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Improving the conceptual understanding of the Darajat Geothermal Field

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ABSTRACT

The Darajat Geothermal Field is the largest vapor-dominated geothermal field in Indonesia with an installed power generation capacity of 271 MWe. For the past 23 years, it has averaged about 90% net capacity factor since commercial operations started in 1994. From the initial 55 MWe, new increments of generation were added in 2000 (95 MWe) and in 2007 (110 MWe; later increased to 121 MWe in 2009). The drilling of wells to support these new increments of generation and continuous resource monitoring has provided key data for integration into the conceptual model and resource simulation modelling.

Recent reservoir characterization studies enabled the delineation of surface structures that impact the geothermal system, correlation of surface and subsurface rocks, determination of the orientation of fractures that correlate with feed zones encountered by wells, and better imaging of the reservoir through use of advanced geophysical interpretation methods. The above analyses have helped better define the conceptual model of the Darajat Field and provided information in targeting future make-up wells.

Star Energy Geothermal Darajat II (SEGD) takes a proactive approach to manage anticipated and emerging resource performance issues. A good example of this approach is provided by adjustments to the injection of steam condensate from the power plants. Injection initially utilized low productivity wells in the central portion of the field. Field monitoring through geochemical, downhole, and wellhead pressure-temperature ("**PT**") measurements indicated that this injection strategy had the potential to adversely affect production from nearby wells by suppressing aquifer boiling and lowering reservoir pressure. Consequently, in 2012, condensate injection was shifted to a new location near the Northeast margin of the field to utilize a well with deep entries. Based on experience and supported with case histories from other vapor-dominated fields, primarily The Geysers, deep injection beneath the feed zones of the production wells is effective at minimizing the impacts of injection breakthrough. Following the change in injection strategy, the central portion of the field has experienced renewed boiling, while only one production well is exhibiting early symptoms of chemical breakthrough from injection in the Northeast.

Going forward, expected reservoir management challenges include requirements to add new well pads and target production wells into undrilled areas, localized increased influx of external fluids as the reservoir pressure drops, and reservoir dry-out leading to high superheat levels and reduced well productivity. By continuing to leverage lessons learned to further improve reservoir management processes along with the proactive response to field management issues, SEGD anticipates that Darajat can maintain its production at current levels for the forseeable future.

1. Introduction

The Darajat Field, located in West Java about 230 km southeast of Jakarta, is currently the largest steam-dominated geothermal resource in Indonesia with an installed capacity of 271 MWe (Fig. 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. 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). A digital elevation model of the Indonesian Archipelago shows a significant concentration of active and inactive volcanoes in the West Java province in some unlike other areas in Indonesia (Fig. 1). The presence

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Fig. 1. Top figure is a digital elevation model showing the topography and bathymetry of the Indonesian Archipelago (from Hall, 2009). Note the large concentration of volcanoes in West Java which differentiates this province from most of the rest of Indonesia. Bottom map shows the province of West Java (Jawa Barat) and the geothermal fields it hosts. Geothermal fields shown as polygon are those operated by Star Energy Geothermal; those in circles are operated by other companies.

of these numerous heat sources and active tectonism probably created the right conditions for geothermal systems to form in this part of the country.

Commercial production commenced at Darajat in 1994 with the commissioning of the 55 MWe Unit 1 (Fig. 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 unit owned by PT PLN (Persero)("**PLN**") and operated by PT Indonesia Power, PLN's subsidiary), and produces electricity from its Units II & III.

For the past 23 years, the Darajat Field has performed well steam supply maintained by managing resource-related issues as they have arisen and drilling makeup wells as needed. For example, implementing edgefield condensate injection, starting in 2012, arrested reservoir cooling due to infield injection, which was in effect 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 reservoir dry-out and expected increased issues with wellbore scaling. Make-up well drilling from new pad locations outside of currently drilled areas and, as the reservoir pressure continues to decrease. 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

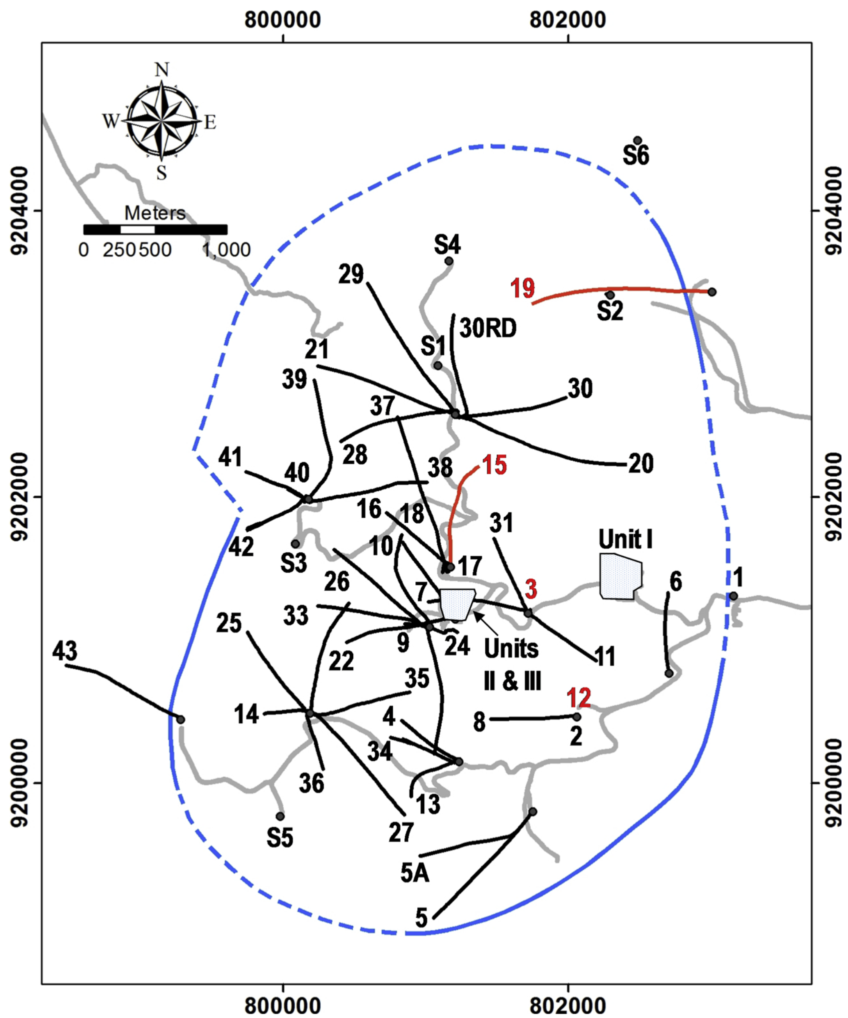

Fig. 2. Map of the Darajat Geothermal Field showing the drilled wells (solid line for producers and dashed for injectors), commercial production boundary (polygon; dashed where poorly constrained by drilling), and road network (gray). DRJ-19 is the current condensate injector while DRJ-3, 12 and 15 are back-up injectors. The slimholes are designated by "S".

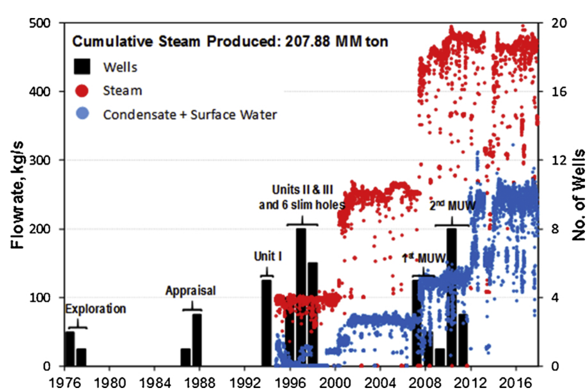

Fig. 3. Historical steam and power plant condensate production and wells drilled at the Darajat Field. The six slim holes drilled during 1996-1998 were part of further delineating the geothermal resource. The power plant condensate volume includes some surface water that accumulates in surface facilities. Note that there was less condensate (and surface water) injected during the make-up well (MUW) drilling campaigns because condensate was used to drill the wells.

Table 1
Current Well Status at Darajat Field

Well Type	Number of Wells
Producers	34
Condensate Injectors	3
Observation	2
Plugged & Abandoned (P&A)	10
Total	49

reservoir. Integration of these interpretations into the conceptual model results in refined make-up well targeting. For reservoir dry-out, plans are underway to review options suggested by the experience from other operators from The Geysers (Sanyal and Enedy, 2010; Khan, 2010), Larderello Field, Italy (Cappetti et al., 1995), and other fields with mature steam caps (e.g., Salak; Mak-Ban and Tiwi, Philippines). The experience from these fields has led the SEGD team to look at various injection strategies including "trickle" injection into the shallow reservoir and hybrid deep and trickle injection. Reservoir simulation is ongoing to evaluate these strategies which would then be followed with phased-in pilot testing.

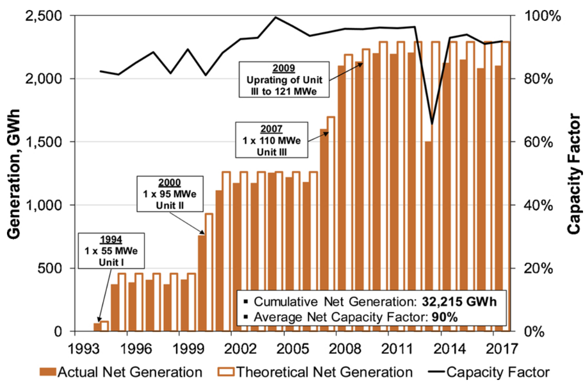

Fig. 4. Annual actual and theoretical net generation and net capacity factor of the Darajat Geothermal Field. The low availability factor in 2013 was due to problems with the Unit II generator. Since 2016, PLN, the state-owned power company, has curtailed Units II and III to allow dispatch of otherpower plants into the national grid.

2. Production and generation history

Geothermal investigations at Darajat began in the early 1970's when the Indonesian Government carried out a surface reconnaissance survey with the assistance of New Zealand foreign aid (Whittome and Salveson, 1990). The exploration survey identified the existence of a potential geothermal resource. The vapor-dominated reservoir was confirmed with the drilling and testing of three exploration wells (DRJ-1, 2, and 3) during 1976-1978 (Fig. 3). In 1987-1988, four deep appraisal wells (DRJ-4, 5, 6, and 7) with depths greater than 1,600 m 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). Development drilling in 1994 provided four commercial producers (DRJ-8, 9, 10, and 11), and the first 55 MWe power plant (Unit I) at Darajat was commissioned in late 1994 (Fig. 3).

The 1996-1998 production and exploration drilling campaign aimed at developing about 140 MW of steam and prove additional reserves, and included the drilling of six continuously cored slim holes designated as S1 to S6 (Fig. 2). This drilling campaign was very successful and added 275 MWe equivalent of steam with the biggest well producing about 40 MWe and four other wells exceeding 30 MW each (Berry, 1998). During 2007-2008, seven make-up wells augmented steam supply to Unit III. The second production make-up drilling campaign, consisting of 11 wells, was in 2009-2011 (Fig. 3). To date, the Darajat Field hosts 49 wells (Table 1).

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 GW h of electricity (Figs. 3 and 4). A comparison of the actual versus theoretical net generation indicates that the Darajat Field has averaged about 90% net capacity factor annually since commercial production began in 1994 (Fig. 4). 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 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. 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 have a greater impact in the future.

3.1. 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 (Fig. 5). 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 (Fig. 5). 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 south-eastern 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 N_2, CH_4, and NH_3 and stable isotope composition shifted towards meteoric waters characterize the MR in the central portion of the field.

At Darajat, and similar to Salak Field (Julinawati and Utami, 2018), the presence of MR coincides with wells that experience wellbore scaling (Fig. 6). Scale deposition has reduced the productivity of wells that necessitated their periodic cleaning. Aside from acid stimulation, some of the cost-effective well workovers currently used at Darajat are the mechanical scale clean-out using the coiled tubing-conveyed rotary jetting and, more recently, wireline-conveyed broaching tools (Cita et al., 2017; Hadi et al., 2014; Fuad et al., 2014). These mechanical scale clean-out techniques have been effective in regaining the productivity of scaled wells.

With continued production and declining reservoir pressures at Darajat, there is an increased risk for influx of cold MR. Sunio et al. (2010) reported an increase in cooler fluid inflow into the mature steam cap after about 30 years of commercial production at Mak-Ban Field, Philippines. At Mak-Ban, drops in steam production by as much as 50 kg/s per year were reported in 2011-2012 (Vicedo, 2012 in Sunio et al. 2015). Although Mak-Ban is not a vapor-dominated system, it has a mature steam cap separated from the brine reservoir, which may be an analog to the Darajat 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. 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.

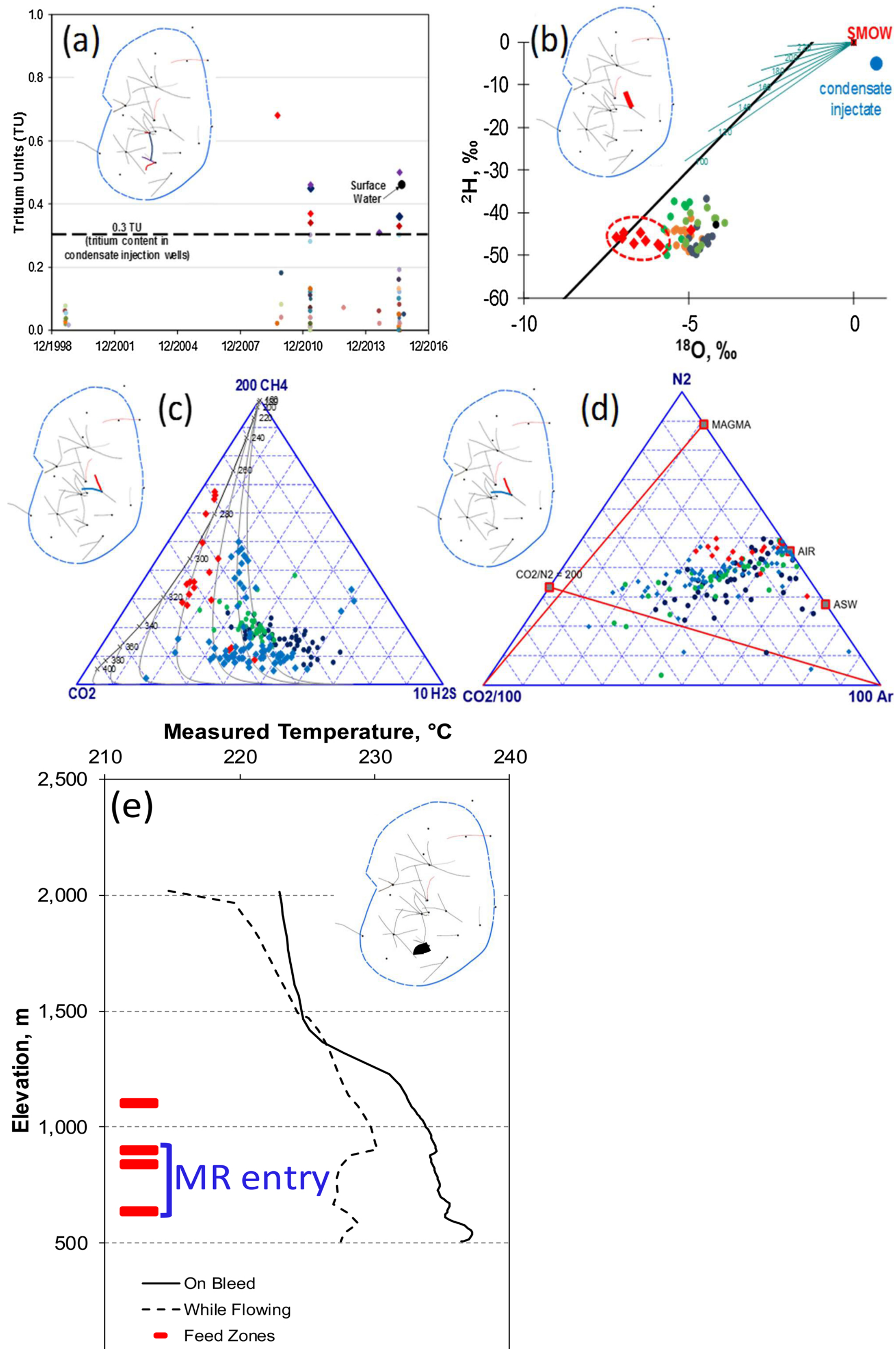

Fig. 5. (a) to (d) Charts showing typical chemical species used to determine the presence of cold MR at Darajat. (a) The Darajat reservoir has very low tritium (< 0.1 TU) concentration and elevated tritium concentration (> 0.3 TU) suggests that young groundwater (or MR) is present in some southern wells. (b-d) In Central Darajat, at least one production well consistently exhibits enrichments in 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.

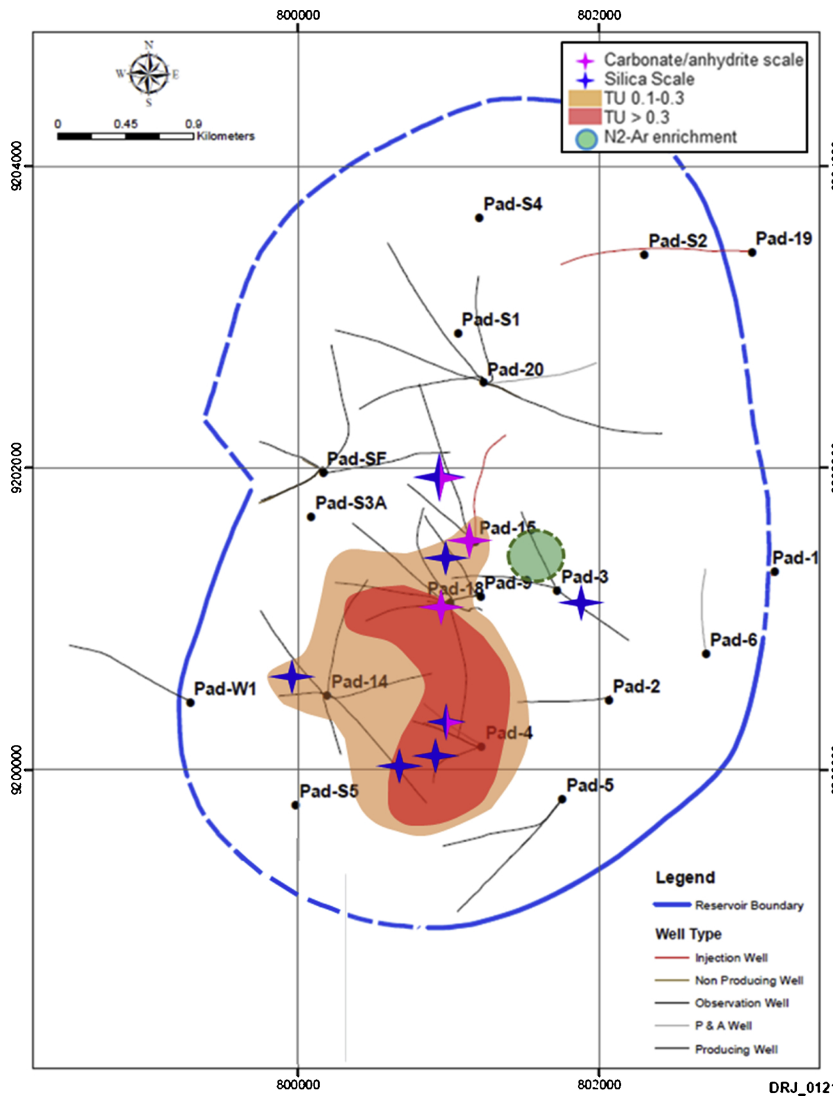

Fig. 6. Map of Darajat showing the area with high tritium anomaly (shaded region). Note that the shaded area mostly overlaps with the wells with wellbore scaling history. The green circled area represents the N_2-Ar enrichment observed at DRJ-31, a well that produces some liquid entrained with the steam.

3.2. 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 superheating, 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. Cases of dry-out in the reservoir at The Geysers, U.S.A. and at the western steam cap at Tiwi Field, Philippines are good analogues for the Darajat Field. At The Geysers, Haizlip and Truesdell (1999) reported that reservoir dry-out was characterized by high chloride concentration (10-120 mg/kg), increase in NCG, hydrogen sulfide and ammonia, and reservoir superheat (about 10-45 °C). At Tiwi Field, reservoir dry-out was distinguished by increases in chloride and NCG in steam, boron in the steam condensate, and surface superheat (Molling and Villaseñor, 1999). In both fields, a decline in steam production accompanied the chemical changes and increase in superheat.

Increases in both surface superheat and NCG that correlate with increasing production decline rate could indicate reservoir dry-out at Darajat (Fig. 7). Surface superheat, measured using non-isokinetic sampling probe on a monthly basis, is ~5 °C lower than reservoir superheat estimates from annual pressure and temperature measurements[1] . The trend of the surface superheat measurements, not the absolute values, is used to evaluate changes in reservoir superheat conditions. Surface superheat is used as a proxy for monitoring reservoir superheat condition because surface measurements are quick and easy to conduct and can be done frequently. Actual values of reservoir superheat can be more accurately determined with downhole surveys.

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 °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

[1] The power plant shutdown schedule governs when pressure, temperature and other surveys can be conducted; thus, not all wells have annual pressure and temperature data.

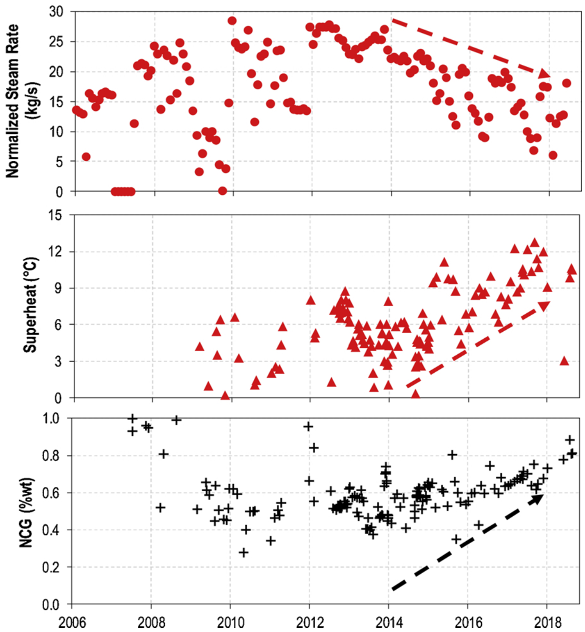

Fig. 7. The increase in decline rate in a Darajat production well correlates with increases in both superheat and NCG concentration suggesting possible reservoir dry-out in the area. This particular well is located at the southern part of the field, which is interpreted to have lower reservoir quality. Both steam rate and superheat were estimated at similar flowing wellhead pressure.

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 (Fig. 8). The highest surface superheats ($> 10\,^{\circ}C$) are observed at southeastern Darajat where reservoir porosity and permeability are relatively lower (Rejeki, 2001).

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.

3.3. 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 (Fig. 2). The change on 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 (Fig. 9). IDS provides a semi-quantitative method 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.

At The Geysers, Enedy et al. (1993) identified wells that are producing injected condensate through the increase in their deuterium content and IDS production. After nearly six years of edgefield injection at Darajat, only one deep production well near the northeastern injector appears to be showing an early chemical signature of condensate injection breakthrough. Fig. 10 shows the lowering trend of deuterium in the deep producer in Pad 20. However, the IDS production in this deep producer at Darajat is relatively low at about 20%. Analysis of microearthquakes (“**MEQs**”) suggests that the injected condensate at the northeastern edge of the field is moving towards the west and deeper than the edgefield injection well (Paramitasari et al., 2018) supporting the interpretation of possible condensate injection breakthrough. A surveillance program consisting of periodic gas and stable isotope sampling of wells near the edgefield injector and analysis to monitor condensate injection breakthrough is in effect.

4. New insights into the conceptual model of the darajat geothermal system

A well-constrained and credible conceptual understanding of the geothermal resource that can be translated into Earth and Simulation Models is critical. This provides the backbone required for developing reservoir management plans and simulation models that can produce credible forecasting, for example, of different injection strategies to mitigate reservoir dry-out and superheat.

Key elements of the Darajat geothermal system have been described in several publications: a high-temperature, vapor-dominated reservoir with benign chemistry and ≤ 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 (Fig. 11). 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 Cibeureum and Toblong Springs in the east.

Hydrothermal alteration assemblages and their paragenesis indicate that a water-dominated hydrothermal system existed prior to the formation of the current vapor-dominated geothermal system (Hadi, 2001; Moore, 2007). This water-dominated geothermal system may have had fluids in excess of 300 °C as shown by high-temperature minerals such as garnet and actinolite in the propylitic hydrothermal mineral assemblage (Herdianita et al., 2001). The main Darajat geothermal reservoir is contained in the Andesite-Intrusive Complex, which is believed to be part of the heat source of the former hot water-dominated geothermal system (Golla et al., 2017). Moore (2007) postulated that a massive decompression event led to the demise of the water-dominated geothermal system and that the Andesite-Intrusive Complex is the subvolcanic portion of that geothermal system. The Andesite-Intrusive Complex consists of andesite lava and subordinate pyroclastic breccias intruded by diorite to microdiorite dikes and sills (Moore, 2007).

At the edge of the production area, epidote occurs at relatively shallow elevation and with measured temperatures in wells below 220 °C. This relict epidote may be related to the earlier water-dominated geothermal system; thus, it is not a good mineral geothermometer in this portion of the field. In the core of the production area, the

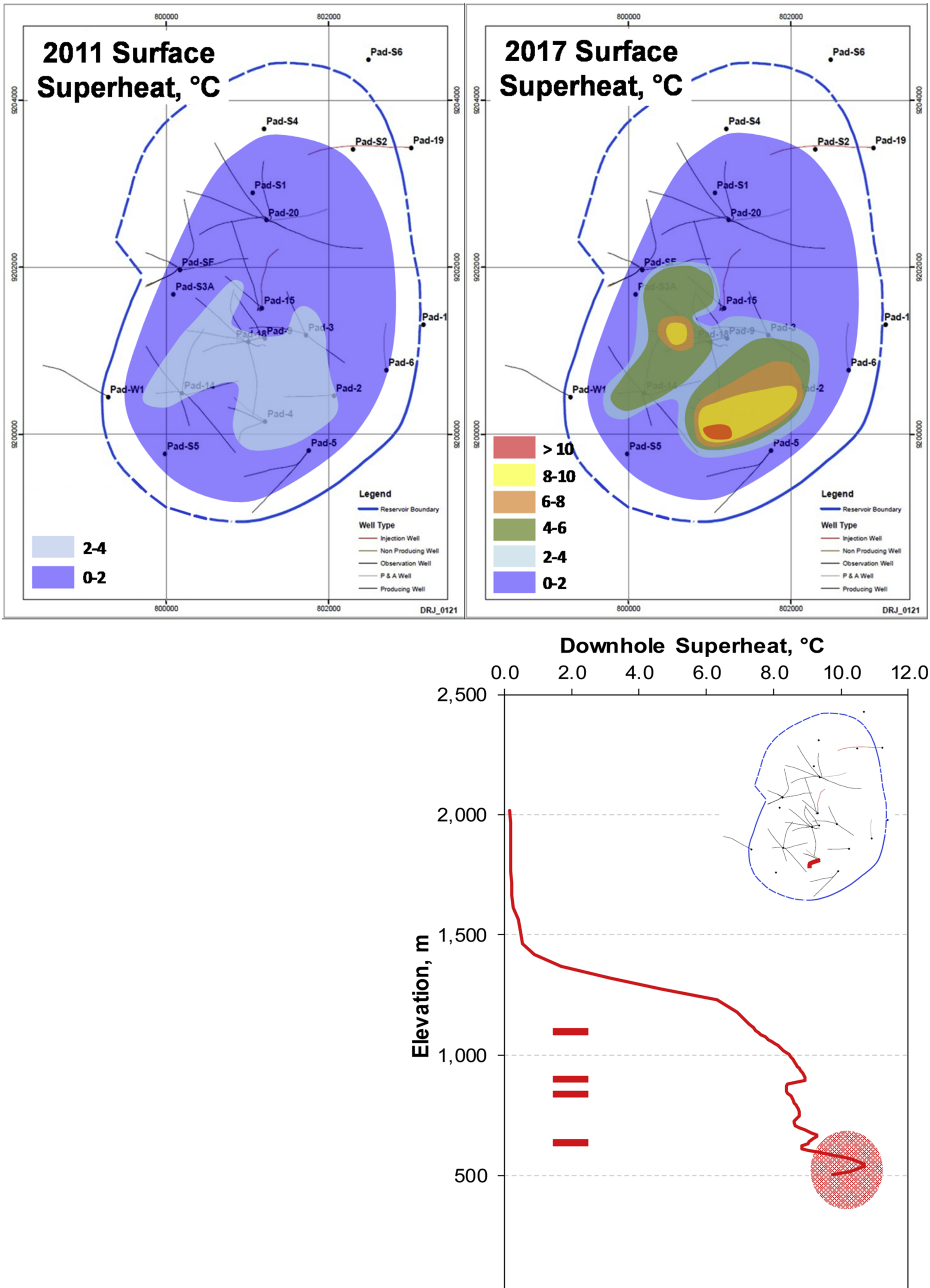

Fig. 8. (Top) Contour maps of surface superheat during 2011 with infield injection and 2017 with edgefield injection. Superheat development occurred due to reservoir boiling and continued mass extraction with poor natural recharge. (Right) Estimated reservoir superheat in one of the southern wells, which validates the contour map of surface superheat in 2017 (top, right).

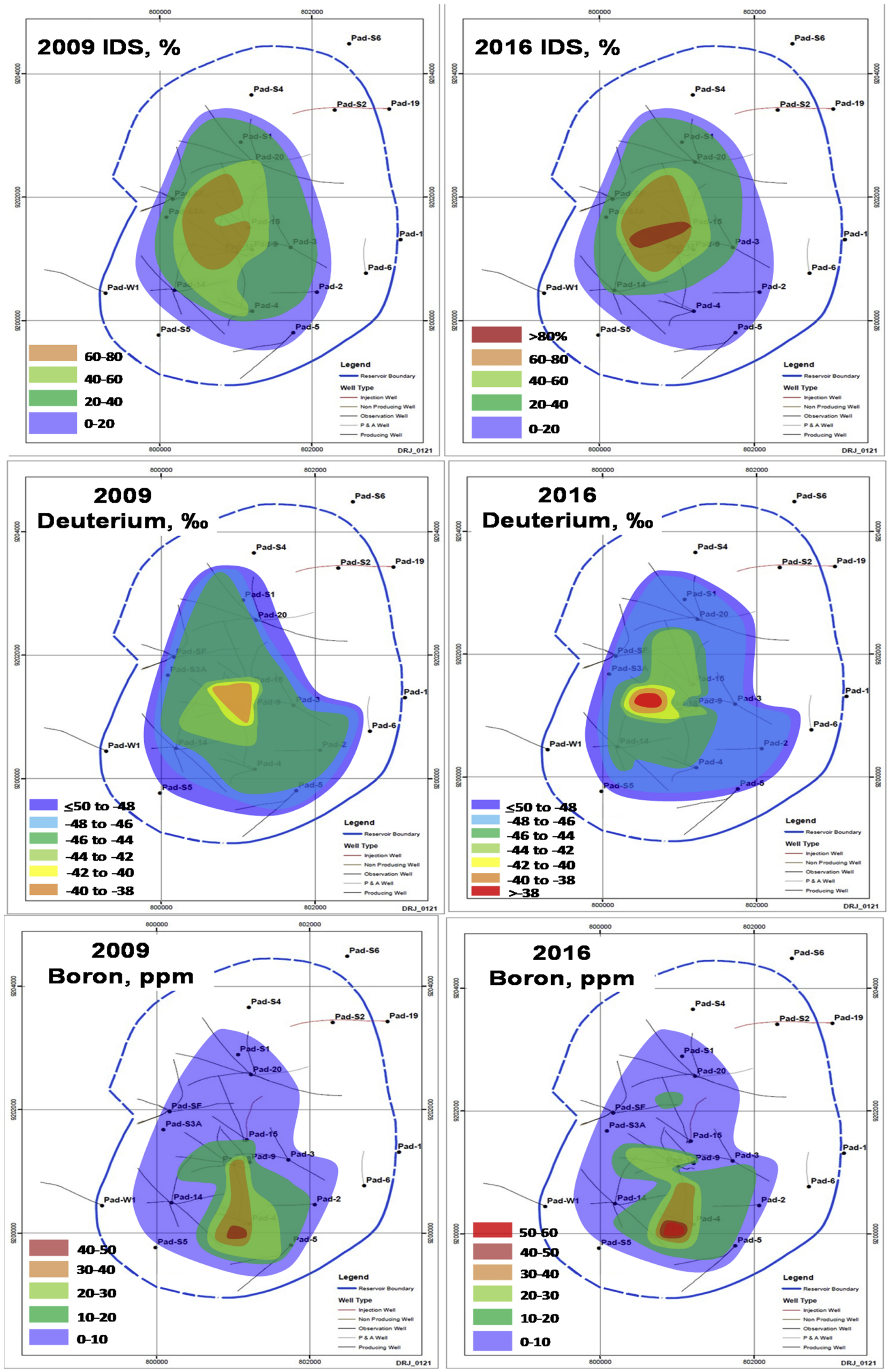

Fig. 9. Maps showing changes between 2009 and 2016 in IDS concentration (in produced steam) and deuterium and boron concentrations (in steam condensate) at Darajat. The increases in IDS, deuterium, and boron are due to reservoir boiling in the central portion of the field after the termination of infield injection.

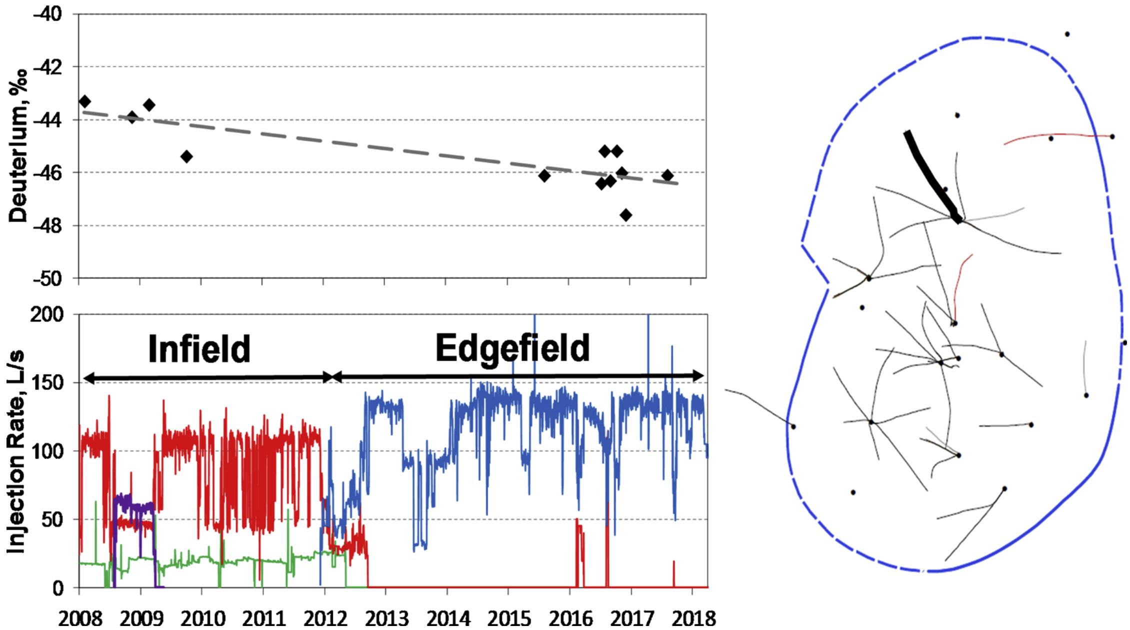

Fig. 10. Chart showing the lower deuterium content of the deep producer at Pad 20 (top) which coincides with the change from infield to edgefield injection (bottom). The map on the right shows the deep producer (thick solid line) suspected to be showing early signs of injection breakthrough from the northeastern edgefield injector (thick dashed line).

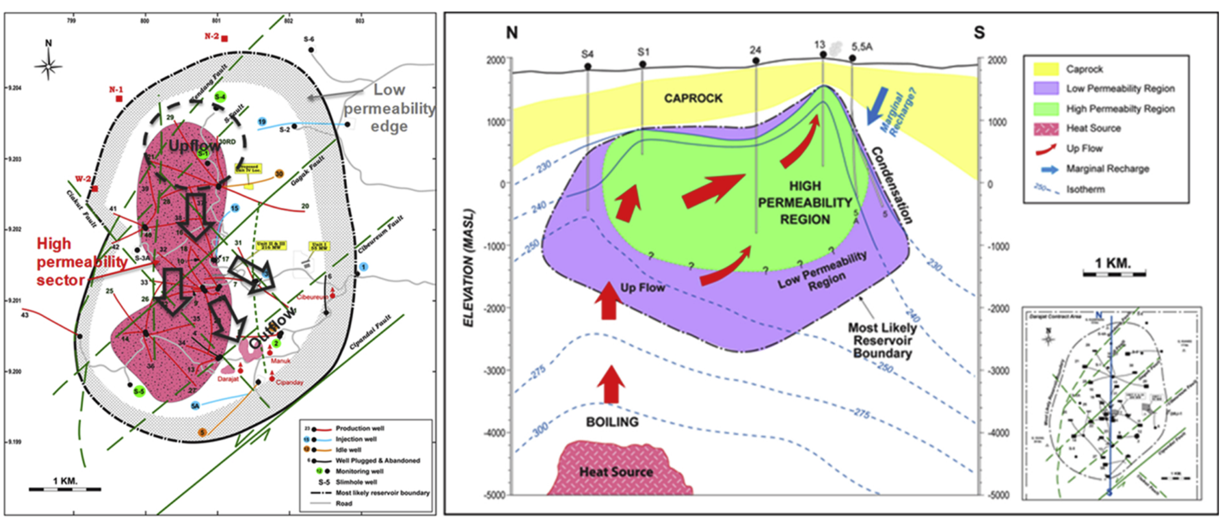

Fig. 11. (Left) 2012 map showing the main components of the Darajat geothermal system. Fluids upflow in the north, move towards the south and east, and finally outflow in the fumaroles and springs. There is a north-south core of relatively high permeability in West Darajat while reservoir permeability decreases at the edge of the reservoir. (Right) A 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.

hydrothermal alteration assemblage is in equilibrium with measured well temperatures.

Since the last published account of the conceptual model of the Darajat geothermal system by Rejeki et al. (2010) and unpublished work done by Pasaribu et al. (2012) and Rohrs et al. (2009), various reservoir characterization studies have been undertaken to better understand this vapor-dominated resource. These studies were based on new subsurface data collected during the 2009-2011 drilling campaign, re-interpretation of borehole image logs, observations from surveillance programs, and application of modern interpretation techniques on existing data. These reservoir characterization studies enabled the updating of the 3D Earth and Dynamic Models and added to the understanding of the Darajat geothermal system.

4.1. *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

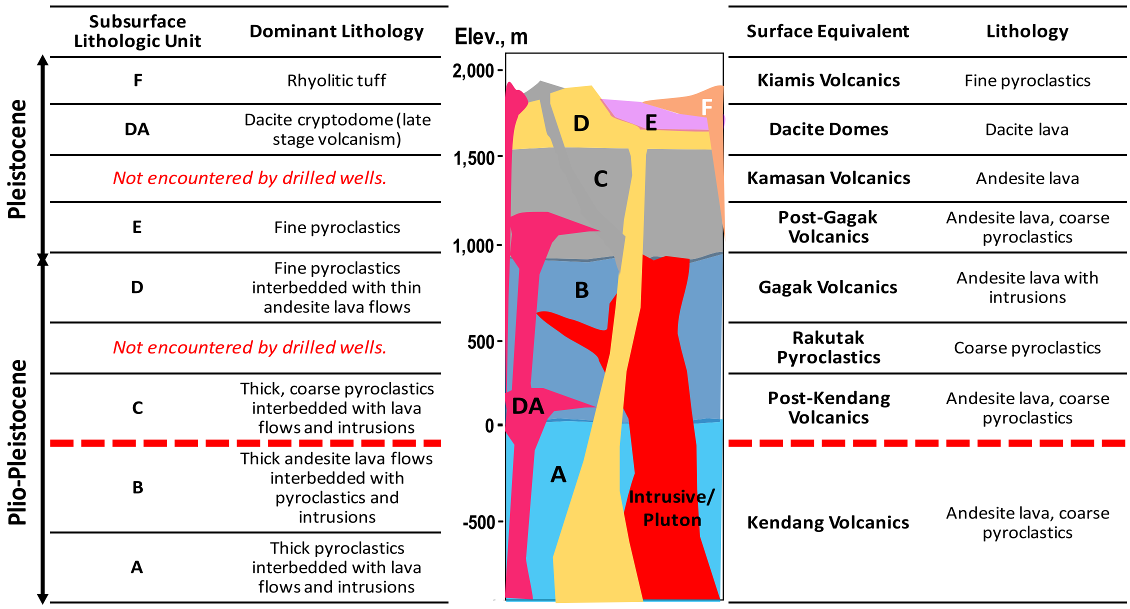

Fig. 12. Schematic diagram showing the interpreted stratigraphy and correlation between surface and subsurface rocks at Darajat Field. Both the Kamasan Volcanics and Rakutak Pyroclastics, located northeast and north of the production area, respectively, appear to be absent in subsurface rock samples. The thick 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.

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 (Fig. 12). Previous workers have identified 12 volcanic facies or lithologic units (Rejeki et al., 2010) but re-analysis of rock samples and thin sections failed to identify the mafic basaltic lava flows, which constitute at least three volcanic facies in earlier analyses. Gamma Ray ("**GR**") logs show high GR values in the previously identified basaltic rocks suggesting that these lava flows are intermediate to felsic, or have higher alkali content than the more mafic rocks. Normally, GR logs are used to identify pure sandstone and shale. However, Stefansson et al. (2000) used GR logs to document that silica-rich volcanic rocks in Iceland have high GR values. We think that the same findings in Iceland are applicable to the volcanic rocks in Indonesia. Satya et al. (2017) also reported the rhyolitic dacite marker that is silica-rich at Salak Field has relatively higher GR count.

The Andesite-Intrusive Complex, which comprises the Darajat geothermal reservoir and the hypothesized sub-volcanic portion of an earlier liquid-dominated geothermal system, belongs to the Kendang Volcanics and makes up subsurface Units A and B (Fig. 12). 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 intrusives 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 (Fig. 13). 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. Lastly, integration of the provisional reservoir stratigraphy delineated the Ciakut structure, which appears to be a product of a sector collapse inside the Gagak caldera (Fig. 13). Work is underway to complete petrographic analysis of infill samples, collect samples for possible age dating, and integration of these data into a coherent volcano-stratigraphy of the Darajat Field.

4.2. 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 (Golla et al., 2017). 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 (Fig. 14). 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

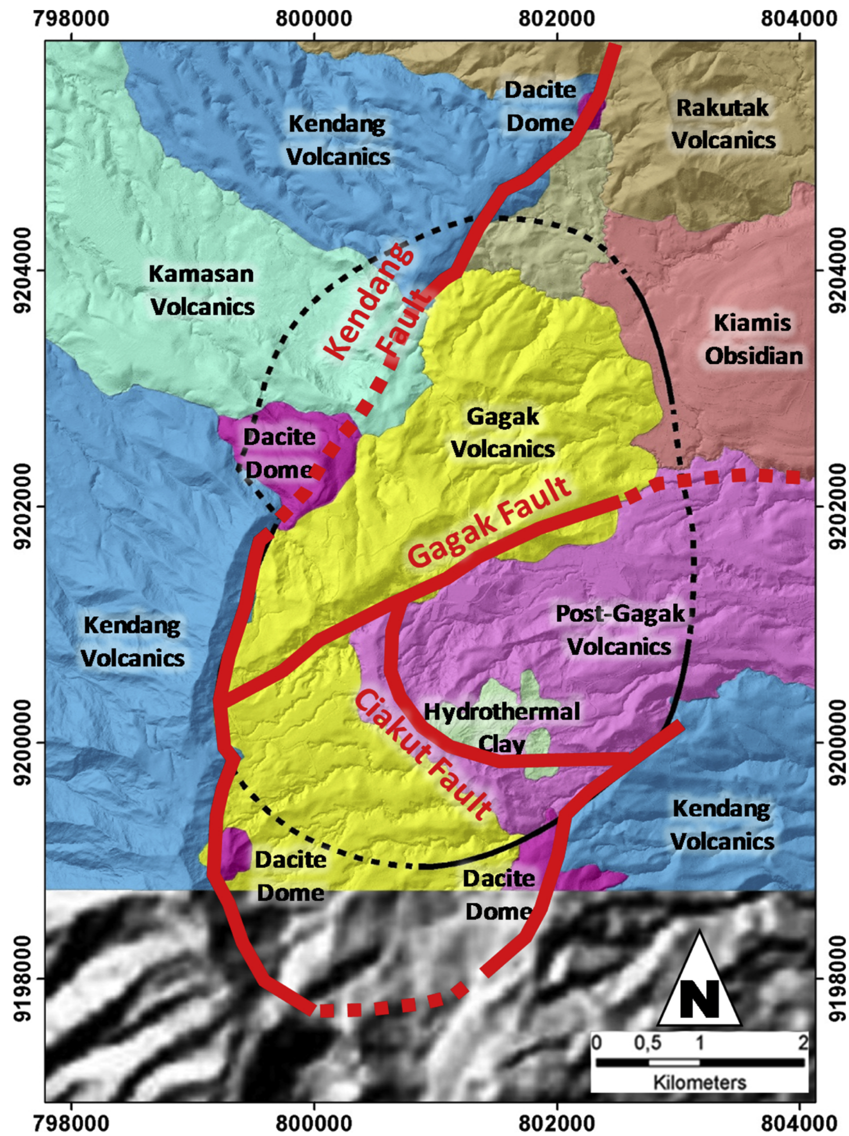

Fig. 13. Provisional geological map of the Darajat Field showing the interpreted structures based on LiDAR data and offset of reservoir rocks. Both Kendang and Gagak are prominent on the surface while Ciakut is buried; structures are dashed where inferred. The LiDAR data covers the colored portion of the map only. Colors correlate with the subsurface rocks in Fig. 12.

fracture orientations (Gunderson, 2015).

Moreover, the majority of the feed zones do not correspond with just a single, prominent fracture. Fig. 15 shows that only 34% of the feed zones correlated with an individual fracture. It was not clear in the rest of the feed zones where the produced geothermal fluids are coming from; thus, multiple or groups of fractures were selected in 63% of the productive entries. These "Groups of Fractures" are assemblages of typical relatively small-aperture open fractures thought to represent the feed zone when a single prominent fracture with large aperture is absent. Lastly, only two feed zones occurred at lithologic contacts indicating that lateral permeability is limited at Darajat Field.

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 (Fig. 16). 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 (Fig. 17). 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

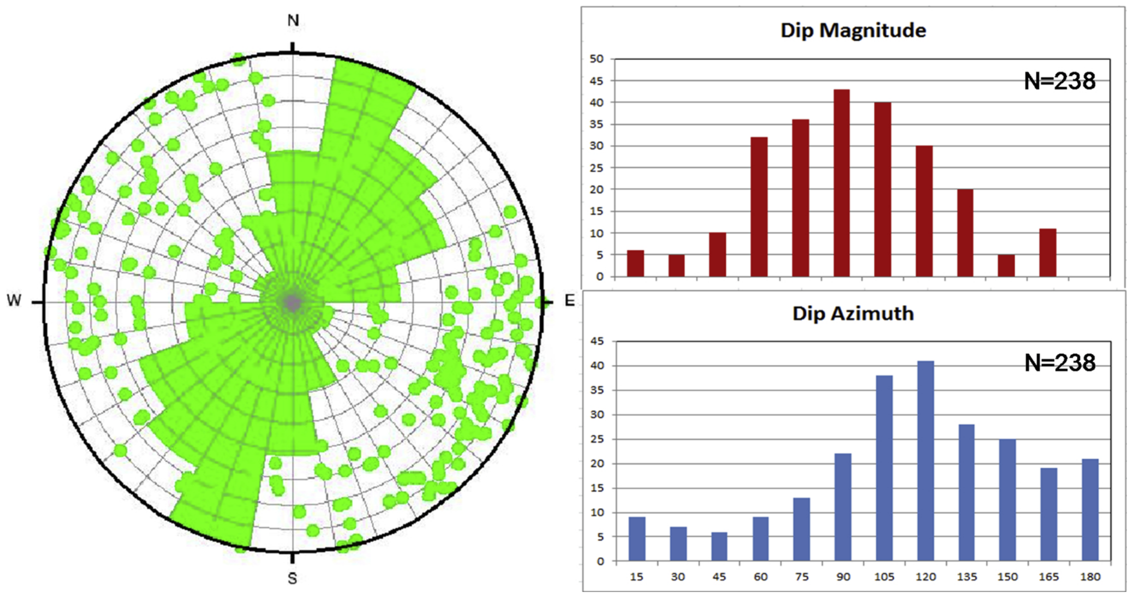

Fig. 14. Rose diagram (in 10° increments) showing the NNE-SSW strike orientation of effective fractures at Darajat. The circles represent the direction and magnitude of the dips of these effective fractures. (Right) Histograms showing the dip angle magnitude (above) and dip orientation (bottom) and of the Darajat effective fractures.

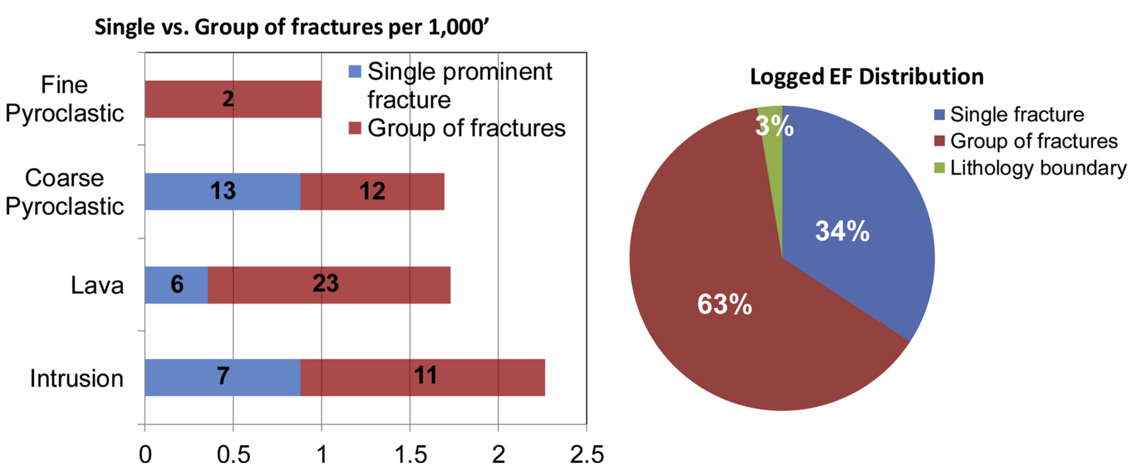

Fig. 15. (Left) Bar chart showing the types of effective fractures encountered in various lithologies per 1,000' of drilled reservoir at Darajat. The numbers inside the bars denote the number of feed zones per lithology. (Right) Pie chart showing about 63% of feed zones correlate with multiple fractures, 34% correspond to single fractures, and only 3% (two feed zones) are related with lithologic contacts.

Central Darajat where the effective fractures have a NE-SW strike direction but ± 50° 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 (Fig. 17).

The above information has been used to plan and target make-up wells in the forthcoming drilling campaign at Darajat in 2019. For example, the Andesite-Intrusive Complex and the upflow location in northwestern Darajat are now prime targets for permeability. Drilling wells with deviations to the northwest or southeast and perpendicular to maximum horizontal stress, on average, will encounter more feed zones. However, a different strategy may be required when drilling wells at the periphery of the field as the orientation of the effective fractures is more variable.

4.3. Improving imaging of the reservoir through geophysical joint inversion

To improve the resolution of potential well targets, such as into the Andesite-Intrusive Complex, SEGD 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

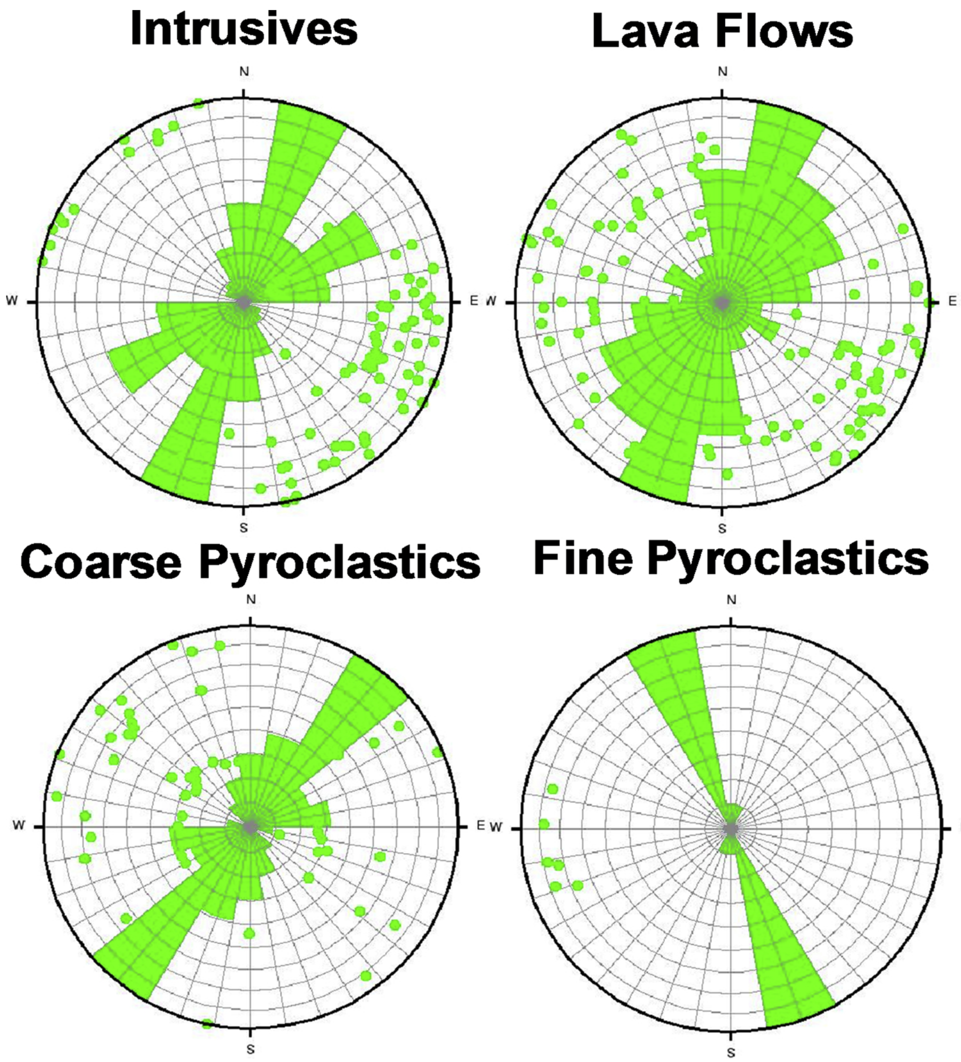

Fig. 16. Rose diagrams showing the strike orientation (bars or petals) and dip azimuth and magnitude (circles) of effective fractures in each of the rock type comprising the Darajat reservoir.

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 (Fig. 18). This high-density trend coincides well with the where the shallow microdiorite intrusions have been encountered in the central and southern wells (DRJ-14 and 18 locations in Fig. 2) and northernmost 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.

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 (Fig. 19). Geologic evidence also supports the results of the joint resistivity inversion west of the Kendang Fault as shown by the contrast in alteration and lithology types in the DRJ-43 as well as significantly lower Methylene Blue values in rock cuttings (Soyer et al., 2017). Methylene Blue ("**MeB**") is an organic dye that exhibits a high selectivity for adsorption by smectitic clays (Harvey et al., 2000). During drilling of a geothermal well, MeB titration is performed on a suspension of rock washed and ground cuttings to quickly estimate the

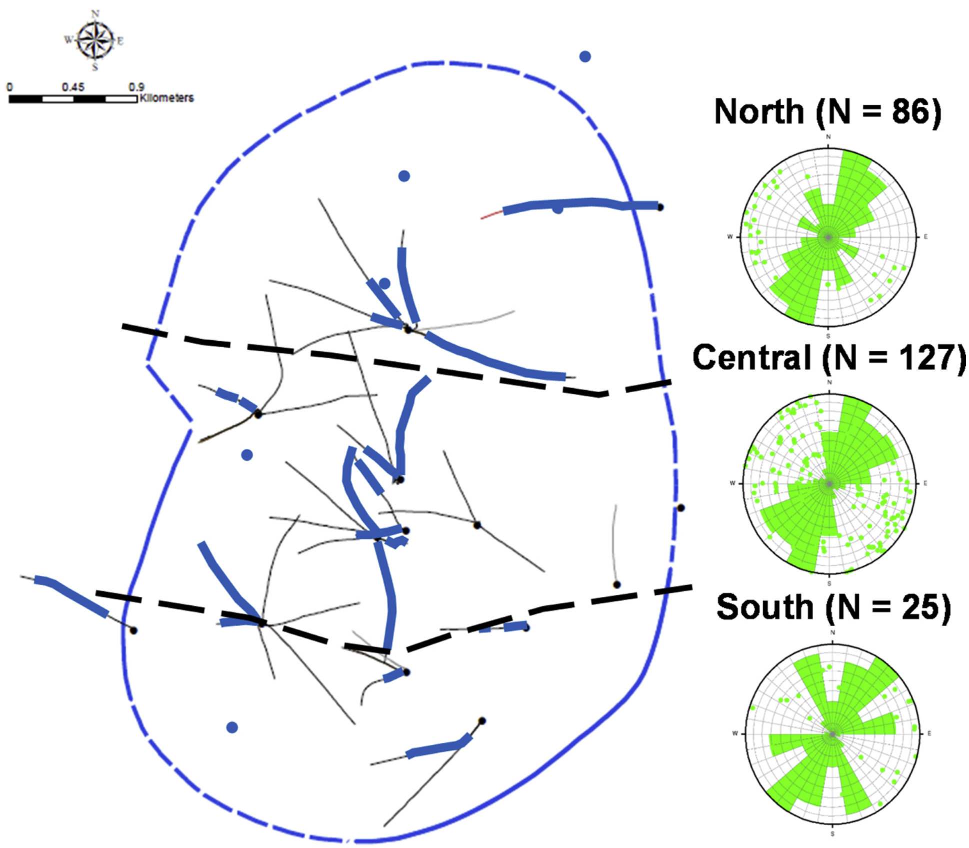

Fig. 17. Rose diagrams showing the strong NE-SW trend of the effective fractures in wells (excluding the slim holes) drilled in north and central Darajat inside the production area (polygon; dashed where poorly constrained by drilling) while effective fractures in south Darajat exhibit more variation. The subdivision of the Darajat Field into three sectors was arbitrary. "N" refers to the number of effective fractures represented in each rose diagram. The thick lines along the well trajectories indicate the portion of the well with borehole image data.

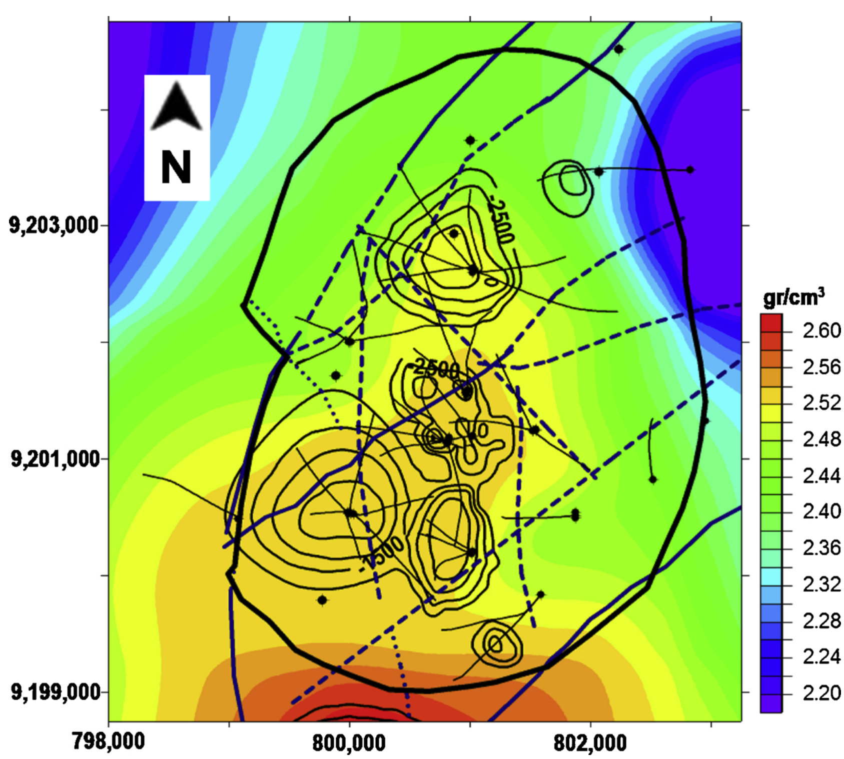

Fig. 18. Map showing density values at Mean Sea Level (MSL) from the joint inversion. The south-north trending higher density feature has been co-located with the currently modeled microdiorite intrusion (shown in elevation contours, m) in the 3D Static Model.

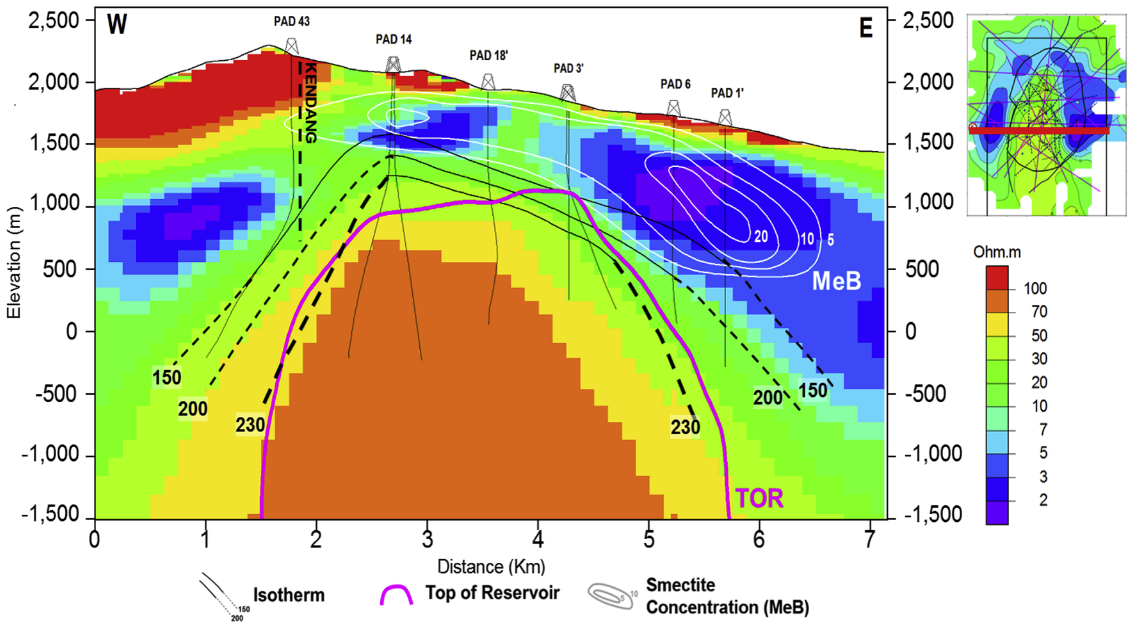

Fig. 19. Cross-section showing the resistivity distribution west of Pad 43 to east of Pad 1. Note the separation of the low resistivity (< 10 ohm-m) conductor bodies near the Kendang Fault. DRJ-43, on Pad 43, did not encounter significantly high concentrations of smectite from MeB analysis. The low resistivity anomalies west of DRJ-43 and east of Pad 1 are attributed to basinal clays and not the hydrothermal clay associated with the Darajat geothermal system. The extensions of the 230 °C isotherm are inferred from the outermost wells.

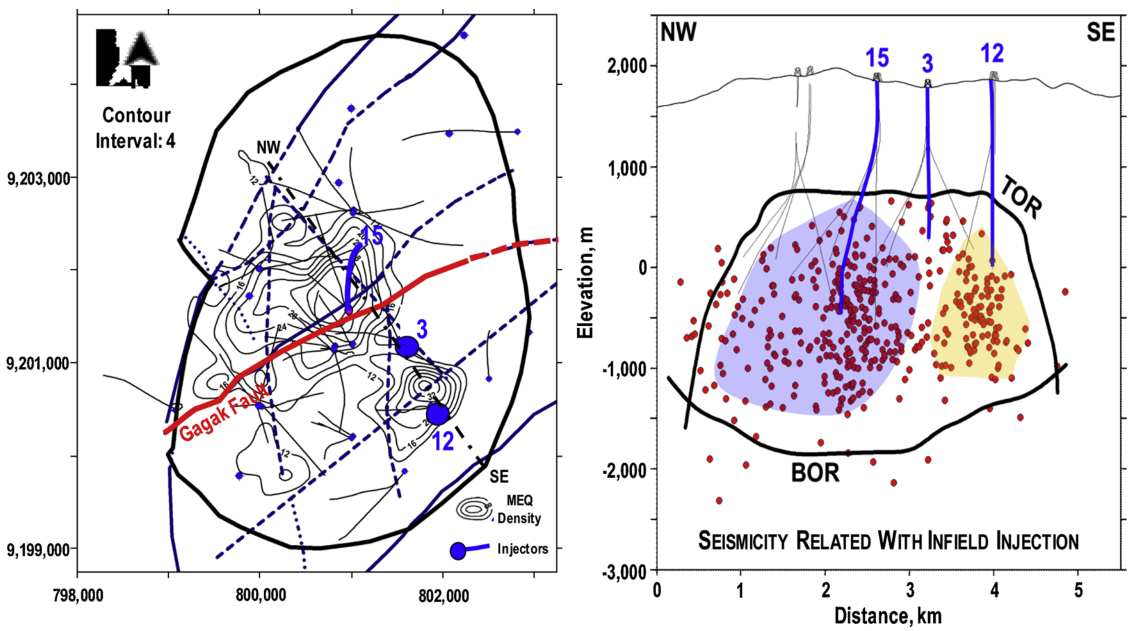

Fig. 20. (Left) MEQ density contours during 2006-2011 representing the period when power plant condensate was injected infield. (Right) Cross-section showing the depths where MEQs occur at Darajat. Note that MEQs occur significantly below the well completion depths, indicating the likely extent depth of the fracture network.

smectite content in the rocks.

4.4. Using microearthquakes (MEQ) for reservoir characterization

Since 2006, SEGD has continuously monitored MEQs, associated with both production and injection activities using a 10-13 station network (Nelson et al., 2018). The majority of these MEQs are related to the injection of power plant condensate and to lost circulation during drilling activities, when the condensate is used to drill the production hole section of the wells. Typical condensate injection rates during the drilling of the production hole section is around 65 kg/s (which constitutes almost half of the total power plant condensate produced at

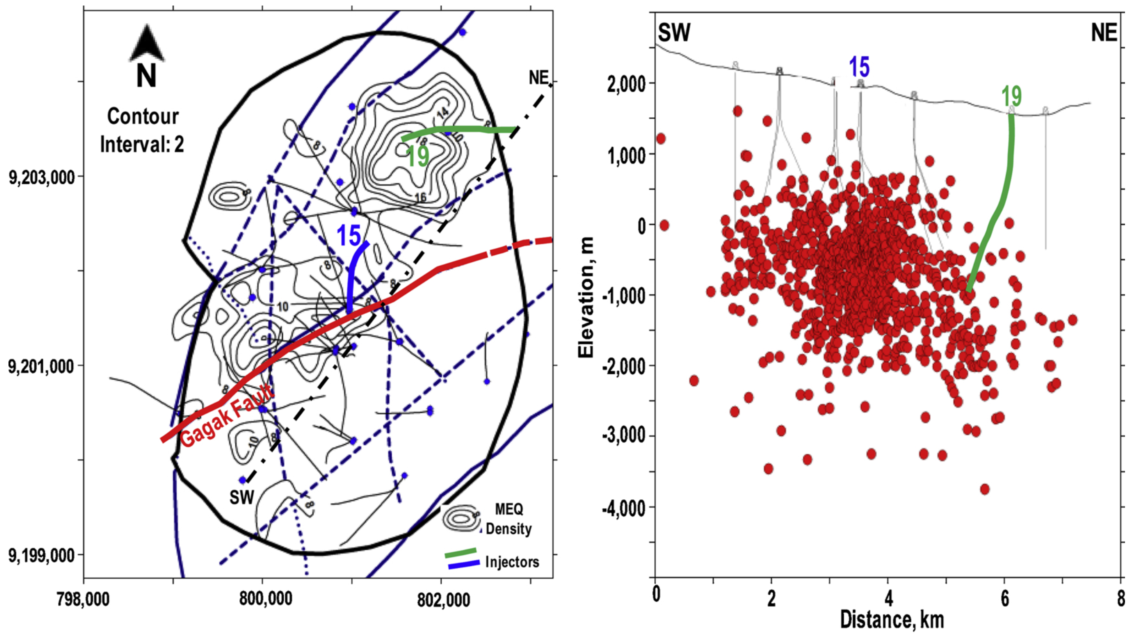

Fig. 21. (Left) MEQ density contours during 2012-2018 when condensate was injected into edgefield well DRJ-19. Note that most of MEQs occur northwest of the Gagak Fault suggesting that this structure may be a compartment boundary in the reservoir. Similar with Fig. 20, the cross-section at the right shows that the MEQs occur deeper than the well's total depth (TD).

Darajat). The primary induction mechanism appears to be the cooling of reservoir rocks and transient pressure increases that occur along the movement paths of the injected condensate (Nelson et al., 2018; Stark, 2003). The interaction of the 40 °C condensate as it moves through the reservoir's fracture system cools the hot reservoir rocks. This cooling results in contraction and lessening of the frictional forces across the fracture and eventually allows failure to take place.

Fig. 20 shows a map of MEQs density contours (epicenters binned at a 250 m x 250 m-grid) based on observed MEQs during the period 2006-2011 when power plant condensate was injected infield into DRJ-3, 12 and 15. Note that the MEQs were concentrated parallel with the NE-SW trending Gagak Fault with the majority on the northwestern flank of the fault. The cross-section shows that most of the MEQs occur deeper than the TD of the wells, reaching as deep as -2,500 m, indicating the stimulation of the deeper connected fracture system of the reservoir (Nelson et al., 2018). This general characteristic of the MEQs is interpreted to map fluid pathways and the base of reservoir ("**BoR**") (Intani and Mahagyo, 2014).

When edgefield condensate injection at DRJ-19 commenced in 2012, the MEQ density contours changed significantly. During 2012-2018, the majority of MEQs occurred immediately west and deeper than the drilled depth of edgefield injector DRJ-19 (Fig. 21). The MEQs that occur southwest of DRJ-19 appear to be production-related as there has been no infield condensate injection there since late 2011.

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 (Fig. 22). These new hypocenter were relocated in the 3D Static Model, gridded, and the updated MEQ density distribution was used to define the BoR.

SEGD is currently looking at using MEQs tomography to investigate changes of Vp/Vs with time. A time-lapse velocity tomography was performed in two separate time windows that correspond to injection realignment from infield to edgefield. The difference in velocity variation between these time intervals is highlighted by the % change of Vp/Vs ratios (Fig. 23). Although the overall difference is relatively small (< 2% change), a systematic pattern appears to show an increased Vp/Vs trend southwest away from DRJ-19, consistent with what would be expected for increased fluid saturation in the fractures and, possibly, the rock matrix (Nelson et al., 2018). A separate study from 4D microgravity monitoring supports this interpretation by exhibiting near zero gravity change in the northern portion of the field due to the effect of DRJ-19 injection (Paramitasari et al., 2018).

5. Summary and conclusions

During the 23 years of commercial production, the Darajat Field has not experienced significant resource issues. Those that have occurred, including 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 recognized that reservoir dry-out and possible reservoir cooling due to the impact of edgefield condensate injection and entry of cooler natural recharge may be experienced with

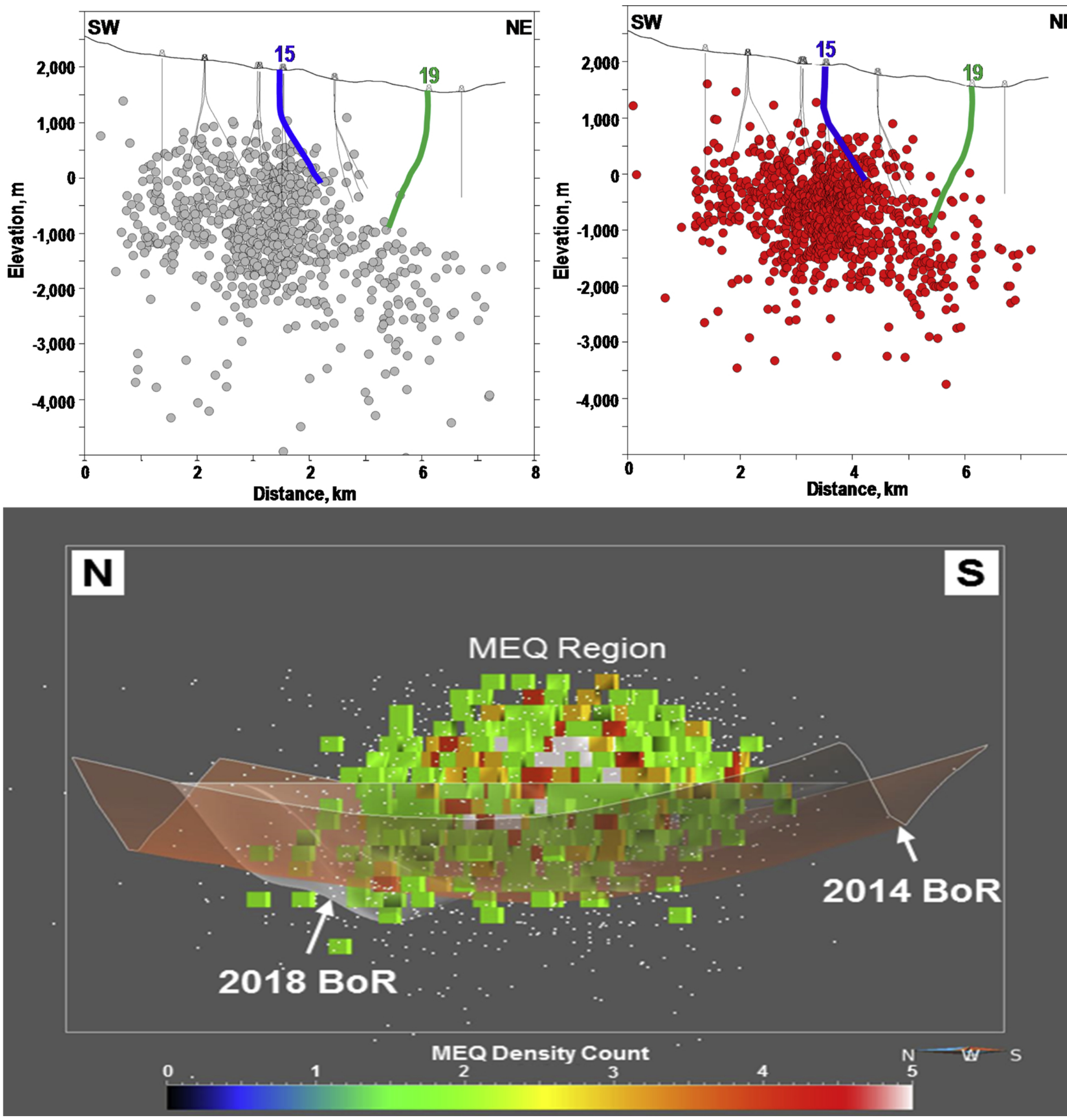

Fig. 22. SW-NE cross-sections showing the distribution of the hypocenters from the original 1D (above left) and final 3D velocity model (above right). In general, MEQ hypocenters are tighter and shifted to shallower depth after applying the new velocity model. At the bottom is a snip showing the slightly deeper 2018 BoR using the 3D velocity model.

continued mass extraction. 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. SEGD can expect to maintain production from the Darajat Field at current levels in the forseeable future.

Recent reservoir characterization studies have provided a better understanding of the conceptual model of the Darajat Field and information to better target make-up wells. Deciphering the volcano-stratigraphy of the rocks comprising the geothermal reservoir helped 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.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

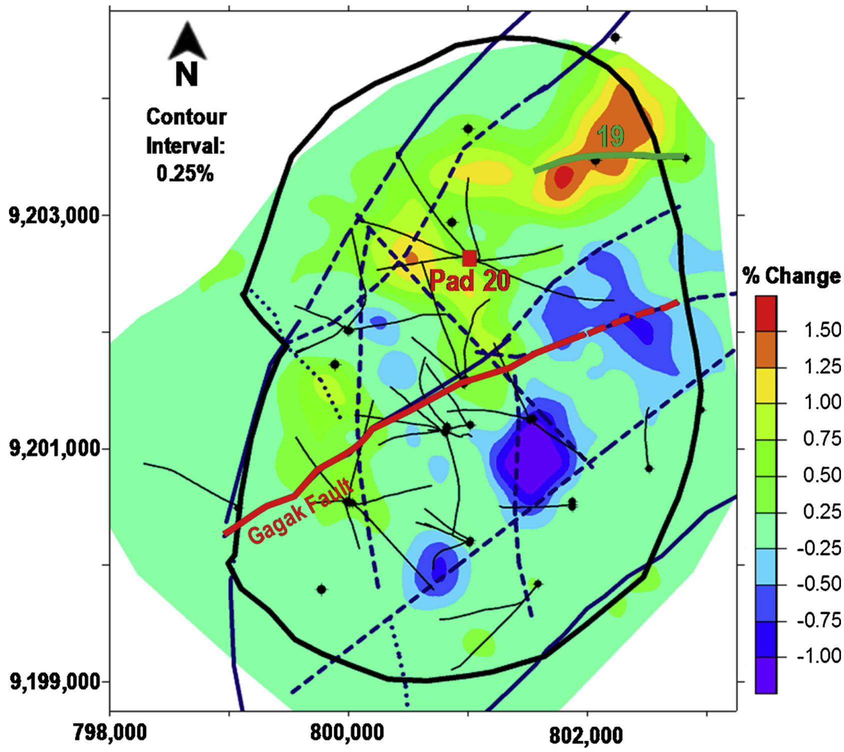

Fig. 23. Map showing Vp/Vs % change at mean sea level between two different tomography windows (2006-2011 and 2012-2016). The warmer color shading indicates the positive % change of Vp/Vs in northern Darajat.

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