

Geologic Conceptual Model Update of the Darajat Geothermal Field, Indonesia

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ABSTRACT

Darajat is a volcanic geothermal reservoir located in West Java, Indonesia, that currently supplies steam to generate 260 MWe from 3 power plant units. Thorough reservoir characterization and modeling was conducted in 2001-2004 as part of the Darajat Unit III reserves assessment. Since that study, additional resource information was obtained from a Magneto Telluric / Time Domain Electro Magnetic (MT/TDEM) survey conducted in 2004, a micro-earthquake (MEQ) array that was established in 2005, and a make-up drilling campaign conducted in 2007-2008. The new information obtained from the geophysical surveys and drilling results has led to an improved understanding of the geology of the reservoir, including the distribution of low porosity reservoir rock, the permeability distribution, and reservoir boundaries. This new information, together with down-hole pressure, temperature, and production logs, has been integrated into an updated geologic conceptual model and incorporated into a 3D earth model through the application of geostatistical modeling tools. The 3D earth model provides the geologic input into the numerical simulation model which is being used to evaluate reservoir performance and to assess the capacity of the reservoir to support additional generation.

1. INTRODUCTION

The geologic evaluation of the Darajat field began in the 1970's. Resource assessment work was conducted by Pertamina with assistance from the New Zealand government. Three exploration wells were drilled by Pertamina in the late 1970's, leading to the discovery of the resource. Amoseas Indonesia, a subsidiary of Chevron, was awarded the project in 1984 and continued exploration and development drilling in 1986. During 1987-1988, Amoseas drilled four wells to confirm reserves for the initial development. The 55 MWe Darajat Unit I, owned and operated by PLN, began operations in late 1994 after Amoseas drilled 6 additional development wells.

To support the installation of a second power plant, geophysical and geochemical surveys were conducted in 1996-1998 together with the drilling of twelve development wells and six slim-hole step-out exploration wells. Unit II, which is owned and operated by Chevron, started commercial operations in May 2000 and currently produces approximately 95 MWe.

Following the success of the 1996-1998 drilling campaign, detailed reservoir characterization and 3D geological modeling was conducted in 2001-2004 to support the reserves assessment for the Darajat Unit III expansion project. The reservoir geology was characterized with a volcanic facies model, which served as the basis for a 3D geologic model (Harrison, 2004). The 3D geologic model

was incorporated into a numerical simulation model in order to forecast reservoir performance. The numerical simulation demonstrated that the reservoir could support additional generation. Unit III, a 110 MW plant owned and operated by Chevron, was commissioned in July 2007, bringing the total installed capacity of the field to 260 MWe. Following the start-up of Unit III, 7 make-up wells were drilled in 2007-2008 raising the total number of wells drilled at Darajat to 37. The geologic model has been updated with new information and interpretations derived from the latest drilling campaign, the most recent geo-scientific studies and field performance data.

2. GEOLOGIC SETTING

The Darajat field is situated along the eastern side of a range of volcanic centers nearly 30 km in length which includes the active volcanoes Gunung Papandayan (last erupted in November 2002) and Gunung Guntur (last erupted in 1840). Darajat is at an elevation of 1750–2000 meters above sea level, and lies about 9 kilometers southwest of the producing Kamojang geothermal field and 10 km east of Wayang Windu geothermal field (Figure 1).

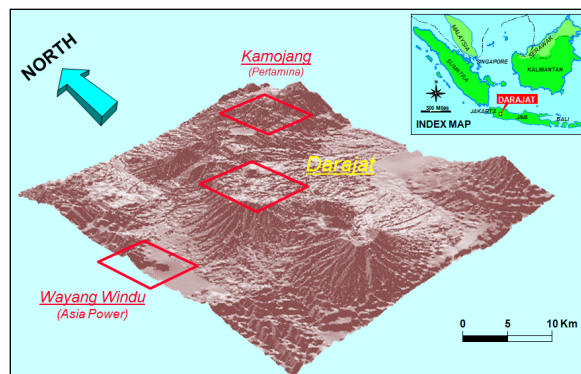


Figure 1: Physiographic map of Darajat and the surrounding area.

Darajat is spatially associated with an eroded andesitic stratovolcano, Gunung Kendang. The volcanics found in the reservoir section are predominantly of intermediate to mafic composition, but younger formations found in the central part of the area consist of hornblende andesite lava, rhyolite obsidian, and related ash tuffs.

Major geologic structures, which are identified as lineaments on remote sensing images and aerial photography, include the Kendang, Gagak, Cibeureum, Cipanday and Ciakut faults. Other geologic structures are mainly inferred from the alignment of MEQ events and entry distributions. Structures trend predominantly in NE-SW and NW-SE directions (Figure 2).

3. PREVIOUS WORK

The geologic model was constructed by combining lithology information from surface data and wells together with interpretations of resistivity and gravity data. The geologic model was initially developed to support the Unit 2 assessment. The model has since been updated by integrating new information obtained from the 2007-2008 drilling campaign, 2004 MT data, microearthquake, geochemistry and reservoir performance data. This integrated study was used as the basis in developing an updated 3D geologic model, including refinements of the reservoir stratigraphy, petrophysical properties and reservoir boundary.

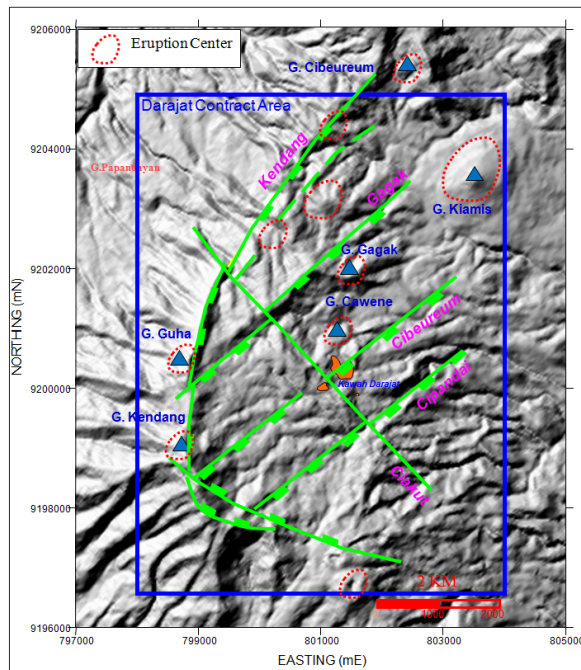


Figure 2: Geologic structures identified from satellite images and the alignment of MEQ events.

Surface and subsurface volcanic facies studies indicate that Darajat is part of an older andesitic stratovolcano that has collapsed to the east and become overlain by volcanic materials deposited from younger eruptions. Lithologic facies have been classified according to the volcanic facies model presented by Bogie and McKenzie (1998). The distribution of rock types suggests that Darajat is underlain by overlapping volcanic products that originate from several volcanic sources. Thirteen different volcanic units have been identified based on similar lithotype compositions. In the lower reservoir sections, thick lavas and intrusions from tholeiitic to calc alkaline magmas dominate the center of the field. This represents the central facies of a basaltic-andesitic stratovolcano. Thick pyroclastics dominate the reservoir margins, representing the proximal-medial facies. The Darajat reservoir is mainly composed of these two major sequences (Figure 3). These sequences are overlain by interbedded pyroclastics and andesitic lavas, with thicker lava flows in the west compared to the center and east. This sequence may come from different volcanic sources (Event II) (Figure 3).

4. GEOLOGIC MODEL UPDATE

4.1 Facies and Lithology Distribution

The predominant lithology within the reservoir is identified as Facies A, which represents a thick complex consisting of

lava and intrusive rocks. Facies A is overlain by predominantly pyroclastic rocks with subordinate lavas. The distributions of permeability and porosity are strongly controlled by lithology, and thus mapping of the distribution of the lava/intrusive complex is an important aspect of the geologic model. The seven new wells drilled in 2007-2008 provide important lithologic information in the southwestern and northwestern portions of the field concerning the extent of the lava/intrusive complex. As shown in Figure 4, a broader distribution of rocks belonging to Facies A became apparent through the completion of more wells on the DRJ 14 and 20 locations.

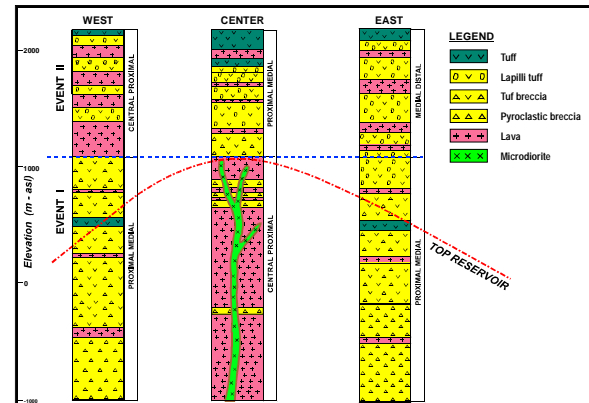


Figure 3: Subsurface lithologies within the Darajat reservoir.

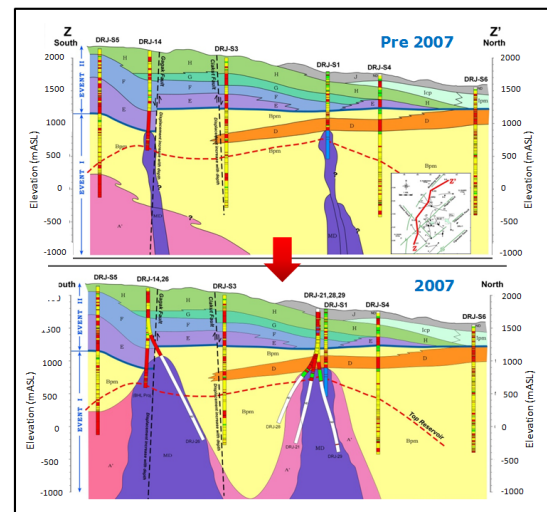


Figure 4: Cross section showing the revised distribution of the lava/intrusive complex as result of lithology information obtained from the recent drilling campaign.

To better define the dimensions of Facies A, the new well data is integrated with a new gravity interpretation. Gravity data shows a gravity high which trends N-NE through the Darajat Field area. The producing field is located along the apex of this gravity high. A simple 3-D model showed that the gravity high can be explained with a higher density body at depths consistent with where the top of the andesite/intrusive complex has been encountered during drilling. Figure 5 shows the gravity model and best fit to the observed data match for Profile 14, a west-east profile through the center of the production area. This match is taken as the most likely location of the andesite/intrusive complex. Estimates for the pessimistic case (P10) and optimistic case (P90) distributions were determined by

adjusting the lateral boundaries of the complex until a mismatch of about 1 to 2 mgals was observed. This mismatch is consistent with the data quality uncertainty for exploration gravity in this terrain. The top of this unit is well constrained over the proven area of the field. It has been drilled into by several wells allowing for contouring the topography of the top of the unit. Density measurements and logs confirm the complex to be high density. Most of the production well's entries are found near the top and within this complex.

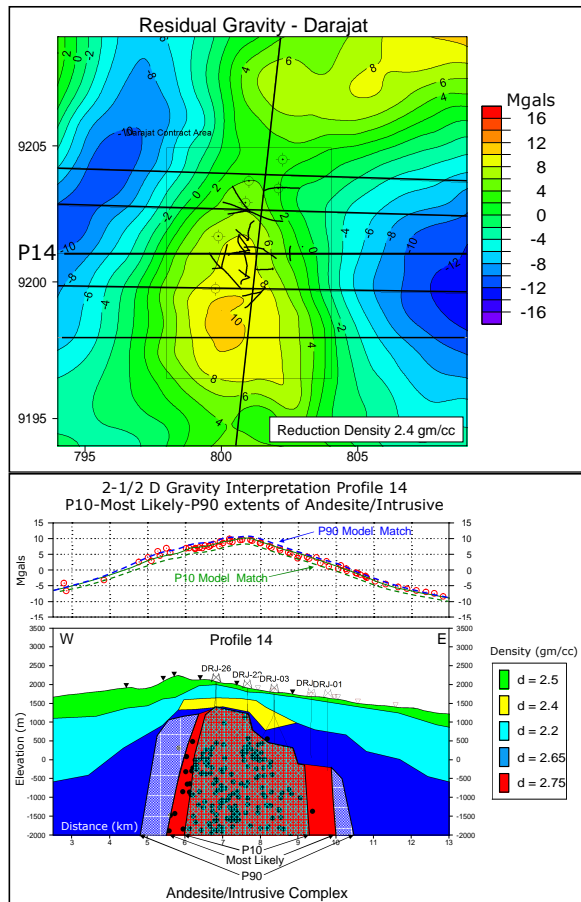


Figure 5: Residual gravity over the Darajat Contract Area and E-W cross section showing the interpretations of andesite/intrusive complex from 3D gravity modeling. The black dots are the location of MEQ hypocenters.

4.2 Reservoir Boundary

4.2.1 Reservoir Top

The reservoir top is primarily determined from two sets of data, the downhole temperature data and the distribution of the clay cap rock as interpreted from the resistivity data and subsurface alteration. At other geothermal fields, the first occurrence of epidote is frequently used to mark the reservoir top. However, at Darajat epidote is an unreliable indicator because the shallowest occurrences of epidote are usually out of equilibrium with the current thermal regime. The primary criteria for choosing the most likely reservoir top is the transition from a conductive temperature regime, which is a characteristic of the clay cap rock, into a convective, nearly isothermal temperature regime that is associated with the permeable reservoir rocks. Typically, the transition between the conductive and convective regimes occurs between 220-240°C.

The reservoir distribution is well defined in the drilled area. The reservoir's lateral extension and geometry of reservoir's top away from drilled area were determined from the clay cap distribution that was defined from detailed mapping of the top and bottom of a low resistivity layer. The low resistivity layer is usually shallower and more intense around the surface thermal manifestations, such as hot springs and fumaroles due to the increased smectite-rich clay alteration associated with upward leakage from the geothermal system along faults and fractures. Smectite clays are stable to temperatures of about 160°C. At higher temperatures the alteration transitions to mixed layer illite-smectite and then to propylitic which are assemblages characterized by higher resistivity alteration (Ussher et al., 2000). The low resistivity layer also tends to thin and its base elevation becomes shallower directly over the shallowest portion of the geothermal reservoir.

To verify the correlation of the low resistivity layer with the clay cap, methylene blue analyses were carried out on cuttings from 16 wells. Methylene blue analysis provides a measurement of the relative percentages of smectite clay (Gunderson et al., 2000). The methylene blue analysis confirmed a very good correlation of low resistivity with increased smectite (Fitriyanto, 2006). This correlation provides confidence that the distribution of the low resistivity layer can be used to map the geothermal system's clay cap and provide estimates of the likely margins of the system. Figure 6 shows the distribution of low resistivity layer and interpretation of the most likely and optimistic reservoir margins based on resistivity, the initial temperatures and methylene blue analyses.

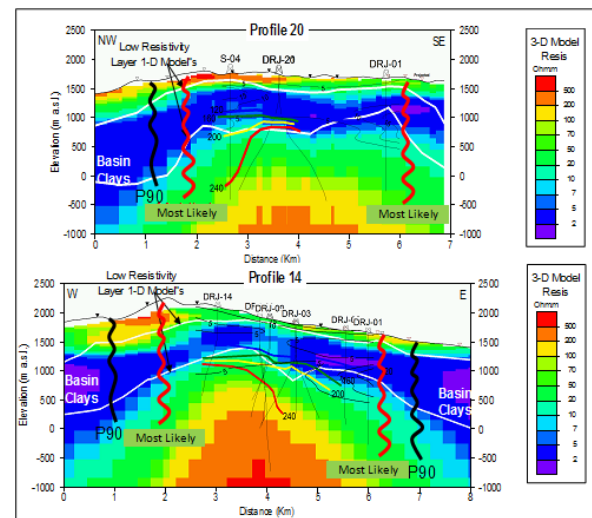


Figure 6: Cross sections showing the distribution of the low resistivity layer (light blue) and comparisons with methylene blue and initial state temperature.

Beneath the low resistivity clay cap the resistivity structure is characterized by a high resistivity body centered beneath the production area. The high resistivity body is centered beneath the proven reservoir and correlates with the location of lava/intrusive complex detected with the gravity data and confirmed with drilling. Higher resistivities beneath the clay cap are a characteristic of geothermal reservoirs dominated with high temperature propylitic clays. At Darajat this is further emphasized by the correlation of the intrusive rocks that are typically lower in porosities. Other areas where high resistivity intrusives have been drilled into include Glass Mountain, Northern California (Cumming, 2007), the

Sibualbuali prospect in Sarulla, North Sumatra, and recently in the Cianten Caldera, west of Awibengkok, West Java.

The reservoir is shallowest in the southern portion of the field near the fumarole areas and gradually dips to the north. The extent of the reservoir is fairly well defined by well data along the northern, southern, and eastern margins. The western margin has poor well control and is less certain.

In the most likely model, the Kendang fault is interpreted to be a structural boundary to the geothermal reservoir. This interpretation is supported by the declining reservoir top observed in well S3 and the high temperatures measured near the base of S3 and S4, which are suggestive of a hot, tight margin. However, the reservoir conditions encountered in S3 could be a local feature affected by down-flow of cooler fluids along the Ciakut fault. The resistivity anomaly and the MEQ data suggest possible extensions of the resource west and northwest of the Kendang fault (Figure 7). However, the actual extent of the reservoir west of the Kendang fault still needs to be tested through drilling.

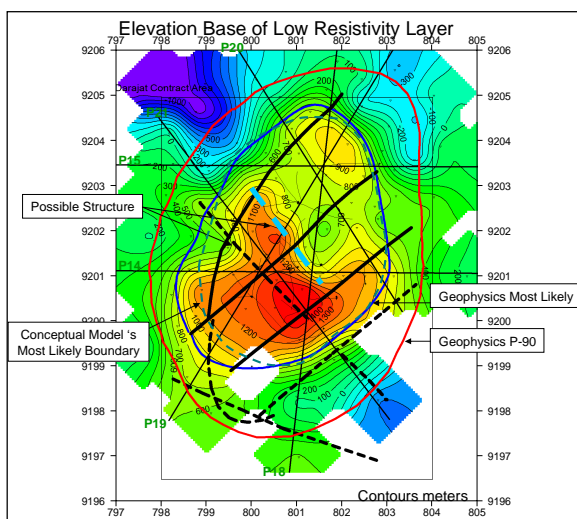


Figure 7: Alternative reservoir margins based on the resistivity anomaly.

4.2.2 Reservoir Bottom

One of main uncertainty in Darajat is the reservoir bottom. No wells drilled to date have encountered the reservoir bottom; therefore the reservoir bottom has to be inferred. Reservoir conditions extend to the depths of the deepest wells, DRJ 19 and 24, which are completed at -908 and -730 meter above sea level, respectively.

The micro-earthquake (MEQ) data provide the only means available to make this interpretation. At The Geysers it is interpreted that the depths of MEQ clusters can be used to map the extent to which injected water is moving deep in the system (Stark, 1991 and 2003), which represent the base of the connected fracture system that contributes to pressure support for the geothermal system.

In Darajat, the MEQ data were recorded during the 1997 and 2003 monitoring surveys as well as continuous monitoring since 2005. A large number of MEQ events have been triggered by the drilling of make-up wells in 2007-2008. The MEQ's are probably caused by thermal stresses resulting from the loss of cool fluids while drilling blind. If so, then the MEQ's are registering some degree of interconnected permeability within the productive reservoir, and thus are providing some indication of potential reservoir conditions.

With the additional MEQ data and coverage obtained by the permanent array, a well constrained map of the base of MEQ activity can be developed. The base of the induced seismicity has remained consistent with time. This observation allows for an interpretation of the most-likely and optimistic case (P90) elevations for the reservoir base. The most-likely boundary is defined by the bottom of the highest density MEQ activity (Figure 8). There is a high degree of certainty that this zone contains fractures that are connected to the productive reservoir. The P90 boundary marks the zone containing significantly fewer earthquakes. These MEQ events are not as clearly related or linked to the reservoir. The distribution of MEQ's indicates a bowl shaped reservoir bottom (Figure 8). This is also suggested by the possible conductive temperature regimes found deep in wells DRJ 5, S3, and S4. The deepest extent of the MEQ's is in the vicinity of the Gagak fault near the DRJ 9 location, supporting the interpretation that this region provides basal recharge to the system through an extension of the fracture system that extends beneath the reservoir.

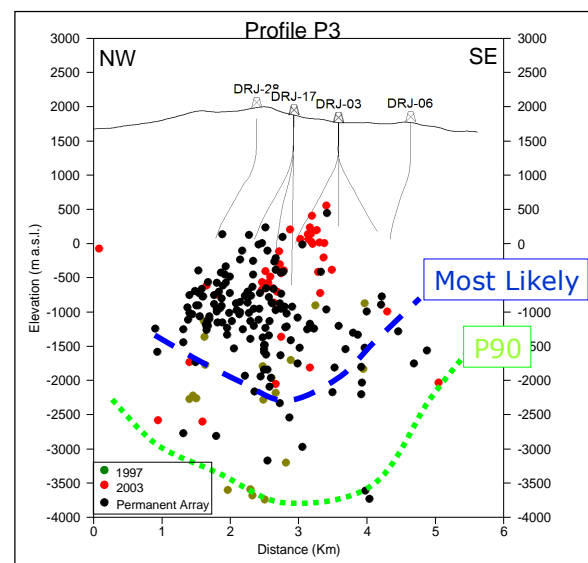


Figure 8: Cross section showing the interpreted reservoir bottom based on MEQ data.

4.3 Permeability

A concerted effort was made to characterize permeability by analyzing and integrating various datasets from all of the wells. Permeability characterization began with fracture interpretations based mainly on fracture data obtained from image logs (FMS and XRMI) and cores. This information was integrated with other key data sets such as drilling information (loss zones, drilling breaks), measured down-hole temperatures and pressures, downhole spinner surveys, and caliper spikes in order to determine which fractures can be classified as "effective". To correlate fractures with permeability, the fracture data were analyzed against the permeability interpretations based on well production rates and entry distributions. Geochemical data and tracer data were used to interpret the fluid flow directions, whereas microearthquake data were used to support the interpretation of geologic structure and base of the permeable zone.

Several regions with different permeability characteristics have been incorporated into the conceptual model. These include a large region of commercial permeability, which is defined by the distribution of productive wells and shallow high temperatures. Generally, the higher permeability region

coincides with where the 230°C isotherm has ascended to relatively shallow depths.

A low permeability envelope along the reservoir margins is a fairly well-recognized feature of geothermal systems, and has been identified at both The Geysers and Salak (Rohrs, et. al., 2005). At Darajat, the low permeability margin is fairly well defined by drilling results along the southern, eastern and northeastern margins of the field. The base of the reservoir is also interpreted to be a low permeability margin. However, the transition between the commercial resource and the low permeability margin is not well-defined. Drilling results at Darajat do show fewer entries with less permeability below sea level, indicating declining permeability with depth. This is consistent with the results of analog studies of Salak and The Geysers.

The analysis of permeability and productivity distribution reveals some patterns of permeability distribution in Darajat. The permeability tends to decrease with depth, with a higher proportion of high permeability entries lying between 200-800 meter above sea level (Figure 9).

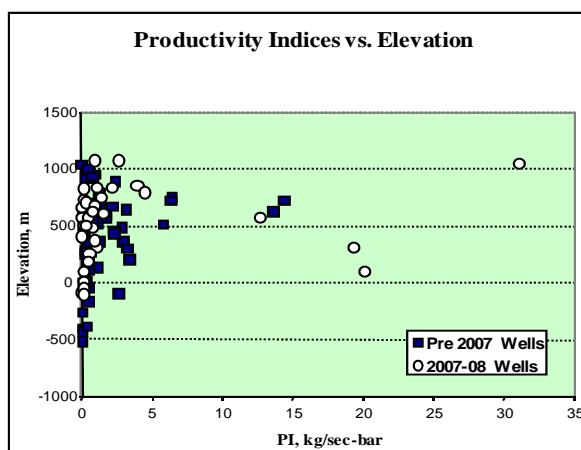


Figure 9: Feed zone productivity as a function of entry elevation.

The productivity and permeability are also higher in the lava/intrusive complex compared to the pyroclastic rocks. The production well data show that most of Darajat's production comes from feed zones encountered in the lava/intrusive complex (Figure 10).

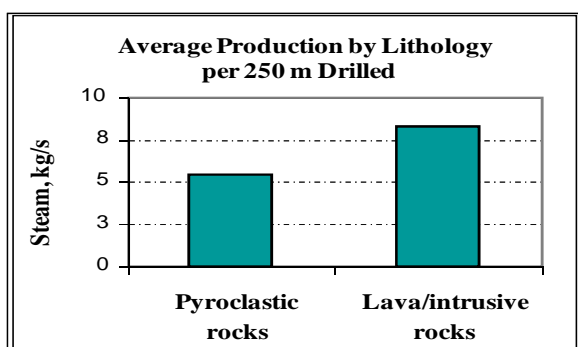


Figure 10: Average production by lithology per 250m drilled.

The area of commercial permeability has a close spatial correspondence to the distribution of the andesite complex as interpreted from the lithologies encountered by the wells and from the modeling of the gravity anomaly. The association of higher permeability conditions with the

intrusive complex is not completely understood. Most likely, because the andesite complex is generally composed of low porosity lavas and crystalline microdiorite, this unit has a high rock strength that allows it to be more brittle and readily maintains open fractures. Additionally, areas of enhanced permeability may have developed along the margins of the dikes, sills, and small stocks during their emplacement.

The relationship between permeability and geologic structure is not always clear. Three distinctive fault zones have been identified based on drilling results. The Gagak fault represents a zone of enhanced reservoir permeability that has served as an important drilling target for many of the production wells. Another permeability sweet spot is the area east of the Kendang fault, which appears to be associated with a lineament defined by MEQ events. Many of the best wells in the field have been targeted into this feature. Now known as the "S-fault", the existence of this high permeability zone is shown by the alignment of feed zones intersected by wells DRJ21, 28, 29 and 30RD. The lower productivity region just east of the Cibereum fault is the third distinctive feature. The wells drilled in this portion of the field have encountered lower initial reservoir pressures, and they produce steam with higher NCG concentrations. Based upon the pressure and chemical data, this region is in the outflow path of the system. The Cibereum fault is likely to represent a partial permeability barrier that separates this region from the higher temperature, more permeable region to the west. The role of the NW-SE trending Ciakut fault is also not well understood. The drilling results are ambiguous as to whether this fault provides enhanced permeability to the system. However, there are indications in the well data from DRJ S3 and DRJ 5 that this fault could be a potential avenue for marginal recharge into the system. Figure 11 shows the integration of all data into the geologic conceptual model.

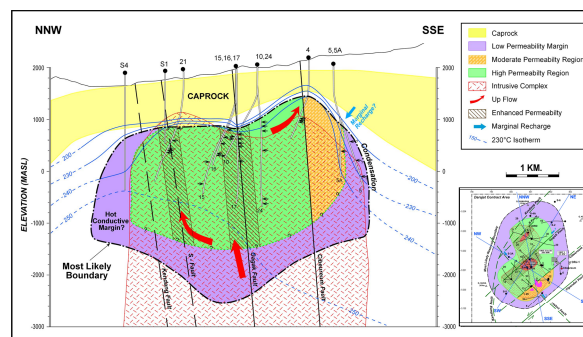


Figure 11: Cross section showing the updated geologic conceptual model.

5. SUMMARY

The geophysics data indicates that the field has a 'bowl-shape' reservoir bottom extending to approximately -3500 meter above sea level. The reservoir rocks are dominantly andesite lavas and intrusives, which are overlain by pyroclastics and thin lavas. This lava/intrusive proved to be very important feature in the field, especially its relationship to permeability and hence well deliverability.

Fracture permeabilities are influenced by reservoir lithology, elevation and fault block region. The most permeable zone is located within the lava/intrusive complex at an elevation of 200-800 meter above sea level in the northwestern portion of the field. Understanding of the fracture and permeability pattern has been improved through the integration of reservoir and geologic data within the framework of a 3D model. Challenges still remain to find the best approach for

integrating fracture data with permeability measurements from the wells.

The new drilling results, along with new geophysics interpretation allow us to better understand the geology of the Darajat field. Combining high quality data with analog studies of geothermal fields has played an important role in developing a representative geologic model. This geologic model has been portrayed in 3D by applying geostatistical modeling tools, which provided better representation of reservoir properties in the geologic model and should improve the predictions of reservoir performance through numerical simulation in the dynamic model.

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