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EVALUATION OF THE HOTTEST IDENTIFIED AREA IN THE SALAK GEOTHERMAL FIELD

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ABSTRACT

Downhole Pressure-Temperature-Spinner (PTS) surveys from Awi 9-7 and Awi 9-8, recently drilled in the southwestern part of the Salak (Awibengkok) geothermal field, show some of the deepest, hottest fluid entries in the field. Flowing temperature measurements as high as 600˚F were measured in Awi 9-7 while static temperatures up to ~585˚F were found in Awi 9-8. These high temperatures were measured even though spent brine has been injected into other wells on the same well pad for the past 19 years, causing considerable cooling of producers in the vicinity.

Geologic interpretation of logs and cuttings shows that the hot entries in these wells occur within the Lower Andesite and Mixed Volcanic and Sedimentary (MVS) rocks at similar elevation. Image logs show that small-scale fractures are well developed within andesite lavas and andesite lithic tuffs in Awi 9-8 with a dominant strike orientation of NW-SE and NNW-SSE. XRD results from Awi 9-7 indicate a predominant alteration assemblage of neutral pH minerals illite, mica, chlorite, and calcite, and the high temperature mineral diopside. This data confirm the interpretation that the deep Salak up-flow is located near the southwestern edge of the field, and thick lower temperature outflow flows across the field to the east.

INTRODUCTION

The Awibengkok geothermal field is located 60 km south of Jakarta on the island of Java, Indonesia (Figure 1). The reservoir is the largest producer of geothermal power in Indonesia (Ibrahim et al., 2005). The Salak geothermal system was initially liquid-dominated but has developed a large steam cap since production began in 1994. The commercial reservoir is a moderate-to-high temperature (464-600˚F) fracture-controlled reservoir with benign chemistry and low-to-moderate non-condensable gas content. The geothermal system is hosted mainly by andesitic-to-rhyodacitic volcanic rocks, and floored by Miocene marine sedimentary rocks cut by igneous intrusions. A proven reservoir area of 18 km^2 and an installed capacity of 377MWe yield a power density of about 21 MWe/km^2 despite all injection being done infield. Salak has been developed and undergone periodic infill drilling and injection realignment to maintain its rated 377 MW production.

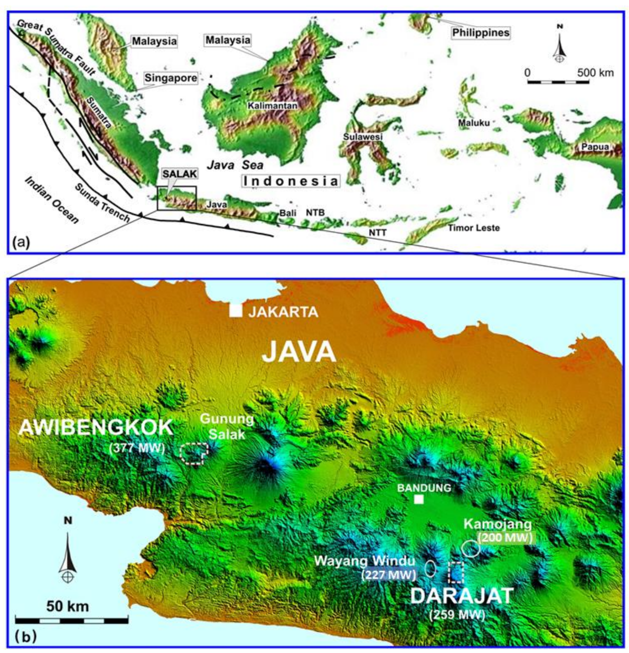

Figure 1: Maps showing the location of the Salak (Awibengkok) geothermal field in West Java. Note the location of the other three producing geothermal fields in the east.

A conceptual model of the Salak reservoir has been developed and maintained since pre-exploitation 1992, with extensive documentation in 1997 and 2005. Stimac et al. (2008) presented the latest update on Salak's conceptual model in Geothermics (Vol. 37, Issue 3, June 2008).

Two new wells were recently drilled from the Awi-9 pad near the western edge of the field: Awi 9-7 in 2009 and Awi 9-8 in 2012. These wells provide key information since they were drilled toward a previously undrilled area near the southwestern edge of the field. Awi 9-7 shows the highest temperature yet measured at Salak and Awi 9-8 confirms a lateral extension of the reservoir margin. Since the results of both wells had not been incorporated into the latest conceptual model update, an effort to evaluate these wells has been undertaken. New information obtained from pressure-temperature surveys has been incorporated with geology, geochemistry and microseismic data and applied to evaluate reservoir geology characteristics, the likely upflow region, and injection flow paths in the southwestern part of Salak field.

GEOLOGIC SETTING OF SOUTHWESTERN EDGE OF SALAK FIELD

The Salak geothermal field is located along the axis of the Sunda Volcanic Arc which extends from Sumatra to Flores (Hamilton, 1979; Hutchinson, 1989). This arc-trench system marks the convergent boundary between the Eurasian Plate to the north and the Indo-Australian Plate to the south. Given this tectonic framework, the prevalence of commercial geothermal systems in western Java may be related to the presence of older and thicker crust and the large supply of terrigenous clastic material to the subduction zone. These factors have promoted the development in western Java of more extensive silicic magmatism, shallow intrusives, and formation of related geothermal systems since the Miocene (Stimac et al., 2010).

Salak subsurface lithologies have been inferred from descriptions of drill cuttings, supplemented by spot, sidewall and continuous cores. Borehole resistivity and gamma-ray logs also provided constraints on major rock types and compositions.

The reservoir rocks at Awibengkok are composed mainly of andesitic and lesser basaltic lava, breccia, tuff and lahar that comprise several long-lived volcanic centers underlying the southwestern margin of Gunung Salak (Hulen et al., 2000; Stimac and Sugiaman, 2000). Thick rhyodacitic-to- dacitic ash-flow tuffs and associated domes, breccias and lahars are interspersed with the more voluminous andesitic to basaltic sequences that date back to Miocene times (Figure 2).

The oldest rocks are mainly shallow-marine carbonates and epiclastic sediments (mudstones and sandstones containing abundant volcanic ash and lithic debris). Fossil assemblages in the carbonates are characteristic of Early-to-Late Miocene shallow-shelf environments.

The Lower Volcanic Formation (LVF), consisting of andesitic to basaltic volcanic rocks, overlies and is interbedded with the Miocene sedimentary section. Where these rocks are interbedded, the formation is called mixed volcanics/sediments (MVS). The lower part of the LVF consists mainly of sub-aqueous lavas and breccias (hyaloclastites are common) interbedded with fossiliferous marine carbonates. This sequence is overlain by andesitic to dacitic lavas, tuffs and breccias that appear to have been deposited in a sub-aerial environment.

Overlying the LVF is a widespread sequence of silicic tuffs known as the Rhyodacite Marker (RDM). This unit is interpreted to represent an episode of silicic volcanism and caldera formation that followed the first major episode of andesitic stratovolcano construction in the area.

The Middle Volcanic Formation (MVF) is another sequence of andesitic-to-dacitic lavas, tuffs, and lahars and debris flows that represent construction, collapse and erosion of stratovolcanoes and lava and dome complexes. This sub-aerial sequence dominates the Salak geothermal reservoir in the eastern portion of the field. The uppermost rock unit is primarily dacitic in composition, consisting mainly of lavas, domes and related breccias, tuffs and lahars. The underlying package is andesitic in composition, consisting dominantly of lavas and tuffs in its lower part, and lahars in its upper part.

The Upper Volcanic Formation (UVF) consists of another andesitic sequence overlain by dacitic to rhyolitic rocks that includes the surface deposits described above. Intrusive rocks consist of silicic-to-intermediate composition dikes and sills containing plagioclase, alkali feldspar, pyroxene, titanite and biotite or hornblende. These occur at shallow levels in the Cianten Caldera to the west of the proven reservoir. A thick hypabyssal quartz-dacite porphyry also intrudes the eastern caldera ring fault. A smaller intrusion in well Awi 1-2 was described as a quartz diorite sill (Hulen et al., 1999). It is generally less altered than the surrounding rocks due to its low inherent permeability.

Intrusive rocks have been identified in many wells in Salak, including in some wells on the Awi-9 pad. Intrusive rock can be recognized based on its relatively coarse-grained texture, and it may represent a dike. In the Awi 9 pad wells, relatively coarse-grained holocrystalline textures in cuttings samples from the deepest sections can be interpreted to reflect the presence of numerous dikes and sills in this area

Observations from cuttings from Awi 9-7 are consistent with the current stratigraphic model of Salak. The well encountered all formations except the continuous sediments at the base of the section. Based on PTS data, all Awi 9-7 entries occur in the deep reservoir within the MVS section. At Awi 9-8, 26 sidewall cores were taken from different depths in the 12-¼” and 9-⅝” hole sections. Based on the sidewall cores, the well encountered volcanic rocks of the LVF. At the bottom of the section, Awi 9-8 encountered marl and siltstone interlayered with tuffaceous pyroclastics and andesitic lava that was interpreted as part of the MVS. Similar with Awi 9-7, all entries in Awi 9-8 also occur within the MVS section down to elevations around 4500’ below sea level (BSL), which is significantly deeper than most other Salak wells. The sequence of thick volcanics overlying the mixed volcanic/sediment sequence formation in Awi 9-7 and Awi 9-8 is confirmation of the previous Salak stratigraphy interpretation.

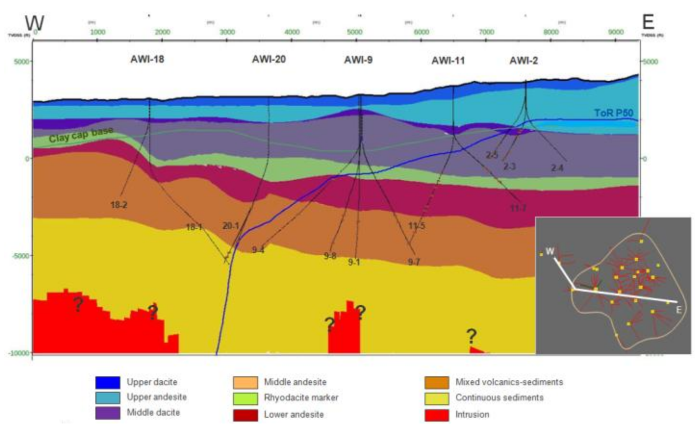

Figure 2: Stratigraphic cross-section of the Salak Geothermal Field showing the different lithologic formations, some of the wells drilled and the interpreted top of reservoir (blue line).

Geologic Structures

Considering the regional structural setting and local fault orientations, there likely is a conjugate set of faults in the Awibengkok development area consisting predominantly of: (1) normal faults with N to NNE orientations, and (2) normal and strike-slip accommodation faults and joints trending NW and NE to ENE (Stimac et al., 2010).

Awi 9-8 Formation MicroImager™ (FMI) and Sonic Scanner logs have been used to better understand the distribution, orientation and characteristic of subsurface fractures at Salak. The logs show a detailed view of the formation where fractures and lithologic changes are clearly seen. Overall, image logs show that open (electrically conductive) fractures demonstrate a dominant NW-SE and NNW-SSE strike orientation, and fracture dip azimuth is mainly NE (Figure 3). Sealed (electrically resistive) fractures were observed showing predominantly NW-SE and NNW-SSE strikes, with fracture dip azimuth at ENE, N, and NW (Figure 4).

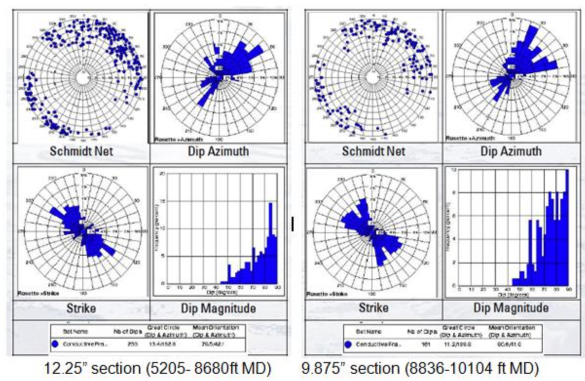

Figure 3: Conductive fractures were observed to demonstrate a dominant NW-SE and NNW-SSE strike orientation at Awi 9-8. Fracture dip azimuth is primarily in a NE direction.

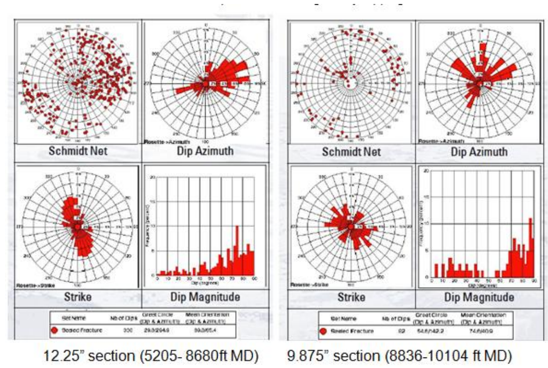

Figure 4: About 400 sealed fractures were observed showing strike dominantly NW-SE and NNW-SSE at Awi 9-8. Fracture dip azimuth is scattered along the ENE, N, NW directions

PTS data indicate that the major entry of Awi 9-8 is located at depth 9775’ measured depth (MD). Other indicators of permeability at that depth prior to flowing the well included mud losses and maximum energy loss from a Sonic Scanner log conducted over this interval (Figure 5). This entry also correlated with the vertical projection of a surface lineament.

Two faults were identified in the 9-⅞” hole section. These faults at 9765’ MD and 10097’ MD show the predominant NNE-SSW strike orientation (Figure 6).

These faults show consistency with surface lineament interpretation and may possibly act as conduit pathways for fluid flow.

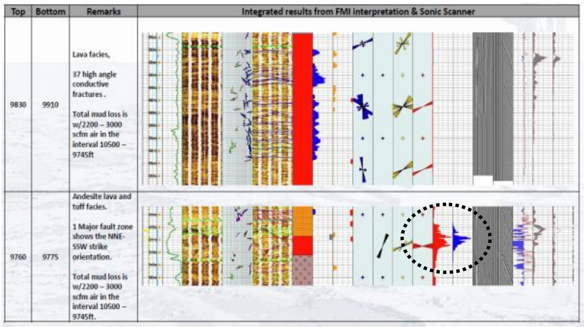

Figure 5 Log of Awi-9-8, incorporating fracture interpretations based on FMI, Sonic Scanner (blue chart) and Dipole Attenuation (red graph). The area highlighted by the dashed black circle indicates loss of energy likely related to an effective fracture / permeable zone.

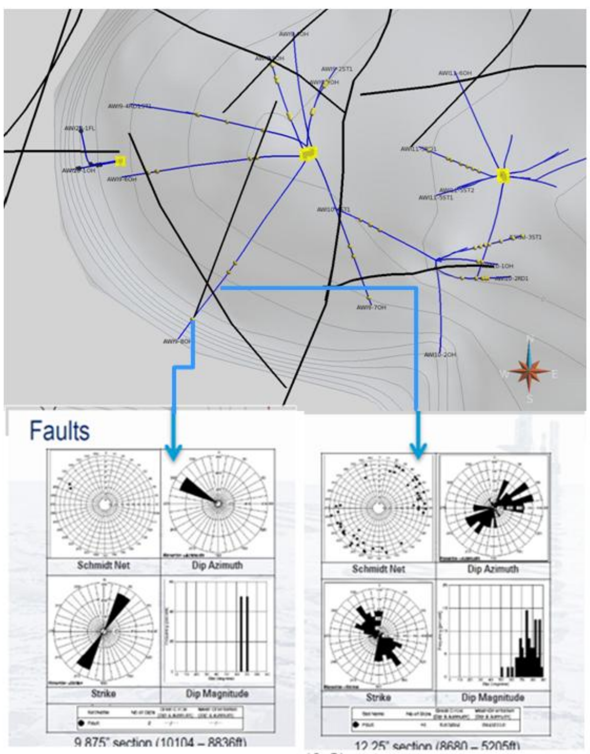

Figure 6: Fault interpretation at southwestern area based on correlation of surface lineaments and downhole FMI data at Awi 9-8.

Alteration Zones and Mineralogy

The Salak reservoir hosts argillic, propylitic, and phyllic alteration assemblages; no advanced argillic alteration has been identified within the high-temperature reservoir. The geothermal system is capped by a zone of intense argillic alteration which is dominated by smectite and smectite-illite mixed-layer clays, with accessory pyrite, silica, hematite, calcite, anhydrite, zeolites and chlorite. This assemblage typically corresponds to temperatures of <200˚C (<390˚F).

In Awi 9-7, the argillic alteration shows a transition to propylitic alteration with increasing depth spanning hundreds of feet. The bottom of the argillic alteration is marked by an increase in mixed-layer illite-smectite clay and chlorite. This zone is classified as the transition between argillic and propylitic alteration. XRD data shows that smectite in this mixed layer clay zone is around 70-80%. Because of its high smectite content, the rocks appear to have been altered at lower temperature than is measured today. The argillic and transition zones probably represent an effective seal to the underlying propylitically altered reservoir section. The propylitic alteration zone is dominated by epidote, illite, and chlorite but also contains albite, calcite, pyrite, and quartz. XRD results also show a significant decrease downward in smectite percentage to only 10-20% in mixed-layer clays followed by significant increase of illite and mica. The propylitic alteration assemblage corresponds to reservoir temperatures of about 220-270˚C (~430-520˚F). Deeper occurrences of diopside indicate reservoir temperatures above 300˚C (570˚F).

In Awi 9-8, the alteration mineralogy has a similar pattern except phyllic alteration is present in the more silicic rocks (dacites and rhyolites) at the bottom section of the well. The phyllic alteration assemblage corresponds to reservoir temperatures of 260-290˚C (500-555˚F) and is dominated by illite, sericite, adularia and quartz, with lesser epidote and chlorite.

FLUID CHEMISTRY

At initial reservoir conditions, when the liquid was not being affected by various reservoir processes and mixing with injectate, the geothermometry of produced fluids usually showed good agreement in reflecting the measured reservoir temperature. After exploitation, the impact of injection breakthrough and other reservoir processes has changed the composition of produced fluids and therefore impacted the interpretation of chemistry in production wells.

Initially, the Salak reservoir fluids had fairly homogenous geothermal chloride concentrations ranging from 6300 ppm to 6700 ppm. In Awi 9-1, initial state chloride concentration was within this range at 6600 ppm. Current measurements in fluid produced from Awi 9-1 revealed chloride around 9000 ppm Cl, and at Awi 9-7 chloride ranges from 6600 to 7900 ppm. The chloride at Awi 9-7 has not risen as much as other nearby producers due to recovery of injected brine, but it definitely is recovering some of that injectate.

In Awi 9-7, comparison between silica and cation geothermometry shows that the silica geothermometry (Qtz) is higher than Na-K-Ca. This condition demonstrates the impact of injection breakthrough in this well. Rapid arrival of injectate to the production wells does not allow silica to re-equilibrate with reservoir conditions and results in higher silica concentrations. Even though the quartz geothermometry yields a temperature close to the measured flowing temperature, it is considerably lower than the measured static temperature.

Downhole temperature measurements show that Awi 9-7 still has higher temperatures than any other production wells in Salak although Awi 9-7 has been impacted by injected brine. Awi 9-7 also has very high enthalpy when it was production tested in May 2012. It is suspected that this well is producing mostly the original mass in place (MIP). Additionally, it was observed that the chloride concentration in this well started to decline. The decline in chloride was accompanied by an increase in NCG indicating more MIP in the produced liquid. This confirms the previous interpretation about the presence of the heat source around the Awi 9 pad.

Table 1: Comparison between Qtz and Na-K-Ca geothermometry of Awi 9-7 liquid

Sample label	Qtz (nsl) (degr F)	Na-K-Ca (degr F)
AWI9-7	594	558

GEOPHYSICS

In Salak, there have been several correlations between microseismic (MS) activity and fluid injection. The majority of microseismic events is less than magnitude M2 and too weak to be felt at the surface. The characteristics of MS events are varied across Salak area. In the eastern part of the field, the base of seismicity correlates with the depth of the low permeability marine sedimentary rocks, suggesting that the permeability does not extend down beneath the sedimentary rocks. In the west (near Awi-9), the MS events extend deeper into the sedimentary rocks (Figure 7). The deepest cluster of MS events around Awi 9 was observed at about 11500' BSL. This may indicate the pressure connection to the deeper zone and probably deeper permeability along vertically extending fractures, confirming the interpretation that the deep Salak up-flow is located near the southwestern edge of the field.

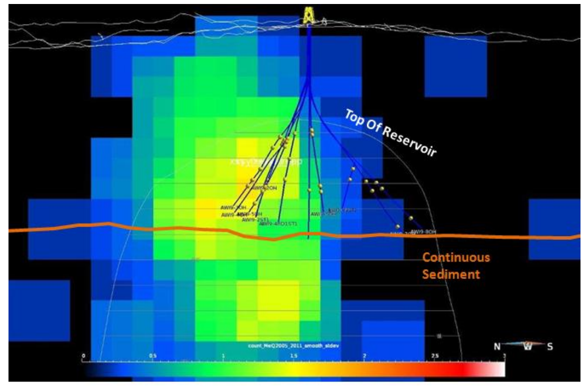

Figure 7: Microseismic event density in the vicinity of Awi 9. Note the occurrence of MS events in the continuous sediments below where the wells were drilled. Cross-section along a N-S direction.

TEMPERATURES OF AWI 9 PAD WELLS

The Awi 9 wells are located near the southwestern edge of the Awibengkok reservoir. This area is known as the high temperature cell and has the highest liquid reservoir temperatures in the field compared to other cells (central and eastern cells). In 2009, Awi 9-7 was drilled and measured as the hottest well in Salak to date with temperature of 620°F. The next hottest well is Awi 9-2 with temperature of 600°F. Therefore, the area around the Awi 9 pad was believed to be the location of the major upflow of the Salak reservoir.

Currently, most of the Awi 9 wells are also utilized as brine injectors. However, Awi 9-1 and Awi 9-7 are now being used as producers. These two wells and most of the western production wells have been impacted by thermal breakthrough from brine injection in the other Awi 9 wells. Recently drilled Awi 9-8 shows a temperature reversal; this well was drilled between the production and injection areas. Enthalpy measurements at Awi 9-7 also indicate that, under flowing condition, its enthalpy is significantly lower than static condition (Figure 9). Enthalpy in static condition is about 650 BTU/lb and decreases to below 600 BTU/Lb during flowing.

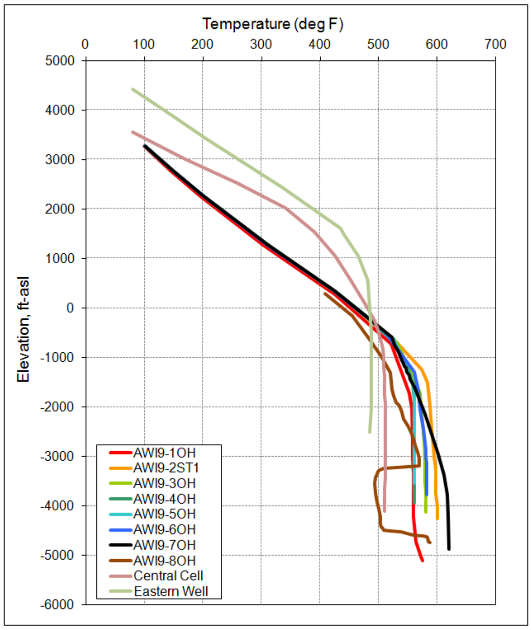

Figure 8: Initial temperature profile of Awi 9 wells. These wells are located in the high temperature cell observed in the western portion of the Salak field.

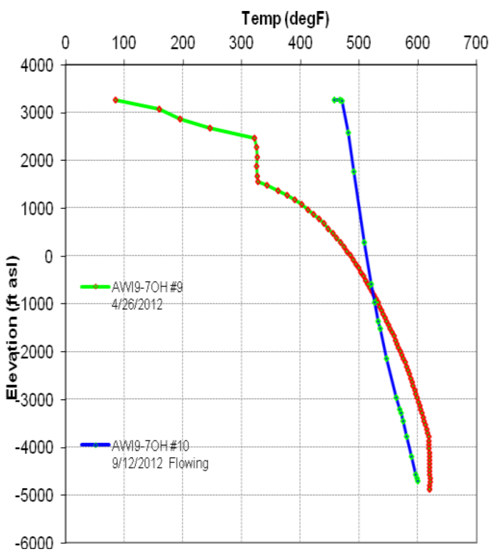

Figure 9: Chart showing the comparison of flowing and static temperatures of Awi 9-7.

CONCLUSIONS

In Awi 9-7 and Awi 9-8, occurrences of high temperature secondary diopside indicates very high temperatures, possibly near an intrusive or metamorphic contact. Most of the Awi 9 wells have coarse-grained holocrystalline textures in cuttings samples from the deepest sections that can be interpreted as the presence of numerous dikes and sills in the area. Permeable entries in the Awi 9 area are located at greater depths compared with other parts of the Salak field. These, along with the hottest well temperatures in the field, suggest that the hot fluid upflow at Salak appears to be controlled by deep intrusion beneath the Awi9 wells.

Geochemistry data shows that this upflow area where Awi 9-7 is producing has been impacted by brine injection, modifying the composition of reservoir fluid by mixing. This mixing process can lead to misinterpretation of the chemistry of the production wells. However, despite the injection influence to produced fluids, measured static temperature measurements from Awi 9-7 show that this well still has higher temperatures than all other production wells in the field. This confirms the previous interpretation regarding the heat source lying beneath the Awi 9 pad. MS data also support this interpretation as indicated by the deep MS events below the Awi 9 wells. The information developed in the study of Awi 9-7 and Awi 9-8 confirms the previous interpretation that the deep Salak upflow is located near the southwestern edge of the field, and that the majority of the producing field represents a thick moderate-temperature outflow flowing up and to the east from Awi 9 (Stimac et al., 2010) (Figure 10).

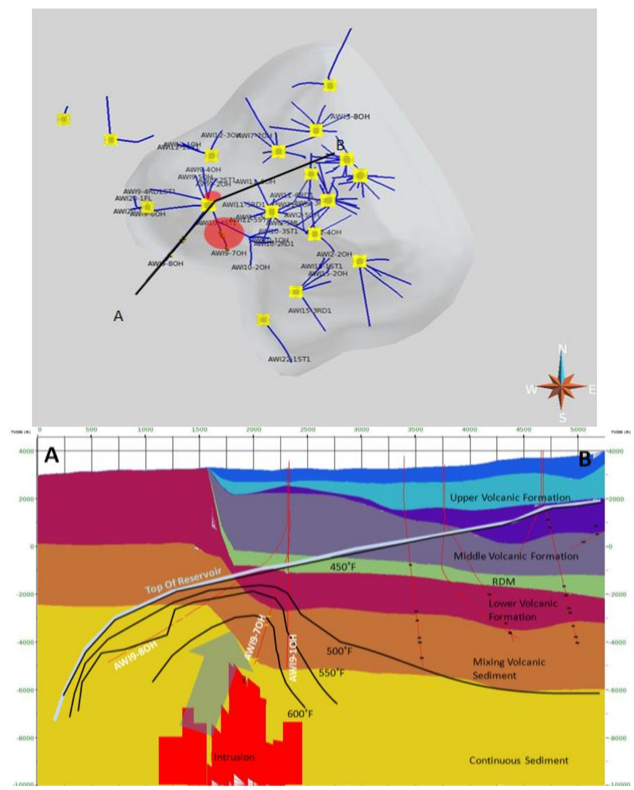

Figure 10: Cross-section showing the different lithologies and distribution of temperature in the Salak geothermal system. Map shows the plan view location of the upflow (red circle) of the Salak reservoir and cross-section A-B.

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