

The Darajat Geothermal Field, Indonesia, After 24 Years of Production

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ABSTRACT

The Darajat Geothermal Field is the largest vapor-dominated geothermal resource in Indonesia with an installed power generation capacity of 271 MWe. Darajat has maintained high levels of production for 24 years through a program of diligent reservoir monitoring, analysis and optimization. Continued production at Darajat Field will lead to lower reservoir pressure and may result in reservoir dry-out especially at the central part of the field and, potentially, invite cold marginal recharge to enter the reservoir. Currently, wells experiencing scaling at Darajat mostly correlate with where marginal recharge has been identified; thus, wellbore scaling may be an issue in the future. Another anticipated resource issue that may affect the field's performance is reservoir dry-out, although an appropriate injection management strategy is expected to mitigate its effects. Lastly, moving condensate injection to the edge of the field seems to have arrested cooling in the central portion of Darajat although there are geochemical signatures that reservoir condensation is occurring in the northern portion of the field. Current analyses indicate that the Darajat Field is capable of generating at its current level in the foreseeable future.

1. INTRODUCTION

The Darajat geothermal field is located about 230 km southeast of Jakarta in West Java, Indonesia. Currently, it is the largest vapor-dominated geothermal resource in Indonesia with an installed capacity of 271 MWe (Figure 1). Darajat lies in a geothermal province that includes Wayang Windu (227 MWe), Karaha Bodas (30 MWe), Patuha (55 MWe), and Kamojang (235 MWe) geothermal fields. Kamojang is Indonesia's only other vapor-dominated geothermal field and lies just 9 km northeast of Darajat. Among all geothermal fields in Indonesia, both Kamojang and Darajat appear to have the greatest vertical extent of the vapor zone, with no base being detected to date (Raharjo et.al. 2012).

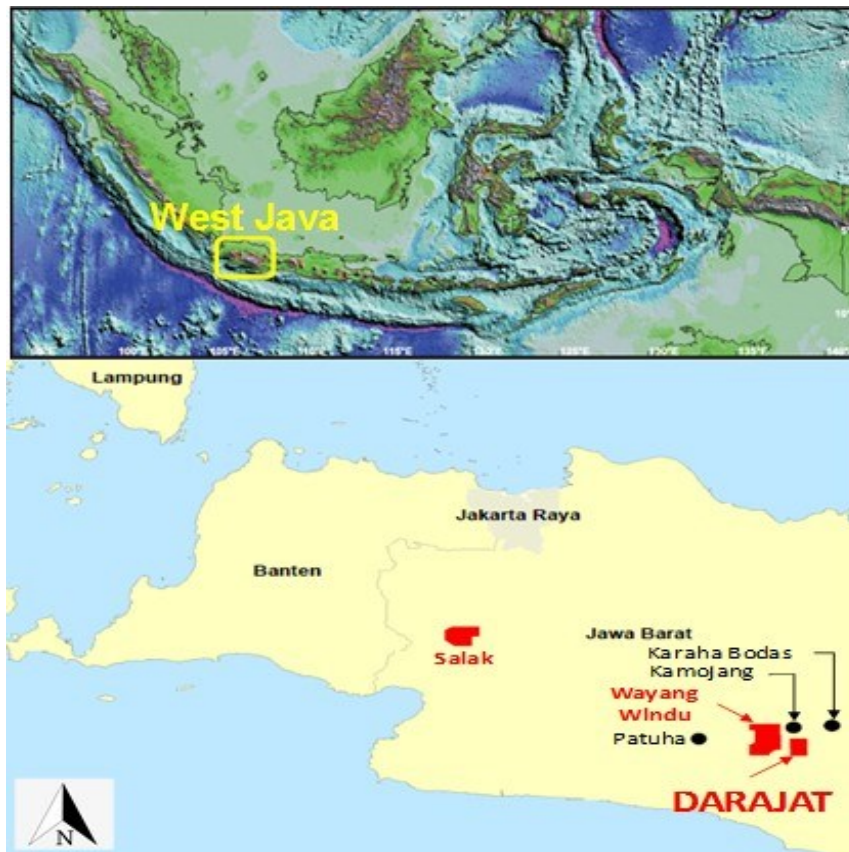


Figure 1: Top figure is a digital elevation model showing the topography and bathymetry of the Indonesian Archipelago (from Hall, 2009). Bottom map shows the province of West Java (Jawa Barat) and the geothermal fields it hosts. Geothermal fields in red font are those operated by Star Energy Geothermal.

Commercial production commenced at Darajat in 1994 with the commissioning of the 55 MWe Unit I (Figure 2). The 95 MWe power plant, Unit II, followed in 2000, while Unit III, a 110 MWe power plant, came on line in 2007. In 2009, the successful drilling campaign in 2007-2008 ensured enough steam supply to allow Unit III to generate at 121 MWe, still within the turbine's design limits. This turbine uprating increased Darajat Field's installed capacity to the current 271 MWe. Under a Joint Operation Contract ("JOC") with state-owned oil and gas company, PERTAMINA (now PT Pertamina Geothermal Energy ("PGE")), Star Energy Geothermal Darajat II Limited ("SEGD") supplies steam to Unit I (power plant owned by PT PLN (Persero) ("PLN") and operated by PT Indonesia Power, PLN's subsidiary), and owns, operates and delivers electricity from Units II & III.

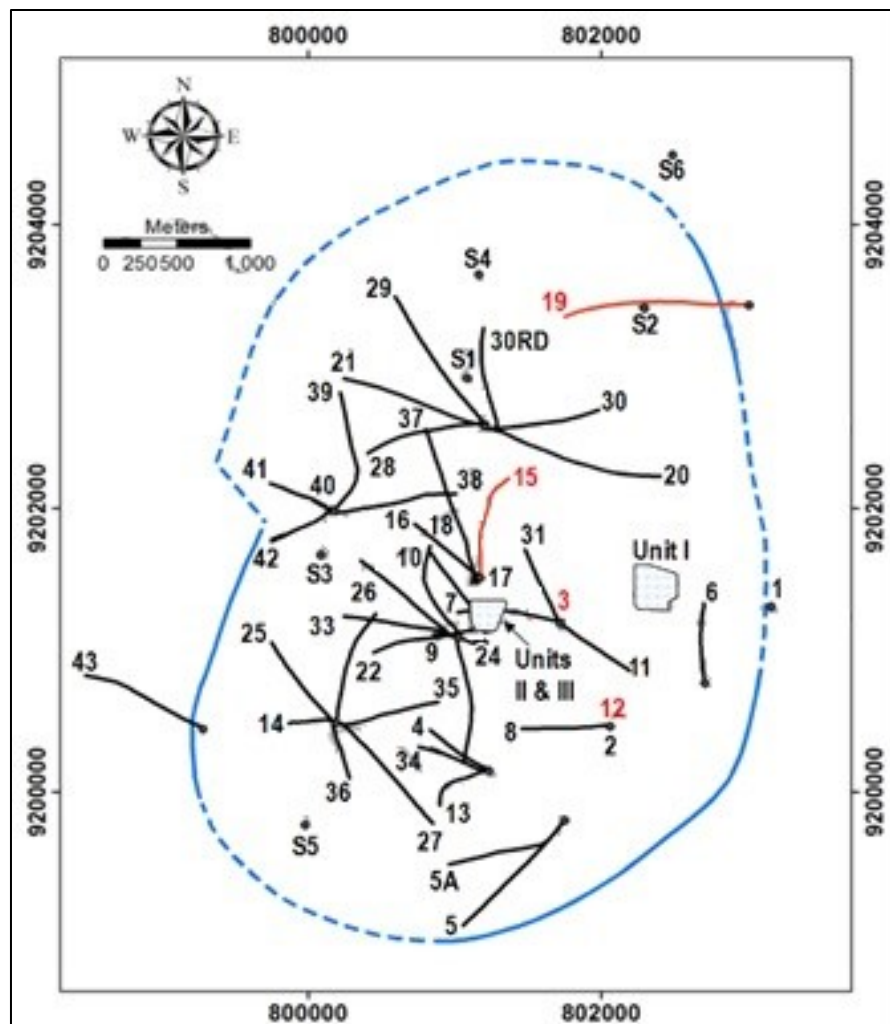


Figure 2: Map of the Darajat Geothermal Field showing the drilled wells (black for producers and red for injectors), commercial production boundary (blue line; dashed where poorly constrained by drilling). DRJ-19 is the current condensate injector while DRJ-12, 3, and 15 are back-up injectors.

The Darajat Field has performed well with steam supply maintained through production optimization, make-up well drilling and managing resource-related issues as they have arisen for the past 24 years. Implementing edgefield condensate injection starting in 2012 arrested reservoir cooling due to infield injection, which was implemented since commercial operations in 1994. Wellbore scaling, associated with the boiling of cooler natural recharge (Syaffitri et al., 2018), is remedied through either acidizing or mechanical clean-outs. Looking forward, key reservoir management issues will include make-up well drilling from new pad locations outside of currently drilled areas, as the reservoir pressure continues to decrease, reservoir dry-out and expected increased issues with wellbore scaling. Reservoir characterization work provides necessary information to make well-informed decisions and define strategies on how best to plan for and mitigate detrimental impacts. In the case of make-up well drilling, detailed characterization of the producing effective fracture characteristics has highlighted the optimum well azimuth and inclinations to intersect the maximum number of feed zones. New interpretation tools, such as joint geophysical inversion and microseismic tomographic modeling, are being applied to improve imaging of the reservoir. Integration of these interpretations into the conceptual model results in refined make-up well targeting.

2. PRODUCTION AND GENERATION HISTORY

A commercial geothermal resource was confirmed at the Darajat Field during 1976-1978 with the drilling and testing of exploration wells DRJ-1, 2, and 3 (Figure 3). In 1987-1988, deep (>1,600 m) appraisal wells DRJ-4, 5, 6, and 7 were drilled: DRJ-4 and 7 were highly successful while DRJ-5 and 6 encountered low permeability conditions along the margins of the system (Dobbie, 1991).

After completing four development wells, namely, DRJ-8, 9, 10, and 11, the first 55 MWe power plant (Unit I) at Darajat was commissioned in late 1994 (Figure 3a).

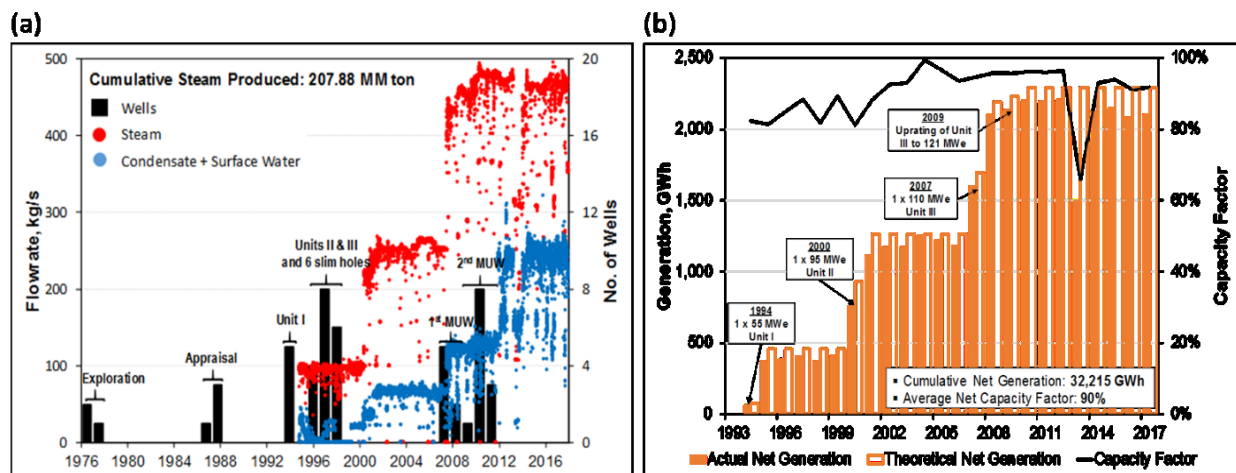


Figure 3: a) (Left) Historical steam and power plant condensate production and wells drilled at the Darajat Field. The six slim holes drilled during 1996-1998 were part of further delineating the geothermal resource. The power plant condensate volume includes some surface water that accumulates in surface facilities. b) (Right) Annual actual and theoretical net generation and net capacity factor of the Darajat Geothermal Field. The low availability factor in 2013 was due to problems with the Unit II generator. Since 2016, PLN has curtailed Units II and III to allow dispatch of other power plants into the national grid.

The 1996-1998 production and exploration drilling campaign aimed at developing 140 MW of steam and proving additional reserves, and included the drilling of six continuously cored slim holes designated as S1 to S6 (Figure 2). This drilling campaign was highly successful in that 275 MWe equivalent of steam was added. This drilling campaign was characterized with the drilling of the biggest well then that produced about 40 MWe and four other wells exceeding 30 MW each (Berry, 1998). During 2007-2008, seven make-up wells were drilled to augment steam supply to Unit III. The second production make-up drilling campaign, consisting of 11 wells, was in 2009-2011 (Figure 3a).

By the end of 2017, the Darajat Field has produced about 207.88 MM tons of steam, which translates to a net generation of about 32,215 GWh of electricity (Figures 3a and 3b). A comparison of the actual and theoretical net generation indicates that the Darajat Field has averaged about 90% net capacity factor annually since commercial production began in 1994 (Figure 3b). If not for the Unit II generator problem in 2013, the annual net capacity factor is about 94% since 2010 after increasing Unit II's output.

Timely production make-up wells, remedial well works, and surface facility optimization projects have maintained steam production at Darajat Field at or above the rated power plant capacity. In addition to make-up drilling, remedial well works restored production by removing wellbore scale. The surface optimization projects emphasized debottlenecking of production pipelines.

3. NEW INSIGHTS INTO THE CONCEPTUAL MODEL OF THE DARAJAT GEOTHERMAL SYSTEM

Key elements of the Darajat geothermal system have been described in several publications: a high-temperature, vapor-dominated reservoir with benign chemistry with <2 wt.% of non-condensable gas (NCG) content (Dobbie, 1991; Hadi, 2001; Herdianita et al., 2001; Rejeki et al., 2010). The field is located in the Kendang volcanic complex, which is a part of a Quaternary volcanic range in West Java that includes the active Gunung Papandayan (last eruption in 2002) and Gunung Guntur (last eruption in 1840) (Hadi et al., 2005; Rejeki et al., 2010). Prior to commercial production, maximum reservoir temperature was measured between 225 and 245°C and reservoir pressure at ~35 bar with the system upflow believed to be in the north (Figure 4). Geothermal fluids generally flowed towards the south-southeast where steam outflows in the Kawah Manuk, Kawah Darajat, and Kawah Cipanday fumaroles in the southeast while sulfate and sulfate-bicarbonate waters outflow in the Cibereum and Toblong Springs in the east.

3.1 Defining Reservoir Stratigraphy and Subsurface Structures

An ongoing reservoir characterization study at Darajat Field is the evaluation of reservoir stratigraphy with the aim of confirming the volcano-stratigraphy of reservoir rocks and validating the structures used in past well targeting. The re-interpretation of the borehole image logs, petrographic analysis of rock cuttings and cores, and other subsurface data from wells drilled during 2009-2011 allowed definition of at least seven lithologic units based on the dominant rock type (Figure 5).

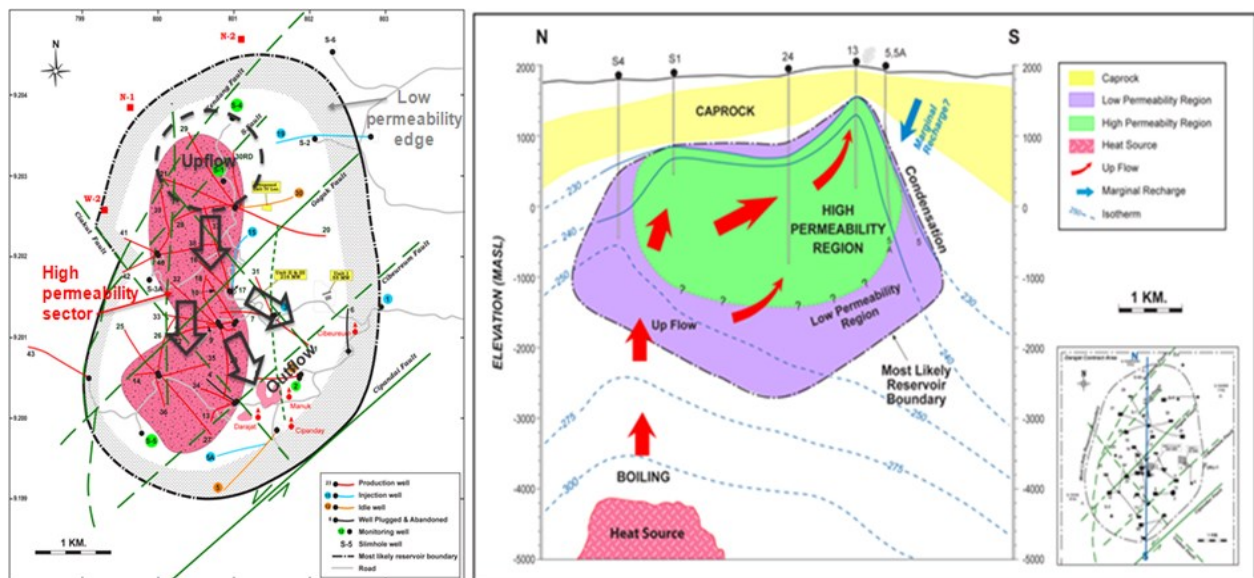


Figure 4. (Left) 2012 map showing the main components of the Darajat geothermal system. Fluids upflow in the north, move towards the south and east, and finally outflow in the fumaroles and springs. There is a north-south core of relatively high permeability in West Darajat while reservoir permeability decreases at the edge of the reservoir. (Right) N-S cross-section shows the basic elements of the conceptual model of the Darajat Field. Notice that the heat source is located under Pad 20 in the northern portion of the field.

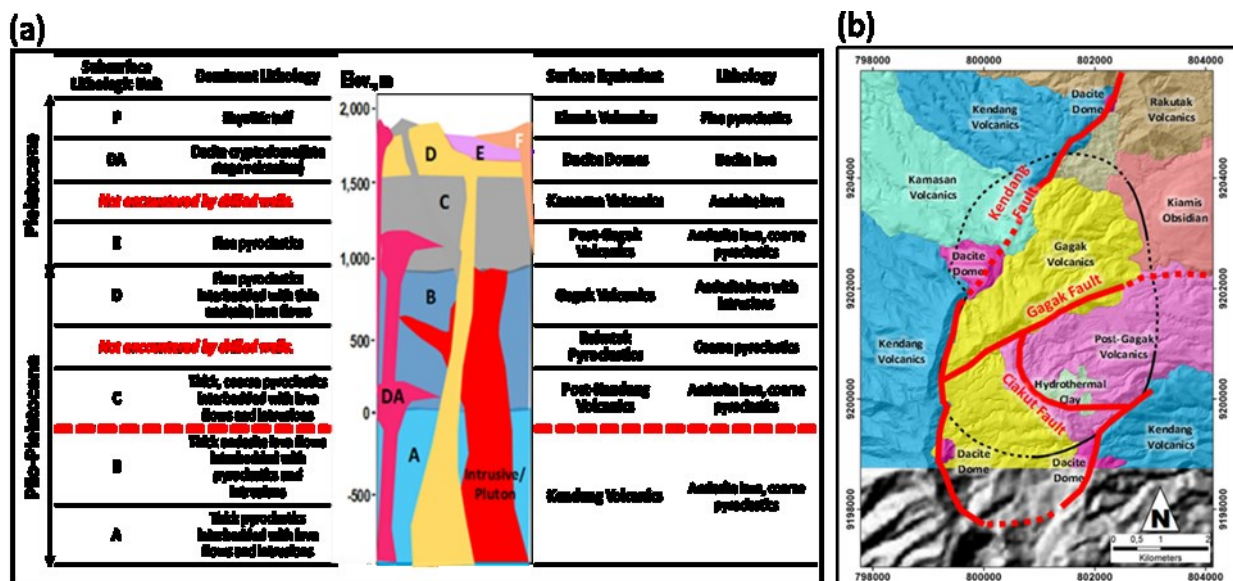


Figure 5. a) (Left) Schematic diagram showing the interpreted stratigraphy and correlation between surface and subsurface rocks at Darajat Field. The red dashed line denotes the decompression event hypothesized by Moore (2007) or the boundary in time between the then water-dominated geothermal system and the vapor-dominated system now. b) (Right) Provisional geological map of the Darajat Field showing the interpreted structures based on LiDAR data and offset of reservoir rocks. Both Kendang and Gagak are prominent on the surface while Ciakut is buried; structures are dashed where inferred. The LiDAR data covers the colored portion of the map only. Colors correlate with the subsurface rocks in Figure 5a.

The Andesite-Intrusive Complex, which comprises the Darajat geothermal reservoir and the hypothesized sub-volcanic portion of an earlier liquid-dominated geothermal system (Moore, 2007), belongs to the Kendang Volcanics and makes up subsurface Units A and B (Figure 5a). Note that the diorite intrusions do not penetrate the Post-Kendang Volcanics or subsurface Unit C. Effective fractures, i.e., the fractures currently producing geothermal fluids, are more abundant in the lava flows and intrusions compared with the pyroclastics (next section). Rejeki et al. (2010) reported that delineating the extent of the Andesite-Intrusive Complex is key to finding permeability at Darajat Field.

Analysis of LiDAR data, drainage patterns, and relative location of eruption centers led to the refinement of the surface geology at Darajat Field and revealed two noticeable surface structures (Figure 5b). The prominent Kendang Fault, which extends to the Kamojang Field in the northeast, may be a section of the ring structure of an earlier volcano, here called Kendang. Although needing further substantiation, we hypothesize that the decompression event postulated by Moore (2007) might be related to the eruption of the Kendang volcano (Intani et al., 2018). The Gagak Fault is another prominent surface structure and believed to form during the eruption of the resurgent Gagak volcano after the eruption of Kendang.

3.2 Characterizing the Reservoir Fracture Network

The Darajat Field has an extensive catalog of borehole image logs with 29 wells (~60% of the 49 wells drilled) having this type of subsurface data. The 29 wells include the six continuously cored slim holes, which provide very good calibration of the interpreted and actual lithologies encountered. Furthermore, these borehole image logs cover 76 feed zones encountered by these wells. From the borehole image logs, effective fractures, or the fractures or geologic features believed to either produce geothermal fluids or accept fluids (in case of injection wells), were identified (Golla et al., 2017). The majority of the effective fractures at Darajat have a N10-30°E strike orientation, with dips >50° to both the southeast and northwest directions (Figure 6). The general orientation of the effective fractures aligns with both the regional horizontal maximum stress (S_{HMax}) orientation at NNE-SSW (Tingay et al., 2010) and interpreted local surface structures and lineaments at Darajat. This suggests that the trajectories of future make-up wells at Darajat should be towards the northwest or southeast directions to target this range of effective fracture orientations (Gunderson, 2015).

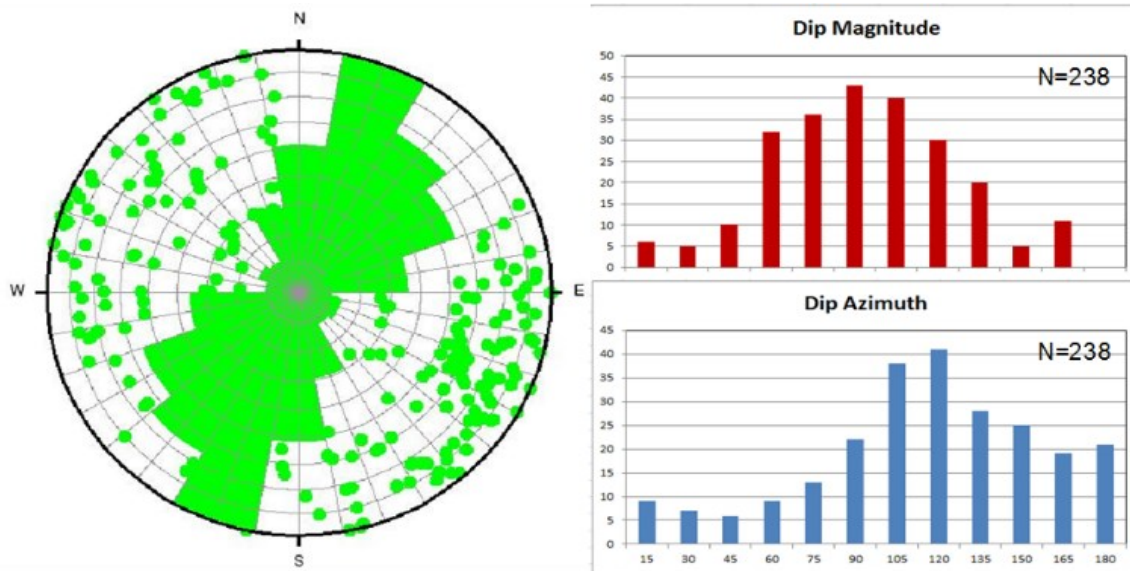


Figure 6. Rose diagram showing the NNE-SSW strike orientation of effective fractures at Darajat. The green circles represent the direction and magnitude of the dips of these effective fractures. (Right) Histograms showing the dip angle magnitude (above) and dip orientation (bottom) and of the Darajat effective fractures.

Intrusives, lava flows, and coarse pyroclastics host effective fractures that strike mostly in a NE-SW orientation and dip to both the southeast and northwest (Figure 7). Interestingly, the few effective fractures in the fine pyroclastics have a largely NNW-SSE strike and dip steeply to the west. The fine pyroclastics, a potential marker horizon, occur in northeast Darajat and the dip direction suggests that the source of the fine pyroclastics is from the east.

Although the majority of effective fractures at Darajat have strike orientations between North and East, there are variations across the field (Figure 7). In South Darajat, effective fractures that trend NNW-SSE and almost E-W are predominant. Note that this area hosts a shallow top of reservoir and younger volcanics atop the Andesite-Intrusive Complex, and it is not yet clear if these affect the orientation of the effective fractures. In North Darajat, minor NW-SE effective fractures occur although the dominant direction is still in the NE-SW quadrant. The NE-SW orientation of the effective fractures indicate that the main control may be the regional S_{Hmax} . A similar trend is dominant in Central Darajat where the effective fractures have a NE-SW strike direction but $\pm 50^\circ$ from the orientation of the effective fractures indicate that the main control may be the regional S_{Hmax} orientation. The above observations indicate that the effective fractures are slightly more consistent within the core of the Darajat production area, and show slightly more variation along the southern edge of the field. A closer analysis to determine adjustments in both well planning and targeting when drilling in the southern sector of the field will be required (Figure 7).

3.3 Improving Imaging of the Reservoir through Geophysical Joint Inversion

To improve the resolution of potential well targets, such as into the Andesite-Intrusive Complex, SEG has applied new interpretation techniques to its geophysical data. The Andesite-Intrusive Complex is geophysically distinct having both high density and resistivity signatures. In this regard, the Darajat magneto-telluric and gravity data were jointly inverted with a cross-gradient link between inversion parameters and referenced to the porosity model from the 3D Static Model (Soyer et al., 2017). Results show delineation of a high-density feature by the 3D joint inversion model. The feature trends N-S from the far south region outside reservoir boundary toward Pad-20 area in northern Darajat. This high-density trend coincides well with the areas where the shallow microdiorite intrusions have been encountered in the central and southern wells (DRJ-14 and 18 locations in Figure 2) and northern-most production wells at Pad 20. In general, the model suggests the possibility of a series of intrusive dikes, or small stocks, which are interpreted to be connected with a continuous intrusive body at depth. However, the exact width of these intrusive bodies is not well constrained by the density model.

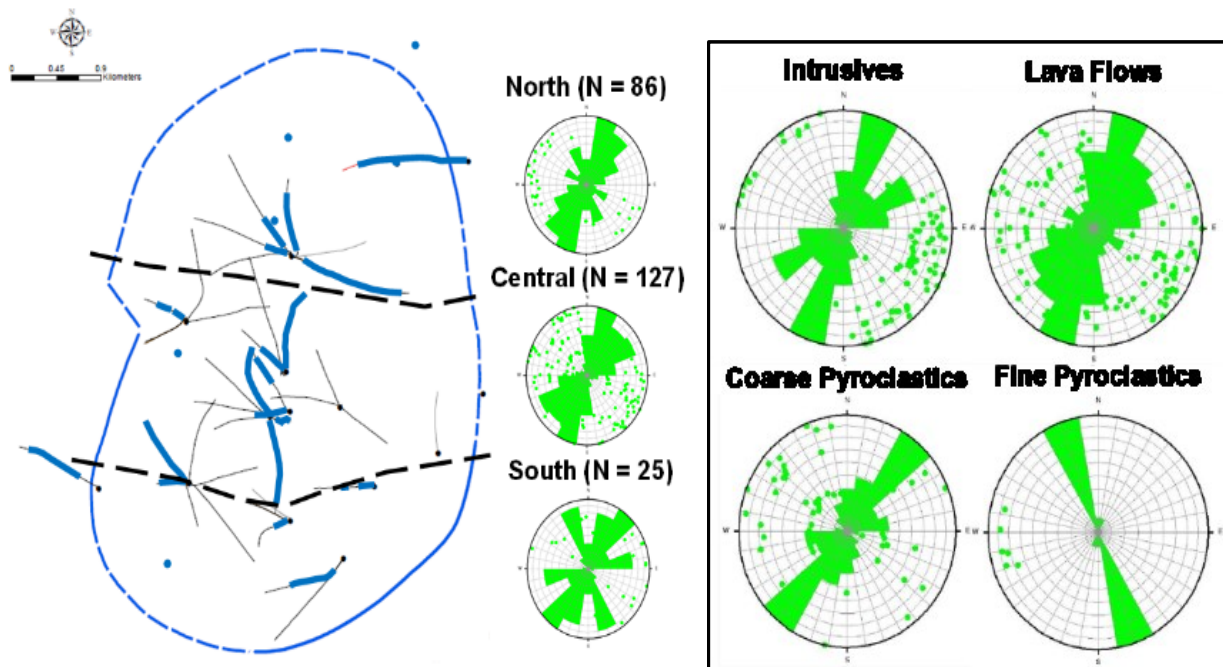


Figure 7. (Left) Rose diagrams showing the strike orientation (bars or petals) and dip azimuth and magnitude (circles) of effective fractures in each of the rock type comprising the Darajat reservoir. (Right) Rose diagrams showing the strong NE-SW trend of the effective fractures in wells (excluding the slim holes) drilled in North and Central Darajat inside the production area (blue line; dashed where poorly constrained by drilling) while effective fractures in South Darajat exhibit more variation. “N” refers to the number of effective fractures represented in each rose diagram. The blue thick lines along the well trajectories indicate the portion of the well with borehole image data.

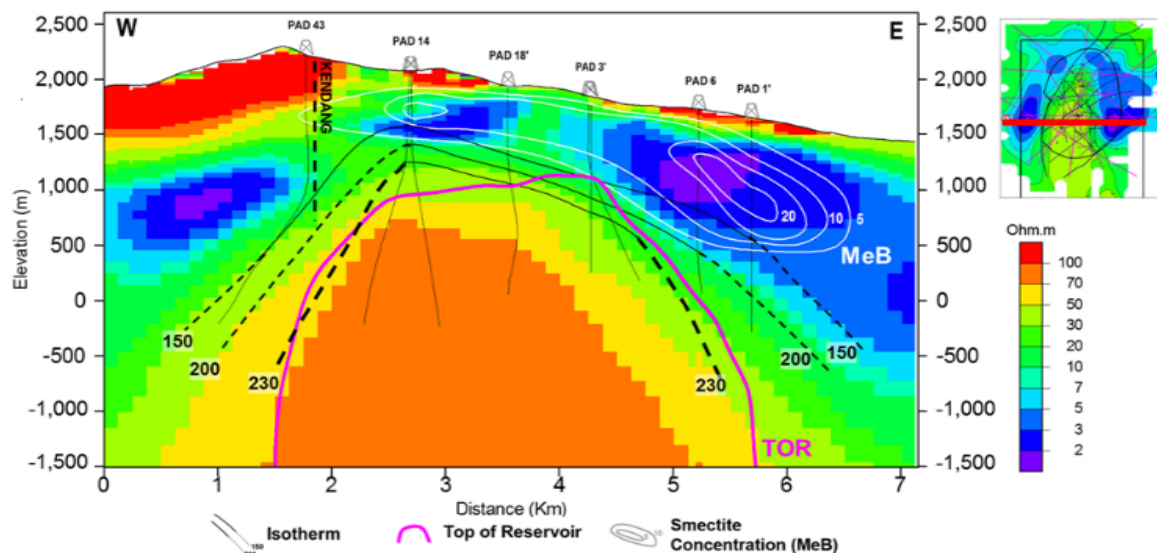


Figure 8. (Right) Cross-section showing the resistivity distribution west of Pad 43 to east of Pad 1. Note the separation of the low resistivity (<10 Ohm.m) conductor bodies near the Kendang Fault. DRJ-43, on Pad 43, did not encounter significantly high concentrations of smectite from MeB analysis.

Joint geophysical modeling results have also resulted in a better resolution of the geometry of the low-resistivity clay cap, as well as the existence of high-resistivity structure in the deeper part of the reservoir. The higher resistivity structure closely coincides with the high-density feature described above. With regards to the low resistivity clay cap, the 3D joint inversion showed a more definitive discontinuity between the conductor (<10 Ohm.m) pattern related with geothermal activity and possible deep regional basin clay west of Pad 43, across the Kendang Fault (Figure 9). Geologic evidence also supports the results of the joint resistivity inversion at the west of the Kendang Fault as shown by the contrast in alteration and lithology types in DRJ-43 as well as significantly lower Methylene Blue values in rock cuttings (Soyer et al., 2017).

3.4 Using Microearthquakes (MEQ) for Reservoir Characterization

To leverage the extensive database of local MEQ events for reservoir characterization, the Darajat velocity model was updated using both 1D and 3D models from the tomography inversion. The original Darajat velocity model was determined with a 1D inversion using a half-space starting model and initial locations derived from the original 1D model (Geosystem, 2003). The new

velocity model for Darajat improved the statistical error ellipsoid and residual means (Nelson et al., 2018). Using the new velocity model shifted the MEQ epicenters to the east-northeast direction and hypocenters became relatively shallower compared to their original locations (Figure 9). These new hypocenter locations were relocated in the 3D Static Model, gridded, and the updated MEQ density distribution was used to define the BoR.

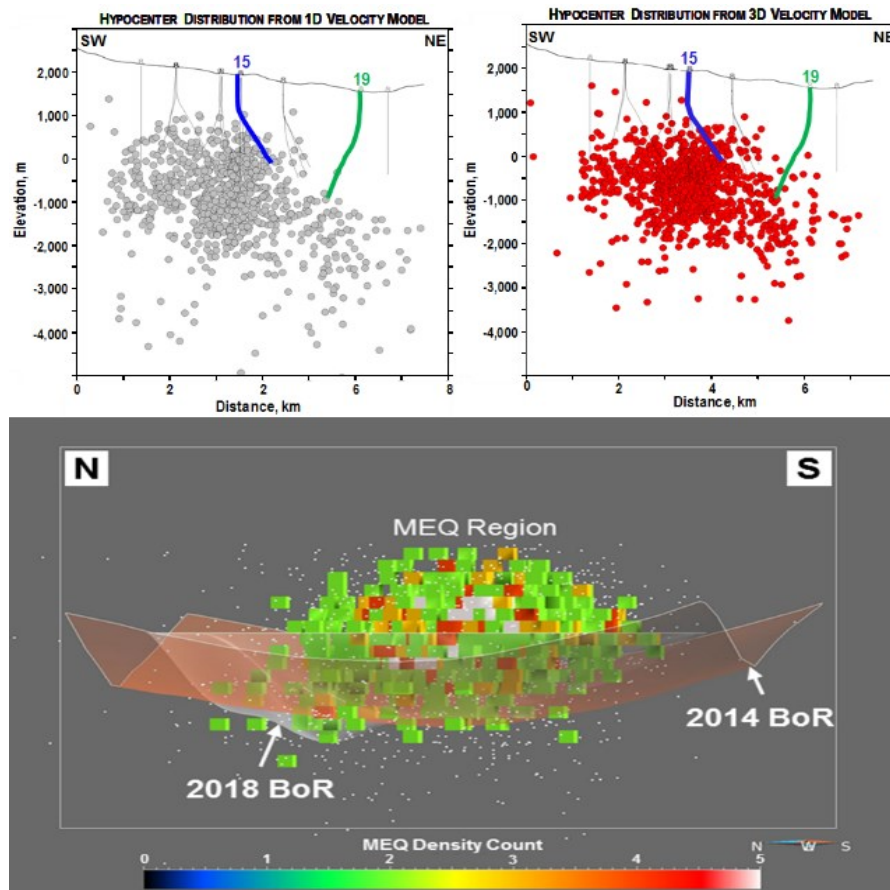


Figure 9. SW-NE cross-sections showing the distribution of the hypocenters from the original 1D (left, grey circles), final 3D velocity model (right, red circles). In general, MEQ hypocenters are tighter and shifted to shallower depth after applying the new velocity model. At bottom is a snip showing the slightly deeper 2018 BoR using the 3D velocity model (grey surface).

4. IDENTIFICATION AND MANAGEMENT OF RESOURCE CHALLENGES

As Darajat Field continues to produce steam and generate electricity, some of the anticipated resource management challenges include influx of shallow and cold meteoric recharge (“MR”), reservoir dry-out, and possible condensate injection breakthrough. As described in the next sections, these resource management issues have been managed effectively but it is recognized they may affect the performance of the Darajat reservoir in the future.

4.1 Influx of Cold Meteoric Recharge (MR)

Vapor-dominated systems are characterized by low permeability boundaries that seal the entire system and prevent entry of significant groundwater (White et al., 1971). The same is true at Darajat, which has an envelope of low permeability clay-altered rocks. Currently, reservoir surveillance has identified the entry of cold MR into the Darajat reservoir mainly through the interpretation of tritium, stable isotope, gas chemistry, and other multidisciplinary data (Figure 4). This cooler, natural recharge can lead to production challenges through wellbore scaling and a requirement for separation facilities to remove entrained water.

Anomalous tritium concentration in the steam condensate is one of the main evidences for establishing the presence of young (<100 years old) MR in the southern portion of Darajat Field (Figure 4). Initially, tritium content at Darajat was very low at <0.1 TU. Tritium in steam condensate started to increase after power plant condensate (with 0.3 TU) was injected back to the reservoir. Wells that consistently show tritium values >0.3 TU are those interpreted to get additional tritium content from MR, and these wells are generally found in the southeastern portion of the field. Minor MR was interpreted in at least one well in Central Darajat (Rohrs et al., 2009; Simatupang et al., 2015). Enrichments in N₂, CH₄, and NH₃ and stable isotope composition shifted towards meteoric waters characterize the MR in the central portion of the field. Work is underway at Darajat Field to estimate the steam production at risk from MR influx, map the distribution of MR, and to evaluate techniques for isolating MR-producing feed zones (e.g., cementing). In addition, the current monitoring program includes downhole sampling to accurately determine the entry location of MR in wells and routine geochemistry and stable isotopes analyses to enable identification of changes in reservoir processes.

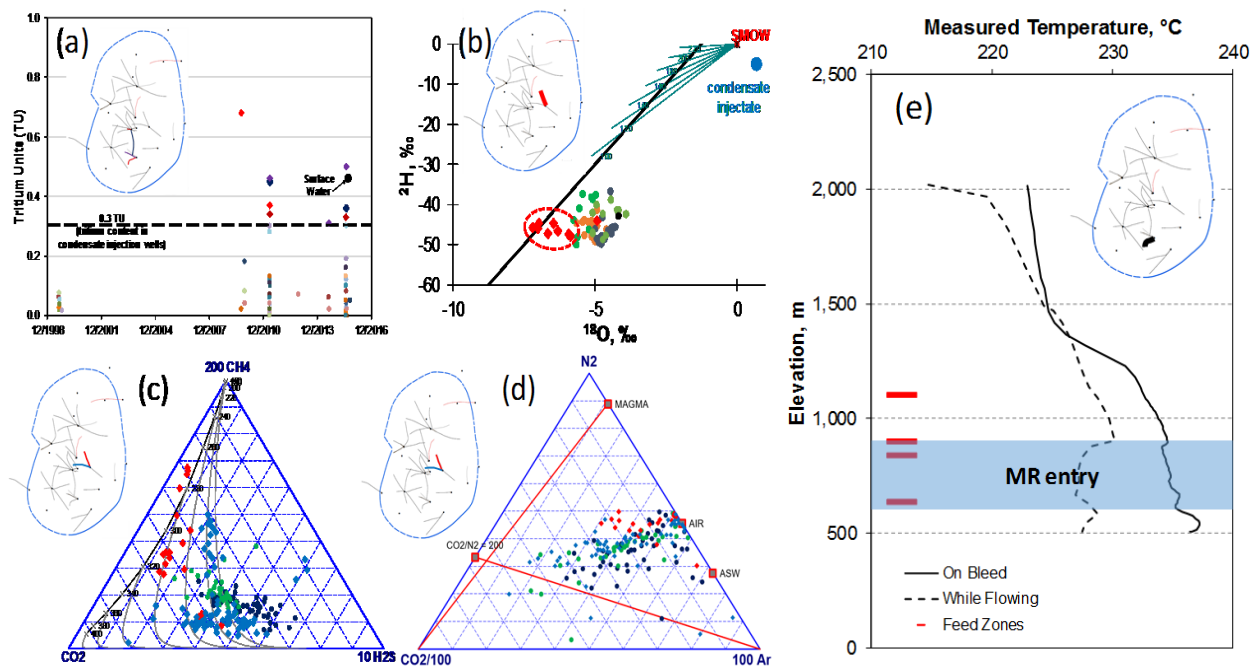


Figure 4. (a) to (d) Charts showing typical chemical species used to determine the presence of cold MR at Darajat. (a) The Darajat reservoir has very low tritium (<0.1 TU) concentration and elevated tritium concentration (>0.3 TU) suggests that young groundwater (or MR) is present in some southern wells. (b-d) In Central Darajat, at least one production well consistently exhibits enrichments N_2 , Ar, and CH_4 , and lighter stable isotopes indicating marginal fluids. The different colors represent specific wells and coincide with the highlighted wells in the inset maps. The temperature chart (e) shows typical temperature reversal in wells with known MR fluids, with the blue horizon signifying where MR was confirmed.

4.2 Dry Out of the Reservoir

A phenomenon expected to occur over time at Darajat is the dry-out of the reservoir. As vapor-dominated geothermal resources are largely sealed from recharge, continued commercial production leads to a decrease in liquid saturation (or dry-out) of the rock matrix. Reservoir dry-out is normally associated with superheat, the condition when measured reservoir temperature is higher than the saturation temperature as a result of pressure decline due to mass extraction in the reservoir. Superheat can be used as one of the parameters to monitor dry-out in the reservoir.

Since commercial generation at Darajat Field started in 1994, infield injection of power plant condensate has been the norm. The injectors were located in the central portion of the field for almost 20 years. Infield injection of the $40^\circ C$ condensate resulted in cooling in the reservoir and impacted nearby producers especially if the injected condensate exited wells at relatively shallow depths. This was indicated by superheat decreases at several Unit I producers in 2000 (Rohrs et al., 2009). To combat the unfavorable effect of infield injection, injection was moved to the northern edge of the field in 2012. This change in the location of the condensate injection induced boiling and the development of superheat in the central portion of the field. By 2017, the central and southern portions of Darajat, areas where production began in 1994, exhibited a more defined area of superheat development (Figure 5). The highest surface superheats ($>10^\circ C$) are observed at southeastern Darajat where reservoir porosity and permeability are relatively lower (Rejeki, 2001).

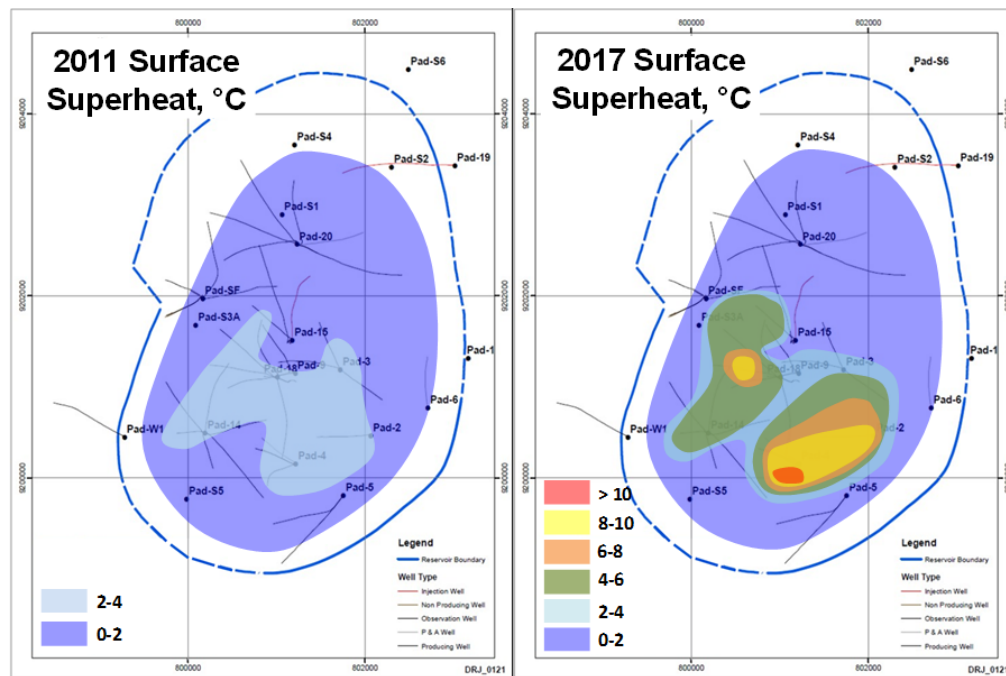


Figure 5. (Top) Contour maps of surface superheat during 2011 with infield injection and 2017 with edgefield injection. Superheat development occurred due to reservoir boiling and continued mass extraction with poor natural recharge.

As the reservoir continues to dry-out and develop superheat, an injection strategy different from the current edgefield injection is required at Darajat. Included in the different injection strategies currently under evaluation are the “trickle injection” approach where small amounts of liquid are injected into the areas of superheat and other potential hybrids that would combine deep injection with shallow “trickle injection”. These options are first being tested using the simulation model and will be pilot-tested in the field later.

4.3 Breakthrough of Edgefield Condensate Injection

In 2012, as part of the long-term injection strategy at Darajat Field, all condensate injection was shifted from the central portion of the field to DRJ-19 in the northeastern periphery (Figure 2). The change in injection location hastened boiling in Central Darajat as shown by increases in the production of Injection-Derived Steam (“IDS”) and deuterium and boron concentrations in the steam condensate (Figure 6). IDS provides a semi-quantitative method used in estimating the proportion of injected condensate being returned as steam (Rohrs et al., 2009). Mixing of the boiled injected condensate with reservoir steam results in lower NCG content in the produced steam, which offers an estimate of the percentage of IDS.

5. SUMMARY AND CONCLUSIONS

Recent reservoir characterization analyses have provided a better understanding of the conceptual model of the Darajat Field and information to better target make-up wells. Interpreting the volcano-stratigraphy of the rocks comprising the geothermal reservoir assisted delineate buried structures, and the overall history of the resource. Re-interpretation of the borehole image logs identified preferred trajectories for future make-up wells; thus, increasing their chances of encountering feed zones. Joint inversion of magneto-telluric and gravity data have provided a better resolution of the depths and aerial extents of a series of intrusive bodies that comprise the main reservoir rocks. Lastly, MEQ tomography inversion have resulted in more accurate hypocenter locations and a better-constrained interpretation of the reservoir’s base of the inter-connected fracture system.

Throughout the 24 years of commercial production, the Darajat Field has demonstrated performance characteristics typical of well-developed geothermal fields and vapor dominated fields in particular. Impacts from the central field condensate injection and scaling of several wells, have been effectively mitigated by moving all injection to near the northeast margin and implementing cost-efficient scale clean-outs. It is expected that continuous mass extraction may lead to reservoir dry-out at the central part of the field and possible reservoir cooling at the edge due to the impact of edgefield condensate injection and entry of cooler natural recharge. Ongoing reservoir surveillance, reservoir characterization studies, and lessons learned from other vapor-dominated geothermal fields are being leveraged to monitor these expected impacts and to provide the data and insights needed for implementing effective mitigation plans. SEG D expects to operate the Darajat Field and maintain high production levels into the foreseeable future.

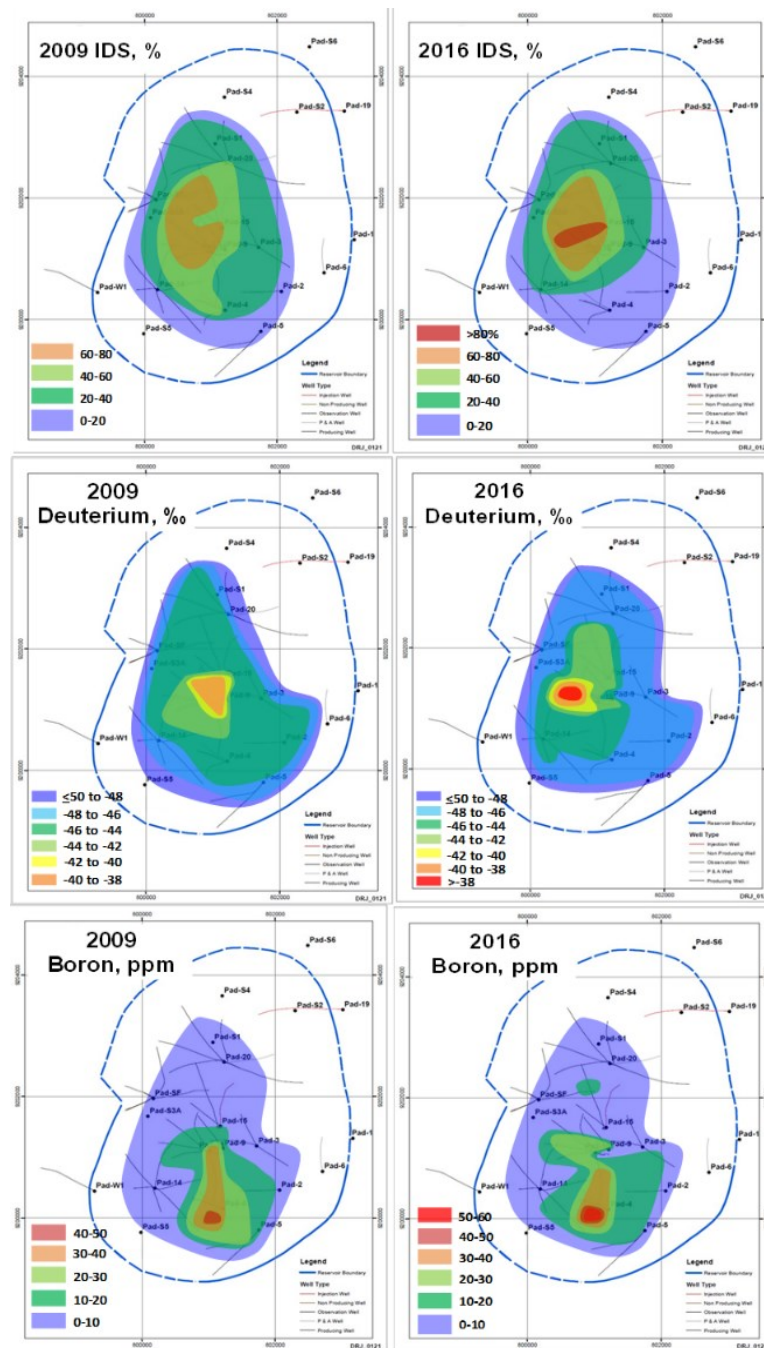


Figure 6. Maps showing changes between 2009 and 2016 in IDS concentration (in produced steam) and deuterium and boron concentrations (in steam condensate) at Darajat. The increases in IDS, deuterium, and boron are due to reservoir boiling in the central portion of the field after the termination of infield injection

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