Production Log Interpretation through A Slotted Liner during Cold Water Injection: Integration with Electrical Borehole Images in a High Temperature Geothermal Development Well, South Sumatra, Indonesia

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ABSTRACT

Borehole electrical resistivity images and cased-hole production logs were acquired over two intervals of volcaniclastic sediments in a geothermal development well. The imaging tool was logged in the open wellbore; production log data were acquired inside a slotted liner. Cold water was injected during acquisition in order to cool the tools.

The image log identified abundant conductive (open) fractures that are concentrated in, but not restricted to, more resistive (brittle) rock. Resistive (healed) fractures are less extensively developed. A number of faults were identified. Fractures and faults strike mainly NNW-SSE / NW-SE, corresponding to the maximum horizontal stress direction determined from drilling induced fractures. These orientations are to be used to optimize future well design and development strategy.

Production logging identified a number of potential steam production zones where water was either injected into or flowed out of the formation at 1,100 m, 1,546-1,554 m, 1,660-1,780 m, 1,917 m and 2,170-2,260 m (TD). These potential production zones are associated with specific geological features, including faults, isolated large fractures and fracture zones.

INTRODUCTION

It is important to characterize fracture systems in geothermal reservoirs in order to determine producible zones and to provide invaluable data for mapping fracture systems on a fieldwide scale. Standard logging tools are generally rated to only 250°C and, rely on the borehole being filled with liquid. Steam-filled geothermal wells with reservoir temperatures in excess of 250°C cannot be logged on wireline while flowing.

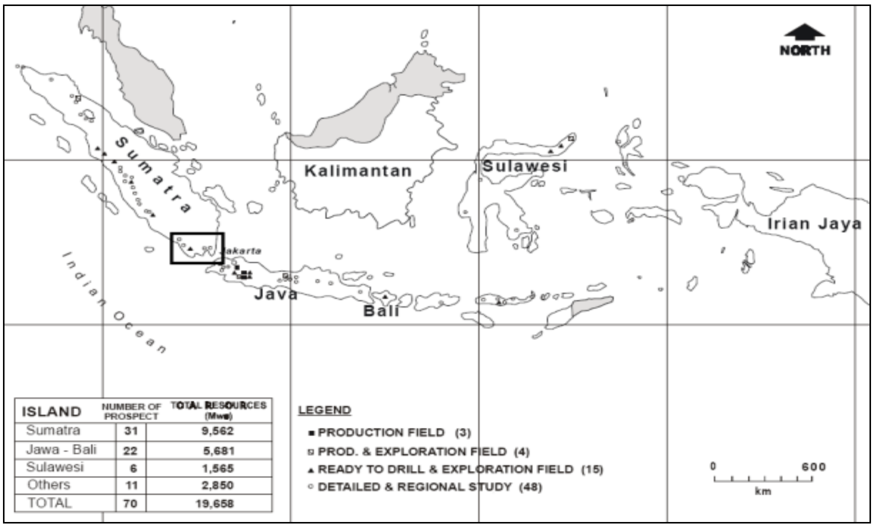
In this case study a borehole resistivity imaging tool and a production log, including spinner, temperature, pressure and fluid density, were logged over two intervals of volcaniclastic sediments (2271-1880m and 1869-880m) during injection of cold water into a geothermal development well drilled in Jambi Province, South Sumatra, Indonesia (Figure 1). The borehole imaging tool was logged in the open wellbore in order to identify, characterise and orientate fractures and other planar geological features that cross the borehole. Production log data were acquired through a slotted liner and were integrated with the open-hole caliper and image log data.

The borehole imaging tool employed has 192 electrical sensors mounted on 8 pads on a lower sonde (Figure 2). An electrical current is injected into the formation from an upper electrode. The return current entering the lower sensors is measured and is proportional to the resistivity of the formation in front of the recording sensor. The 192 resistivity readings are normalized and colour scaled into 164 colour bins, ranging from white, representing the most resistive formation encountered in the logging run, through yellow, orange, brown to black, representing the most conductive formation encountered. The resulting resistivity image has a resolution of 0.2 inch / 5 mm, with 64 % coverage in 12.25 inch and 80 % coverage in 8.5 inch borehole diameters. The imaging tool also records two orthogonal borehole calliper measurements.

Slotted production liners of size 9.625 in OD and 7 in OD were installed in the 12.25 in and 8.5 in openhole sections. Thereafter a production logging tool was run separately in both the sections in order to identify productive zones. The toolstring comprised of a fullbore spinner with calliper, an inline spinner and high temperature basic measurement sonde for temperature, pressure and density (Figure 3). The same toolstring configuration was used for both the sections.

Several passes were logged with PSP in both the sections. In the 9.625 in slotted liner section, 3 down and 3 up passes were recorded with cable speeds of 50, 100 and 150 ft/min; whereas in the 7 in slotted liner section, 2 down and 2 up passes were recorded with cable speeds of 100 and 150 ft/min. The number of passed were limited in 7 in slotted liner section in order to prevent tool damage due to excessive temperature. Also, shut-in passes were not carried out owing to the same reason.

Dynamic flow data from the production log was integrated with geological information from the electrical borehole image.



ISLAND	NUMBER OF PROSPECT	TOTAL RESOURCES (Mwe)
Sumatra	31	9,562
Jawa - Bali	22	5,681
Sulawesi	6	1,565
Others	11	2,850
TOTAL	70	19,658

Figure 1. Indonesia geothermal resources with location of Jambi Province, South Sumatra (Fauzi et al. 2000)

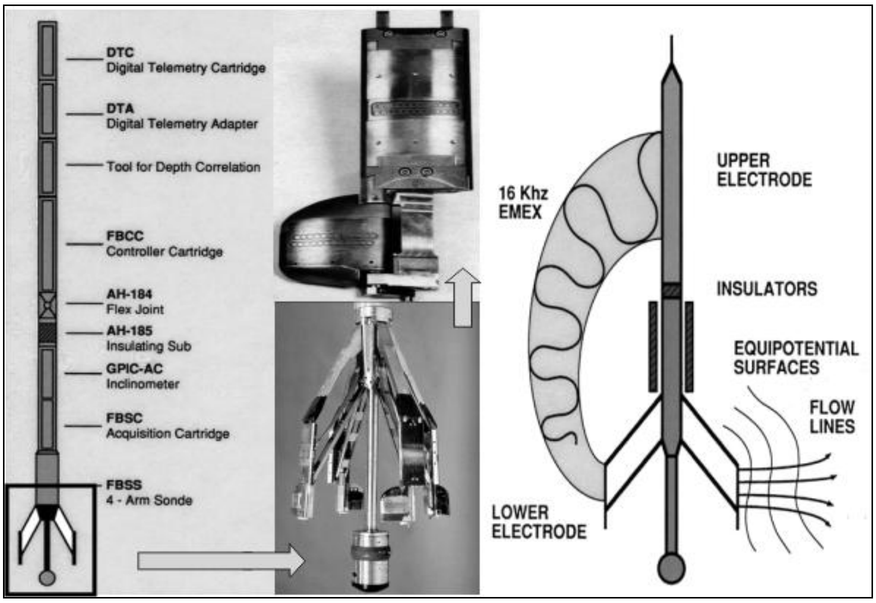


Figure 2. Electrical borehole imaging tool used in the study well

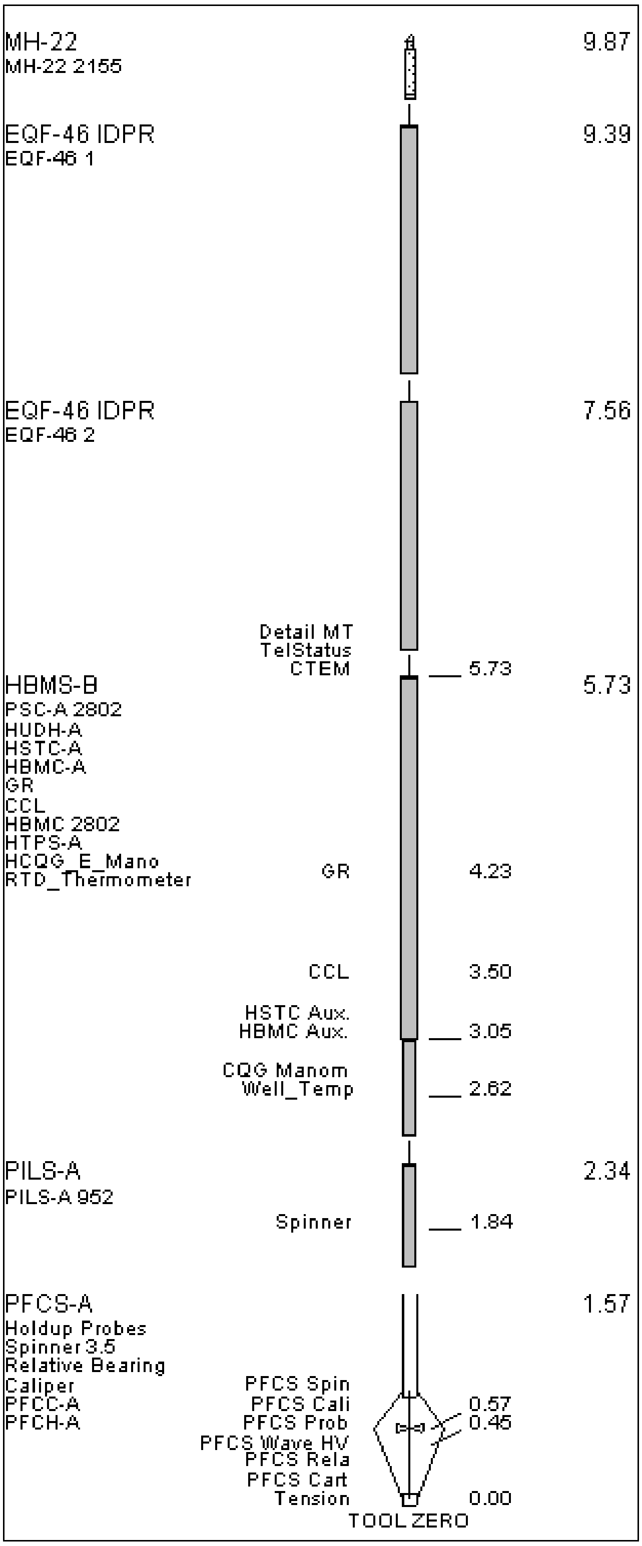


Figure 3. Production logging toolstring employed in the study well

LOGGING PROCEDURES

The acquisition of wireline logging data in geothermal wells generally requires the use of specialized high temperature logging tools that are rated above 300 ^{o}C (e.g. Solbau et al. 1983; Stevens, 2000). As a result, wireline log suites in geothermal wells at temperatures in excess of 300 ^{o}C are rare or tend to be of limited scope. In Indonesia, for a number of years, it has been the practice to inject untreated river water into geothermal wells in order to cool them and, thereby, facilitate the running of standard pressure and temperature rated wireline logging tools. This also allows the running of tools that require the borehole to be filled with liquid, such as electrical borehole imaging, sonic and production logging tools.

RESULTS

Fracture analysis

Conductive fractures appear dark on the electrical borehole image (Figure 4) and can be interpreted as being open (invaded by conductive drilling fluid) or clay-filled (e.g. chlorite). They are most abundant within, but are not restricted to, more resistive and, therefore, more brittle (cemented) rock, rather than more conductive and argillaceous rock. In the absence of fracture permeability diagnostic information, such as Stoneley Wave acoustic data (see Borland et al. 2002), conductive fractures are assumed to be open rather than clay-filled. This assumption is supported to a large extent by the production log data. Resistive fractures appear light on the electrical borehole image (Figure 4) and are healed by electrically resistive minerals such as quartz or calcite, are less extensively developed than conductive fractures and, may be concentrated in both resistive and conductive rock. Faults (Figure 4) were identified based on evidence for movement, including truncation of bedding and changes in lithofacies or lithology across a fault plane. All fractures and faults show a dominant NNW-SSE / NW-SE strike orientation (Figure 5). This is in agreement with the maximum horizontal stress direction determined from the orientation of drilling induced fractures (Figure 6).

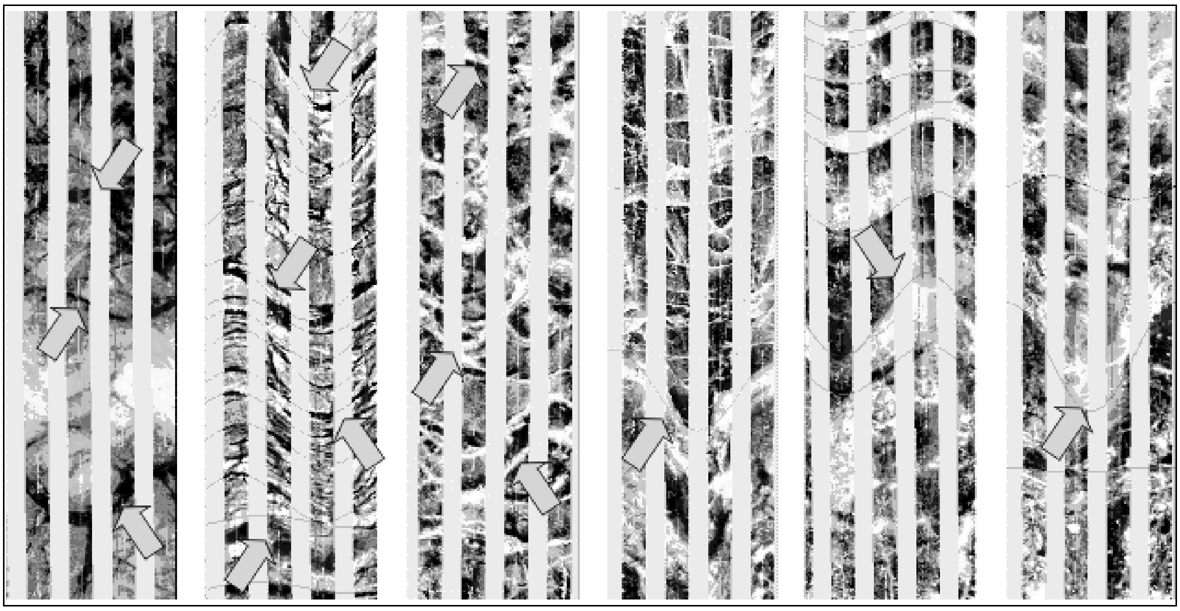


Figure 4. Examples of natural fractures and faults on the electrical borehole image log in the study well. Far left and left: conductive (dark) open fractures. Centre left: resistive (white) cemented fractures. Centre right: fault (arrow) below a network of small resistive (white) cemented fractures. Right and far right: faults.

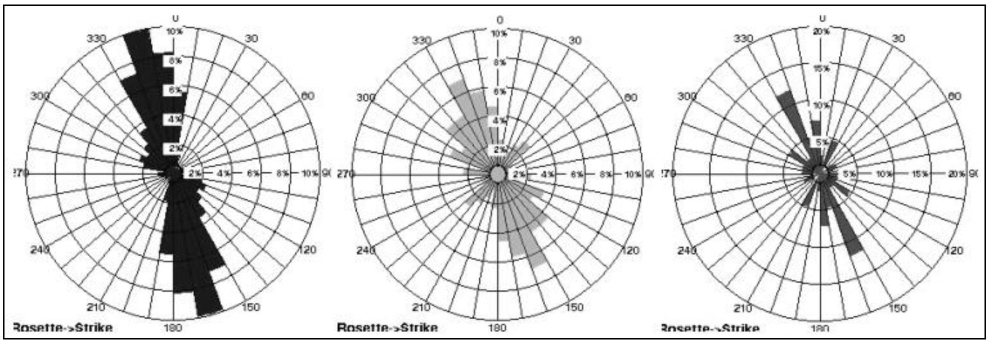


Figure 5. Strike rosette plots of fractures. Left: conductive (dark) open. Middle: resistive (light) healed. Right: faults. All show strong NW-SE strike which is parallel to maximum horizontal stress.

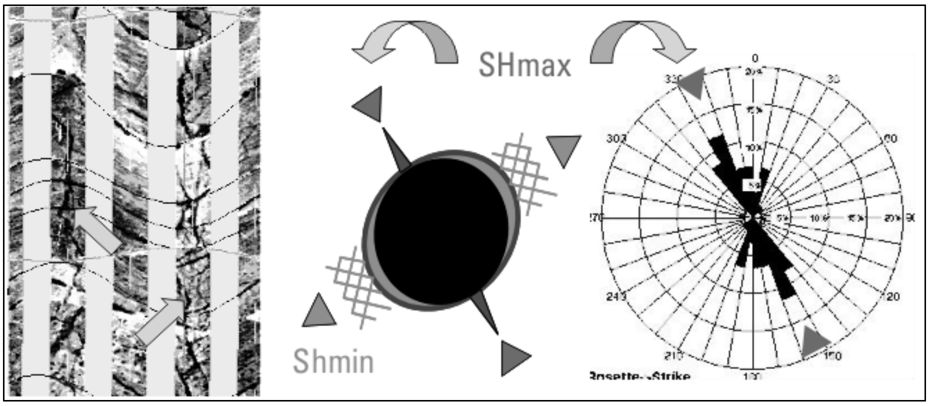


Figure 6. Drilling induced fractures and maximum horizontal stress (SHmax). Left: drilling induced fractures on the electrical borehole image log in the study well. Middle: relationship of drilling induced fractures to SHmax. Shmin is orthogonal to SHmax and is indicated by borehole breakouts and / or borehole ovalization, neither of which were observed in the study well. Right: Strike rosette plot of drilling induced fractures in the study well indicating NW-SE striking SHmax.

Flow analysis

Upper 12.25 inch interval: 870-1,800 m

Approximately 23,000 barrels of water per day (BWPD) were injected into the upper 12.25 inch diameter borehole section below 870 m and, spinner and temperature events were interpreted in terms of fault and fracture distribution and major borehole washouts (numbered zones on Figure 7 correspond to numbered paragraphs below).

1. Immediately below 1,100 m there is a major increase in flow rate according to the spinner readings and, there is a corresponding temperature increase and a fluid density decrease. Flow into the borehole from the formation is calculated at about 8,900 BWPD. This depth corresponds to a high angle fault seen on the borehole image (Figure 8) and is the main potential production zone in the well.

2. At 1,180 m there is a localized and minor increase in flow rate according to the spinner response but, there is no permanent change in spinner response below this event compared to above. At this depth the borehole image is poor (Figure 8) because the tool was caught ("sticking") on an irregularity on the borehole wall. At this depth, according to both the gamma ray response and the borehole image log, there is a major change in lithology that is probably responsible for the tool sticking and flow anomaly might be a result of borehole rugosity behind the slotted liner.

3. Over the interval 1,180-1,550 m there is flow of about 2,100 BWPD into the formation. This amount is minor and there are considered not to be any potential major production zones over this interval.

4. Below 1,550 m the spinner reading indicates a total flow of about 21,100 BWPD into the formation down to a depth of 1,780 m. This water loss into the formation is associated with highly resistive and strongly (open-) fractured lithology over the two intervals 1,546–1,554 m (Figure 8) and 1,660-1,780 m. This is a significant potential production zone.

Lower 8.5 inch interval: 1,865-2,270 m

Outflow from the upper 12.25 inch borehole section into the lower 8.5 inch section is calculated at about 8,900 BWPD. Again, spinner and temperature events were interpreted in conjunction with the borehole image data (numbered zones on Figure 9 correspond to numbered paragraphs below).

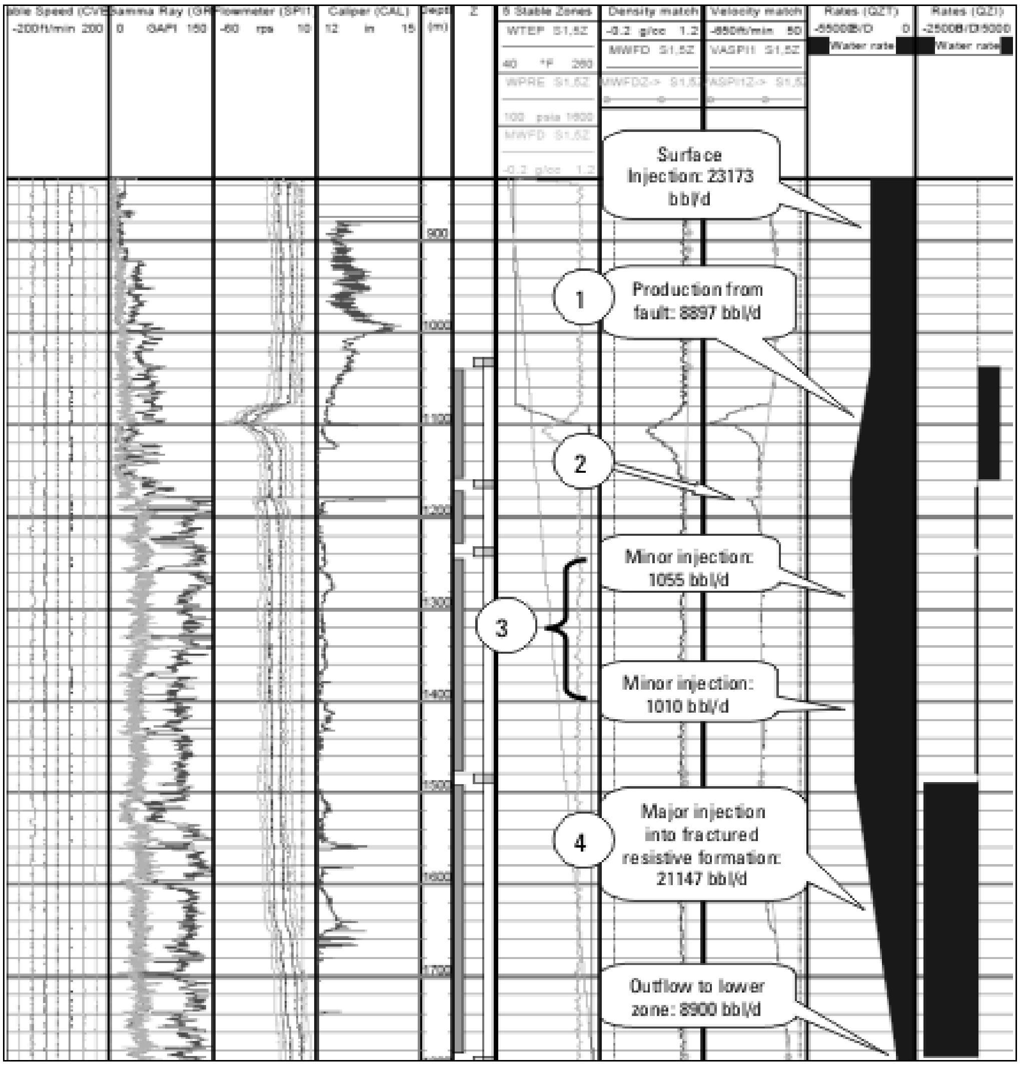


Figure 7. Flow interpretation, upper zone: 870-1,800 m

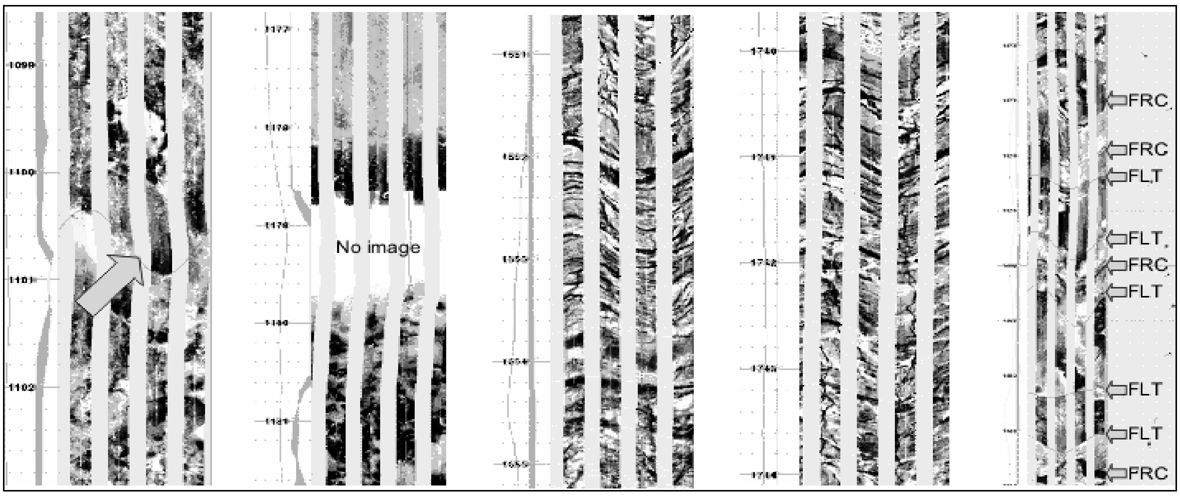


Figure 8. Features of interest in the upper 12.25 inch interval. Far left: large fault at 1,100 m produces 8,900 BWPD. Left: sticking zone at 1,180 m with washout and no formation image. Middle: fractured resistive formation over the interval 1,546-1,554 m which, in combination with interval 1,669-1,780 m, takes 21,100 BWPD. Right: fractured formation over interval 1,660-1,780 m which, in combination with interval 1,546-1,554 m, takes 21,100 BWPD. Far right: examples of faults (FLT) and conductive fractures (FRC) over interval 1,660-1,780 m which, in combination with interval 1,546-1,554 m, takes 21,100 BWPD.

5. Over the interval 1,830-1,860 m there is minor flow of approximately 800 BWPD out of the formation into the wellbore. Due to the absence of open hole callipers over this zone, the confidence in this flow rate is very low. However, this event could be associated with a wide fault at 1,831 m and a conductive fracture zone below. This is potentially a minor production zone.

6. Below 1,917 m a decrease in the spinner rate indicates injection of 4,760 BWPD into the formation. The electrical borehole image indicates the presence of a high angle fault at this depth (Figure 10), which will contribute significantly to steam production.

7. Near the bottom of the well, over the interval 2,170-2,260 m, a decrease in spinner rate indicates injection of 2,335 BWPD into the formation. According to the image log, water loss is associated with a zone of open fractures and faults (Figure 10) that occur within a conductive, argillaceous formation. This zone will probably make a significant contribution to steam production.

8. Residual downward flow of 2,650 BWPD is calculated below the last logged depth of PLT. No standing water column was observed in this case. A standing water column is used generally to characterize "no flow spinner rotation" during various passes. Therefore, the 2,650 BWPD, which is calculated as flowing below 2260 m MD, is most probably either due to calculation error or due to actual downward flow into the unlogged part of 7 in slotted liner section.

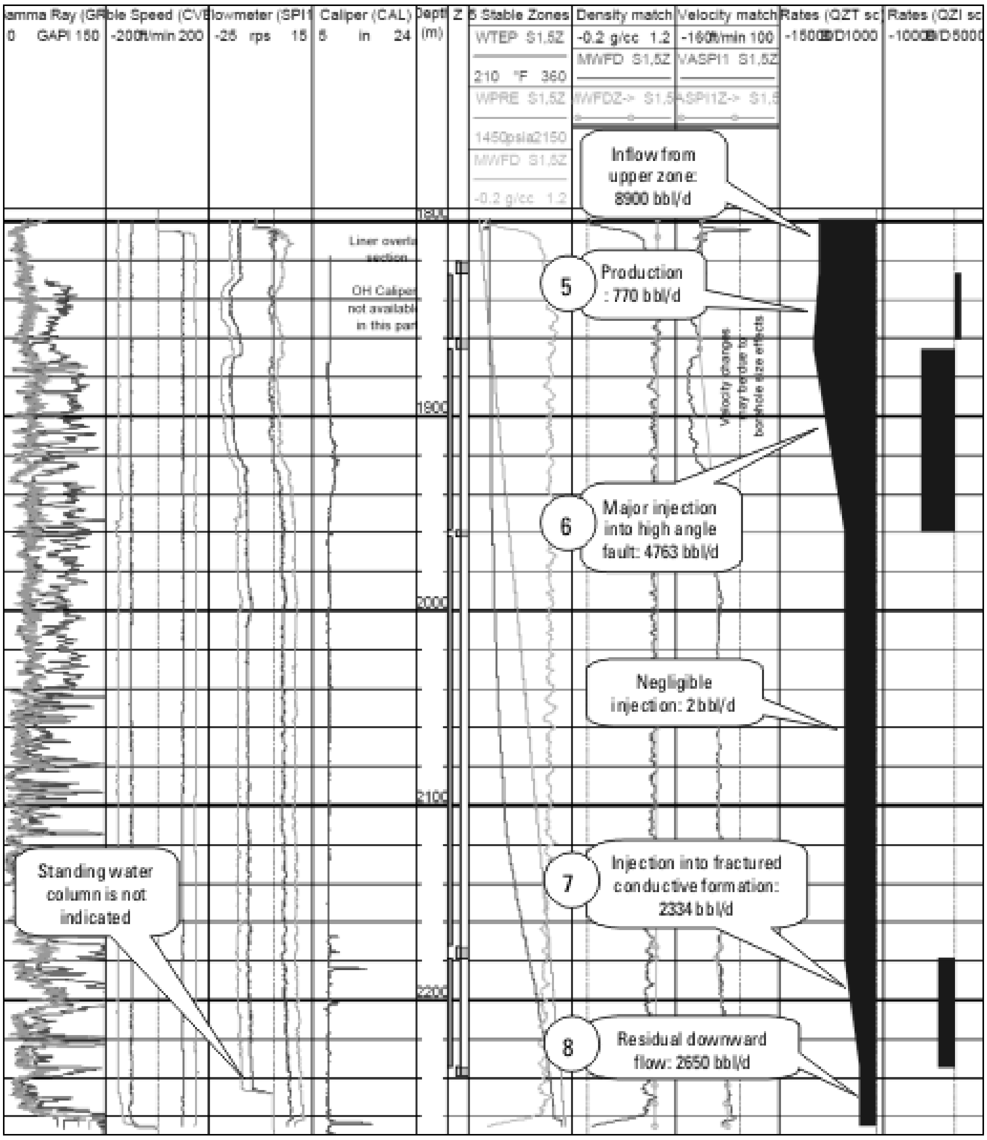


Figure 9: Flow interpretation, lower zone: 1,865-2,270 m

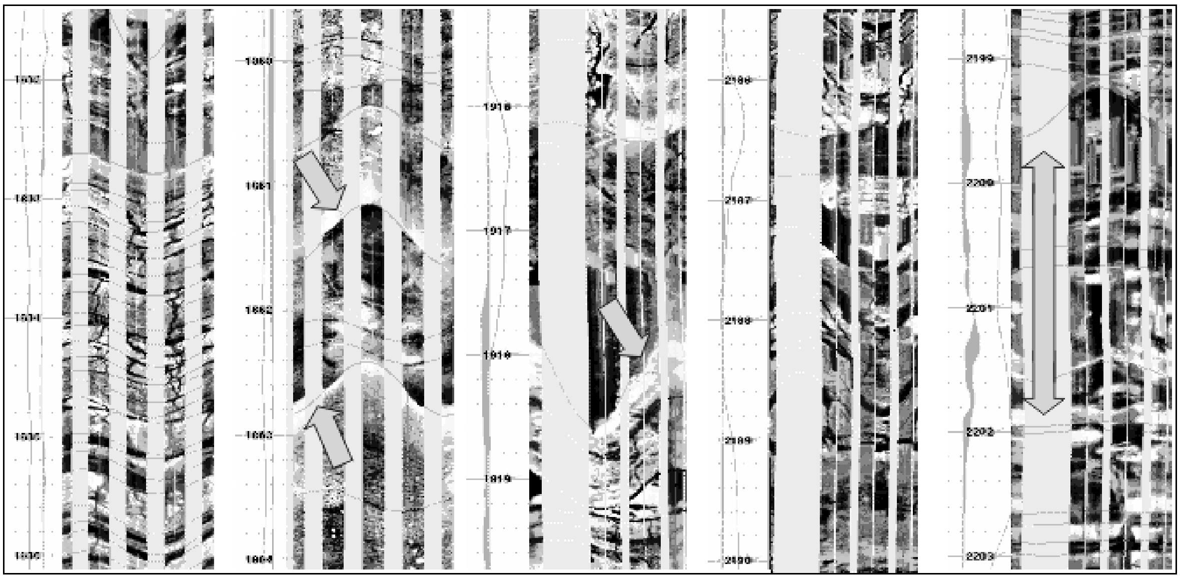


Figure 10. Features of interest in the lower 8.5 inch interval. Far left: conductive fractures and drilling induced fractures over the interval 1,830-1,860 m which produces 770 BWPB. Left: twin fault planes at 1,831 m, in the interval 1,800-1,865 m which produces 770 BWPB. Middle: fault at 1,917 m takes 4,760 m BWPD. Right: wide conductive fractures in conductive lithology over the interval 2,170-2,260 m, which takes 2,335 BWPD. Far right: fault and associated washout over the interval 2,170-2,260 m, which takes 2,335 BWPD.

CONCLUSIONS

The injection of cold water into geothermal wells allows the acquisition of wireline logging data using standard pressure and temperature rated tools. In combination, electrical borehole images and production logs are powerful tools for identifying and characterizing potential steam production zones, in particular fractures and faults. Over intervals where production logging data are absent (e.g. between logging runs), image logs combined with bottom of well flow rate can provide a confident indication of production potential.

In addition, natural fracture distribution and orientation and, present-day maximum horizontal stress, can be used as inputs for future well design and field development strategy.

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