Innovative Methods and Data Analytics of Multiple Realizations for Natural Fracture Modeling in the Darajat Geothermal Field, Indonesia

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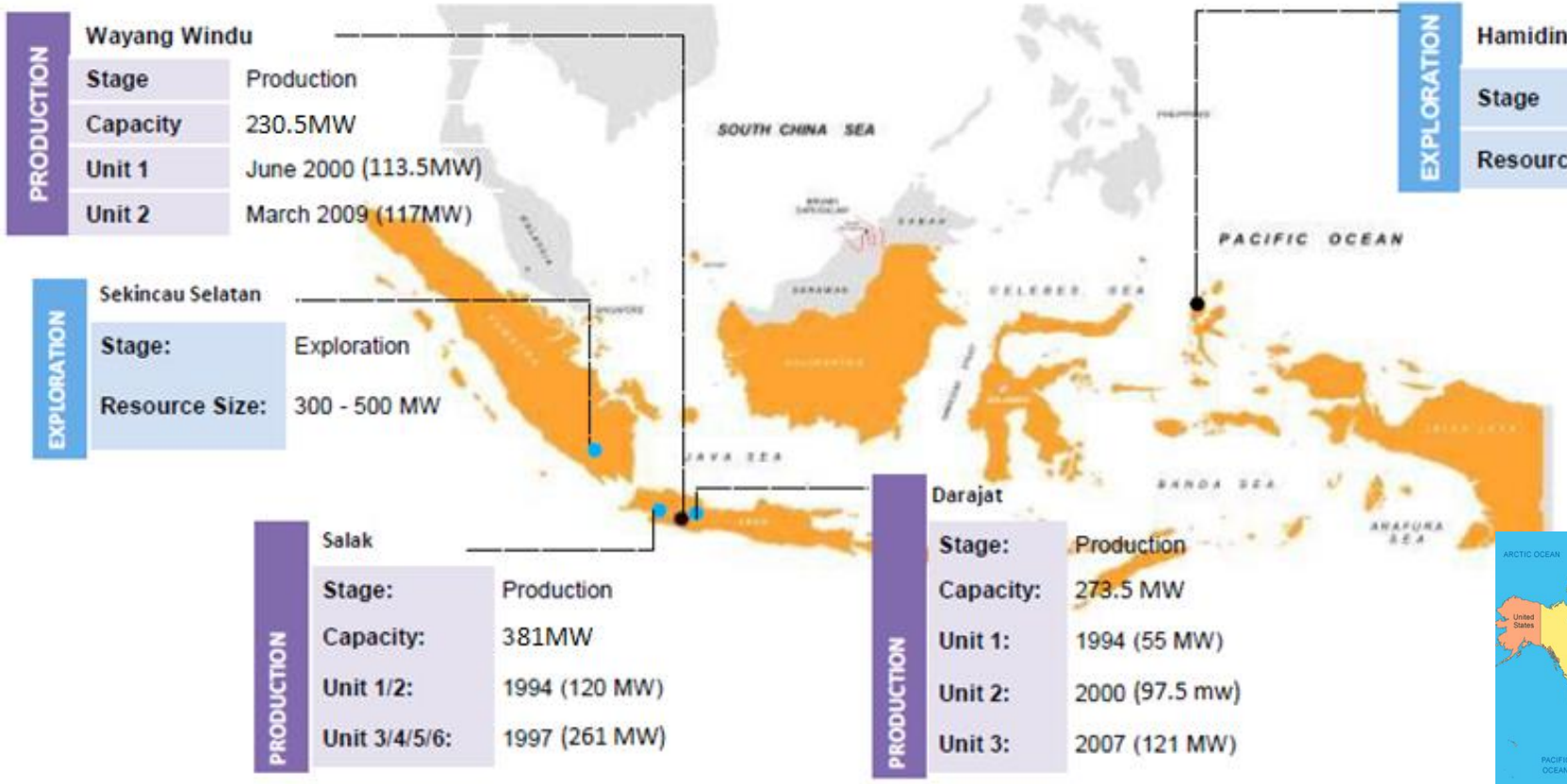
Introduction

Star Energy Geothermal

Total Installed Capacity of 885 MW

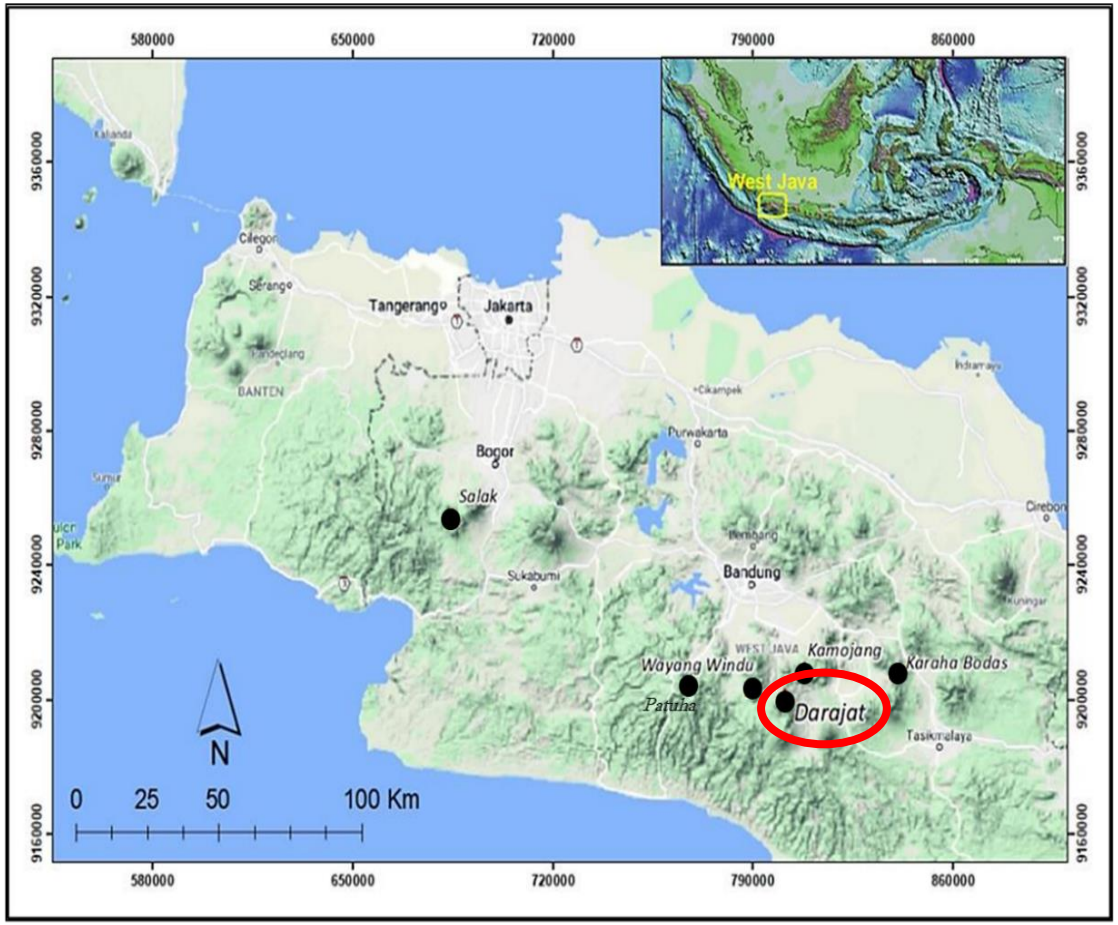


The third largest geothermal IPP globally and the largest in Indonesia (1)

(1) Source: World Energy Council, and company website (capacity as of Jan 2022)

Introduction

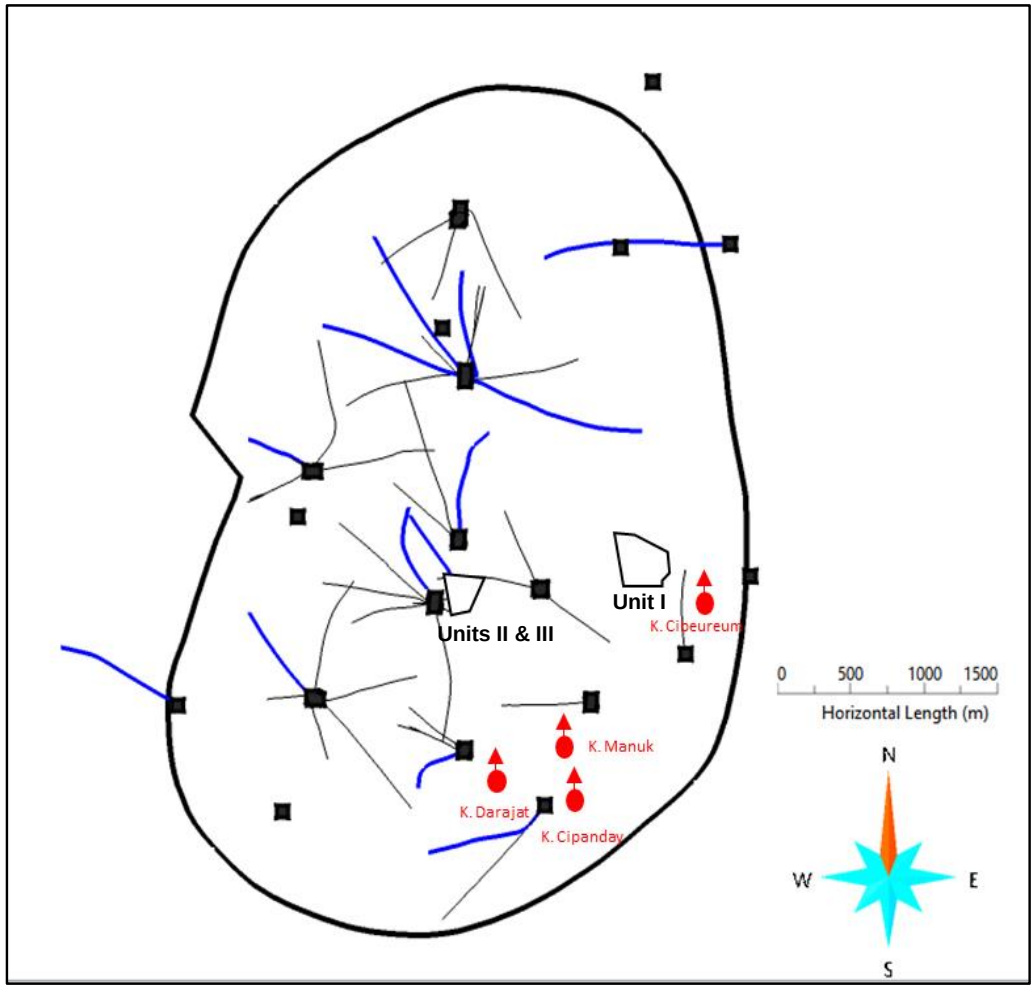
Darajat Field Overview



- 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 273.5 MWe
- One of the few steam-dominated geothermal systems in the world
- Geothermal investigations at Darajat began in the early 1970's
  - Commercial production started in 1994 with the commissioning of the 55 MWe Unit I (owned and operated by PLN)
  - Units II (97.5 MWe) and III (121 MWe) were added in 2000 and 2007, respectively; both are owned and operated by Star Energy Geothermal Darajat

Introduction

Darajat Field – Well Data distribution



Note: The black polygon surrounding the wells delineate the commercial production area.

- 48 production wells
  - 8 wells supply steam to Unit I
  - 23 wells supply steam to Units II & III
- 3 injection wells
- 2 monitoring wells
- 7 wells are inactive/idle
- 10 wells have been plugged & abandoned

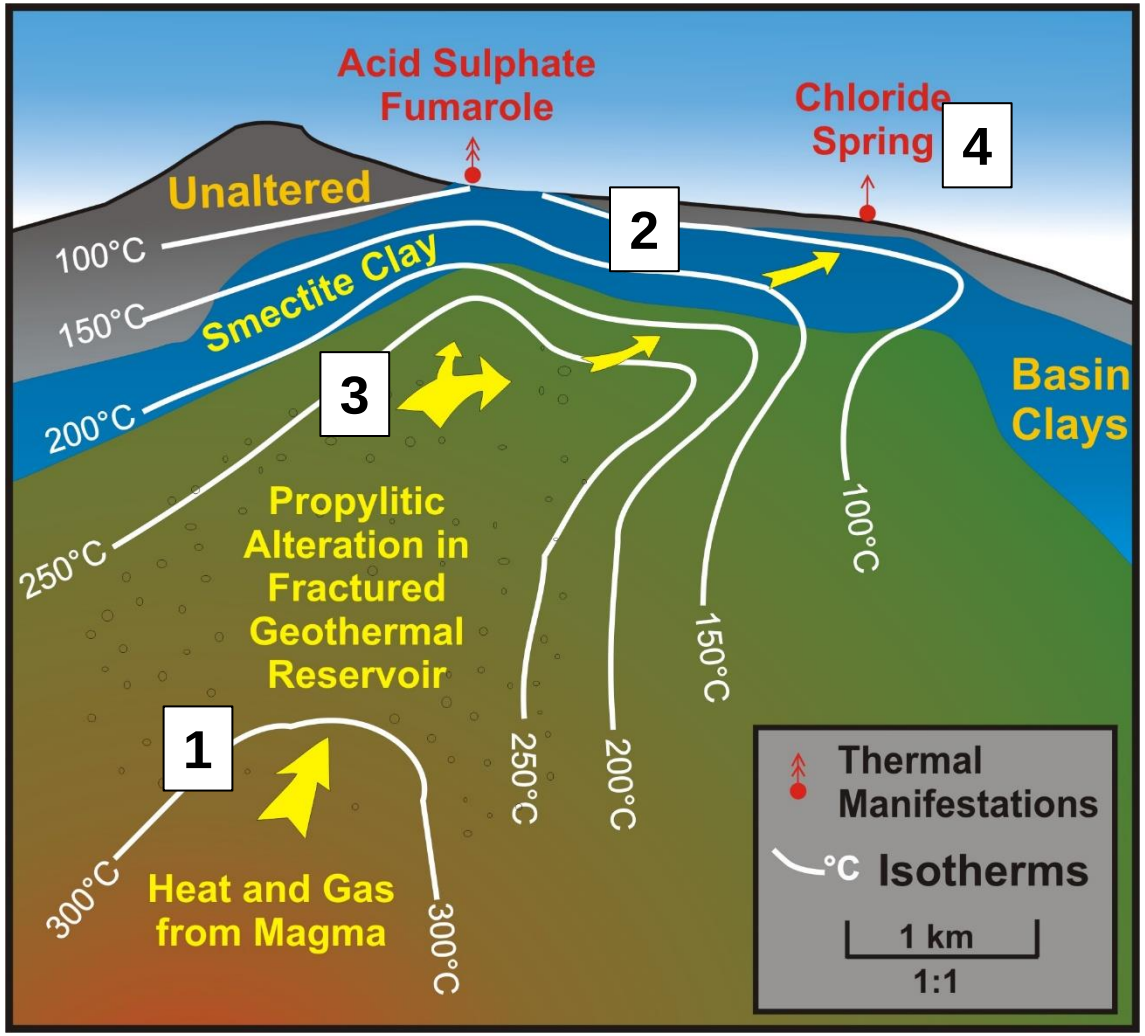
Borehole image logs of the blue highlighted wells were used in this analysis (18 wells)

Introduction

Geothermal Conceptual Model

The Kettle Concept

The elements of a geothermal system works like boiling water in a kettle



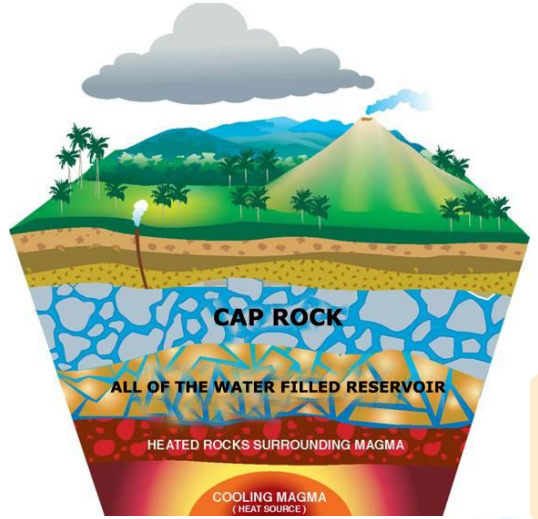
Legend:

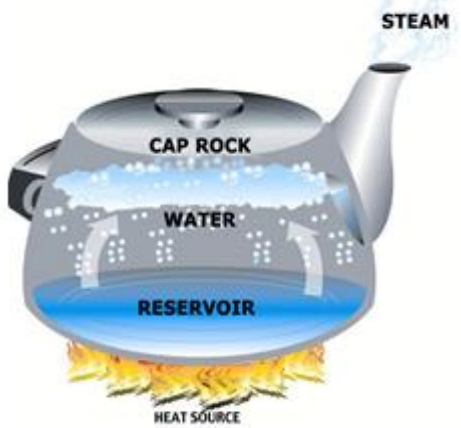
1: Heat Source

2: Clay Cap

3: Upflow

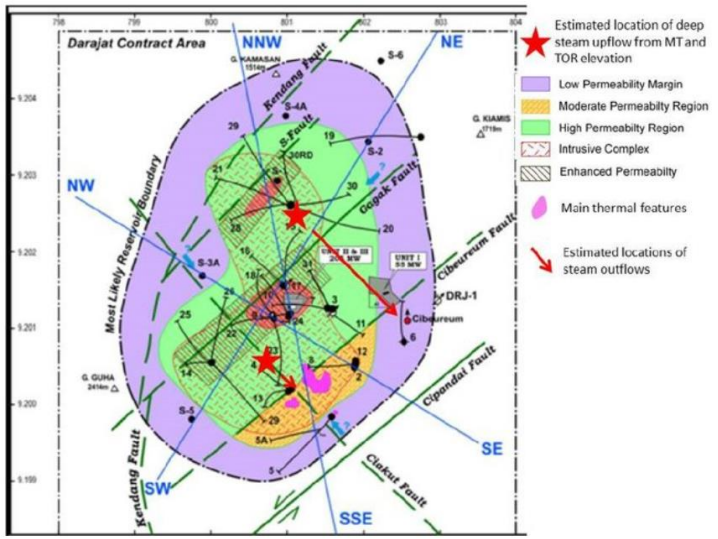
4: Outflow





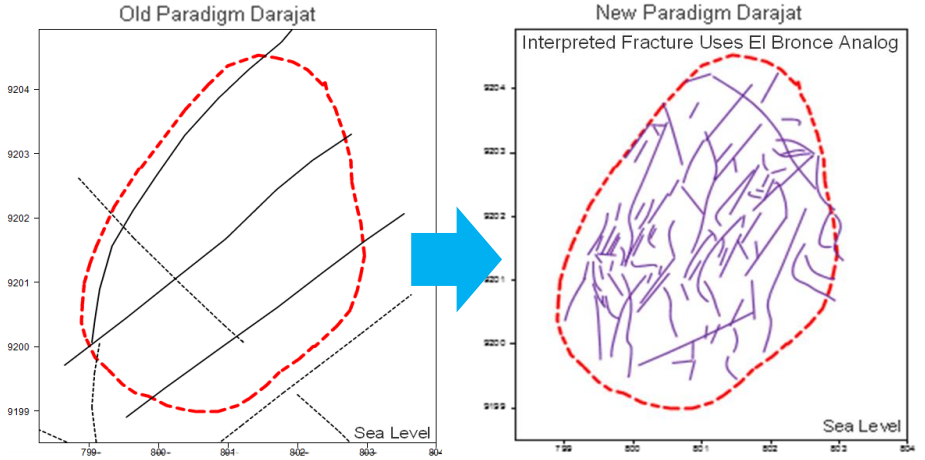
Well Targeting Evolutions

Geological Structures Targeting

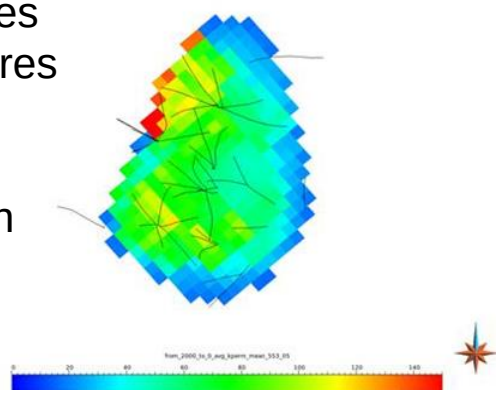


Well Targeting to the mapped geological structures which were interpreted as sub-vertical faults

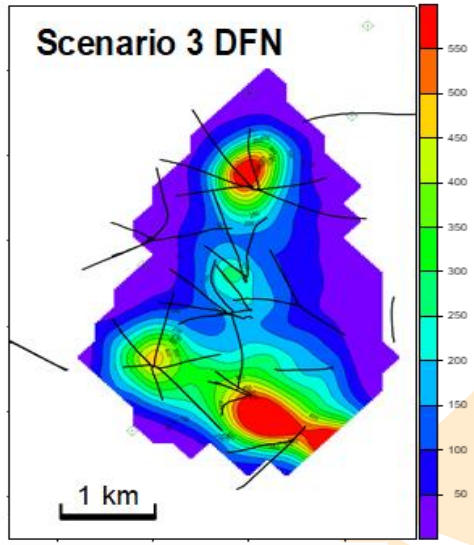
Naturally Fractured Reservoir (NFR)



NFR Study indicates the effective fractures may related to distributed permeability shown by the fracture permeability distribution.



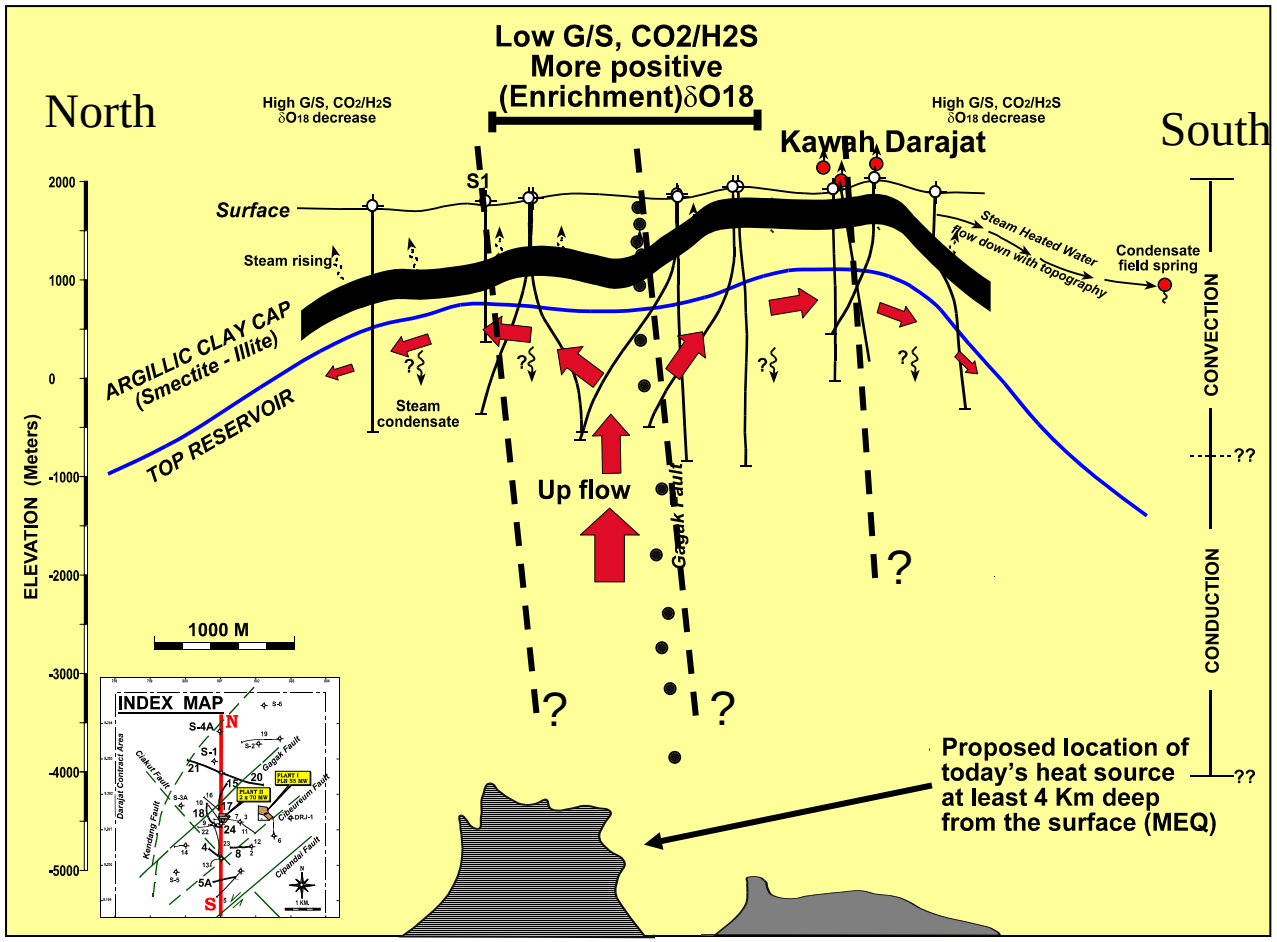
Fracture Characterization and Optimized Well Placement (FCOWP)

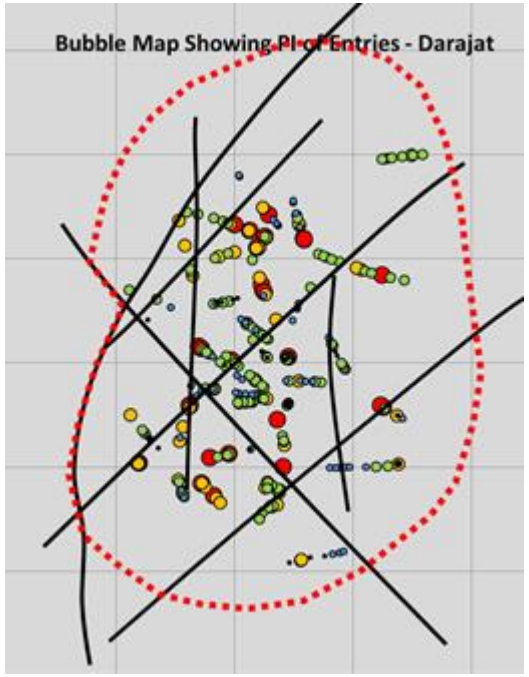


Probability of Permeability Map encouraged targeting wells in the undrilled area, since from the NFR Study only limited to the area have wells data.

Well Targeting Evolutions

Geological Structures as Well Targets





Colored bubbles represent different productivity values; Warm color is showing higher productivity

- The geological structures were interpreted as sub-vertical dipping
- Not all productivity from the feedzones correlate to geological structures

Well Targeting Evolutions

Naturally Fractured Reservoir (NFR) as Applications for Well Targeting

Old Paradigm

Specific Targets

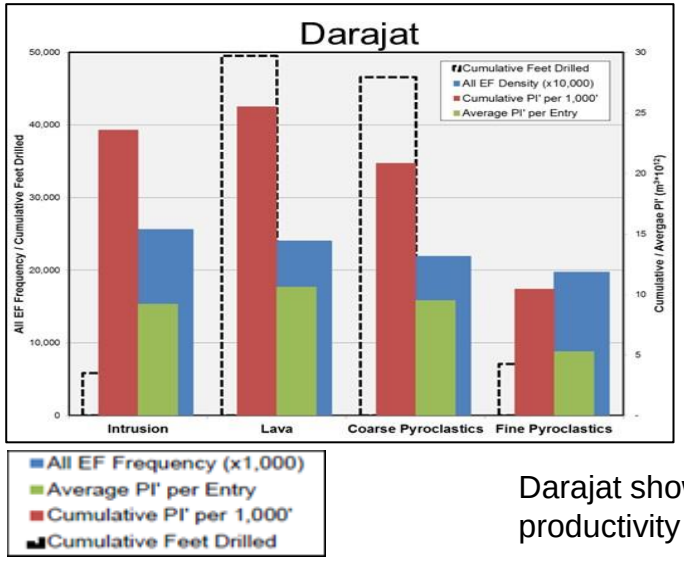
Individual points that are intended to be specific fracture intersections, selected based on projection of surface structures, feed zones in other wells, or lithology contact

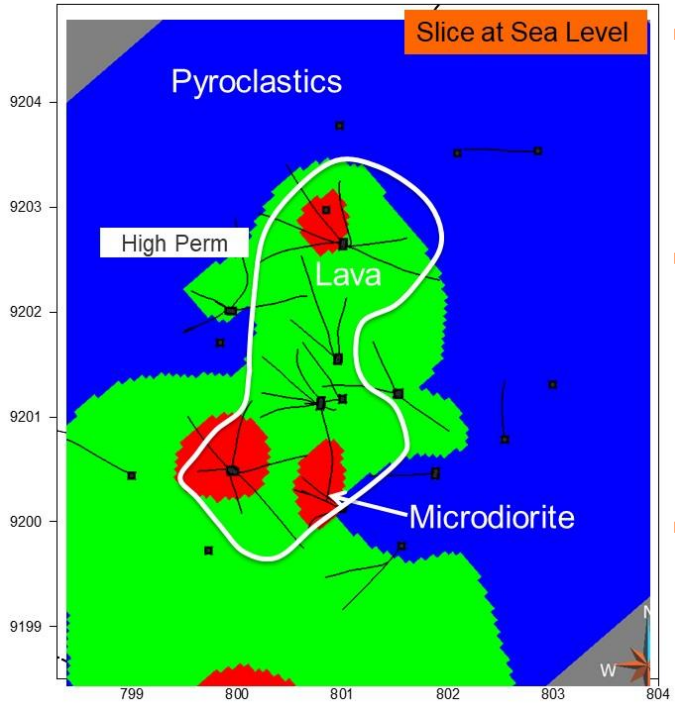
New Paradigm

Non-Specific Targets

Target and drill wells to have characteristics that integrated data correlations and conceptual models have shown to have greater likelihood of encountering more or higher-productivity fractures, i.e.:

- Lithologies
- Depth ranges
- Azimuths & deviation angles





- Area of high permeability is centered over the lava (green) and intrusive (red) rocks
- It is believed that the fracture network in lava flows has been enhanced by the emplacement of intrusives
- Higher average productivities appear to be associated with microdiorite/intrusion

Darajat shows correlation between Fracture Frequency and relatively higher productivity for the Effective Fractures in the lava flows and intrusive

Fracture Characterization and Optimized Well Placement (FCOWP)

Domain/Manual Work

Structural Model Review

- Fault model scenarios
- Intrusion model scenarios

Fracture Data Analysis

- Analog analysis

Model Fracture Drivers

- Fault model scenarios
- Intrusion model scenarios

Automation/Probabilistic Modeling

Fracture Network Model

- Review of DFN creation
- Driver input and uncertainty parameters
- Review of fracture aperture and length modelling

Upscaling

- Upscaling and generation of log data
- Comparison with measured log data
- Alternative comparison strategies

Validation

- Review uncertainty management workflow
- Objective measures
- Case management and naming convention

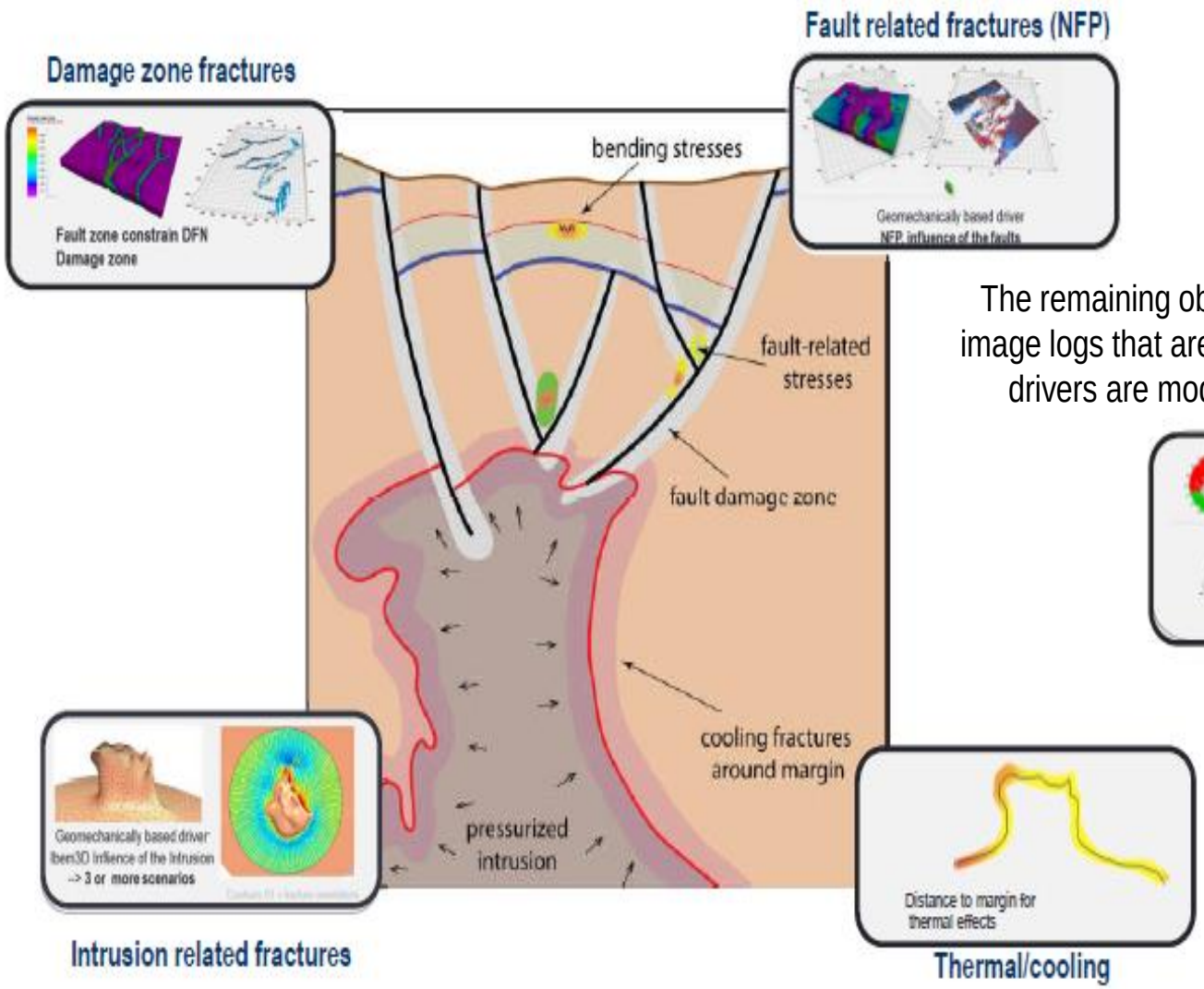
AUTOMATION

Uncertainties

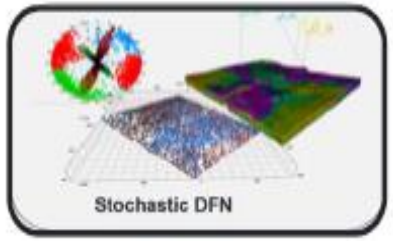
- Regional stress and orientation
- Decay Law
- Fracture orientation and length
- Aperture mean and standard deviation

Fracture Characterization and Optimized Well Placement (FCOWP)

Fracture Drivers to Map Location of Producing Fractures



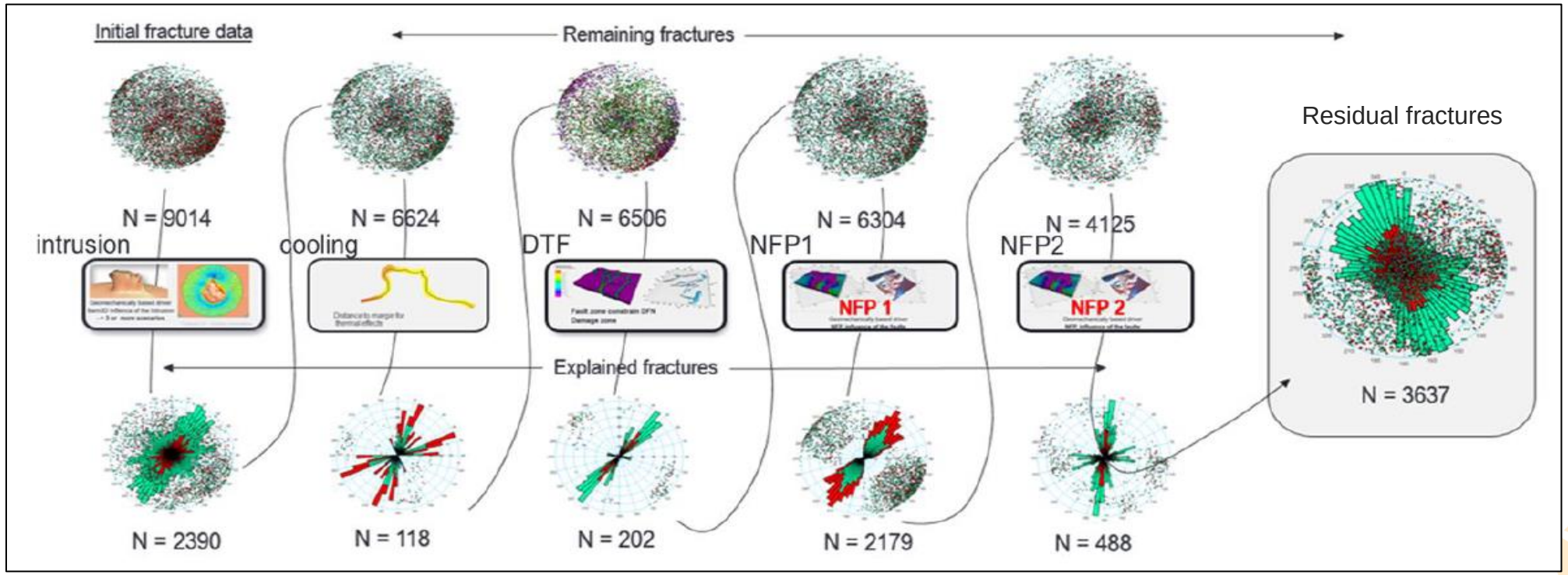
The remaining observed fractures from the borehole image logs that are not explained by any of the fracture drivers are modeled with a stochastic approach.



Stochastic

Fracture Characterization and Optimized Well Placement (FCOWP)

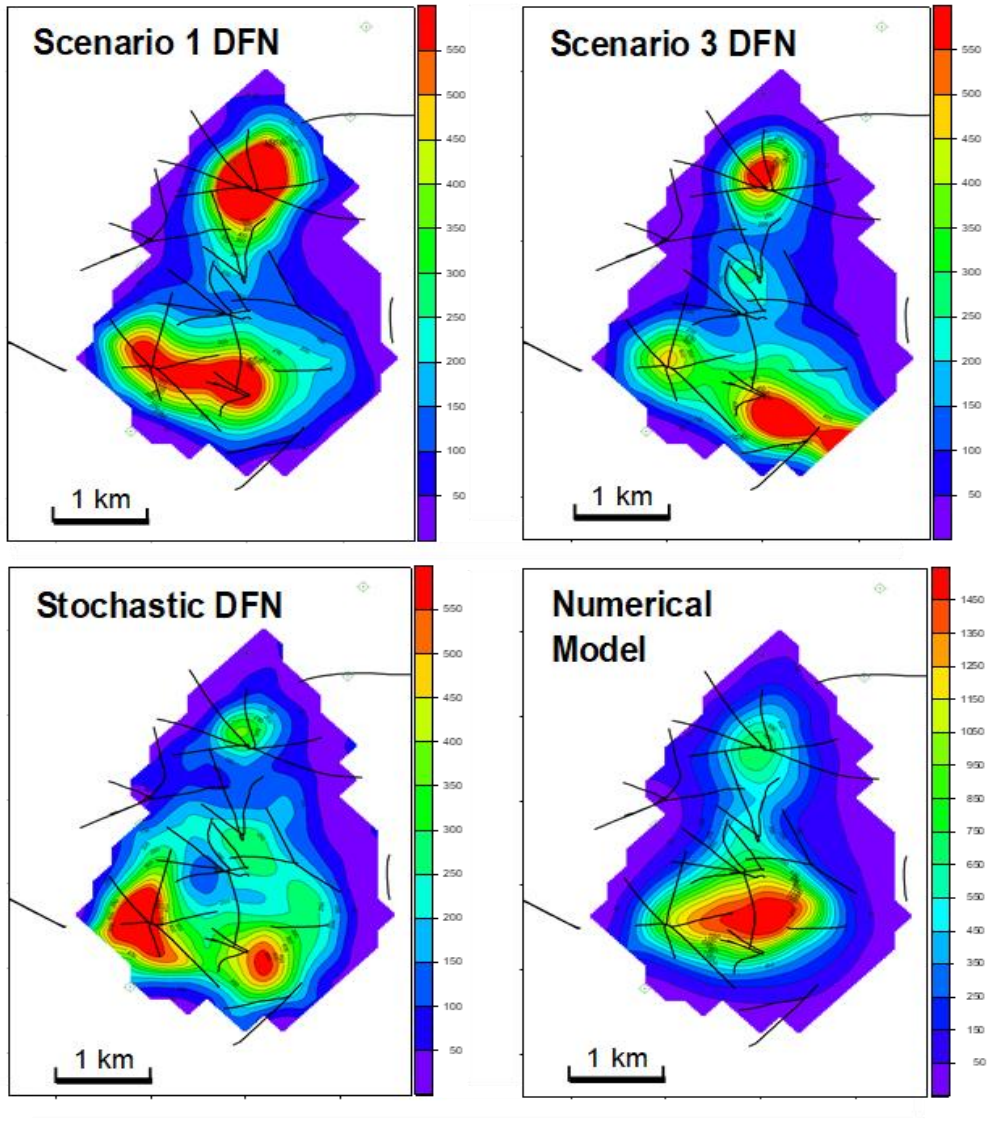
Application of the Fracture Drivers



- About 9,014 open, partially open and effective fractures were identified from the borehole image logs of 18 wells
- Application of the fracture drivers explained about 60% of the observed fractures leaving the remaining or residual fracture to be matched stochastically

Fracture Characterization and Optimized Well Placement (FCOWP)

Evaluating of the Test-of-Concept



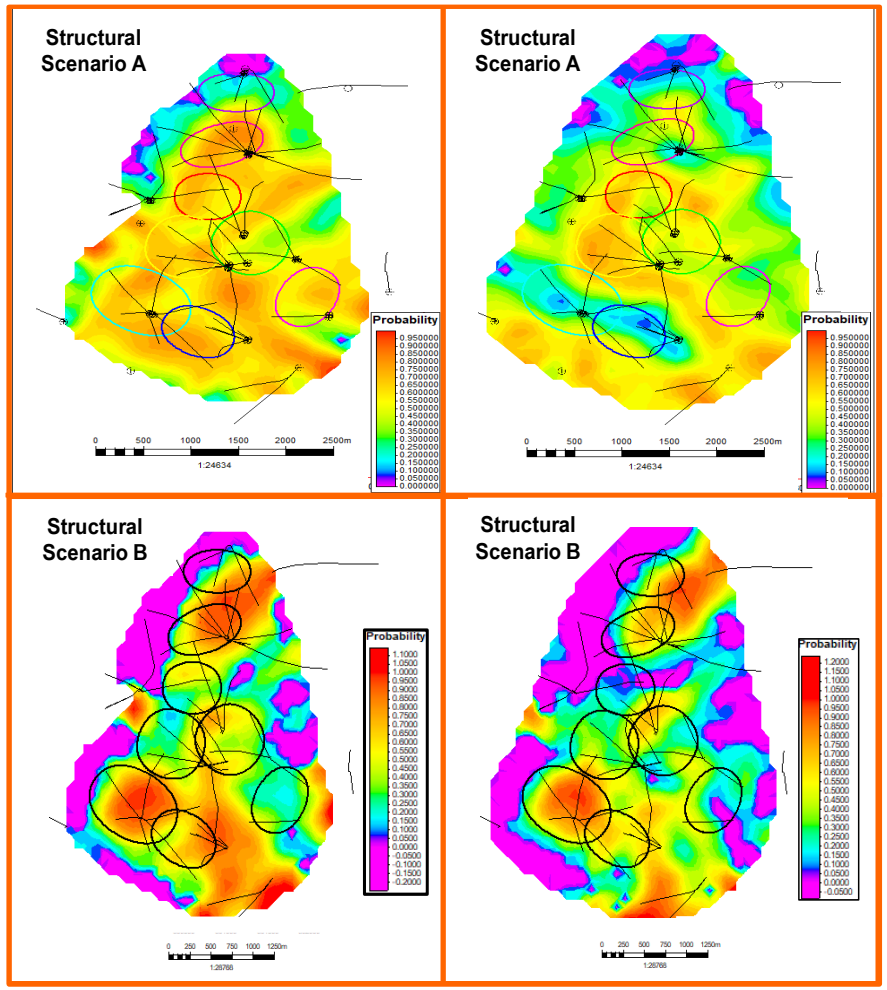
- Discrete Fracture Network (DFN) models for two structural scenarios (Scenarios 1 & 3) and the stochastic (residual) fractures were developed
- Comparison of the fieldwide trends of fracture permeability derived from the DFN models and those from the Darajat numerical model was promising
- Trends of high permeability delineated by the upscaled DFN models resulted in trends that are like those found in the Darajat numerical model and show the following key features: high permeability hot spots in the north and south and lower permeability through the central portion of the field
  - The numerical model is the mathematical representation of the Darajat static model that was built to simulate and reproduce the mechanisms of the Darajat geothermal system

Fracture Characterization and Optimized Well Placement (FCOWP)

Provisional Probability of Permeability (PoP) Maps

Provisional Probability of Permeability (PoP) Maps (ki) >30 mD

TOR – 1,800 ft. ASL | **1,800 – 1,500 ft. ASL**



- Provisional PoP maps for two different structural scenarios for different reservoir volumes were initially built
- The ovals on the maps represent the reservoir volume that will be validated with well data
- Warm colors denote regions with high probability to encounter fracture permeability (i.e., ki >30 mD) and should be good for wells targets
- Work is under way to refine the PoP maps and include sensitivity analysis of changing the fracture aperture and length and uncertainties in the structural interpretations using multiple DFN realizations

Note: TOR refers to the Top of Reservoir; ASL is Above Sea Level.

Summary

- Star Energy Geothermal is always innovating and pursuing new ideas and technology to further develop and lead in the field of geothermal where its use is expected to increase the understanding of our fields.
- NFR approach focuses on understanding where fractures are and how permeable they are in drilled areas; thus, improving model accuracy and our ability to target successful wells within drilled areas.
- FCOWP focuses on understanding why fractures are there and where they are likely to be in undrilled areas to improve our ability to target successful wells in undrilled areas and in new exploration prospects; aims to determine the Probability of Permeability (PoP) in certain sectors of the field.
- 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 Oil and Gas application while Star brought extensive knowledge of geothermal naturally fractured reservoirs.