CHARACTERIZATION OF FLOW ZONES IN A GEOTHERMAL WELL USING ELECTRICAL BOREHOLE IMAGES AND PRODUCTION LOGS: AN EXAMPLE FROM SOUTH SUMATRA, INDONESIA

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SUMMARY - Borehole resistivity images and cased-hole production logs were acquired over two intervals of volcaniclastic sediments during injection of cold water into a geothermal well. The imaging tool was logged in open wellbore; production log data were acquired inside a slotted liner.

Abundant conductive (open) fractures are concentrated in 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 discrete flow events both into and out of the formation at 1,100 m, 1,546-1554 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.

1 INTRODUCTION

Gamma ray and electrical borehole images were acquired over two open hole intervals (8.5 inch section 2271-1880m and 12.25 inch section 1869-880m) of volcaniclastic sediments in a geothermal appraisal well drilled in Jambi Province, South Sumatra, Indonesia (Figure 1).

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 isolated upper electrode. The current exiting the formation into the lower sensors is measured. The 192 resistivity readings are normalized and colour scaled, producing a high-resolution (0.2 inch / 5 mm) resistivity image (Figure 3) 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. A slotted production liner was installed in the well and then a production logging tool was run in order to identify productive zones. The production log records spinner (for flow rate), temperature, pressure and fluid density. Dynamic flow data from the production log was integrated with geological information from the electrical borehole image.

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

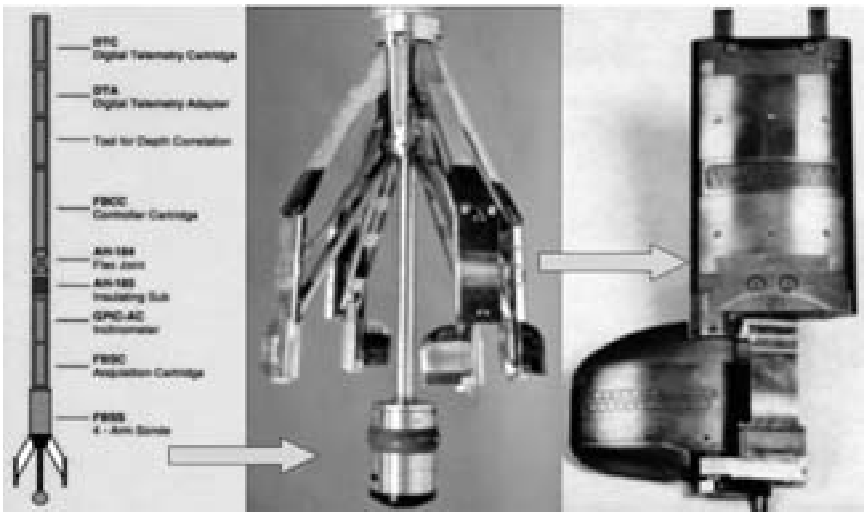

Figure 2: Electrical borehole imaging tool used in the study well.

2 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 °C (e.g. Solbau et al. 1983; Stevens, 2000). As a result, wireline log suites in geothermal wells at temperatures in excess of 300 °C are rare or tend to be of limited scope. For a number of years it has been the practice in Indonesia 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.

3 RESULTS

3.1 Fracture analysis

Fractures that appear conductive (dark on Figure 3) on the electrical borehole image can be open (invaded by drilling fluid) or clay-filled. They are abundant and, although not exclusively so, tend to be concentrated in more resistive and, therefore, more brittle (cemented) 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. Resistive (light on Figure 3) fractures are healed by electrically resistive minerals such as quartz or calcite, are less extensively developed and, may be concentrated in both resistive and conductive rock. Faults (Figure 3) 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 in agreement with the maximum horizontal stress direction determined from the orientation of drilling induced fractures (Figure 4).

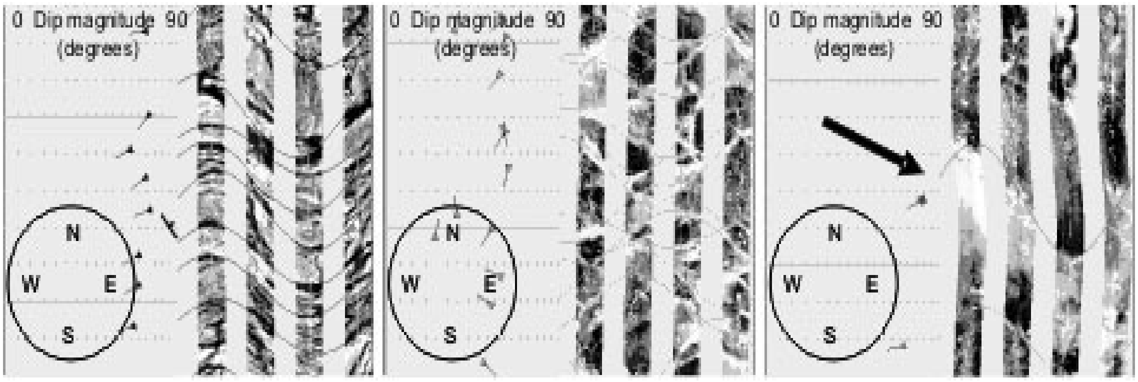

Figure 3: Left: conductive (dark) open fractures over interval 1,551-1,553 m. Middle: resistive (light) healed fractures. Right: fault at 1,100 m flows 8,900 BWPD into the borehole.

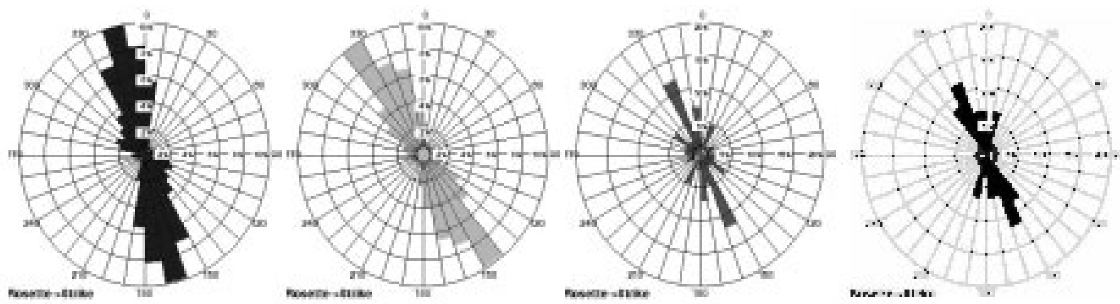

Figure 4: Strike rosette plots of fractures. Left: conductive (dark) open. Middle left: resistive (light) healed. Middle right: faults. Right: drilling induced indicating SHmax is NW-SE.

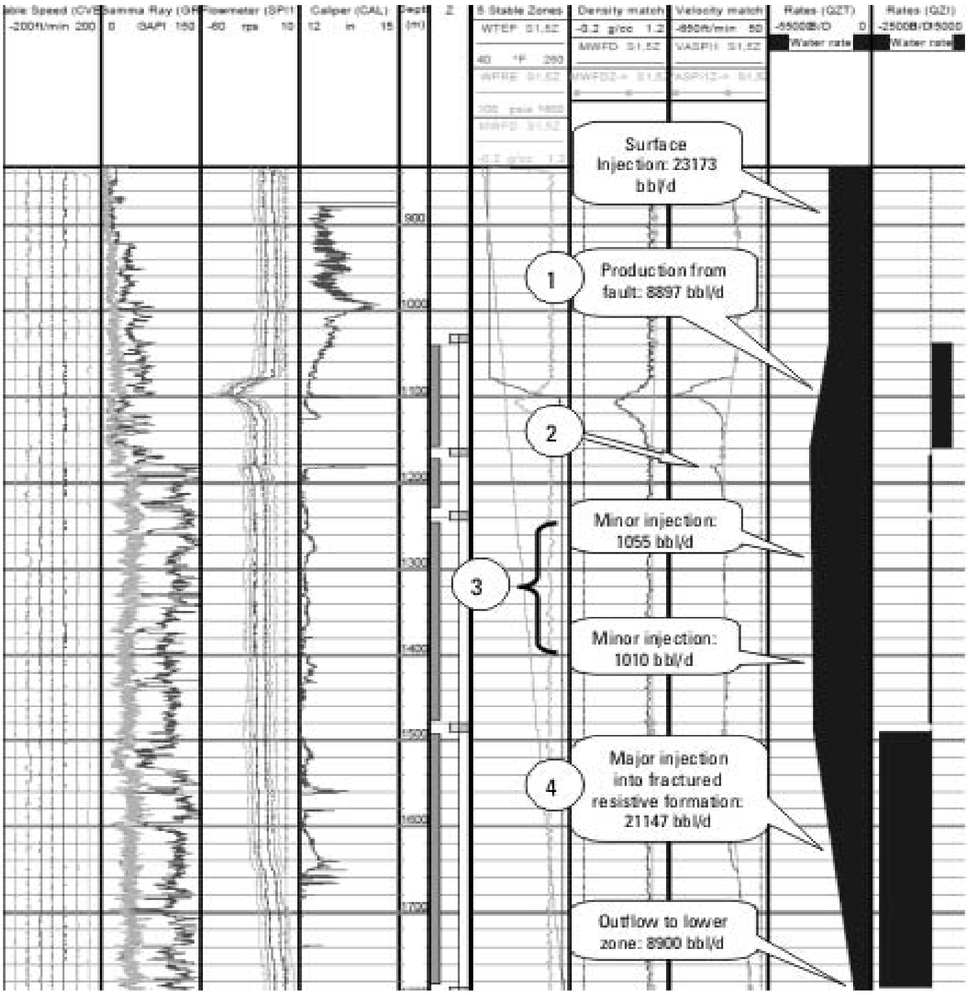

Figure 5: Flow interpretation, upper zone: 870-1,800 m.

3.2 Flow analysis

3.2.1 Upper 12.25 inch interval: 870-1,800 m

23,200 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 (Figure 5, numbers on figure correspond to paragraphs below).

1. Below 1,100 m there is a major increase in flow rate according to the spinner readings and, corresponding temperature increase and fluid density decrease. Flow into the borehole from the formation is calculated at 8,900 BWPD. This fluid entry point corresponds to a high angle fault seen on the borehole image (Figure 3) and is the main potential production zone.

2. At 1,180 m there is a very minor increase in flow rate, but below this depth flow rate returns to the same as above. A geological feature is not seen on the borehole image but sticking tool and irregular tool motion associated with a lithology change probably affect the spinner response.

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

4. Below 1,550 m the spinner reading indicates a total flow of 21,100 BWPD into the formation down to a depth of 1,780 m. This flow decrease is associated with highly resistive and heavily (open-) fractured lithology over the two intervals 1,546–1,554 m (Figure 3) and 1,660-1,780 m.

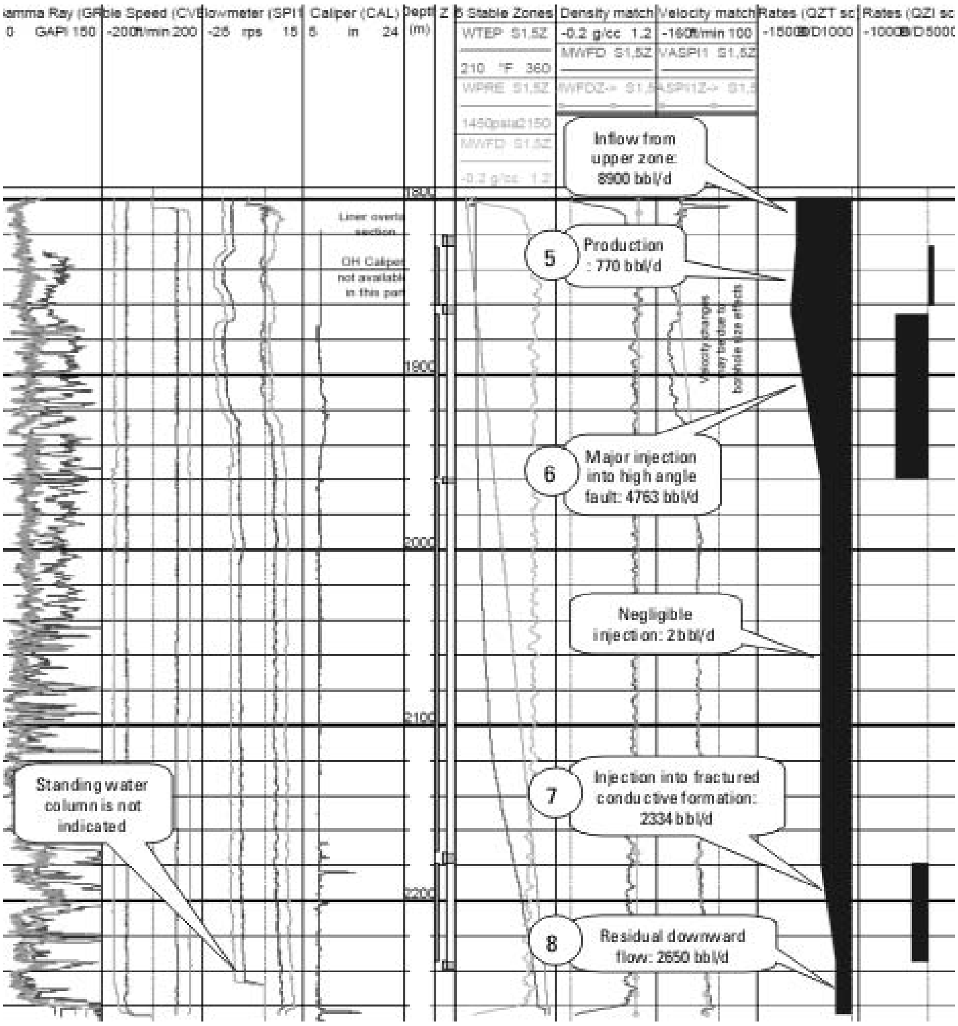

Figure 6: Flow interpretation, lower zone: 1,865-2,270 m.

3.2.2 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 8,900 BWPD. Again, spinner and temperature events were interpreted in conjunction with the borehole image data (Figure 6, numbers on figure correspond to paragraphs below).

5. Over the interval 1830-1860 m there is minor flow of approximately 800 BWPD out of the formation into the wellbore. Due to absence of open hole callipers in this zone, the confidence on this flow rate is low. However, this event probably 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 associated with a high angle fault.

7. Near TD, over the interval 2,170-2,260 m, a decrease in spinner rate indicates injection of 2,335 BWPB into the formation associated with a conductive lithology containing faults and major open fractures.

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

4 CONCLUSION

Injection of cold water into geothermal wells allows the acquisition of wireline logging data using standard pressure and temperature rated tools. Combined, electrical borehole imaging and production logging tools provide an excellent method for identifying and characterising productive fractures and faults in geothermal wells. 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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