

## UNCERTAINTY QUANTIFICATION BY USING STOCHASTIC APPROACH IN PORE VOLUME CALCULATION, WAYANG WINDU GEOTHERMAL FIELD, W. JAVA, INDONESIA

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### ABSTRACT

This paper presents the application of a stochastic approach and Experimental Design techniques to a volcanic geologic system in order to quantify the uncertainty of Pore Volume estimations for Wayang Windu geothermal field in West Java, Indonesia. The Pore Volume is a key element when defining the total resource available in the field. The uncertainties being addressed include (i) Geometry (top of reservoir, intrusions and base of reservoir), (ii) Reservoir Continuity (rock type and facies distribution) and (iii) Petrophysical Properties (porosity).

The range of uncertainty for each of the parameters was developed using information from varying sources, including data from 30 wells, comparable geothermal fields, Micro Earth Quake (MEQ) measurements, MT/TDEM surveys, etc. Facies groups were modeled based on distance of deposition from the volcanic center, i.e., Central-Proximal, Proximal-Medial and Medial-Distal. The model was controlled by the locations of present day volcanic centers, XRF, age dating, etc. Each facies group consists of different proportions of 5 rock types; lavas, breccias, tuff breccias, lapilli tuffs, and tuffs. Porosity consistent with the rock type and facies distribution was generated within the 3D static model comprised of approximately 26 millions cells using Petrel.

The uncertainty was quantified by evaluating the results of multiple realizations through the Plackett-Burmann experimental design technique. The results were then used to generate a range of theoretical pore volumes via Monte Carlo simulation. From this distribution, low, medium and high cases were extracted. The selected cases were upscaled and are

currently being evaluated through rigorous dynamic flow simulation modeling. The results show that the pore volume was most sensitive to the following parameters (in order); base of reservoir, porosity values, rock type proportions, top of reservoir, intrusions and facies distribution.

### INTRODUCTION

The Wayang Windu Geothermal Field is situated in the West Java province of Indonesia, about 150 km southeast of Jakarta (capital city of Indonesia) and 35 km south of Bandung (capital city of West Java) (Figure 1).



Figure 1. Wayang Windu Geothermal Field Location

In geothermal development the estimated sustainable resource potential is the most important assumption made as this forecast naturally imposes constraints on the type and scale of future developments. Currently, reservoir simulation is the most accurate method for assessing the power generation capacity of geothermal fields under production (PB Power, 2000). Fluid reserves in a single or two phase system such as Wayang Windu are believed to be stored within the porosity in the rock matrix. Understanding the geologic framework of the reservoir, especially

rock type and distribution, fault structure and alteration, is important in a geothermal reservoir. This framework governs key reservoir parameters for simulation, such as porosity, connectivity and permeability.

Interpreting rock types and distributions in a volcanic setting is complex due to alteration and discontinuity of lava and pyroclastic rocks, however using an integrated geological approach has led to the development of a consistent reservoir rock framework. A detailed geological model to better represent the 3D distribution of petrophysical properties at Wayang Windu is important, especially for estimating the porosity and permeability distribution in the reservoir. One of the key processes of this study is focused on identifying and understanding key drivers of pore volume (PV) and to include those uncertainties in a probabilistic resource assessment. Since PV is a key element when defining the total resource available in the field, this overview will be focused on processes to assess this critical parameter.

Because most geothermal fields are related to a geologic volcanic setting, “Experimental Design techniques” should be employed as a standard workflow in the geothermal industry to acquire reliable results during resource assessment.

## **RESERVOIR CHARACTERIZATION**

### **Reservoir Top and Bottom (Volume)**

In geothermal field development, wells are targeted to penetrate zones with permeability and high temperature. Downhole pressure-temperature (P-T) surveys indicate that the top of the reservoir is marked by a change in temperature gradient and pressure within the reservoir. For most of the Wayang Windu production wells, the point at which they penetrate the top of the reservoir is indicated by a distinct change in the temperature gradient reflecting a reservoir temperature of approximately 240°C. The most reliable tool to interpret the top of the reservoir is from the downhole P-T survey, however temperature-dependent minerals, alteration and geophysics can be used to predict top of reservoir both between the wells and outside of well control.

The bottom of the Wayang Windu reservoir was previously defined by the deepest drilled well in the reservoir (@ -700 masl (low case). A recent micro earthquake (MEQ) survey however indicates seismic events occurring 4 km below the surface suggesting that defining the bottom of the reservoir based on well control may be too conservative. Deep MEQ data interpreted to represent “thermal stress” produced from cold injected fluid entering a hot geothermal reservoir has been used to estimate

reservoir thickness at the Geysers. At Geysers the deepest MEQ responses (at - 5 km) are used tentatively to interpret the bottom of the reservoir (Stark, 1990).

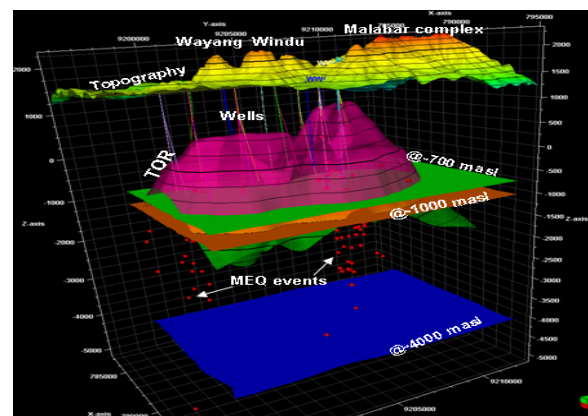


Figure 2. 3D reservoir model shows top of reservoir, MEQ events, base of reservoir at -700 masl (low case), at -1000 masl (base case) and at -4000 masl (high case).

In summary, the base case volume geometry of the reservoir follows the top of reservoir contouring using well control and the bottom of the reservoir at -1000 masl. Deep MEQ events induced by water injection are used to define the high case reservoir bottom at -4000 masl (Figure 2).

### **Reservoir Geology Model (2D)**

#### ***Rock Interpretation***

Detailed review of all cores and cuttings from 4 deep core holes and 26 wells was conducted, supported by FMS imagery analysis, to develop a consistent rock definition. However, the following order of priority (confidence level of data) was always used to interpret the rock facies: thin section, core examination, FMS imagery and cuttings.

#### ***Surface Geology Interpretation***

Surface geology mapping and air photo interpretation identify eruptive centers and circular features in the area that were active in the past and are the likely source the Wayang Windu reservoir rocks. Most of the eruptive centers observed are located on the north and east sides of the field (Figure 3).

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. Gunung Kencana, situated far to the south of the field, may have contributed to the reservoir rocks at the southern end of Wayang

Windu. No obvious eruption center can be located to the west.

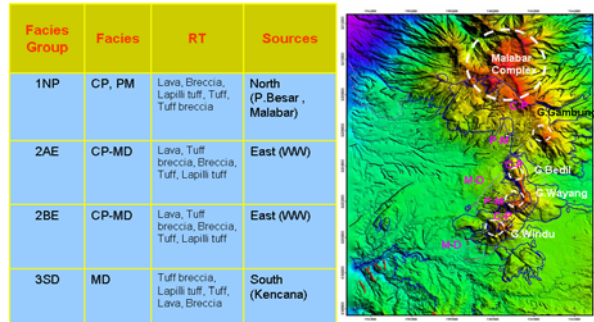


Figure 3. Facies, rock types and eruption centers

### Subsurface Rocks Distribution

For reservoir modeling purposes, 5 geologic cross sections were constructed through the reservoir tied to wells with good rock data. Each cross section was selected to minimize projections and properly represent the field's complexity. Typical of many volcanic complexes, well to well correlations were difficult; consequently it was found that the interpretation was facilitated by grouping the rocks into "packets" of similar origin facies. To correlate subsurface rocks from wells, the facies model of a structurally undisturbed andesitic stratovolcano was used (Bogie and McKenzie, 1998) (Figure 4). The model suggests that the occurrence of intrusive rocks and thick lava flows are associated with central and proximal facies compared to thick pyroclastics and lahars which are related to medial and distal facies.

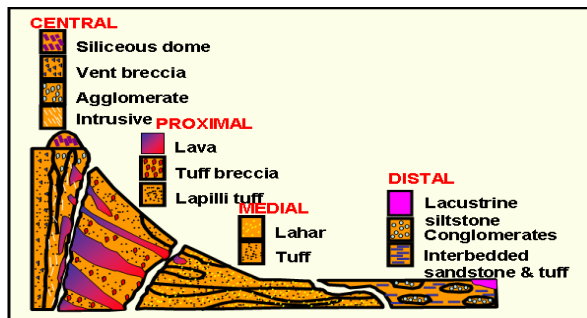


Figure 4. Facies model used to assist subsurface geologic mapping.

The rock units encountered in the Wayang Windu field were classified into 4 facies, namely, Central – Proximal facies consisting of Lava and Breccias, Proximal – Medial facies consisting of Breccias and Tuff Breccias, and Medial – Distal facies consisting of Lapilli and Tuffs. In the shallow reservoir section, wells in the northern part of the field intersected thick lava flows. In the middle section, wells in the central and southern parts of the field are dominated by thicker lava flows and breccias (Proximal–Medial). The deeper reservoir sections all wells penetrated thick pyroclastics (Medial-Distal). In general, only a few wells have indications of intrusive rocks at TD.

These observations postulated the occurrence of several eruptive events; the lower parts of the wells reflecting a medial-distal facies sourced from the south (Kencana), in the middle and shallow sections of the wells in the central and southern parts of the field reflecting a facies group derived from the east (Wayang Windu) and the shallow section in the northern part of the field reflecting an eruption source in the north (Malabar), (Figure 5).

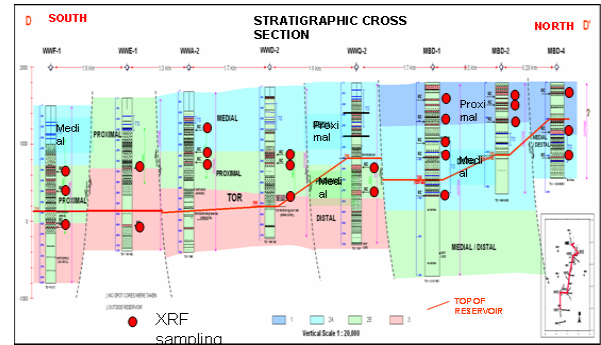


Figure 5. North-South stratigraphic cross section showing correlation of facies groups.

### Validation of Geologic Model

Key samples were collected and X-Ray Fluorescence (XRF) analysis conducted to validate the geologic model. XRF analysis is frequently used by igneous petrologists (SGS-Canada) to identify rock types and show trends in the evolution of magmatic sources (eruption centers). Thirty-nine lava samples from the field were collected for XRF analysis to confirm the facies correlation within the field (Figures 5 & 6).

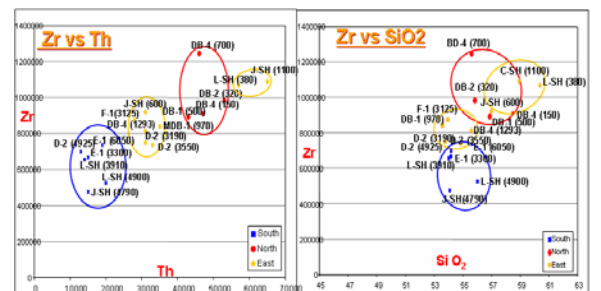


Figure 6. Rock Chemistry Analysis (XRF), the Zr vs Th and Zr vs SiO<sub>2</sub> cross plots show sample groups derived from North, East and South sources.

The samples are all derived from a tholeiitic to calc-alkaline magma series where a parental tholeiitic (primitive mantle derived) magma erupts with varying amounts of silicic andesites, which could be derived from a local magma chamber. This interpretation verifies the facies correlation made between the wells.

### **Reservoir Geology Model (3D)**

The objective of constructing the detailed geological model is to create a 3D distribution of rock types and petrophysical properties (porosity and permeability).

Interpreting rock types and their distribution within a volcanic setting is complex due to heterogeneity and discontinuity of the rocks. In these models, the stochastic approach, i.e., geostatistical methodology was used within a 26 million grid cell model built using PETREL software. Using this approach, multiple models can be generated to quantify various uncertainties that may exist. Additionally, the approach also honors well data as well as the spatial relationships between these data.

The technique used to complete the model includes Facies Transition Simulation, Sequential Indicator Simulation (SIS) and Sequential Gaussian Simulation (SGS). Facies Transition Simulation was used to distribute Facies (Central-Proximal, Proximal-Medial, and Medial-Distal). Subsequently, rock types (Lava, Breccia, Tuff Breccia, Lapilli and Tuffs) within each facies setting are simulated using SIS. Finally, porosity is simulated using SGS constrained to the rock type within each facies. Using this method the result of porosity distribution is consistent with its geologic framework. Additionally, the method also provides a way to quantify the uncertainty of the porosity distribution through multiple realization models. With this information, better decisions can be taken with respect to the future development of the field.

The overall strategy used to evaluate the uncertainty in the volumetric calculation is as follows: First, a base case was generated using “most likely” descriptions for all parameters. Subsequently, using the Experimental Design technique, different combination of parameters (low and high scenarios) were used to generate multiple models, producing the probabilistic estimates of the results and the ranges of the pore volume. Finally, representative models which represent Downside, Upside and Most Likely Pore Volumes were then used as inputs to the dynamic reservoir simulation.

### ***Model Overview***

The reservoir characterization for Wayang Windu has several hierarchies of data integrated within geologically consistent 3D frameworks. The hierarchies fall into 2 basic groups:

- 1) Overall ‘container’ volume for the reservoir (geometry of the reservoir; Top of Reservoir surface + Base of Reservoir, structural configuration).
- 2) Rock types and Petrophysical properties (facies, rock type and porosity distribution).

The data in each of these hierarchies has significant uncertainties which can impact the metrics for the proposed Wayang Windu expansion (e.g. Pore Volume, production profile). In this study a key objective was to estimate the uncertainties in the input data and to incorporate these uncertainties into probabilistic estimates of the reservoir performance. This was accomplished by generating a suite of 3D models which effectively sampled the range of possible characterizations constrained by the framework of the geologic model, the input data and the associated uncertainties.

As described below, all of the 3D models had common extents (areal, vertical and cell sizes) and used the same representation of the major fault plane geometries. These elements were held invariant throughout the modeling. In contrast, the facies and rock type proportions and the petrophysical properties distribution input to the 3D models were systematically varied over ranges estimated from the uncertainties in the original source data. This methodology allowed probabilistic estimates of the key reservoir metrics to be estimated and appropriate models to be passed through to the dynamic simulation process for the probabilistic performance prediction.

### ***S-Grid Geometry***

The reservoir model grid in Petrel was designed to extend beyond the proven area of the field and to include the potential Northern and Western field extensions within the Wayang Windu concession. A uniform 50m cell size was used to allow 3 or more cells between wells, resulting in a 219 x 291 cell areal mesh. The Petrel grid layers were distributed within each sequence such that the surface to the base of the model at -4000m elevation was represented by 412 layers. Placing the base of the model grid at the minimum postulated depth (based on MEQ interpretation) enabled the sensitivity of predicted field performance to the base of reservoir depth to be evaluated by applying progressively shallower base depths during the subsequent dynamic simulation.

All models used the same conceptual stratiform volcano geometry for gross layering of the reservoir. At Wayang Windu this subdivides the sequence into 4 sequences, the deeper sequence referred to as the **3SD** facies group, overlain by the **2AE** and **2BE** facies groups (Proximal - Distal facies) and the upper section developed in the northern side of the field was called **1NP** facies group. The reservoir is almost entirely within the facies group of 3SD and 2BE sequence.

### **Base Case Model**

The Base Case model represented a plausible scenario generated by using best-guess/most-likely inputs at each hierarchy, with the notable exception of the porosity histograms. The porosity histograms in the Base Case model were based only on the small dataset of core porosities available in the study and, as a consequence of their distribution, are believed to represent low side (conservative) estimates of the actual porosities in the reservoir. It is important to note that the probability of the Base Case model and of the other models generated during the study were not assumed (P50, P10, P90) as is often the case, however this was evaluated and is provided as part of the conclusions of the study.

### ***Facies and Rock Type (lithotype) Modeling***

For the Base Case model the facies picks in the wells were matched to the interpreted facies boundaries supplied as a set of digitized well-tie cross sections. These data were used as the basis for generating a set of consistent spatial distributions in 3D. Typically some of the 5 rock types are present within a given facies region. To simplify the model process, the rock type proportions were combined for each facies group and then populated geostatistically using SIS, where the distribution is constrained to the proportion and its spatial relationship (distance of volcanic center as source of rocks in the model), (Figure 4).

In the Base Case reservoir model approximately 78% of the reservoir pore volume is within Facies group 3SD, 15% within Facies group 2BE and 7% within Facies group 2AE.

### ***Petrophysical (Porosity) modeling***

Porosity data available for the study were derived from core data. Porosity is a key component of reservoir Pore Volume and hence of the resource base for the field. Although high temperature geothermal fluids have resulted in the alteration of portions of the reservoir, the porosity used for the model was not constrained to the altered and fresh rocks. Since the porosity defines the volumes of moveable geothermal fluids in the reservoir, measurements of the effective porosity of the reservoir rock is also required. Fine-tuning of the model will be conducted after effective porosity data is acquired during the next field development phase. The 3D distributions of porosity were simulated geostatistically using the SGS technique, constraining them to the rock type distribution according to the histogram of porosity of the rock types (Figure 7).

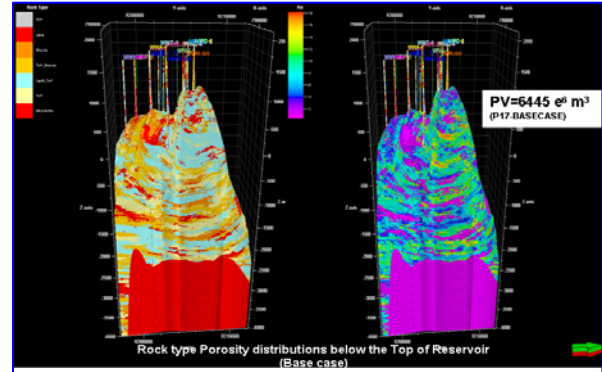


Figure 7, 3D porosity distribution (right) shows consistency with the corresponding rock type distribution (left).

### ***Fault Planes***

The model's grid was oriented to have a primary axis oriented along the major fault trends at Wayang Windu (Figure 8) with the aim of simplifying fault geometries in the dynamic model. The faults were interpreted after integrating air photos, surface mapping data and stratigraphic / facies correlations. The 6 major faults modeled in 3D were constrained by surface traces, well penetrations, and facies correlations. The positions of fault planes were not varied between models.

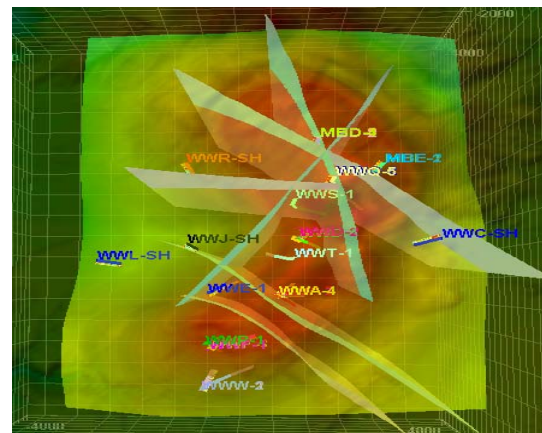


Figure 8. Fault planes used in the models.

### **Uncertainty Assessment**

The Base Case model was intended to provide the most likely scenario based on the current facies interpretation, core data and well production data. However, this was not known to represent the P50 or expected case. For assessment of the range of possible outcomes for the Phase II expansion project, several scenarios were generated to capture the impact of the key PV uncertainties in the model building.

Key uncertainties in the static model were pore volume, whose variations can greatly impact the total resource base for the project, and the connectivity of the reservoir, which will alter drainage areas and well performance predictions for the project. This second area of uncertainty was not investigated in the current study. In combination these impacts strongly influence plateau length for the field.

In the hierarchical approach to this study, the uncertainties were categorized at some basic levels:

### Rock Volume Uncertainty

The gross rock volume uncertainty represents the uncertainty in the overall ‘container’ volume (geometry of the reservoir; structural configuration + base of reservoir elevation + top of reservoir surface). The internal geometry of the model layering is constrained by the Top of 1NP facies group. As defined by well penetrations, the major part of the reservoir is within the 3SD facies group, so the variations in geometry which impact the pore volume are primarily a consequence of uncertainty in Base of Reservoir, rock type porosity, rock type proportion within facies groups and the Top of Reservoir (ToR).

The Base Case for the reservoir was generated at -1000 masl where MEQ events predominately occurred. The downside for the model is constrained by the deepest drilled well at -700 masl. The upside is defined by the deepest MEQ events at -4000 masl (Figure 2).

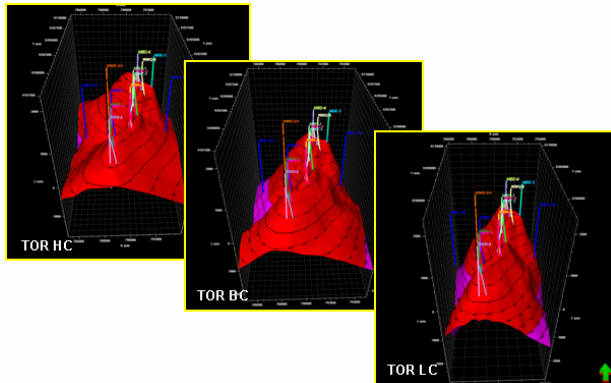


Figure 9. High case, base case and low case TOR surfaces used for modeling.

The Base Case ToR surface incorporates the well picks (PT data), the hand contoured ToR maps, isotherm map at sea level and the MT contour data (Figure 9). In the uncertainty assessment the well picks for Top of Reservoir (measured from PT data) remained fixed while the MT contours were discarded. The optimistic (high case) ToR surface was generated in Petrel based on the well picks and applying flattened, hand contoured trends on the flanks of the field. A pessimistic (low case) ToR

surface also used the well picks as control nodes, but used a steeper, hand contoured ToR map to constrain the flanks.

### Facies Group and Rock Proportion Uncertainties

As described above, the main facies group components of the Base Case model in terms of Pore Volume are facies groups 3SD (78%), 2BE (15%) and 2AE (7%) respectively. Uncertainty in the proportion of these key facies groups within the reservoir was captured from alternative interpretation of the well-tied cross sections which provided optimistic and pessimistic versions for the spatial distribution of Proximal to Distal facies boundaries. These distributions were used to redefine the extent of facies group 3SD and the complementary facies groups of 2AE and 2BE.

Within each facies, an assemblage of rock proportions comprised a rock types, and the facies were characterized by the proportion of rock types. The basecase model used rock types proportion for each facies which were identical to those observed in the wells and honored the statistical nature of rock type distribution (Figure 10). However, the actual rock type proportion within each facies is uncertain since the observed data is biased as a consequence of the restricted location of the wells. In this study uncertainty was capture by alternative proportions into the analysis including the variogram. In terms of Pore Volume, optimistic cases have higher proportions of the pyroclastics (tuff breccias, lapilli tuffs, and tuffs) where is higher porosities rock type and whereas pessimistic cases have greater proportion of lavas and breccias (lower porosities rock type).

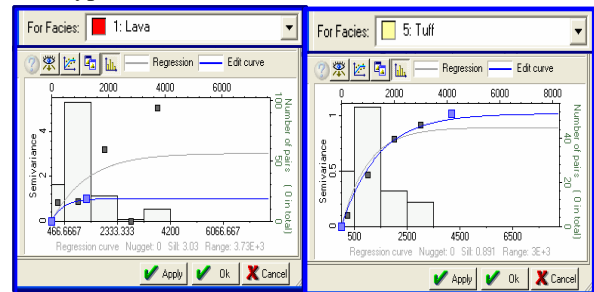


Figure 10. Rocks Type distribution was simulated by honoring variogram, lavas have a lower range than tuffs.

### Petrophysical Property (Porosity) Uncertainties

The porosity distributions in the Base Case model were based on sparse (core sample) data and therefore they have significant uncertainties associated with them. In terms of analyzing the pore volume, porosity distribution within the reservoir was constrained to rock type proportion in each facies by honoring the statistical nature of the parameter using SGS method. In the model, there is no differentiation

between altered and fresh porosity. Uncertainty in the porosity value was captured from the alternative value of the rocks and the statistical nature of the parameter. To capture the porosity uncertainties in the models the characterizations used the core-only histogram (Figure 11) for the Base Case, the broader histograms (with the higher mean porosities) for the high porosity cases and the lower histograms (with the lower mean porosities) for the pessimistic porosity cases.

The matrix permeability and saturations will be evaluated as part of the history matching in the reservoir simulation phase of the study.

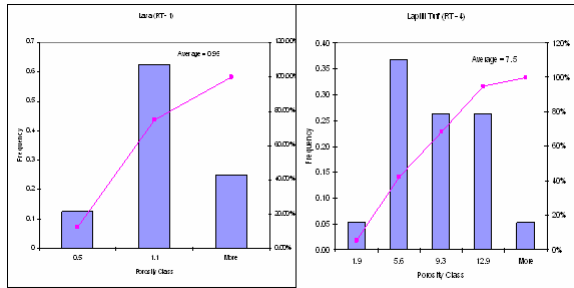


Figure 11. Porosity histograms of lavas and lapilli tuffs have unique distributions used in the model.

**Assessing the impact of uncertainties**

As describe above, there are several potentially significant uncertainties which impact the model’s pore volume. Traditionally, to assess the uncertainty, a Monte Carlo simulation was run, sampling the independent parameters based on statistical distributions, ignoring the geologic model as describe above. In order to properly quantify the distribution of the pore volume based on 3-D geological modeling and the interaction effect of the properties inside the model, an experimental design technique is applied.

**Experimental Design process**

Experimental design (ED) is an approach technique to investigate the effect of the various variables simultaneously in a series of experimental runs (in this case a multiple realization of the 3-D geological model). A specific combination of properties (input variables) at different levels (low, mid and high) that make up multiple realizations of the 3-D geologic model was set up in a predefined pattern to investigate the experimental pore volume response. The results were analyzed to obtain the relationship between the input variables (properties) and the output responses (pore volume). These relationships act as a proxy function for the pore volume in the 3-D geologic model. A pore volume probability curve was then generated using the Monte Carlo technique based on this proxy function.

The simplest ED methods are the 2-level designs which consider only High and Low values for each factor and ignoring the non-linear response. If this is inadequate, a 3-level design (full factorial design) using Low, Mid and High values for each factor may be necessary to capture the non-linear response.

To reduce the number of experiment runs, a fractional factorial design such as Plackett-Burman (P-B) is applied to investigate the effects of the main input variables. For the simple case of 7 factors (variables) and 2 levels (high/low only) the full factorial requires 128 scenarios, whereas P-B only needs 12 scenarios to be generated. For larger numbers of factors the differences rapidly increase.

For the Wayang Windu Base Case reservoir characterization, the key variables selected for inclusion were:

- 1) Facies geometry
- 2) Rock types proportions
- 3) Porosity Histogram/Variogram
- 4) Top of Reservoir surface
- 5) Base of Reservoir surface
- 6) Intrusion bodies
- 7) Seed number

See (Figure 12) for Plackett-Burman design matrix and Base Case runs.

**Experimental Design results and discussion**

The Experiment Table data determines the analytical response surface. The associated Pareto chart indicates that the most significant factors for Pore Volume are the geometry of the base of reservoir and the porosity histograms (Figure 13).

PLACKETT BURMAN DESIGN FOR PV CALCULATIONS								
Run#	Structure	RT	Porosity	Seed#	TOR	Base	Intrusion	PV (10 <sup>6</sup> m <sup>3</sup> )
1	High	Low	High	Low	Low	Low	High	4286
2	High	High	Low	High	Low	Low	Low	2763
3	Low	High	High	Low	High	Low	Low	7979
4	High	Low	High	High	Low	High	Low	20731
5	High	High	Low	High	High	Low	High	4788
6	High	High	High	Low	High	High	Low	28500
7	Low	High	High	High	Low	High	High	31982
8	Low	Low	High	High	High	Low	High	7671
9	Low	Low	Low	High	High	High	Low	16730
10	High	Low	Low	Low	High	High	High	24071
11	Low	High	Low	Low	Low	High	High	15379
12	Low	Low	Low	Low	Low	Low	Low	2695
Basecase	Base	Base	Base	Base	Base	Medium	Base	6445

Structure=Facies, RT=Rock type, Porosity=Porosity, TOR=Top of Reservoir, Base=Base of Reservoir, Seed#=Stochastic uncertainty, Intrusion=Precentage of Intrusive body, PV=Pore Volume

Figure 12. The Experimental Design table results versus Base Case model.

The final step in the Experimental Design method is to evaluate the analytical response surface over the range of possible input parameters using a Monte Carlo process. This provides a probabilistic summary of outcomes for the model (Figure 14).

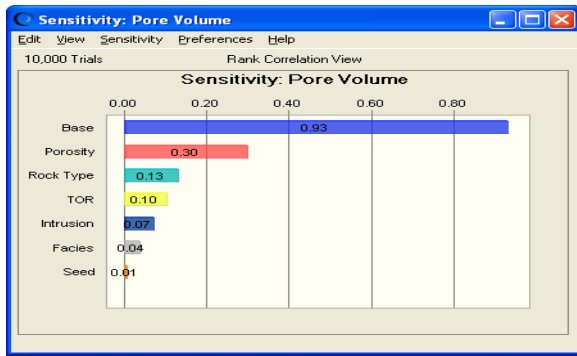


Figure 13. Pareto chart showing significance rank of the input variables to Pore Volume.

From Figure 14, the P10, P50 and P90 Pore Volume estimates based on this analysis are 5.7, 10.2 and 16.8 km<sup>3</sup> respectively.

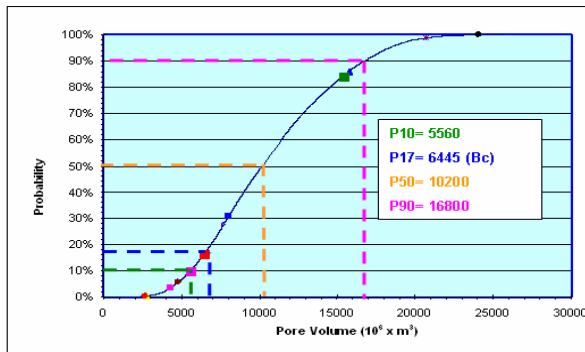


Figure 14 . Probabilistic Pore Volume Calculation via Monte Carlo process. Note that Base Case was sited at P17 (6445 10<sup>6</sup> m<sup>3</sup>) instead of P50 (10,200 10<sup>6</sup> m<sup>3</sup>).

Note that in the S-curve from the Monte Carlo analysis, the Base Case model lies below the P20 estimate.

## CONCLUSIONS

1. All XRF samples indicate Wayang Windu is related to a tholeiitic to calc-alkaline magma series derived from the same parental magma.
2. Age dating, tuff-soils and XRF data support well to well facies correlations.
3. The reservoir rocks consist of medial-distal facies, dominated by higher porosity pyroclastic rocks.
4. The primary factors controlling Pore Volume uncertainty in the model are base of reservoir and porosity histogram. Secondary factors are rock type proportion and top of reservoir.
5. The Base Case model was conservative as indicated by P17 on the S-curve.
6. The Base Case at P17 shows that the paradigm of Base Case at P50 is misleading

and possibly not capturing the upside potential.

7. In order to recognize the upside potential of geothermal fields, Multiple Realization / Experimental Design techniques should be employed as part of the standard workflow in the geothermal industry.

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