Feed Zone Evaluation in Hululais Geothermal Field, Bengkulu, Indonesia

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ABSTRACT

Hululais geothermal field is situated within an overlapping area between the Musi and Ketahun Segment. These segments are part of the NW-SE Sumatra Fault Zone. These NW-SE structures and also its local lithological factor is hypothesized to influence the permeability of feed zone in Hululais by certain degree.

Drilling campaign in Hululais has been started in December 2010, this activity provides subsurface data such as rock cuttings and cores, drilling parameters, borehole logging, and completion test data. Spinner data, temperature measurement, loss circulation while drilling, rate of penetration, weight on bit, cuttings, cores, interpreted fracture from borehole logging is integrated and analyzed to evaluate and characterize the feed zone of the wells.

The study depicts that the feed zone distribution and also its permeability is quite unique which is influenced both by structure and lithological factor. The feed zones can be divided into three groups based on their vicinity to the surrounding structure and their lithological factor. This grouping also correlates with its permeability from high to low. Identifying factors that control the distribution and the permeability of the feed zones will reduce the subsurface uncertainty for well targeting in the future field development.

1. INTRODUCTION

Hululais geothermal field is located in Lebong, Bengkulu Province, Sumatra, Indonesia. It can be reached by land around 5-6 hours' drive from Bengkulu toward the Bukit Barisan, north of Bengkulu City (Figure 1).

Hululais geothermal field is one of the projects that are being developed by Pertamina Geothermal Energy (PGE). As part of the project development stage in Hululais, drilling campaign is conducted by PGE. Drilling campaign in Hululais has been carried out by Pertamina Geothermal Energy up until now since the first exploration well spudded in December 2010. These drilling activities provide numerous subsurface data to be studied and to be utilized in order to reduce the subsurface uncertainty in Hululais.

By integrating the data obtained from drilling campaign such as spinner data, temperature measurement, loss circulation while drilling, rate of penetration, weight on bit, cuttings, cores, and interpreted fracture from borehole image logging, we could evaluate and characterize the feed zones in Hululais which are the main topic on this paper.

2. METHODOLOGY

In order to evaluate and analyze the feed zones in the well, several data are needed. The required data can be grouped into four groups, cuttings and cores, drilling parameters, borehole logging and completion test data.

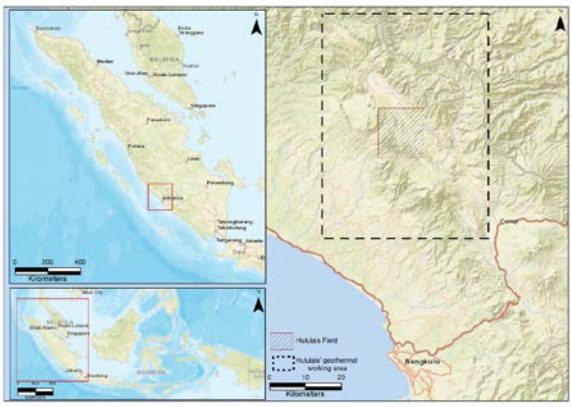

Figure 1: Hululais geothermal field location (Topographic taken from ESRI Database Online, 2020)

Drilling parameters such as loss circulation during drilling, rate of penetration (ROP) and weight on bit (WOB) are needed as the early tool during drilling to recognize the potential feed zone. The drilling break ratio (ROP/WOB ratio) is just the ratio between the rate of penetration (m/hr) and weight on bit (klbs). It is inferred that the drilling break occurs when the ratio is close to 1 or more than 1.

Cuttings and cores are used to infer the lithology and the alteration that occurred from the subsurface. Borehole logging especially resistivity borehole image logging is used to analyze the fracture around the borehole and it could help by some degree to infer the lithology when there are no cuttings due to total loss circulation. Fracture interpreted from borehole image is categorized into two, conductive and resistive fracture. Conductive fractures are either open to fluids, or infilled by conductive minerals such as clay minerals and pyrite, thus exhibit darker colour on the image due to its low resistivity value. Resistive fractures are fractures filled by veins composed of calcite, quartz or other minerals, hence not permeable and have brighter colour due to its higher resistivity value. The number of fractures within the fair-good image quality section is processed into histogram with bin width for every 3 m and plotted with its cumulative fracture to infer the intensity of the fractures along the logged section. Meanwhile, the bad image quality intervals are removed from any interpretation.

The completion test data such as pressure, temperature, spinner data (PTS) during injection and heat up temperature is used to confirm the feed zones location. In Glynn-Morris, et al., (2011), PTS data could be analyzed further to infer the nature of the permeability whether it has diffuse or sharp profile. Diffuse profile reflects the more widespread and less concentrated permeability due to formation permeability or diffuse interconnected fracture set. Sharp profile reflects the more concentrated permeability due to a sharp lithological contact, or a concentrated fracture cluster. Later on, transmissivity data from completion data is used to group the

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well permeability. These data are used to analyze what controls the feed zones permeability on each well and rank each factor.

3. RESULT AND DISCUSSION

Geological setting

The Hululais geothermal field is located on the NW-SE volcanic arc of Sumatra Island. This NW-SE volcanic arc of Sumatra is correlated with the subduction process in the south. The northwardly movement of India-Australia Plate beneath the southern part of Eurasian Plate is accommodated by the oblique subduction.

The subduction forms the NW-SE Sumatra Fault Zone (SFZ) that can be observed along the Sumatra Island. The Sumatra Fault Zone which has 20 major fault segments along its path provides the pathways for magma from beneath due to partial melting of the oblique subduction (Natawidjaja, 2018). Thus, influence the formation of volcanoes in Sumatera island which are mostly located close to the NW-SE Sumatra Fault Zone (Figure 2).

Within the Sumatra Fault Zone, Hululais is located on the overlap area between the right-stepping faults of Ketahun Segment and Musi Segment. Because this area is located at the extensional overstep, the pull-apart basin geometry north of Hululais field can be observed (Figure 2).



Figure 2. Tectonic map of Sumatra showing the relative location of Hululais at the clustered volcanoes within the Sumatra Fault Zone (SFZ) (modified from Muraoka, et al., 2010, Barber, et al., 2005, Darman & Sidi, 2000, Sieh & Natawidjaja, 2000). Hululais location is at the overlap area of the right-stepping faults, in between Ketahun Segment and Musi Segment of Sumatra Fault Zone (Koestono, et al., 2015).

WELL P and P-4

Based on spinner data, 1200 gpm of water is injected to the well and it is observed that well P has feed zone from -350 to -450 masl (Appendix 1). Below the 13-3/8" casing shoe, the injected water temperature decreases and flows out of the well into the surrounding formation. Below -450 masl until the bottom of the well there is no or little indication of permeable zone. At -350 to -450 masl the temperature profiles are heated up quite fast from injection to heating up 1 day to heating up 4 days subsequently. It increases from around 30 ^{o}C to an average of 100 ^{o}C that indicate permeable zone. The three temperature profiles below -450 masl increase until it reached 200 ^{o}C at -700 masl and still constant down to the bottom of the well. Below -450 masl those three temperature profiles are close each other that indicate little permeability as there is little gap in between temperature profiles. Based on the spinner profile, this well has sharp profile on its major feed zone.

During drilling at this elevation, there is no loss circulation observed. The loss circulation below 5 barrel per minute (bpm) then occurred around -500 masl and then became continuous from -550 masl onwards. Drilling break ratio perhaps occurred but not too significant within this depth. There are other drilling breaks might be occurred at the rest of the section yet they do not permeable.

The borehole image logging was carried out within the 12-1/4" section. At depth around of -350 to -450 masl there is little amount of observed conductive fractures although at this depth is permeable based on the spinner and temperature data (Figure 3). At around -650 masl and -1100 masl there are significant increases on conductive fractures but it is might be the conductive fractures are not continuous or not well connected.

At -350 to -450 masl is comprised of altered pyroclastic rocks such as chloritized-silicified tuff and chloritized-silicified breccia tuff based on cuttings data (Figure 3). In addition, the borehole image also depicts that the intercalation of tuff/breccia tuff section at this depth experienced artificial fracturing during drilling as it has many induced fractures and drilling enhanced fracture.

Although it seems that the spinner profile is sharp on this well, the spinner profile from the adjacent well (Well-P4) which were drilled later shows diffuse profile (Appendix 2). It is due to the casing shoe depth on this well is set lower or deeper than the latter well. The deeper casing shoe depth makes the permeable major feed zone on this well narrower interval. The diffuse and widespread permeability on this well is interpreted to be controlled by the occurrence of the tuff-tuff breccia unit at -350 to -450 masl.

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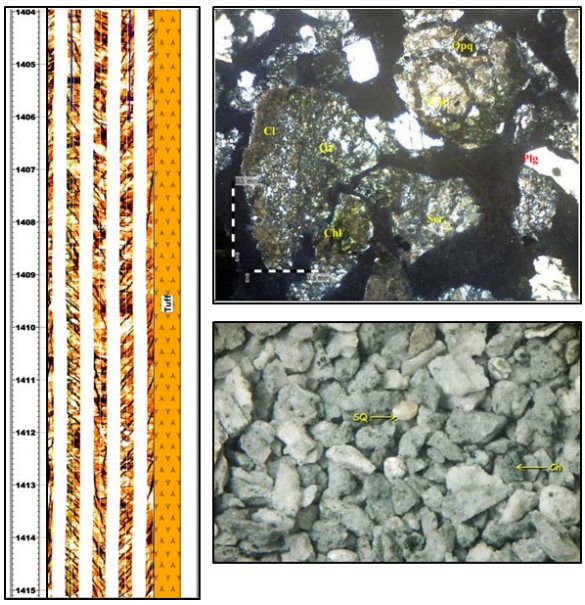

Figure 3. The borehole image from Well P where the feed zone is located at -400 masl. The chloritized-silicified tuff-breccia tuff on cuttings and on its thin section.

WELL H

It is observed based on spinner data with 800 gpm of injected water the permeable zone is located below -750 masl down to the bottom of the well (Appendix 3). The temperature profiles from injection, and two subsequent heating up shows heated up temperature from 30 to 100 ºC and depict convective profile from top to bottom. There are little temperature changes or deflection due to insignificant flow changes. The spinner profile from -750 masl to the bottom of the well has diffuse profile that indicate the permeability is more widespread at larger depth interval.

Based on the drilling parameters the losses started from -200 masl and continued down to -1350 masl with rate loss below 5 bpm. It is also observed that in the 9-7/8" section the drilling break ratio is generally higher than the previous section especially at depth around -800 to -1000 masl. This 9-7/8" section has more fractured rock and thus more permeable.

Borehole image logging covers both the 12-1/4" and 9-7/8" section. Generally, the fracture intensity on the 9-7/8" section is slightly higher than the 12-1/4" section which also confirms the trend in drilling break ratio data. It is also observed that the resistive fractures decrease in the lower section. At depth around -650 to -700 masl the fracture intensity increases significantly and beneath that depth feed zones are encountered.

Based on the cuttings and core data most of the lower section is comprised of silicified granodiorite along with moderate amount of chlorite and epidote which starts from -810 masl. The core from -872 masl shows the occurrence of calcite-pyrite vein, calcite-quartz vein, chlorite-epidote vein within granodiorite (Figure 4). Below -810 masl to the bottom of the well, borehole image data also shows relatively higher resistivity value than the upper section.

The diffuse permeability on this well is controlled by diffuse interconnected fracture set within the granodiorite body at the lower section of the well. It is also observed that fracture set in the upper part gives no or little contribution based on the spinner data. It is interpreted that the fracture set in the upper part is not well connected compared to the fracture set within the granodiorite body.

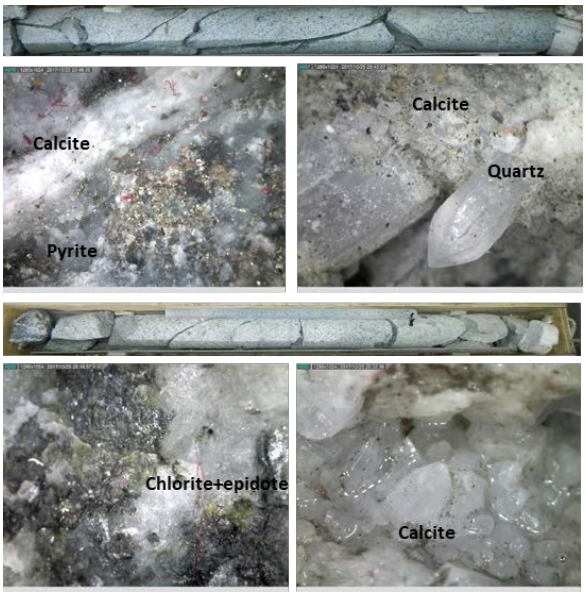

Figure 4. Recovered granodiorite core from the lower section of Well-H at -872 m.

WELL C

On the temperature and spinner data plot show the major feed zone is located at around 75 to 0 masl while the other minor feed zones are around -400 to -550 masl (Appendix 4). Around 67% of 1000 gpm injected water were loss at the major feed zone meanwhile the other feed zones took the rest of the injected water.

At depth 75 to 0 masl depicts sudden deflection on those three temperature profiles (during injection, heating up day 1, heating up day 3). The gap between the temperature profile of heating up day 1 and day 3 is also very tight at this depth. This reflects that the feed zone at 75 to 0 masl is highly permeable as it requires little time to heat up and reaches the maximum temperature. Meanwhile the feed zone at -400 to -550 masl both heating up temperature profiles show decreasing temperature with wider gap in between that reflects lower permeability compared to the main feed zone at 75 to 0 masl. Nevertheless, the overall permeability of this well is quite good as heating up temperature on day 1 and day 3 jumped high compared to the temperature during injection from 50 ºC to around 250 ºC and also show convective temperature profile. Based on this spinner profile the major and minor feed zones of well-C have sharp profiles which indicate that the permeability is concentrated at narrow interval.

The drilling parameters at 75 to 0 masl indicate that the drilling had encountered potential major feed zone. It was started with 5 bpm loss circulation of water polymer mud which later on the loss increased significantly. This significant rise changed the mud system into aerated water to compensate larger losses. The drilling break ratio at this major feed zone depth is generally higher compared with the rest of the well. Meanwhile at -50 to -600 masl encountered higher losses that caused total loss circulation along with up-trending drilling break ratio from -500 to -600 masl.

Borehole image logging on this well only covers the lower section. Logging in the upper part encountered temperature issue that exceeded the maximum temperature limit of the

borehole image logging tool (±150-160°C). The lower section depicts relatively high fracture intensity from -600 to -1200 masl. The peak of fracture intensity at -575 and -875 masl also aligned with the increasing drilling break ratio and also the loss circulation data.

The major feed zone at the upper section is interpreted controlled by the occurrence of concentrated fracture as shown by sharp profile PTS and significant increase on drilling break ratio. Moreover, there is a sudden rise from no loss circulation to 15 bpm loss circulation that may reflect the occurrence of large fracture aperture. The major feed zone emplaced on highly silicified andesite and andesite breccia with moderate amount of epidote and high abundance of chlorite (Figure 4).

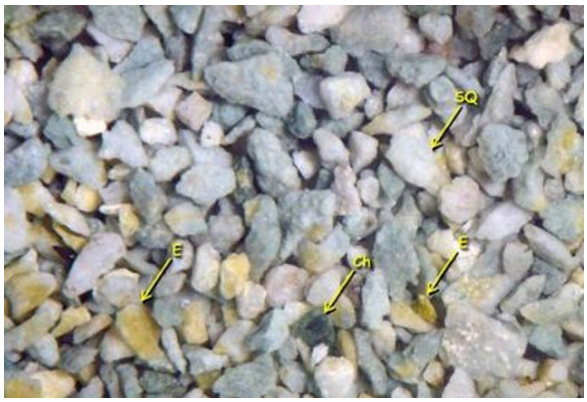

Figure 4. Cuttings from the major feed zone at 0 masl of Well-C. E for epidote, Ch for chlorite, SQ for Secondary quartz.

WELL E

The major feed zones on this well are located around 110 to 90 masl and between 30 to -75 masl. Meanwhile the deeper feed zones at -375 masl and -550 masl also play some contribution (Appendix 5). The major feed zone between 110 to 90 masl is probably concentrated at 100 masl as there is a 'jump' on temperature profile during injection. Both heating up temperature profile also shows significant increase compared to the injected temperature profile. The convective temperature profile starts at around 200 masl down to the bottom of the well.

During drilling, the first loss was encountered at 150 masl then slightly rose to around 3-4 bpm at 100 masl. Then significant drilling break occurred shortly after the loss at depth around 100 masl causing continuous total loss circulation. At depth around 100 masl, significant jump on drilling break ratio is also observed which correlates with the first encountered total loss circulation. The other feed zones are indicated by higher and increasing drilling break ratio at -75 masl, -400 masl, and -550 masl.

On the third plot, it is observed that the fracture intensity is increasing from the top of 12-1/4" to the bottom of 9-7/8" section. The most intense fracturing is found at depth around -640 masl although based on spinner data there is no contribution at that depth. Although the upper section statistically has lower intensity, the better permeability is accommodated by fractures with wider opening in the upper section (Figure 5). This condition makes the fractures in the upper section contribute highly to the permeability of the well.

The last cutting before total loss circulation occurred is chloritized andesite breccia with clear quartz crystal and trace amount of epidote (Figure 6). On the lower section at depth around -400 masl close to the feed zone, a 1 m coring section was recovered. It is observed there is a contact between andesite breccia and andesite lava. The andesite breccia is silicified, chloritized, with disseminated pyrite and some quartz-calcite-pyrite vein (Figure 7). Meanwhile the andesite has veins that predominantly consists of quartz-calcite-pyrite-epidote. The sharp profile on the major feed zones in this well are accommodated by concentrated fracture cluster at several depths. When the fractures have wide opening, they will contribute more to the permeability of the well.

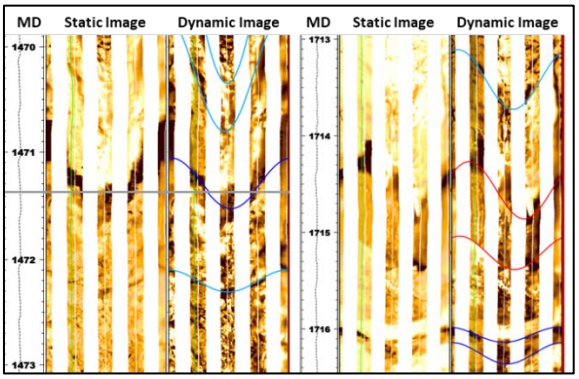

Figure 5. Borehole image log showing fractures with wide opening at the upper section of the Well E (blue=conductive fracture, red=interpreted micro-fault).

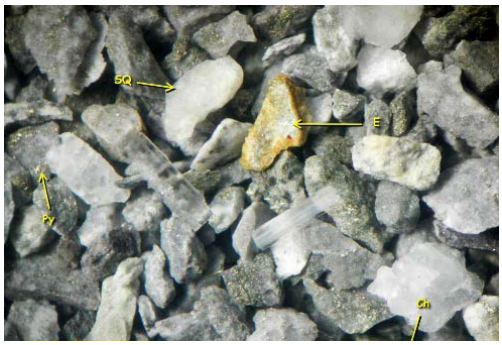

Figure 6. The last cuttings before total loss circulation occurred at around 100 masl in Well E. E for epidote, Ch for chlorite, SQ for Secondary quartz.



Figure 7. Recovered core that depicts contact between andesite breccia and andesite lava at -400 masl.

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Feed zones characterization

Based on observed data from four wells, fracture is not the only factor that controls the permeability. There is a lithology control on the permeability as shown by Well P and Well H. The highest fracture intensity is not a really reliable indicator whether a certain depth is permeable or not as it is evidenced on four wells. This could be due to the fractures are filled by high temperature clay minerals such as smectite-illite, illite or sealed by conductive minerals such as pyrite with others associated minerals that occurs as veins or veinlets. The occurrence of wide fractures opening is more reliable as the indicator for permeable zone. Nevertheless, the feed zone emplaced at certain depth also has some degree of fractures intensity.

A simple approach by grouping the wells transmissivity (kh) into what controlled the permeability could help to depict the permeability distribution of the well (Figure 4). The wells were divided into three groups, the diffuse distributed fracture within granodiorite body (Well H group), the diffuse permeability on tuff-tuff breccia unit (Well P group), and both the sharp profile of Well E and Well C (Sharp profile). The well P and well H also use the adjacent wells within the same well cluster.

It can be noticed that the sharp profile has more permeability than the Well P and Well H group subsequently. The sharp profile from two wells in this paper is accommodated by concentrated fracture cluster where the well is targeted to hit the major faults in Hululais. These major faults hit by the wells are based on the NW-SE regional lineaments of Sumatra Fault Zone, gravity anomaly and the occurrence of surface manifestation around the fault. As the fractures formed in the fault zone is very well connected and cut deep through the rocks thus the permeability is much higher.

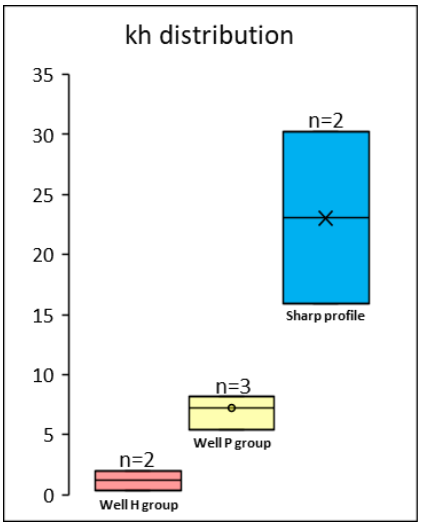

Figure 4: Transmissivity distribution (kh) of each group. The sharp profile due to hit the fault target provides the most permeable well.

5. CONCLUSION

By integrating the cuttings and cores, drilling parameters, borehole logging and completion test data, the permeability of each well has been better characterized. The permeability of each well is then separated into feed zones which may reflects either sharp or diffuse profile. Four wells have been analyzed which resulted in three permeability distribution group. In terms of the permeability, the sharp profile of concentrated fractures due to fault zone is the most permeable followed by the diffuse permeability within the tuff-breccia tuff unit and the distributed fracture within granodiorite body.

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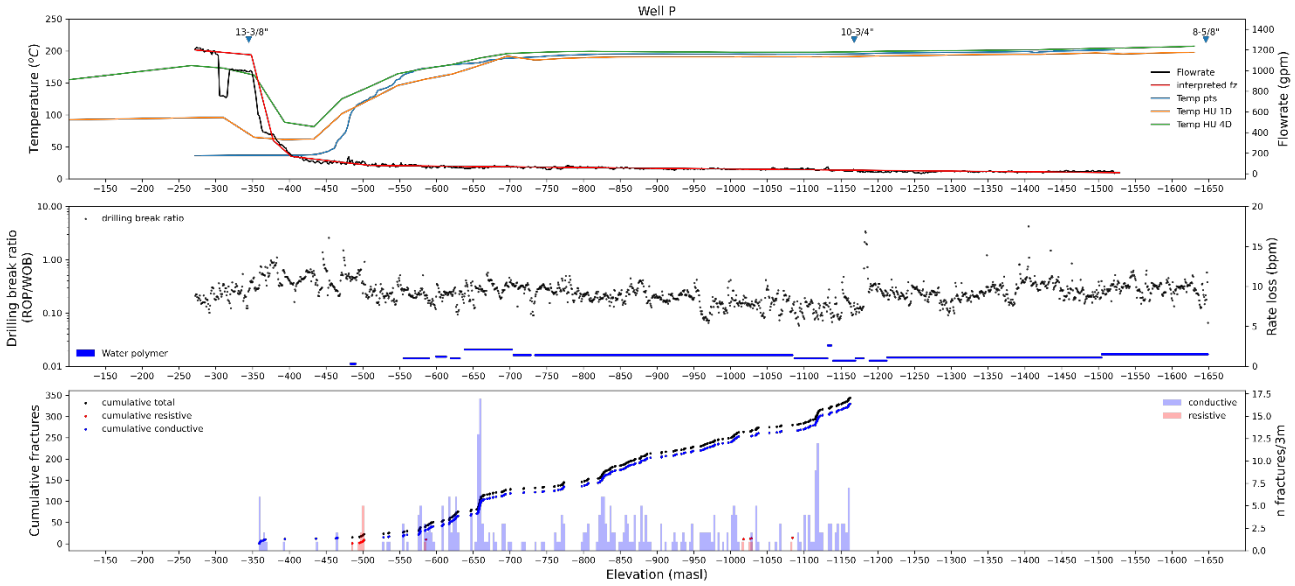
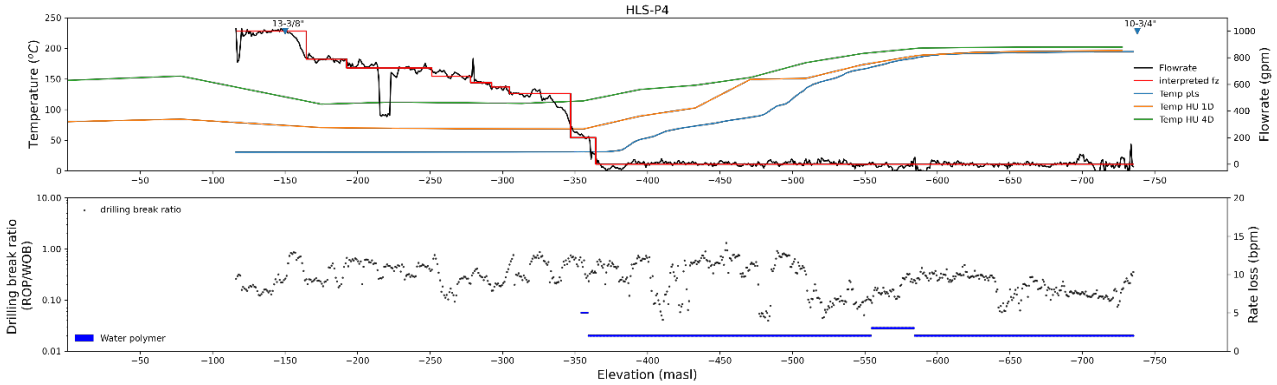
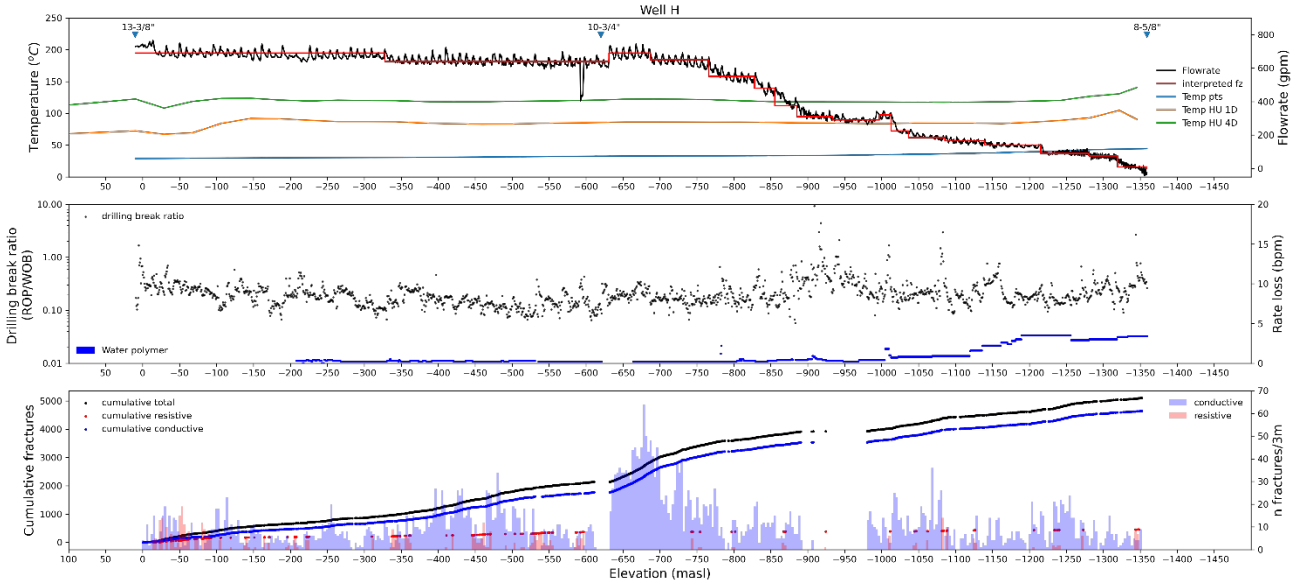


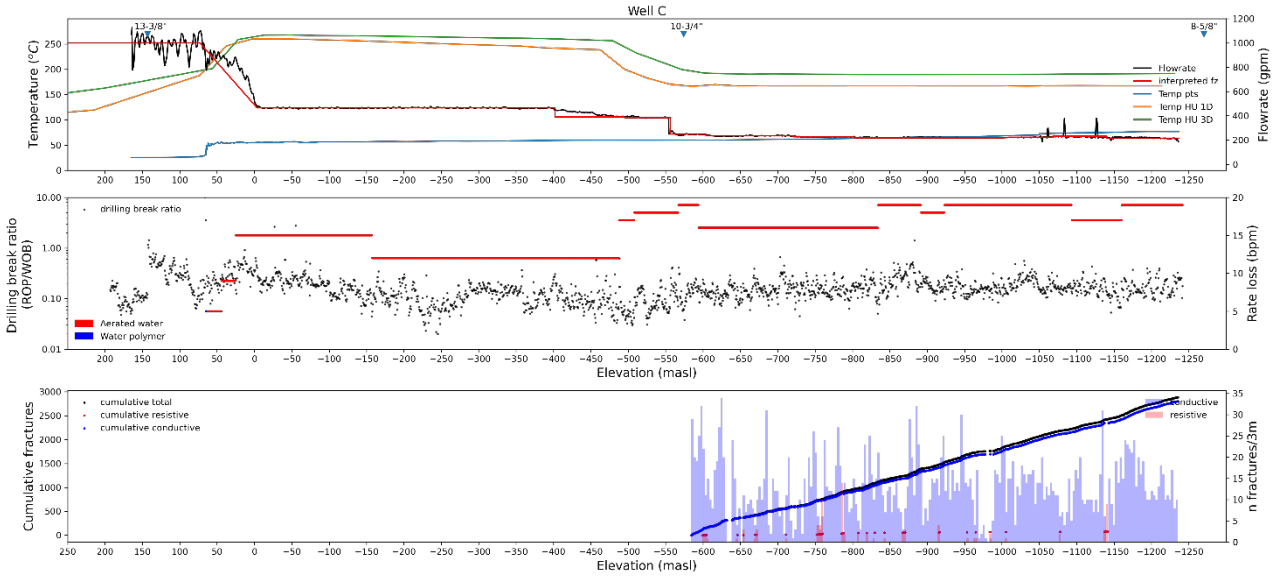
Appendix 1. The PTS and temperature heating up plot, drilling break ratio and loss circulation plot, cumulative and fracture intensity plot of Well P. Notice the feed zone location at -300 to -450 masl aligns with higher drilling break ratio and low fracture intensity.



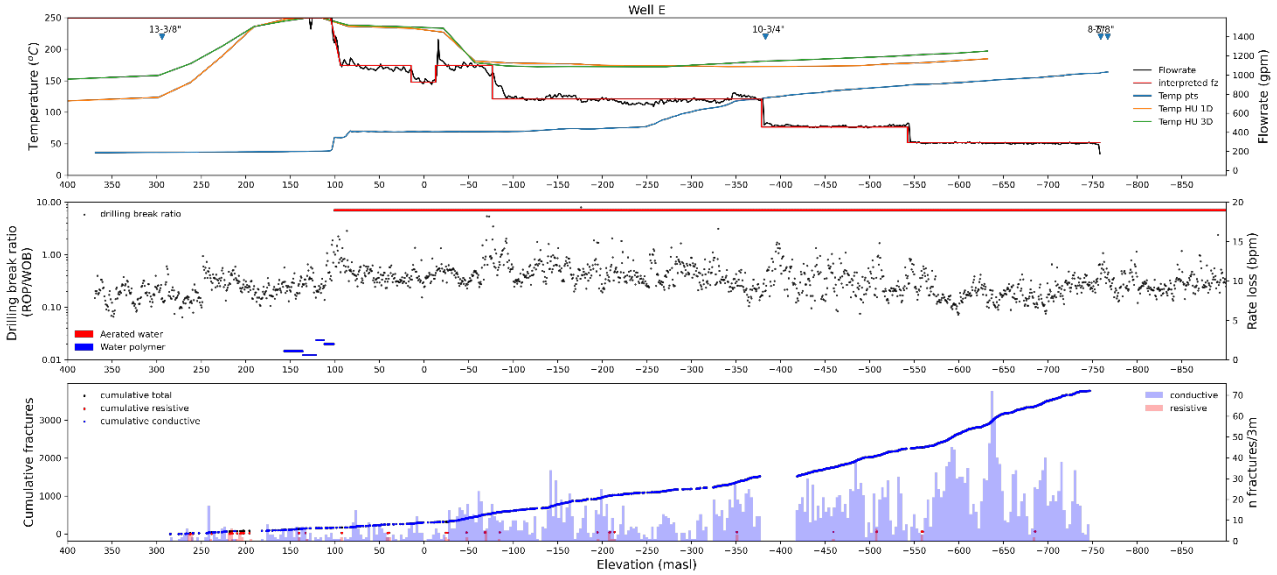
Appendix 2. The PTS and temperature heating up plot of Well P-4. Notice the wider feed zone location at -150 to -400 masl showing diffuse profile.



Appendix 3. The PTS and temperature heating up plot, drilling break ratio and loss circulation plot, cumulative and fracture intensity plot of Well H. Notice the diffuse profile that starts from -750 to the bottom of the well aligns with higher drilling break ratio and slightly increased trend fracture intensity.



Appendix 4. The PTS and temperature heating up plot, drilling break ratio and loss circulation plot, cumulative and fracture intensity plot of Well C. The major feed zone at -75 to 0 masl correlates with a jump in temperature profile, significant increase in drilling break ratio and loss circulation. The borehole image only covers the lower section.



Appendix 5. The PTS and temperature heating up plot, drilling break ratio and loss circulation plot, cumulative and fracture intensity plot of Well E. Most feed zones show sharp profile. The major feed zone at 110 to 90 masl also correlates with a sudden increase in temperature and loss circulation which shortly after became total loss circulation.