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# Pioneering the use of natural fracture modeling for well placement at Darajat Field, Indonesia

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## ABSTRACT

A key consideration in the development of geothermal resources is the placement of each new well to maximize production. A slight increase in production based on improved subsurface characterization can have a major impact on the economic success of a project. In this paper we describe a novel method to model the fracture network and generate permeability maps to site new drilling locations in the Darajat geothermal field in Indonesia, operated by Star Energy Geothermal. Despite the more than 50 wells drilled in this field, relatively high uncertainty remains in the success of future steam make-up wells, as the new wells will be in step-out (previously undrilled) locations. This project is an attempt to reduce the performance uncertainty in these future wells by modeling the natural fracture system, applying methods used successfully in oil and gas reservoirs, matching the known distribution of permeability in drilled portions of the field, and predicting its distribution in undrilled portions.

The modeling of natural fractures uses "fracture drivers" to generate and attempt to match fractures interpreted from borehole image logs. Each fracture driver generates a limited fracture set, which are combined into a full reservoir fracture model. The drivers depend on the interpreted distribution of lithology units, the largest faults, and igneous intrusions in the field and perturbed stress fields or empirical rules around these geological features to generate fracture sets. Two of the drivers are fault-related and two are intrusion-related. The geologic features are characterized using remote sensing methods, geophysical studies (gravity, resistivity, microseismic), subsurface geology (core, cutting), and surface geology. The drivers are applied in sequential steps, and fractures generated from the driver-specific constraints are used to define fieldwide volumetric fracture intensities. The intensity and orientation of fractures generated by each driver are combined, and these composite parameters are used as input for creating a discrete fracture network (DFN) across the field. The DFN models are used to calculate fracture permeabilities throughout the geothermal field using measured productivity indices to help calibrate fracture apertures and length distributions. The completed models show a heterogeneous permeability distribution in the field that shows promise for planning and optimizing future well planning.

This is the first known application of this fracture modeling technique to a large geothermal project. A second phase of this project has now been undertaken to incorporate uncertainty modeling. We envisage that the tools and methods developed for the natural fracture characterization in this study will be applicable to other geothermal fields, and also to oil and gas fractured reservoirs.

## 1. INTRODUCTION

The Darajat geothermal field in West Java, about 230 km southeast of Jakarta (Figure 1), is the largest steam-dominated geothermal resource in Indonesia with an installed capacity of 271 MWe. Commercial production at Darajat commenced in 1994 with the commissioning of the 55 MWe Unit I (Figure 1). This was followed by Unit II (95 MWe) in 2000 and Unit III (110 MWe) in 2007. In 2009, the successful drilling campaign in 2007-2008 developed enough steam to allow Unit III to generate at 121 MWe; thus, increasing the installed capacity to the current 271 MWe. Under Joint Operation Contract ("JOC") with PT Pertamina Geothermal Energy ("PGE"), a subsidiary of PT Pertamina (Persero) (a state-owned oil and gas company), Star Energy Geothermal Darajat II, Limited ("SEGD") supplies steam to Unit I, owned by PT PLN (Persero) and operated by its subsidiary, PT Indonesia Power, and produces electricity from Unit II and III.

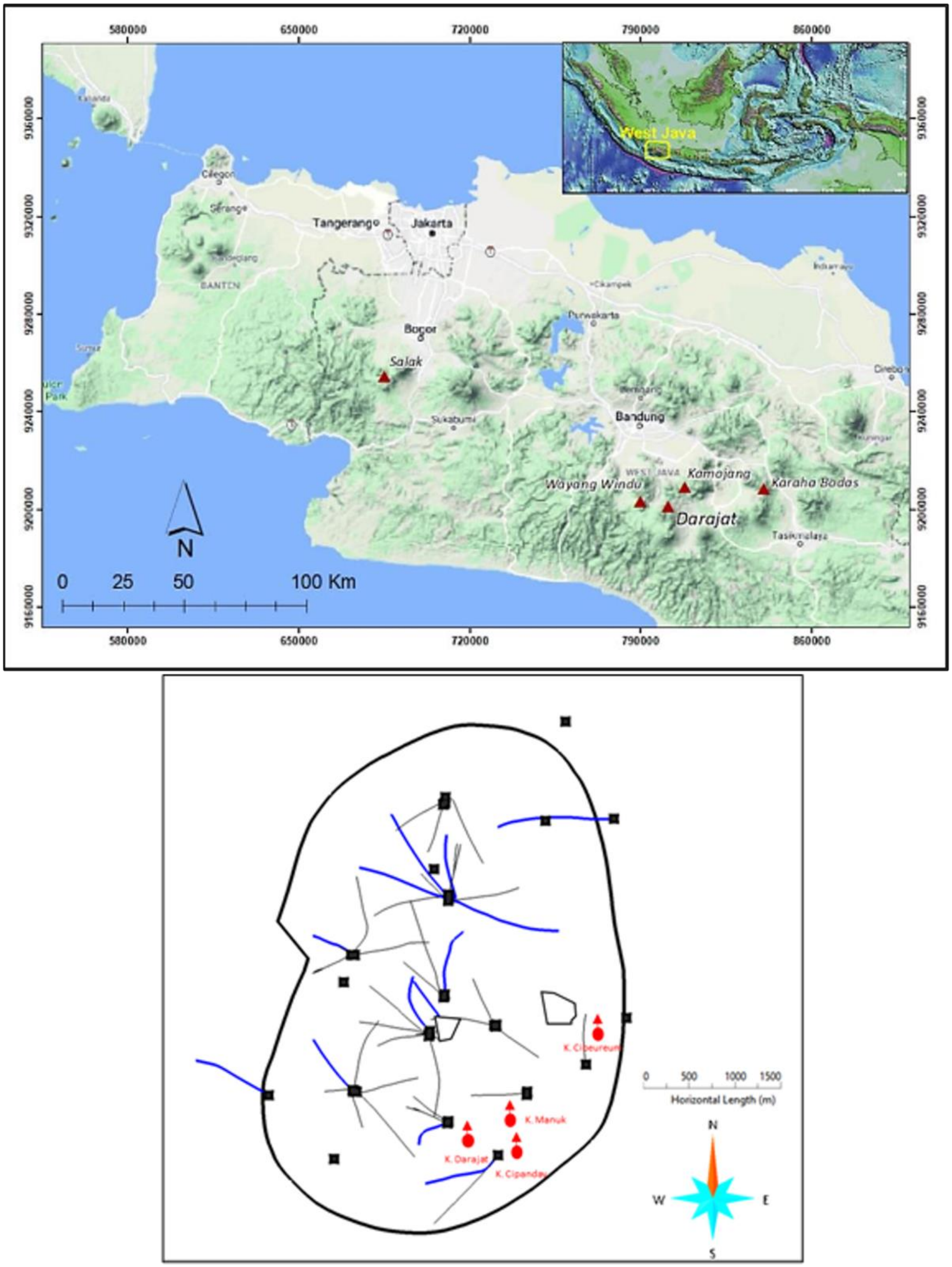


**Figure 1. Map of the Darajat Geothermal Field showing drilled wells, power plant and thermal area locations. Borehole image logs of the blue highlighted wells were used in this analysis. The black polygon surrounding the wells delineate the commercial production area. The top map shows the province of West Java (Jawa Barat), Indonesia and the geothermal fields it hosts. Geothermal fields in West Java are shown as red triangles.**

To date, the Darajat Field hosts 54 wells with 39 production wells supplying steam to the power plants (Figure 1). Only a single injector is used to dispose of the power plant condensate although there are two back-up injectors. Also, two wells are used to monitor reservoir pressure and temperature and 10 wells have been plugged abandoned at Darajat (Table 1).

**Table 1. Current Well Status at Darajat Field**

| Well Type | Number of Wells |
|---|---|
| Producers | 39 |
| Condensate Injectors | 3 |
| Observation | 2 |
| Plugged & Abandoned (P&A) | 10 |
| **Total** | **54** |

## 2. GEOLOGY OF THE DARAJAT GEOTHERMAL FIELD

The Darajat geothermal is a high-temperature, vapor-dominated reservoir with benign chemistry and <2 wt.% of non-condensable gas (NCG) content as described in several publications (Hadi et al., 2005; Herdianita et al., 2001; Intani et al., 2020; 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). 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 northwest. Geothermal fluids 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; Intani et al., 2020). 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. It is believed that a massive decompression event led to the demise of the water-dominated geothermal system and that the Andesite-Intrusive Complex is the sub-volcanic 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.

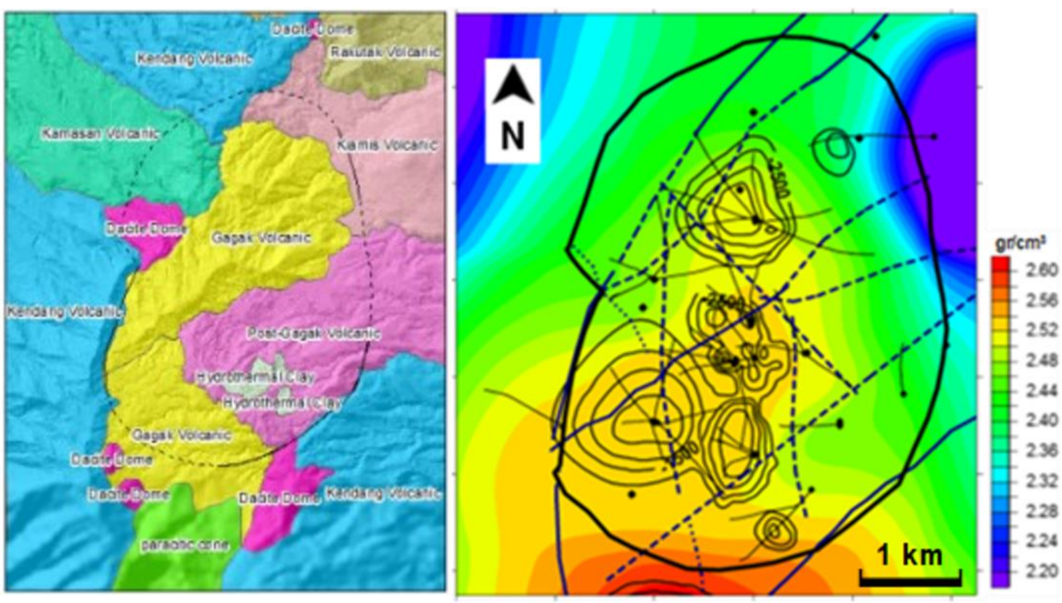


**Figure 2.Left: Surface geological map of the Darajat Field showing the interpreted structures based on LiDAR data and offset of reservoir rocks. Both Kendang and Gagak are prominent on the surface while Ciakut is buried; structures are dashed where inferred. The LiDAR data covers the colored portion of the map only. Right: 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 intrusions (shown in elevation contours, m) in the 3D static model.**

Intani et al. (2020) documented results of recent reservoir characterization studies at Darajat field including key resource management objectives. A key undertaking was 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. This study enabled delineation of the Andesite-Intrusive Complex, which comprises the Darajat geothermal reservoir and the hypothesized sub-volcanic portion of an earlier liquid-dominated geothermal system. Another key finding in this stratigraphy work was the refinement of the surface geology at Darajat Field and revealed noticeable surface structures that are believed to be affecting reservoir processes (Figure 2). 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. 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. The other prominent structure is the Ciakut Fault which appears to be a product of a sector collapse inside the Gagak caldera (Figure 2).

Further application of new interpretation techniques (i.e., joint inversion of the magneto-telluric and gravity data) with a cross-gradient link between inversion parameters and referenced to the porosity model from the 3D static model (Soyer et al., 2017) to existing geophysical data enabled further delineation of the Andesite-Intrusive Complex, geophysically distinct having both high density and resistivity signatures (Figure 2). This high-density trend coincides well with where the shallow microdiorite intrusions have been encountered in the central and southern wells 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. The above results from the intrusion and fault interpretation form the fundamental geometry in the subsurface models impacting the fracture modeling (Figure 3).

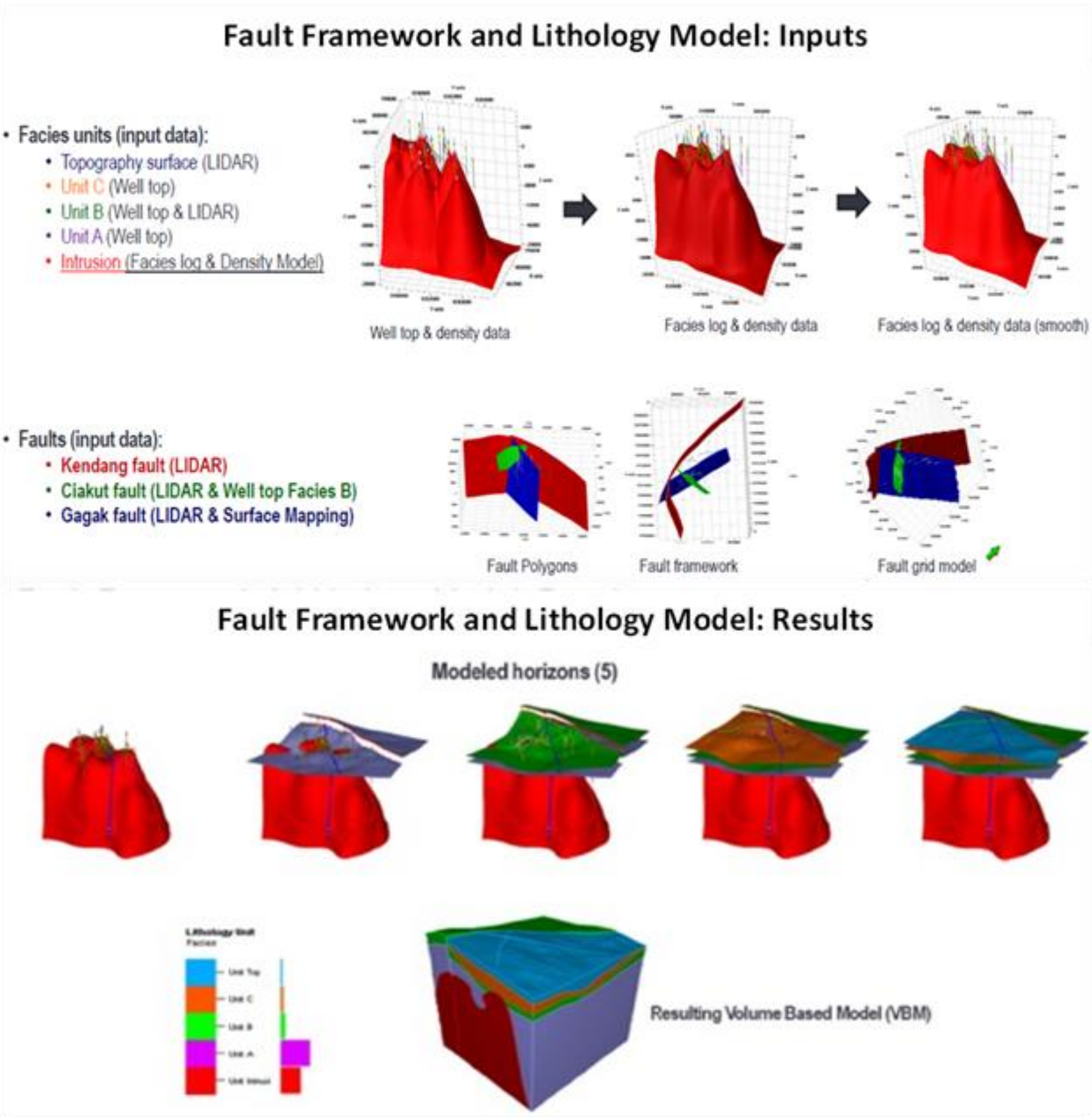


**Figure 3. 3D static model in Petrel of the intrusion, faults and volcanic facies comprising the Darajat geothermal reservoir.**

## 3. USING FRACTURE DRIVERS TO MAP THE LOCATION OF PRODUCING FRACTURES

As geothermal fields mature, reservoir characterization work provides necessary information to make well-informed decisions and define strategies on how best to plan for infill wells and mitigate the risk of dry holes. Each geothermal field will eventually include drilling of make-up wells to shore up both steam production and injection capacity in its lifetime. As future capital expenses will entail mostly drilling of make-up wells, it is imperative that these wells are drilled in areas with the greatest change success applying a methodology to efficiently locate the producing fractures.

At Darajat, recent re-analysis of borehole image logs and Pressure-Temperature-Spinner (PTS) surveys enabled detailed characterization of the producing (effective) fractures. Instead of characterizing all the fractures identified from image logs, we focused on the effective fractures associated with the feed zones identified from PTS logs to better understand their fieldwide distribution and the magnitude of their permeability. Focus on the effective fractures was to improve the static model's accuracy and the ability to target successful wells in areas with expected higher productivity within the drilled portions of Darajat. This work also provided constraints for fracture properties (i.e., fracture aperture, fracture permeability, fracture spacing, permeability anisotropy) for validation in and acceleration of numerical model development. Additionally, this study has highlighted the optimum well azimuth and inclinations to intersect the maximum number of feed zones in the reservoir (Intani et al., 2017). Despite success in applying this methodology in drilled areas, Star Energy Geothermal did not have workflows to extend the analysis to undrilled portions of the reservoir for future well pads and make-up wells.

The need to predict the distribution of effective fractures capable of producing geothermal fluids in the undrilled portions of the reservoir prompted Star Energy Geothermal to collaborate with Schlumberger, a technical leader in the Oil and Gas industry. We felt that predicting the location of effective fractures in the undrilled areas of the reservoir was attainable with the combination of Schlumberger's experience in fracture modeling in oil and gas reservoirs and Star Energy's >20 years' experience in exploring, developing, and managing geothermal fields. It was envisioned that predicting the density and orientations of potentially producing fractures will improve targeting of make-up wells in undrilled areas and optimize the location of new well pads.

From the 30 wells that have borehole image logs at Darajat, 18 wells were chosen for this study based on their fieldwide location (Figure 1). High confidence open, partially open, and effective (producing based on PTS logs) fractures have been interpreted from the image logs. In this case, we have included open fractures as those with a potential to add to the production. These natural fractures, in the subsurface, develop in response to physical mechanisms. Efficiency in fracture modelling in reservoirs requires knowledge of the type of factures for instance joints or shear fractures expected for driving mechanisms that are mechanical developing within a perturbed stress field around faults or intrusions or geometric related to the distance to the fault or intrusion margin. To model the distribution of fractures through the reservoir in the Darajat field we applied a methodology that includes four fracture drivers (Figure 4):

1) A driver for fractures related to pressurized emplacement of igneous intrusion(s) into the host rocks in and below the geothermal system. The intrusions perturb the regional stress field of the country rock into areas of higher and lower magnitudes. For this driver, a pressurized cavity is created to model the intrusive event, and fractures caused by the intrusions (both joints and shear fractures) are inferred from the calculated resultant stress field in the surrounding rock).

2) A driver for fractures caused by thermal expansion and contraction of the intrusion(s) and host rocks. As intrusive rocks cool, fractures often form around the intrusion/host margins. To model this process, a distance to the intrusion margin was applied with fracture intensity decaying exponentially away from the margin in the host rock but constant inside. The fracture orientations near the margins are considered subparallel to the local margin orientation but subvertical inside the intrusion;

3) A driver for fractures within a damage zone around faults (also known as Distance to Fault or DTF). Fractures are commonly observed within a prescribed distance on either side of a mapped fault with orientations sub-parallel to the local fault plane, and with a decreasing frequency away from the fault up to a distance of 20 to 50 meters An exponential decay law was applied for the five largest Darajat faults over a distance of 200 meters but with an effective width of strong contributions less than 20 meters with fractures oriented +15° to the local fault dip and azimuth.

4) A driver for the fractures that result from stress perturbations throughout the reservoir rock volume at the bends, intersection, and tips of interpreted faults (also known as Natural Fracture Prediction or NFP) (Maerten et al., 2002). This driver uses geomechanical simulation and stress inversion techniques to model a heterogeneous local paleo-stress field from the interpreted fault geometry and interpreted regional stress field (Maerten et al., 2016). The far field modeled paleo-stress is applied to the fault geometry to model a distribution of fractures within the perturbed stress field in the region of the interpreted faults. Both joints and shear fractures are interpreted from this stress-based driver.

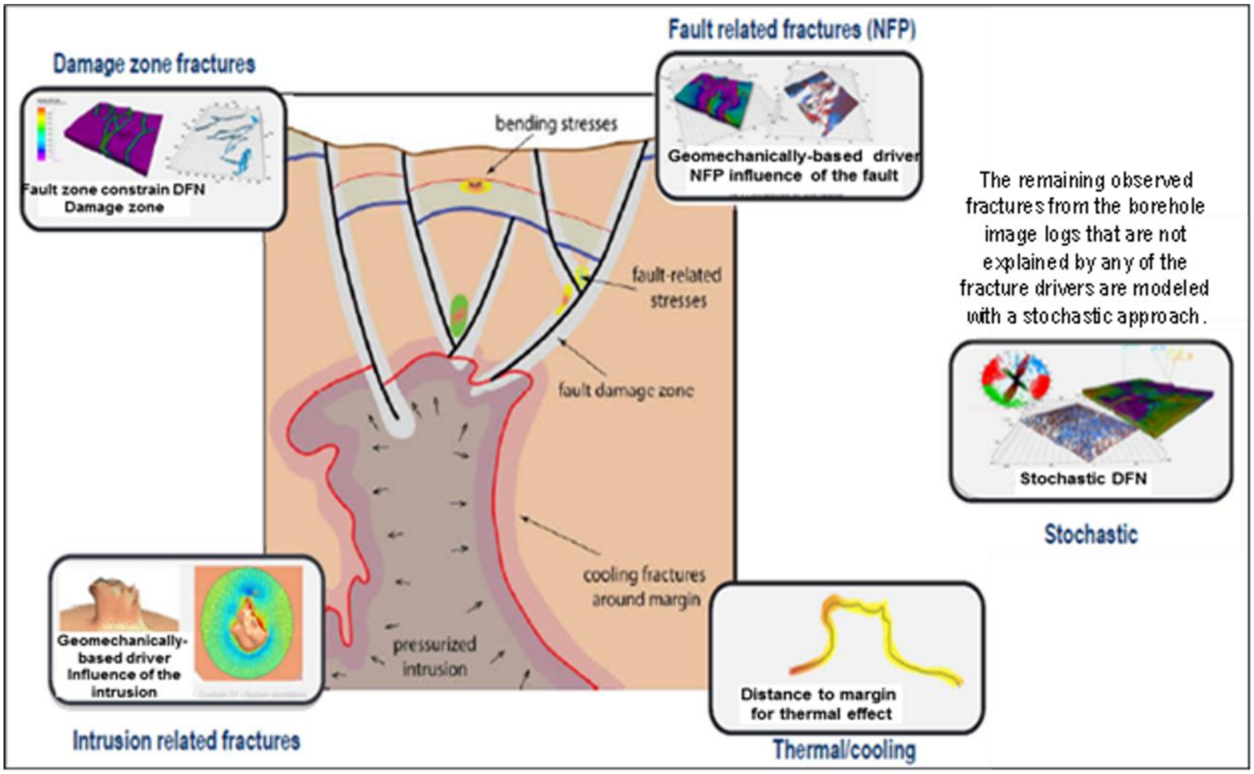


**Figure 4. 3D static model in Petrel of the intrusion, faults and volcanic facies comprising the Darajat geothermal reservoir.**

These four drivers are sequentially compared to the fractures observed in the well image logs. Those fractures in the logs that have characteristics that are consistent with the drivers are assigned to the individual drivers. Any remaining fractures that are not consistent with any of the four drivers are assigned to a fifth group. This final group is effectively a residual fracture set not modeled from the other drive constraints and is stochastically distributed throughout a discrete fracture network for the field. We consider this stochastic modeling as a fifth driver.

At least three geochronological scenarios of the formation of the Darajat geothermal system were considered to compare the impact of the separate drivers on the fracture frequency. The selected scenario for modeling fractures focused first on the influence of the intrusions (i.e., stress perturbation and thermal effect drivers) and then the influence of the faults (i.e., DTF and NFP drivers) and was named the Scenario 1. Alternative structural scenarios include the occurrence of faulting prior to the intrusive rocks (Scenario 2) and a general chronology of the formation of the Darajat geothermal system (Scenario 3). As each separate fracture driver is applied sequentially to the model, fractures from the image logs are compared against the model-derived fracture driver constraints in orientation and spatial distribution. Observed fractures from the image logs consistent with the driver constraints are consumed (or explained) with the remaining fractures available for subsequent fracture drivers.

As illustrated for Scenario 1, a residual set of fractures, not modeled or consumed by the associated drivers, remains following the sequential driver application. These residual fractures were modeled between wells using stochastic algorithms to develop a 3D fracture population. The modeled fracture sets from the four drivers and stochastic analysis deliver a fracture intensity spatial distribution (P32) and orientation throughout the 3D static model; both orientation and intensity are required inputs to develop the discrete fracture network (DFN). Figure 5 shows the application of the fracture drivers for the selected scenario using the 9,014 open, partially open and effective fractures identified from the borehole image logs of the 18 wells. The fracture drivers explained about 60% of the observed fractures leaving the remaining to be matched stochastically.

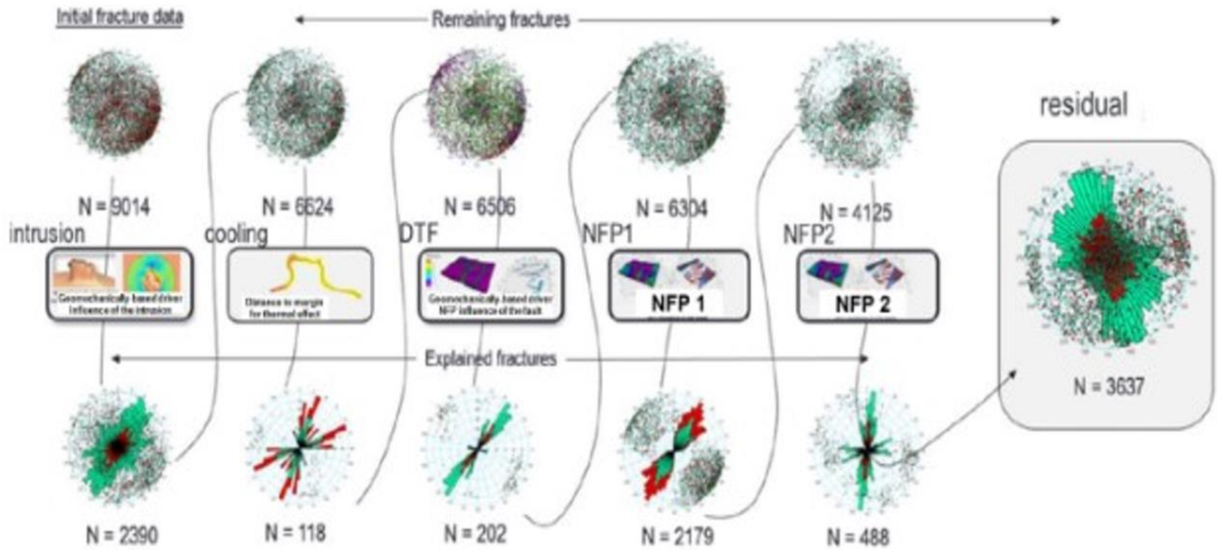


**Figure 5. Schematic of structural Scenario 1 that shows the intrusive rocks prior to faulting (please refer to thumbnails below the stereo nets at the top row). From an initial population of 9,014 fractures identified from the borehole image logs, each fracture driver was able to explain some of these observed fractures ("N" denotes the number of observed fractures explained by each driver). The remaining unexplained, or residual, fractures (N = 3,637) was modeled stochastically.**

## 3. EVALUATING THE TEST-OF-CONCEPT

The DFN model is used to obtain a continuum approximation of reservoir fracture system properties, equivalent fracture porosity and permeability, as well as exchange mass factor (sigma) between matrix and fractures to model permeability. The combination of the fracture intensity, dip angle and dip azimuth from the drivers is modeled with a range of fracture length and aperture to create the fracture reservoir properties before upscaling. Changes in the distribution and orientations of both fracture length and aperture will affect the fracture properties distribution as well as their absolute values. Upscaling of permeability maintains an uncertainty in fractured reservoirs because of the potential range in length, aperture, and density. The size of the model and the algorithm used for upscaling purposes also impacts the contribution of the fractures to the reservoir property calculation.

For this work, we have used the Oda method to upscale the DFN model for the modeled set of fractures (Oda, 1985). Oda uses vector addition to add all fractures with a weighting factor as a function of direction. This method does not consider the interconnectivity of the fractures and tends to overestimate the permeability when the intensity or interconnectivity is low. To resolve this issue in this first stage of the project, the workflow included a sensitivity analysis with varying fracture aperture and length applied during the upscaling of the DFN properties. The sensitivity analysis showed an average fracture aperture of 0.22 mm and length from 120 to 1000 m resulted in reasonable average reservoir permeability consistent with those in the history matched simulation model.

Comparison of the fieldwide trends of fracture permeability derived from the DFNs and those from the Darajat numerical model was promising (Figure 6). The numerical model is the mathematical representation of the Darajat static model that is built to simulate and reproduce the mechanisms of the Darajat geothermal system. Trends of high permeability delineated by the upscaled DFN models resulted in trends that are similar to those found in the Darajat numerical model and show the following key features: high permeability hot spots in the north and south and a connection, but of lower permeability through the central field (Figure 6). A significant difference was the magnitude of permeability in the hot spots with the values from the DFN models being too low.

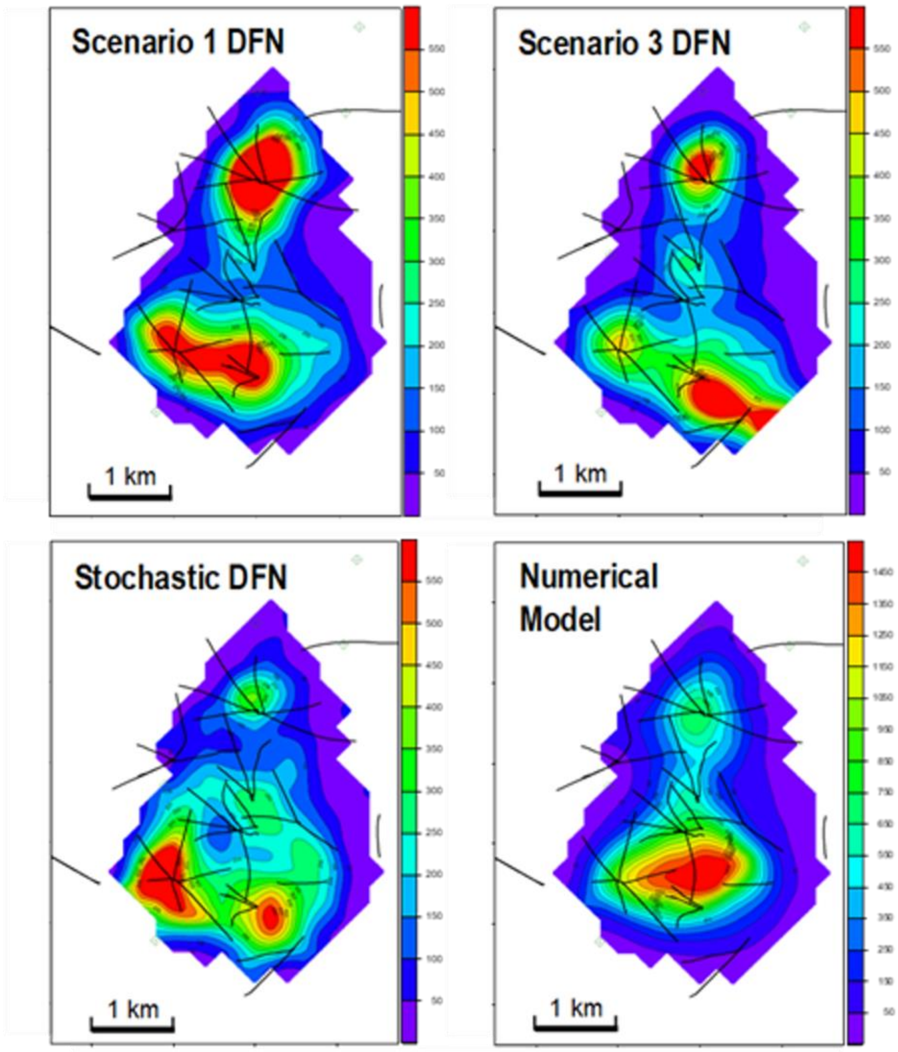


**Figure 6. Comparison of the cumulative vertical fracture permeability (ki) trends from the top of reservoir to 565 m above sea level between the DFNs and the Darajat numerical model. Scenarios refer to the different structural scenarios conjured for the Darajat geothermal system (please refer to Section III); Scenario 1 was the selected scenario for further modeling. The Stochastic DFN did not use the fracture drivers.**

## 4. EVALUATING THE TEST-OF-CONCEPT

The promising results from comparing the fracture permeability trends derived from the DFNs with those from the Darajat numerical model have led to a decision to move forward with a second phase of fracture modeling work which is nearing completion. The focus in Phase 2 of the project is incorporation uncertainties in the model by selecting plausible alternative structural models and defining ranges for the fracture constraints applied to respective fracture drivers. Additionally, Phase 2 will incorporate a range in fracture aperture and length to result in multiple possible realizations of the upscaled permeability distributions. Figure 7 shows the general workflow for the uncertainty and sensitivity analyses.

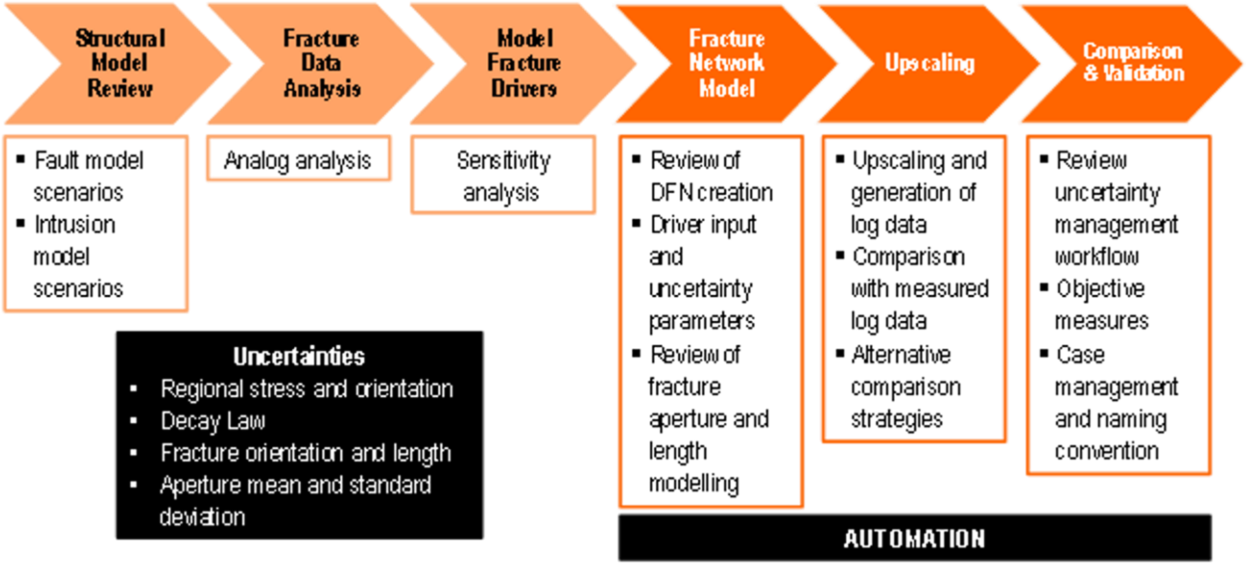


**Figure 7. Generic workflow sequence and key workflow activities during the second phase of fracture modeling work.**

Because of the large amount of work and computational time involved in the sensitivity analysis and creation of the alternative upscaled models as much as possible of the process will be automated. This will allow hundreds of models to be run, creation of unique DFNs, and upscaling to permeability for creation of permeability maps. The goal is to create credible Probability of Permeability (PoP) maps to delineate areas with higher probability for encountering commercial permeability (Figure 8). Verification of the applicability of the PoP maps for make-up well targeting will require a rigorous quantification of the match of the PoP against the well data in the drilled portion of the field and an integrative "reality check" for interpretations outside the drilled area.

## 4. SUMMARY AND CONCLUSIONS

Application of the fracture driver approach has shown encouraging results. Areas of high permeability were delineated and when compared with the permeability distribution map derived from the Darajat Numerical model showed comparable results although the magnitude of permeability between the DFNs and Numerical model is different. Phase 2 of this fracture modeling work focusses on uncertainties in the structural models and constraints and ranges for the explained fractures resulting from the respective fracture drivers to develop more realistic upscaled permeability distributions.

Staffing the project team with subject matter experts from both Schlumberger and Star Energy was key. Schlumberger brought to the table the expertise of implementing the fracture drivers in an Oil and Gas application, while Star brought extensive knowledge of geothermal naturally fractured reservoirs. By working together, the project team member each brought an important perspective and level of expertise, which working separately would not have been possible. This integration of expertise significantly improves the chance of success for these projects.

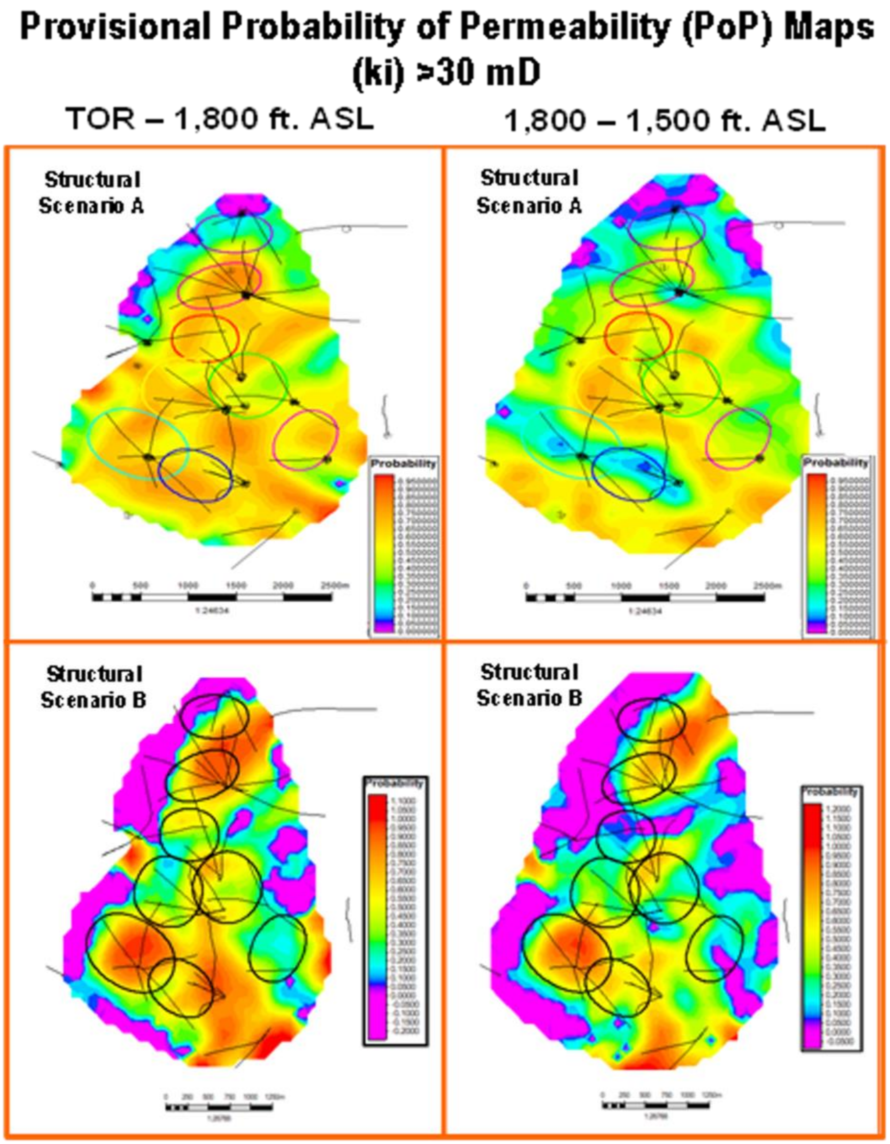


**Figure 8. Provisional PoP maps for two different structural scenarios for different reservoir volumes. Warm colors denote regions with high probability to encounter fracture permeability (ki) >30 mD and should be good targets for infill wells. Work is under way to refine the PoP maps and include more realizations. The ovals represent the reservoir volume that will be validated with well data. TOR refers to the Top of Reservoir; ASL is Above Sea Level.**

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