Simulation of the Habanero Enhanced Geothermal System (EGS), Australia

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ABSTRACT

A TOUGH2 reservoir model has been developed for the Habanero EGS, located in the Cooper Basin. The reservoir, interpreted to be the sub-horizontal Habanero fault, was defined by the extent of the stimulated seismic cloud. A 1D natural state model was used first to calibrate the rock properties: specific heat capacity, thermal conductivity, heat generation and the heat flux at the base of the model. The temperature distribution was matched against measured down-hole data from well Habanero 1. A 3D model was then developed with 9 horizontal layers and aligned along an impermeable eastern boundary fault. Gravity potentially plays an important role so the model was tilted to the west-south-west. Since the fine 72,000 cell model only extends to 20 km^2 whilst the reservoir rock (Innamincka Granite) extends to over ~1,000 km^2, Dirichlet boundary condition (large block volumes) was used for the sides with closed boundaries at the top and bottom. These large cells simulate the extension of the reservoir beyond the limited dimensions of the basic model. The permeability of the stimulated and mud damaged zones was calibrated using stable closed-loop (doublet) production and injection history data. The porosity was calibrated by simulating the two tracer tests carried out at Habanero. In preparing future production forecasts, three different well layouts were considered: staggered line drive; inverted 4-spot and regular 5-spot. For each scenario, closed-loop circulation was modelled for a production period of 20 years. For a larger-scale development plan, recommendations to provide the best outcome, balancing short-term temperature against long-term extensibility are presented.

1. INTRODUCTION

The Habanero EGS has been developed by Geodynamics Limited (GDY) within a resource collectively known as the Innamincka granite. The majority of work has been at the Habanero location where four wells have been drilled to depths between 4,205 m to 4,420 m located close to an early petroleum well, McLeod 1 (McL). The naturally fractured granite is water-saturated and thermally insulated by ~3,650 m of overlying sedimentary formations (Holl et al., 2013). The EGS reservoir within this granite is confined to a critically stressed low angle sub-horizontal fault zone, the Habanero Fault which is prone to slip. GDY has recently demonstrated the technical feasibility of EGS at Habanero with the completion of the Habanero Pilot Plant project in October 2013 (Mills and Humphreys, 2013). This work outlines the first numerical reservoir model built for Habanero using the TOUGH2 (Pruess et al., 1999) thermodynamic simulator.

In 2003, Habanero 1 (H01) was hydraulically stimulated, resulting in 28,000 seismic events within an approximately planar seismic cloud (McMahon and Baisch, 2013). The well was re-stimulated in 2005, adding a further 16,000 events and extending the seismic cloud. In November 2012, stimulation was conducted at Habanero 4 (H04) with the intent to expand the existing reservoir and to gain a better understanding of the geothermal system. Over 36 ML of water was injected and over 27,000 events were recorded. The seismicity around H04 (Figure 1) grew elliptically but was constrained by an apparent eastern boundary. Figure 1 shows the hypocenter locations of the induced seismicity from the 2003 and 2005 stimulations (grey dots) as well as the stimulation in H04 (bright colors). Each seismic event is displayed by a globe scaled to the event magnitude. Color encoding denotes occurrence time.
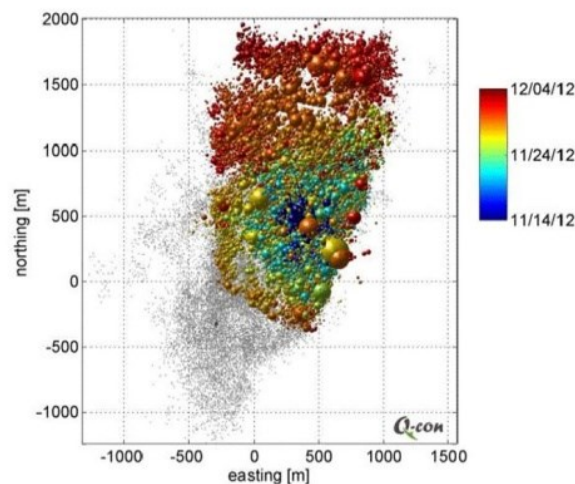

Figure 1: Hypocenter locations of the induced seismicity in Habanero (after McMahon and Baisch, 2013).

2. CONCEPTUAL MODEL

The extent of the seismic cloud was used to define the area of the stimulated reservoir. A damaged zone, the "mud ring", has been modelled around H01 as evidenced by limited seismicity around the well during stimulation of H04 and the low injectivity of H01. These porosity and permeability variations have been incorporated into the reservoir as shown in Figure 2: existing stimulated area (cyan), un-stimulated fault zone (yellow), damaged area (red) and eastern boundary fault (blue). The orange zone represents a hypothetical extended fracture as discussed later in Section 6. Gravity is potentially playing an important role on the inclined Habanero Fault. Hence, the full 3D model with horizontal layers is tilted 10° to the west-south-west. The dimensions of the grid used for the model are 4×5×5 km in the x, y and z directions, respectively. The x-axis has been set-up approximately east-west and the y-axis approximately north-south, running parallel to the strike of the eastern boundary fault.
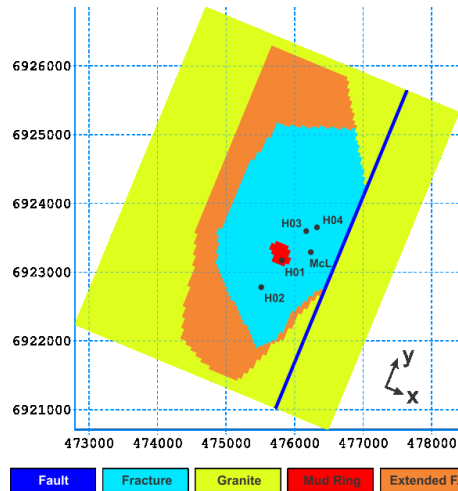

Figure 2: Plan view of the reservoir showing the existing and extended fractures, mud damage zone and impermeable fault.

A review of the geology and natural state temperature profile recorded at H01 provided definition for layers in the conceptual model (Figure 3). The model was broken into 9 layers which represent segments of constant temperature gradient, labelled from top to bottom as Layers 1 to 9. Each layer has 50×50 m cells, i.e. 8,000 cells per layer for a total of 72,000 cells. The granite section (blue and green layers) is modelled with five layers: two thick layers (5 and 9) representing the bulk of the unfractured granite; two 25.6 m thick unfractured layers (6 and 8) above and below the reservoir to give good resolution of the stimulated area; and the 5 m thick reservoir layer itself, Layer 7. The low permeability eastern boundary fault crosscuts the model from layers 5 to 9. The top of the model (Layer 1) is modelled as planar and so does not follow the topography of the Habanero area. However, since there are no natural surface outflows of geothermal fluid and there is no hydraulic connection between the over pressured reservoir and the normally pressured shallow sediments, the topography of the surface is hydraulically irrelevant. The model has been set up with all side boundaries closed, meaning that there is no heat or mass transfer from the sides of the model. Similarly, because there are no surface outflows of geothermal brine and rain is scarce, heat and mass transfer at the top of the model is ignored. At the bottom boundary, a constant heat influx was applied and in-situ heat generation was assumed in all the granite blocks.
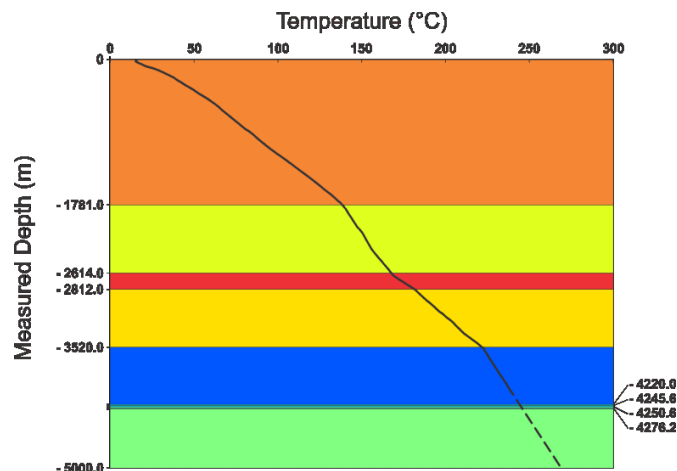

Figure 3: Cross section of the TOUGH2 model and H01 temperature profile.

3. 1D NATURAL STATE MODEL (1DNS)

A 1D version of the full 3D model was used for this step of the process. The same 4×5×5 km volume was used but with only one cell per layer. The model was layered as follows: 50 m thickness layers above 4,100 m and from 4,500 to 5,000 m. The 400 m in between, which contains the reservoir of interest, was represented by 18 layers. This means a total of 111 layers. 125 mW/m² heat flux at the bottom and 10 µW/m³ heat generation in all the granite blocks were assumed. The thermal conductivity of the layers was adjusted until a good match in the temperature profile was found, as presented in Figure 4. The values obtained for the thermal conductivity of the zone of most interest were 3.7775 W/(m.K) for layer 5 and 3.3950 W/(m.K) for layers 6 to 9.

4. 3D NATURAL STATE MODEL (STATIC MODEL – 3DNS)

After establishing appropriate values for the thermal conductivities, heat influx and in-situ heat generation, these values were used in the 3D model. Having a tilted model complicated the creation of the natural state. There were several convergence issues with the initial attempts making it necessary to force the model into the measured natural thermal distribution. Therefore values of temperature and pressure were assigned to each cell in the initial conditions or '.incon' file, allowing for the tilting of the model and the temperature and pressure profiles observed in H01. The natural state model was set-up with open boundaries and allowed to run for >10 million years. The temperature versus depth profile generated by this natural state simulation is shown in Figure 4 along with the down-hole temperature data for H01.
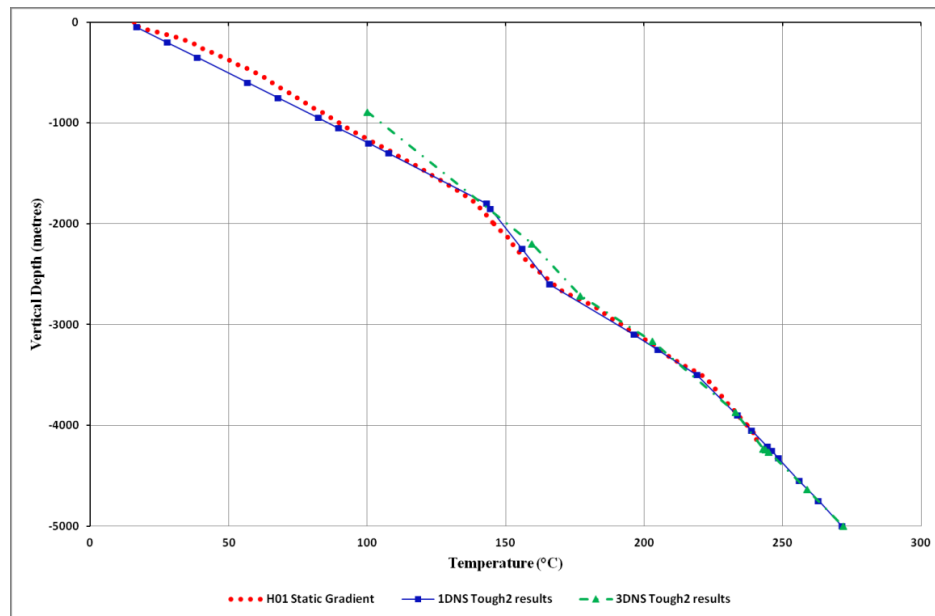

Figure 4: 1DNS and 3DNS modeled vs. measured temperature profiles (m vs. °C).

5. PRODUCTION MODEL CALIBRATION

5.1 Permeability Calibration

The permeabilities of the stimulated and mud damaged zones were calibrated using stable H01-H04 closed-loop production and injection data corresponding to the period from 16th to 21st August, 2013. The wellhead pressure reported for H01 was 44 MPa while for H04 it was 33.5 MPa. These measured surface production and injection pressures were first corrected to bottom-hole conditions, allowing for frictional and gravitational pressure changes down each well. In order to match the bottom-hole pressure at H04, estimated at 72.50 MPa, the permeability of the stimulated fault zone was adjusted until a good match was found. The best match was obtained using a value of 800 mD in x and y directions or 4,000 mD.m for the transmissibility of the stimulated fault zone. For the damaged zone around H01, the target value of injection pressure to match was 83.3 MPa and the best fitting permeability value for the damaged zone was 28 mD, giving transmissibility of 140 mD.m.

5.2 Porosity Calibration

The porosities of the stimulated and damaged fault zones were calibrated by simulating the two tracer tests carried out through injecting tracers into Habanero. The simulated tracer concentrations were matched to the field data as analysed by the Energy and Geoscience Institute, University of Utah (Ayling and Rose, 2013).

Between 18th December, 2008 and 22nd February, 2009 a H01-H03 closed-loop circulation test was conducted (Yanagisawa et al., 2009). Two tracers were injected into H01: 100 kg of 1,3,5-naphthalene trisulphonate (1,3,5-nts); and 50 kg of uranine (sodium salt of fluorescein). The 1, 3, 5-nts tracer injection was modeled using the calibrated natural state model. The porosity obtained for the stimulated fault zone (fracture) and mud damaged area (mud ring) were 0.5% and 0.36% respectively.

The H01-H04 tracer test was conducted over the period 4th June to 6th September, 2013. The tracer used was 2, 6-naphthalene disulphonate. The porosity obtained from matching this test were 1.4% for the stimulated zone and 0.36% for the damaged area.

5.3 Permeability Anisotropy

In considering the overall shape of the seismic cloud (Figure 1), it is apparent that there is a distinct elongation of the seismic cloud along the north-south or y-axis. In view of this elongation, it is considered most likely that there is anisotropy in the permeability of the stimulated area. This is consistent with laboratory studies on shearing of fractures by Auradou et al. (2006). The spread of the tracer with 2:1 ratio between permeability in y direction and the permeability in the x direction for Layer 7 seems to match reasonably well with the shape of the observed seismic cloud, so 2:1 permeability anisotropy (k_y = 1,200 mD, k_x = 600 mD) has been adopted for the base case reservoir model as well as the forecast (future) scenarios.

To validate this permeability anisotropy, the H01-H04 tracer match was re-run. The best fitting model retained porosity of 1.4% in the stimulated fault zone but required permeability for the mud zone of 58 mD in the y and 29 mD in the x direction.

6. FORECAST SCENARIOS

Because the model only extends over 20 km^2 (4×5 km) whilst the Innamincka Granite extends over ~1,000 km^2, for the purpose of this forecast study, the edge cells of Layer 7 have been increased in size from the standard 0.125 E+05 m^3 (50×50×5 m) to 0.125 E+10 m^3. These large cells simulate the extension of the Habanero Fault beyond the limited dimensions of the basic model.

Hogarth et al. (2013) suggested replacing H01 by H04 as an injector in order to achieve greater flows and concluded that the reservoir is capable of delivering closed-loop rates between 25 – 45 kg/s. For each scenario, closed-loop circulation at 25, 35 and 45 kg/s per well were modelled for a production period of 20 years, assuming a bottom-hole re-injection temperature of 95°C. Three different well layouts have been considered: staggered line drive (SLD); triangular grid or inverted 4-spot and rectangular grid or 5-spot. The work was also carried out considering a hypothetical extended geometry for the seismic cloud, assuming that the Habanero reservoir is extended by further hydraulic stimulation (orange zone in Figure 2).

A thermodynamic model of the wellbore was developed by Bour (2013) using a commercial wellbore modelling package. Calibration was done using recorded temperatures and two different flow rates in H04: the 19 kg/s flow rates at the end of the H01-H04 closed-loop; and the 6 kg/s open flow rate from H04 after the end of closed-loop test. The actual flowing temperature recorded at site at 6 kg/s was 193°C versus 192°C from the model Bour (2013). The calibrated wellbore model was used to estimate flowing wellhead temperatures (FWHT) after three months of continuous flow for a range of flowing bottom-hole temperatures (FBHT) and a range of flow rates. For each TOUGH2 production run, values of flowing bottom-hole enthalpy were obtained per producer and used to calculate the corresponding saturated fluid temperature. The values estimated with the wellbore model were used to convert the simulated FBHT to their equivalent flowing wellhead temperatures.

The heat energy delivered at surface over 20 years was estimated for each producer for the different cases. The enthalpy of the injected fluid at surface conditions (410 bar and 80°C) was subtracted from the enthalpy at flowing wellhead conditions. The mathematical integration of this temperature change multiplied by the circulation rate used provides the amount of heat delivered at surface.

6.1 Results and Discussion

In applying the idealised patterns to the reservoir, H04 has been assumed in all cases to be an injector (I1). Other well locations were selected within the existing seismic cloud so that penetrating the Habanero fault could be assured. Because of this constraint, each well layout has only three injectors and three producers, as shown in the gray inset on Figure 5. The well patterns were stretched to about the maximum well separation available within the seismic cloud, i.e. a spacing of ~1,100 m. The results in Figure 5 show the sweep pattern plots obtained for all these cases. These plots show the temperature distribution in Layer 7 after 20 years of circulation at 35 kg/s. The colour coding depicts the coolest areas in blue (80°C) and the hottest in red (240°C). The effect of the mud ring around H01 is visually evident as a small red hot spot on each plot. The total recovery of heat of the producers per case is also shown.

The effect of permeability anisotropy is more noticeable with the extended cloud because the re-injected fluid is less constrained by the permeability boundary at the edge of the seismic cloud. The re-injected fluid propagates more elliptically which results in sweeping of larger, hotter areas and a more sustained temperature behavior for each producer.

Requiring all wells to be within the seismic cloud inevitably lead to some skewing of the idealised patterns as well as short distances between I1 and producers nearby. This proximity to I1 and the influence of gravity cause these producers to cool down quicker. This is due to the accelerated movement of cooler brine from the up-dip injectors to the down-dip producers. Gravity plays less of a role at higher rates. The estimations of the heat delivered at surface after 20 years indicate the SLD layout delivers the most heat whilst the 5-spot layout delivers the least. In all layouts, heat recovery is directly proportional to the circulation rate.

A comparison of the average flowing wellhead temperature for each of the three well layouts at 35 kg/s is presented in Figure 6. The staggered line drive (SLD) starts out with the highest average temperature because all the producers are down dip and maintains this advantage over 20 years. Producer 1 (P1) cools off faster as its distance to I1 is shorter than in any other layout. Producer 2 (P2) remains the best production well for this arrangement. The SLD layout clearly shows the highest swept area of all these scenarios.

In the 4-spot scenario, although P1 and Producer 3 (P3) are located in spots which are slightly hotter than P2, their production temperature falls off quicker due to the closeness to I1 and gravity effects. Additionally the permeability anisotropy and the mud ring reduce the swept area in comparison to the SLD. Of the three layouts, the most even temperature behavior of the three producers appears to occur when a 4-spot is used.

The production temperatures indicate that the 5-spot pattern cools off faster than the other two arrangements. This is because the pattern aligns producers and injectors along the orientation of the likely maximum permeability. P1 and P2 are equally affected by I1 and P3 cools down faster than in any other case as a result of having two injectors nearby.

On average, the hypothetical extended seismic cloud delivers 10°C higher production temperatures compared with the results using the existing seismic cloud. Over 20 years, this increase in temperature delivers approximately 3 PJ of additional heat.

For a larger-scale development, extending the layout is important from both the engineering and cost perspective. Both the triangular (4-spot) and rectangular (5-spot) layouts are relatively easy to extend compared to the staggered line drive. For the SLD, adding another row of injectors to the west implies the producers must have massive stimulations to extend the seismic cloud and this stimulation will cool the reservoir around each producer.

Of course, the actual shape of the seismic cloud following stimulation of future production and injection wells is impossible to predict, but this analysis has shown that extending the stimulated fault zone with further hydraulic stimulations is an important and valuable step in establishment of an EGS development.
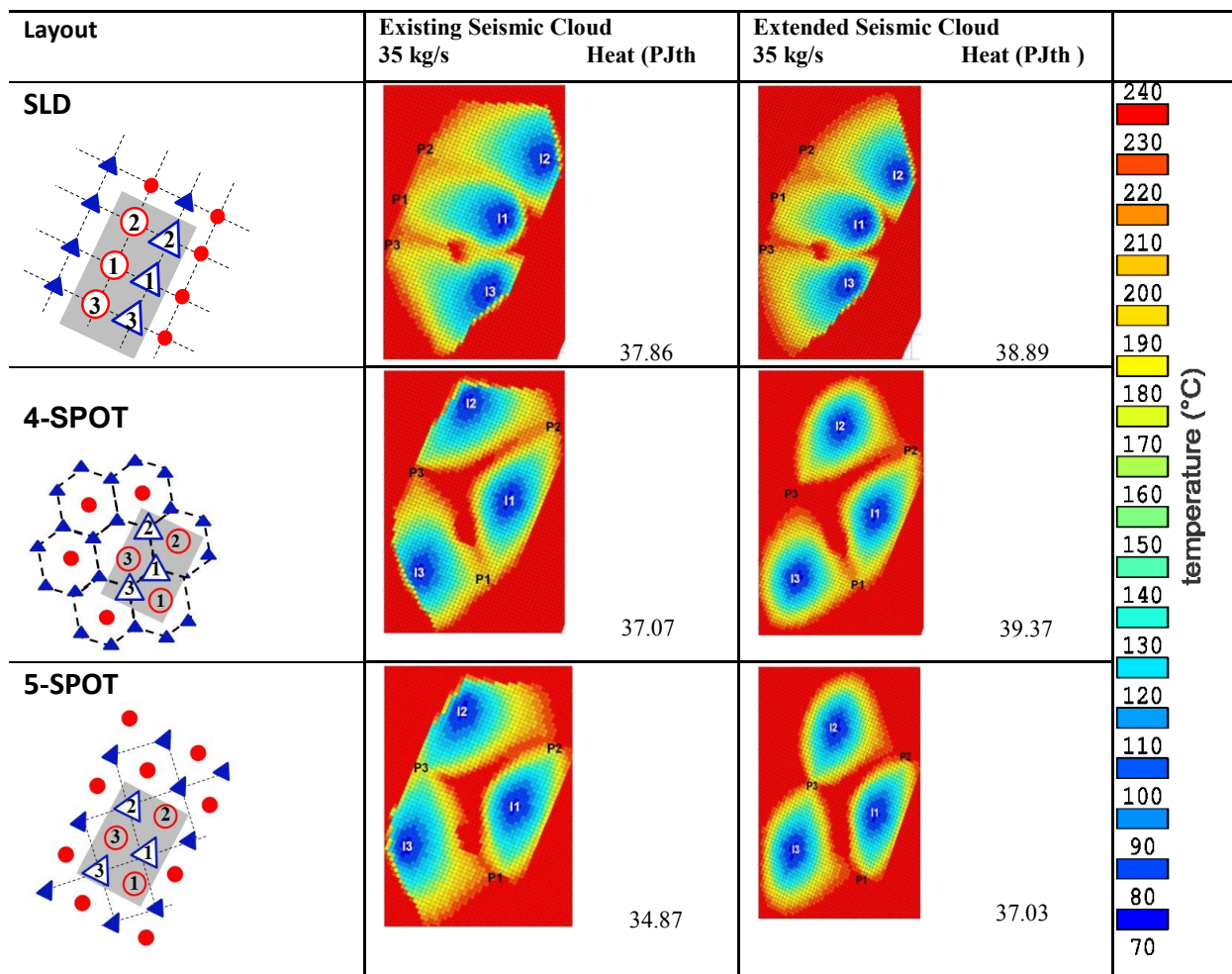
Layout	Existing Seismic Cloud 35 kg/s Heat (PJth)	Extended Seismic Cloud 35 kg/s Heat (PJth)	
SLD	37.86	38.89	
4-SPOT	37.07	39.37	
5-SPOT	34.87	37.03	

Figure 5: **Forecast Scenarios - Sweep pattern profile obtained for each layout after at 35 kg/s after 20 years.**
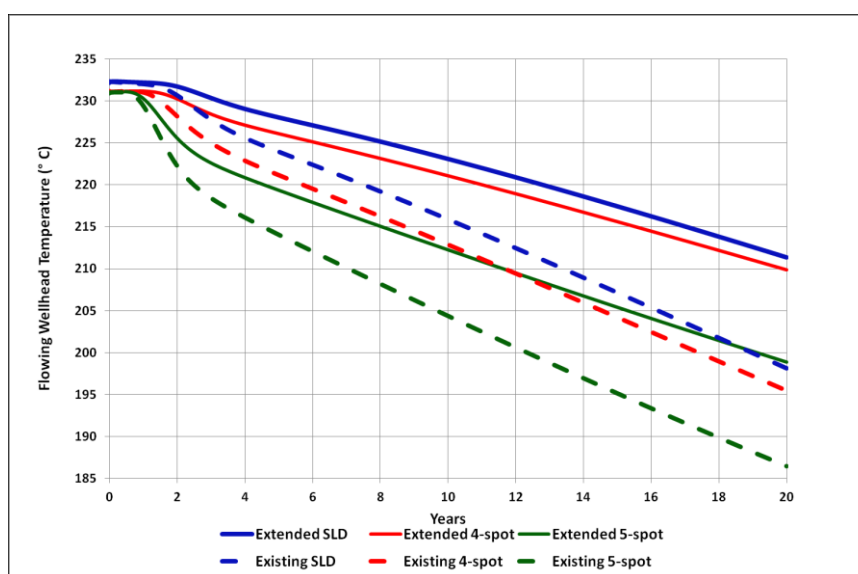

Figure 6: Existing Vs Extended Seismic Cloud - Average Flowing Wellhead Temperatures at 35 kg/s.

Interesting results are obtained when testing a staggered line drive layout running east-west in the hypothetical extended cloud as depicted in Figure 7. The resulting flowing wellhead temperatures indicate that this could be the best of all modeled layouts as the temperatures of the three producers remain fairly flat throughout the 20 year simulation. This layout, termed the E-W staggered line drive, appears to provide the best balance of production/temperature performance and extensibility.
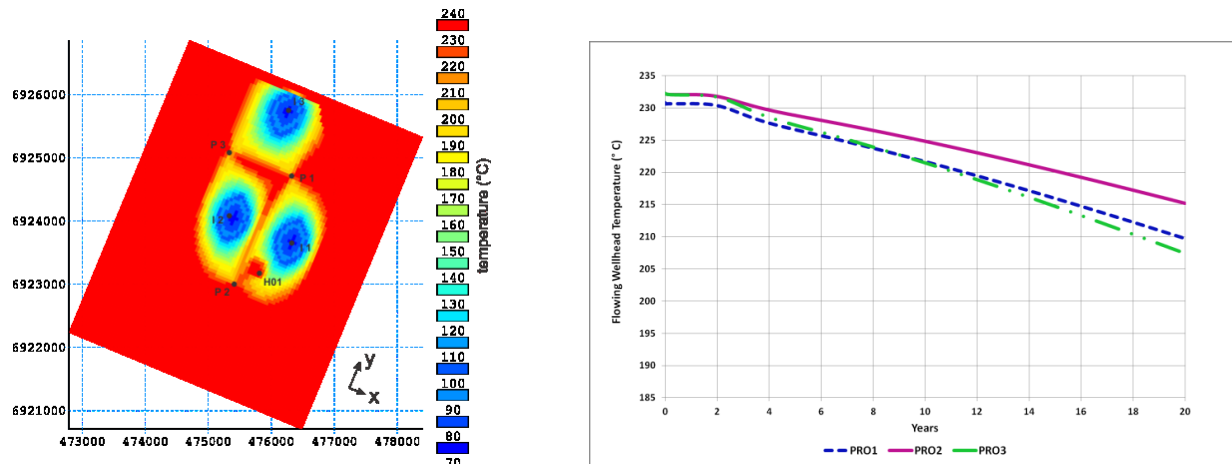

Figure 7: **Extended Seismic Cloud - Sweep pattern profile and Wellhead Temperatures: E-W SLD, 20 years, 35 kg/s.**

7. CONCLUSIONS

A numerical thermodynamic geothermal reservoir model has been developed for the Habanero EGS in the Cooper Basin, Australia. The 3D model grid was built around the seismic cloud that was observed during multiple hydraulic stimulations carried out on the Habanero fault since 2003. The model grid was aligned in the y direction with the interpreted boundary fault at the edge of the seismic cloud and tilted to align with the 10° dip of the Habanero fault. A natural state (static) model was used to calibrate thermal properties by matching the temperature profile of H01. The production model was calibrated by matching production and injection pressures and tracer tests between H01-H03 and H01-H04, respectively. The calibrated model showed that a permeability anisotropy ratio of 2 to 1 between the y and x directions matches well with the shape of the seismic cloud. Four well layouts were considered for the future development of the Habanero EGS, each of which was modeled over 20 years of production to examine the impacts of permeability anisotropy and gravity across the tilted fault zone. Each layout was established with six wells, three producers and three injectors, and modeled at three production and reinjection rates.

The principal conclusions from this study of the Habanero reservoir are that:

- The permeability anisotropy was shown to be a key parameter controlling the fluid flow in the production forecast model;
- The permeability boundary at the edges of the existing seismic cloud constrains flow patterns and reduces production temperatures;
- Better temperature performance is obtained when wells are not aligned with the permeability anisotropy;
- Better temperature performance is obtained from an extended seismic cloud, which implies that stimulation of future production and injection wells is worthwhile;
- The best temperature performance is obtained with a staggered line drive layout oriented East-West;

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