

Figure 4: APS-FMS and core porosity correlation

2.2. Effective Porosity

Since porosity values are critical for pore volume estimation, an effective porosity necessary for geothermal fluids to move was evaluated and effective porosities for the reservoir rocks were acquired. A new data set consisting of 70 rock samples were collected and Mercury (Hg) Capillary Pressure porosimetry applied to "fill in" porosity gaps in the reservoir and to permit comparisons between effective and total porosity values. Based on Karsten Pruess' previous work (personal communication - 2003), a 0.0025 micron pore throat radius was used as an effective porosity cut-off. This is thought to represent sufficient pore throat diameter for water vapor to easily pass through the throat. This number agrees with a water adsorption characteristic study of vapor dominated reservoir rock conducted in The Geysers (Satik, et.al., 1996). Unlike in oil and gas, if the geothermal pore throats are blocked to steam flow by capillary water, the capillary water evaporates to make steam (Powell, 2003 - pers. comm.). Comparison between Hg total porosity and Hg effective porosity (> 0.0025 micron pore throat radius) is similar. The existing Helium (He) total porosities were corrected by applying an equation obtained by comparison between He total porosity and Hg effective porosity (Figure 5). By applying effective porosity, which is rarely used in vapor field modeling, conservative porosity value for reserves assessment have been used for Darajat.

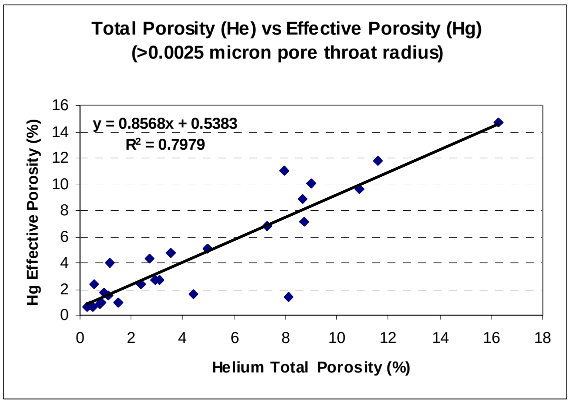

Figure 5: Comparison between He total porosity and Hg effective porosity (> 0.0025 micron pore throat radius) and equation used for He total porosity correction.

2.3 Factors controlling porosity

2.3.1 Porosity versus rock type

Detailed rock interpretation suggests that the Darajat reservoir is composed of different types of lava (andesite, pyroxene andesite, hornblende andesite, basaltic andesite, and basalt), microdiorite intrusion and pyroclastics (pyroclastic breccia, tuff breccia, lapillistone, lapilli tuff and tuff) with andesitic to basaltic composition. Lava generally has variations in the original structure, textures, phenocryst size and abundance. Plagioclase was found to be the most common phenocryst, in addition to pyroxene and hornblende with cryptocrystalline plagioclase as groundmass. Pyroclastics has a larger variation of grain size and fragment abundance than lava. These variations, along with the hydrothermal replacement and dissolution of primary minerals, may be related to the porosity variations of each sample from the same lithology characteristic. Even though the individual porosity value of lava varies, generally they can be assumed as homogeneous rock.

Core measurements as well as wireline logs indicate that matrix porosity of lava is much smaller compared to pyroclastic. Matrix porosity of brecciated lava or autobreccia found in several areas, shows higher values than massive lava. In general, highest to lowest matrix porosities of relatively fresh rocks are: tuff, breccia, lapilli, and lava (including microdiorite) (Figure 6). Due to the complexity and high variation of the reservoir rock that leads to difficulties in reservoir modeling, the lithology classification were simplified into group of rocks with similar characteristics. Rock classifications used for reservoir modeling are lava, pyroclastic breccia, and tuff.

2.3.2 Fracture and alteration related porosity

In geothermal systems fractures provide the conduit for fluids to move, which results in fluid-rock interaction. Fracture density work from continuous core and FMS interpretation showed that pyroclastic rocks were commonly less fracture, but more altered compared to lava. Alteration can occur both in the fractured and non-fractured zones. In contrast, fractures are more developed in lava (brittle rock). However, the alteration intensity is less. Lavas and intrusive rocks are mostly relatively fresh to moderately altered. The alteration of the groundmass is usually more intense than that of phenocryst. Pyroclastic rocks are usually more intensely altered. Tuff is usually completely altered, even at shallow depth. Probably this is a function of the degree of interlocking between clasts that allows fluids to move. More intense alteration in lava usually occurred along the fractured zone and less altered away from fractures.

The effect of alteration intensity to porosity was determined from thin sections observations. Alteration intensity of each sample were examined by the point counting method and classified by using Browne's (1989) classification. There appears to be no systematic correlation between alteration intensity and porosity. However, wide ranges of porosity were found related to moderate and intense alteration (Figure 6).

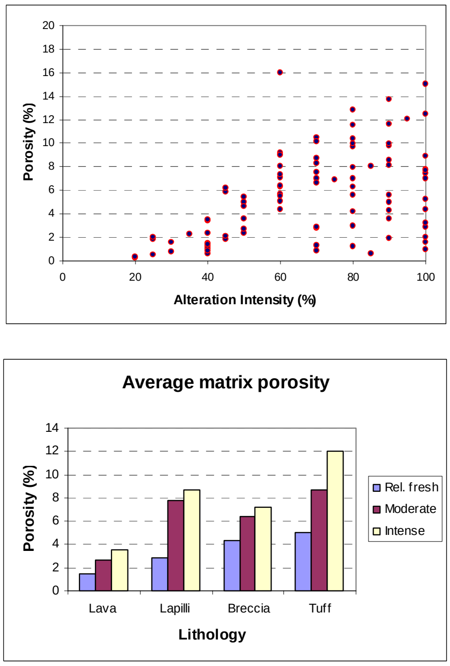

Figure 6: The relationship between alteration intensity and porosity, and average porosity of each litho type within reservoir.

Porosity studies suggest that hydrothermal fluid flow and geochemical reaction processes are largely responsible for the development of fluid storage or porosity in geothermal reservoirs.

In Darajat, multiple geothermal events occurred in the past leading to the formation of different types of alteration. Secondary pores consist of leach cavities in calcic plagioclase and primary minerals, vugs, mouldic porosity and veins filled with hydrothermal quartz, calcite, chlorite, illite or epidote are common in the Darajat reservoir (Figure 7).

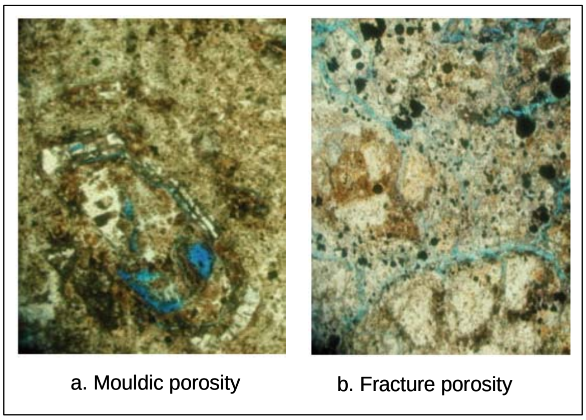

Figure 7: Example of alteration related porosity types that commonly found in Darajat reservoir identified from optical observation: a). Mouldic porosity type (showed in blue color) due to dissolution of plagioclase found in intensely altered lapilli tuff. b). Fracture and alteration enhanced porosity (showed in blue color) found in intensely altered andesite lava.

Plagioclase, whether as phenocryst or groundmass, are usually replaced partly or fully by calcite, chlorite, epidote, clays and opaque minerals. Besides alteration intensity, the proportion of each alteration minerals plays a significant role in the increasing or decreasing porosity. The main secondary minerals that control porosity are: clays, calcite, silica and epidote. A porosity versus clay trend suggests that clay content significantly increase porosity. The swelling clays, smectite and illite/smectite, tend to give higher porosity values compared to illite (Figure 8).

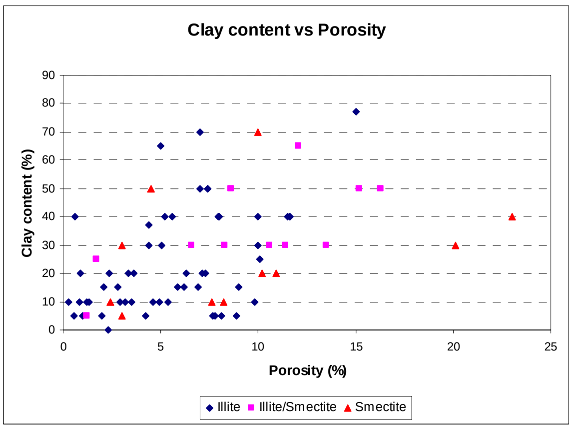

Figure 8: Correlation between clay content and its type with matrix porosity from samples inside and outside of the reservoir. Porosity range of illite rich rocks are generally smaller compared to smectite and illite/smectite rich rocks.

Chlorite, the most common clay in the Darajat reservoir, shows a slight correlation with porosity. It appears that matrix porosity decreases with increasing chlorite content.

Chlorite usually completely fills voids and mafic minerals that it replaces. Calcite is mostly present at shallow depths and its abundance decreases with depth. It shows a positive correlation with porosity. Samples with higher calcite content generally show higher porosity, probably due to the effect of reservoir water intensively dissolving calcite. Calcite is not a stable mineral in Darajat because CO_2 concentrations in the Darajat reservoir are low (Powell, 2004 – pers. comm). Other non-clay minerals that were found to have a relationship with porosity are silica and epidote. Increasing silica content appears to decrease matrix porosity, while increasing epidote content appears to increase matrix porosity (Figure 9).

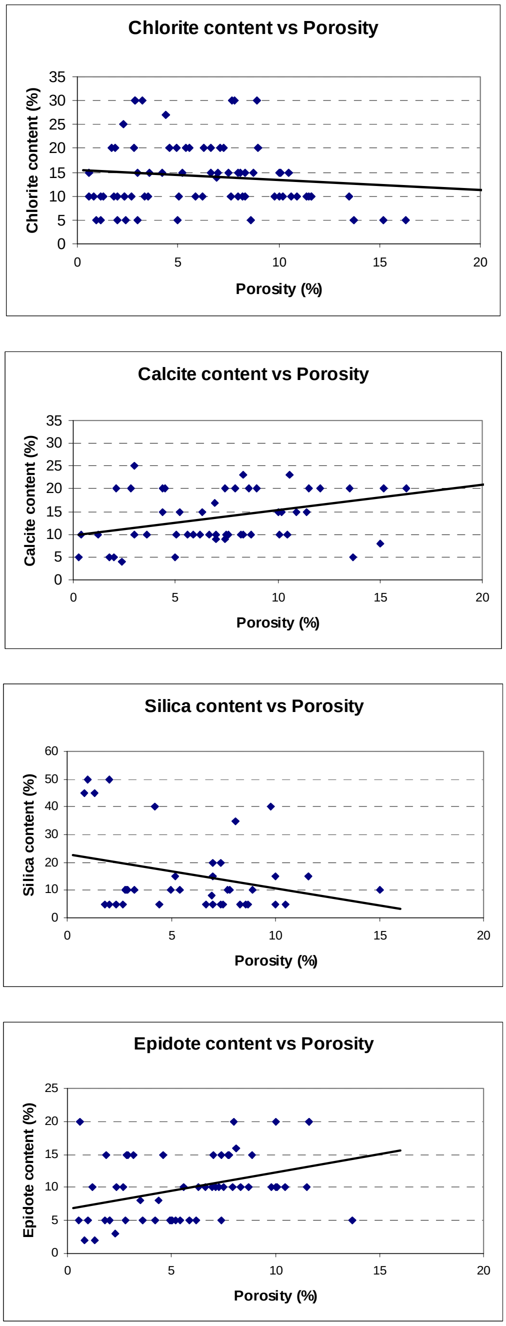

Figure 9: Graphs showing correlation between chlorite, calcite, silica and epidote content and porosity.

The composite log from well S3 shows the direct correlation between porosity, alteration intensity and main secondary minerals that control porosity (Figure 10).

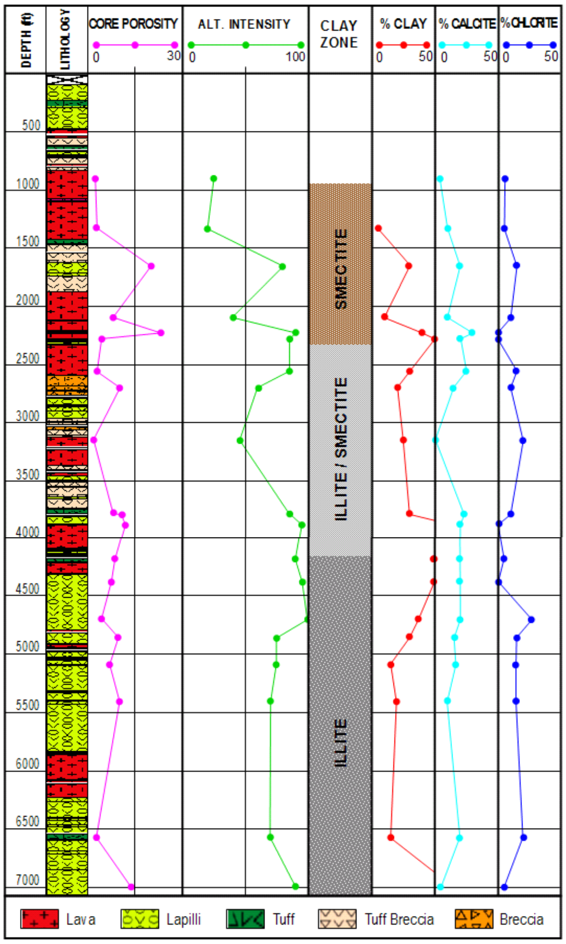

Figure 10: Composite log of well S3 showing the correlation between porosity, lithology, alteration intensity, mineral assemblages and clay zone.

2.3.3. Porosity versus depth trend

The porosity distributions within the reservoir are scattered. In general, porosity versus depth trends from all core samples in the reservoir do not show any significant trend of decreasing porosity with depth, either in lava or pyroclastic rocks (Figure 11). This phenomena suggests that burial effects do not plays significant role in reducing porosity in the Darajat reservoir.

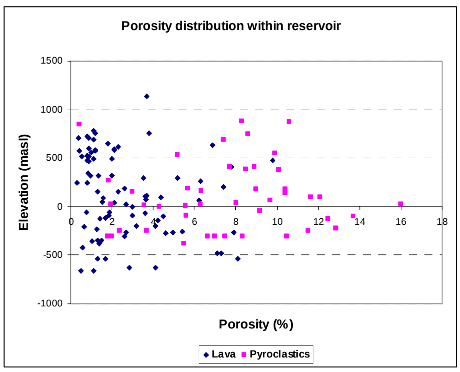

Figure 11: Porosity versus depth trend of each lithology type within reservoir.

3. CONCLUSION

Results from this study show that porosity is mainly controlled by rock type and alteration processes. Variations in original rock texture, grain size and fragment abundance, along with dissolution or replacement of primary minerals leads to variations in porosity values for each sample. The effect of overburden pressure to porosity development in the reservoir is not significant, either in lava or pyroclastics. The porosity distribution that shows no significant decreasing porosity with depth indicates that no significant diminishing resource potential at the deeper part of the reservoir.

Matrix porosity results exhibit a range of porosity by rock type from highest to lowest: tuff, breccia, lapilli, lava (and intrusive) rocks. Low porosity lava and intrusive dominates the center part of the field, while higher porosity pyroclastics dominates the field's margins.

There appears to be no direct relationship between alteration intensity and porosity. However, moderate to intense alteration leads to a wide range of porosity values. Alteration mineral assemblages and clay type play a significant role in enhancing or reducing primary porosity. Illite alteration provides a lower porosity compared to smectite and illite/smectite. Chlorite and silica have a negative correlation with porosity, while calcite and epidote provides increased porosity.

In a vapor dominated geothermal reservoir, an effective porosity of greater than 0.0025 micron pore throat radius can be considered as a reasonable porosity cut-off for water vapor to easily move the pore throats.

The effect of fractures on porosity is less than those related to alteration. Integration of the core study, APS, FMS and thin sections indicates that the majority of the Darajat reservoir is composed of a dual porosity environment in which fractures form the main conduits for fluids to move (high permeability, more alteration) and the rock matrix has very low permeability and is less altered.

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