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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Outline

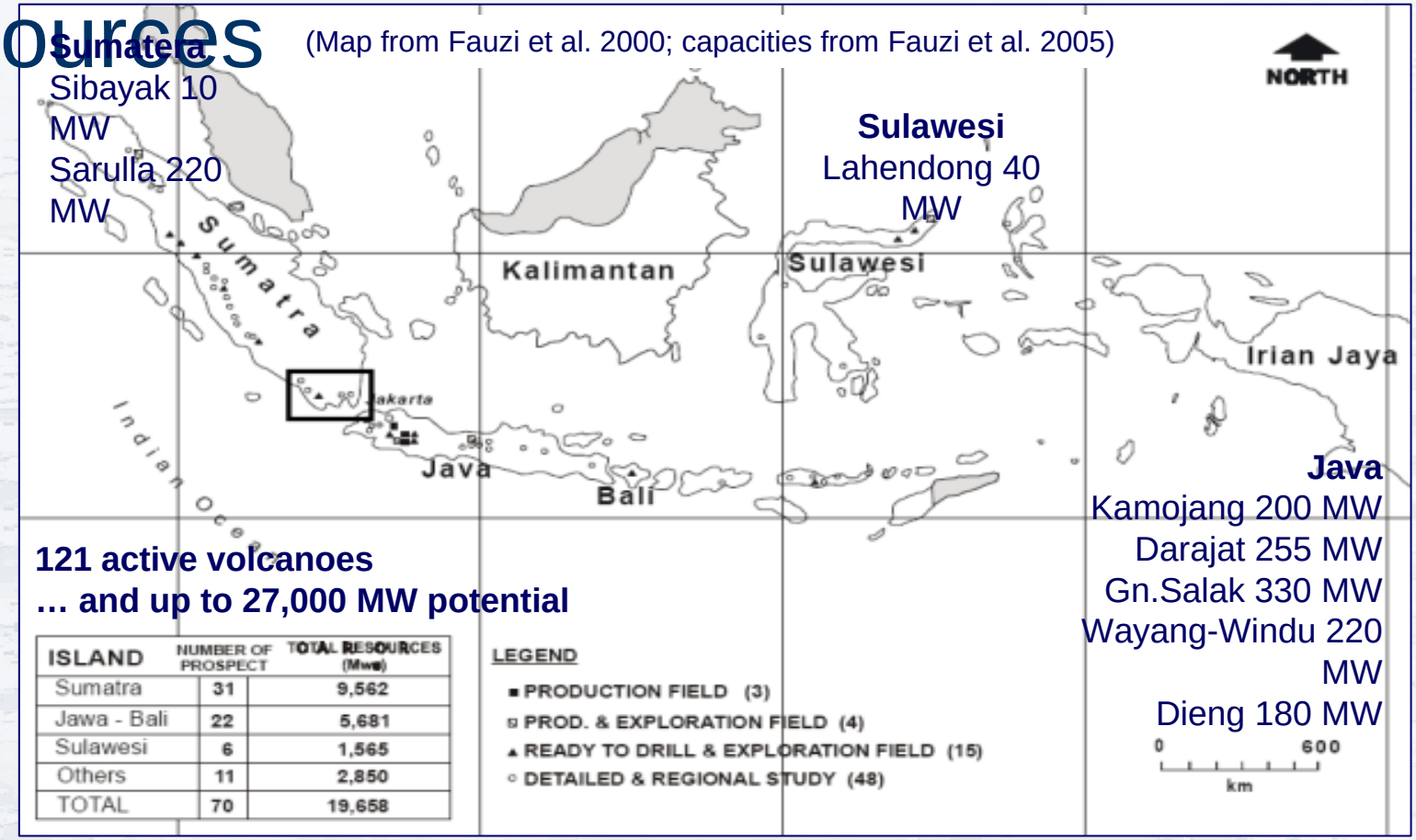
- Introduction
  - Indonesia's geothermal resources
  - Wireline log acquisition in geothermal wells
  - Electrical borehole images and production logs
- Interpretation
  - Fractures, faults, drilling induced features
  - Integrated fracture and production log analysis
- Conclusions

Indonesia, Geothermal Resources

(Map from Fauzi et al. 2000; capacities from Fauzi et al. 2005)

Sumatera
Sibayak 10 MW
Sarulla 220 MW

Sulawesi
Lahendong 40 MW



Java
Kamojang 200 MW
Darajat 255 MW
Gn.Salak 330 MW
Wayang-Windu 220 MW
Dieng 180 MW

121 active volcanoes
… and up to 27,000 MW potential

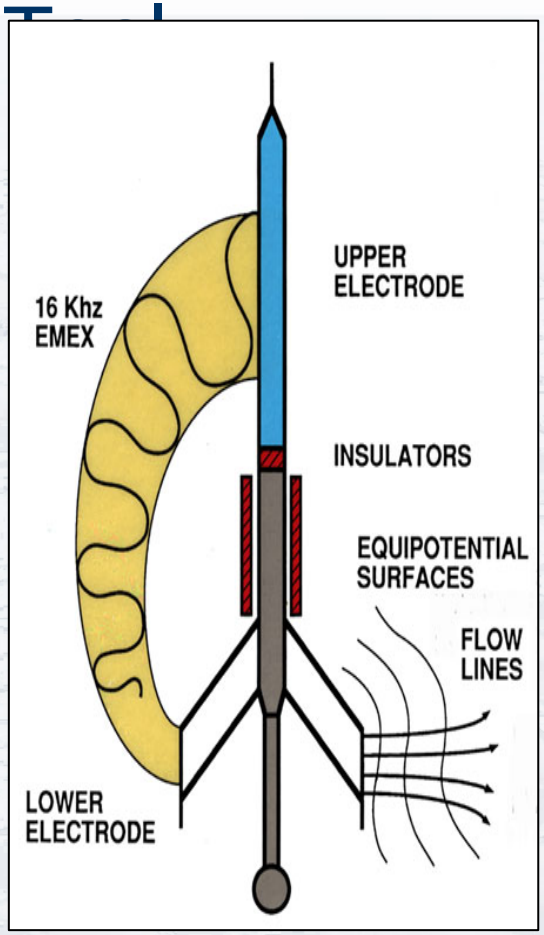
ISLAND	NUMBER OF PROSPECT	TOTAL RESOURCES (Mwe)
Sumatra	31	9,562
Jawa - Bali	22	5,681
Sulawesi	6	1,565
Others	11	2,850
TOTAL	70	19,658

LEGEND
- PRODUCTION FIELD (3)
- PROD. & EXPLORATION FIELD (4)
- READY TO DRILL & EXPLORATION FIELD (15)
- DETAILED & REGIONAL STUDY (48)

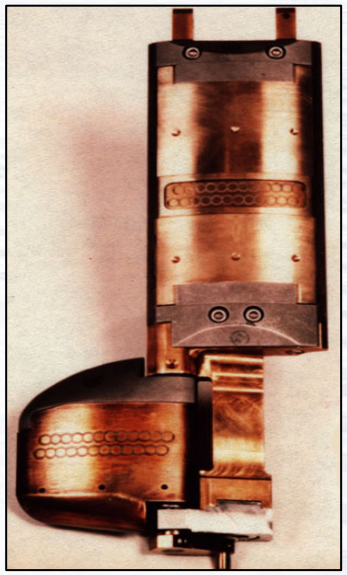
Wireline Log Acquisition In Geothermal Wells

- Issues
  - Temperatures recorded at >350°C
    - Tools commonly rated only to 250°C, often <250°C
  - Steam in wellbore
    - The physics of most tools depend on water filling the wellbore
- Solutions
  - Special Hi Temp tools
    - Few, very expensive and generally inferior
  - Cooling flasks for some tools
    - Limited tools, and not for image and production logs
  - Cooling the borehole with water
    - Also provides the correct borehole medium for logging
    - Uses untreated river water
    - Only in >/= 8.5” borehole. 6” borehole produces “rocket” effect and cable pull-off
    - The suite: electrical borehole imaging tool – in open hole
    - Production logging tool – inside slotted liner

Electrical Borehole Imaging Tool

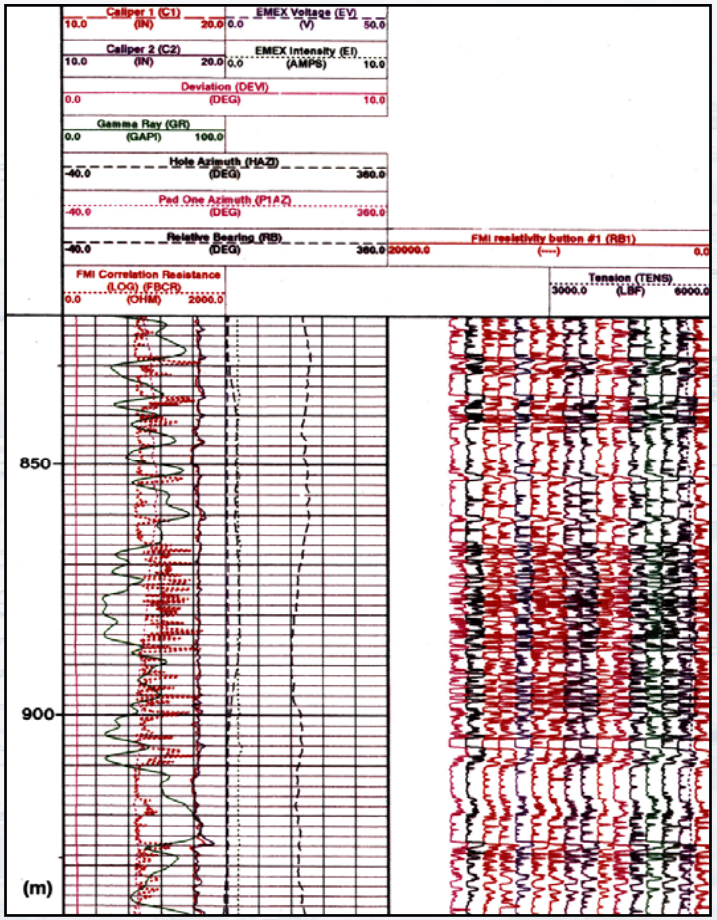


- Alternating current is emitted from an upper electrode
- Passive focusing: lower electrodes form an equi-potential surface parallel to borehole wall
- Detected current is determined by the formation resistivity
- Constant feedback optimizes input current for formation characteristics



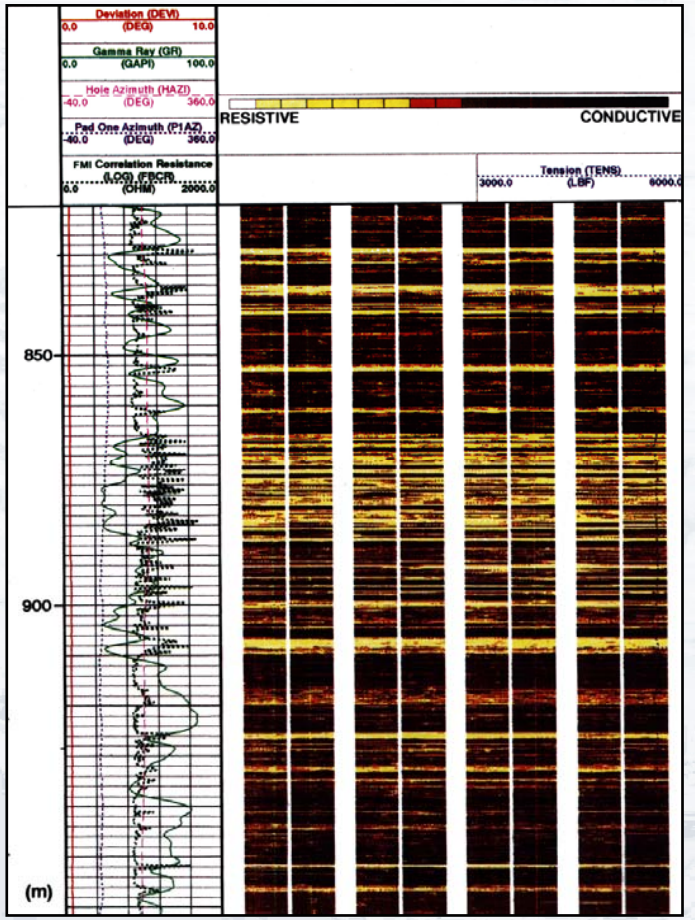
P / T	20,000psi / 350 oF
Tool diameter	5”
Maximum Aperture	21”
Image resolution	0.2” (0.5 cm)c.1”
Borehole coverage	80% in 8” hole
Combinability	Bottom of string

Electrical Borehole Image

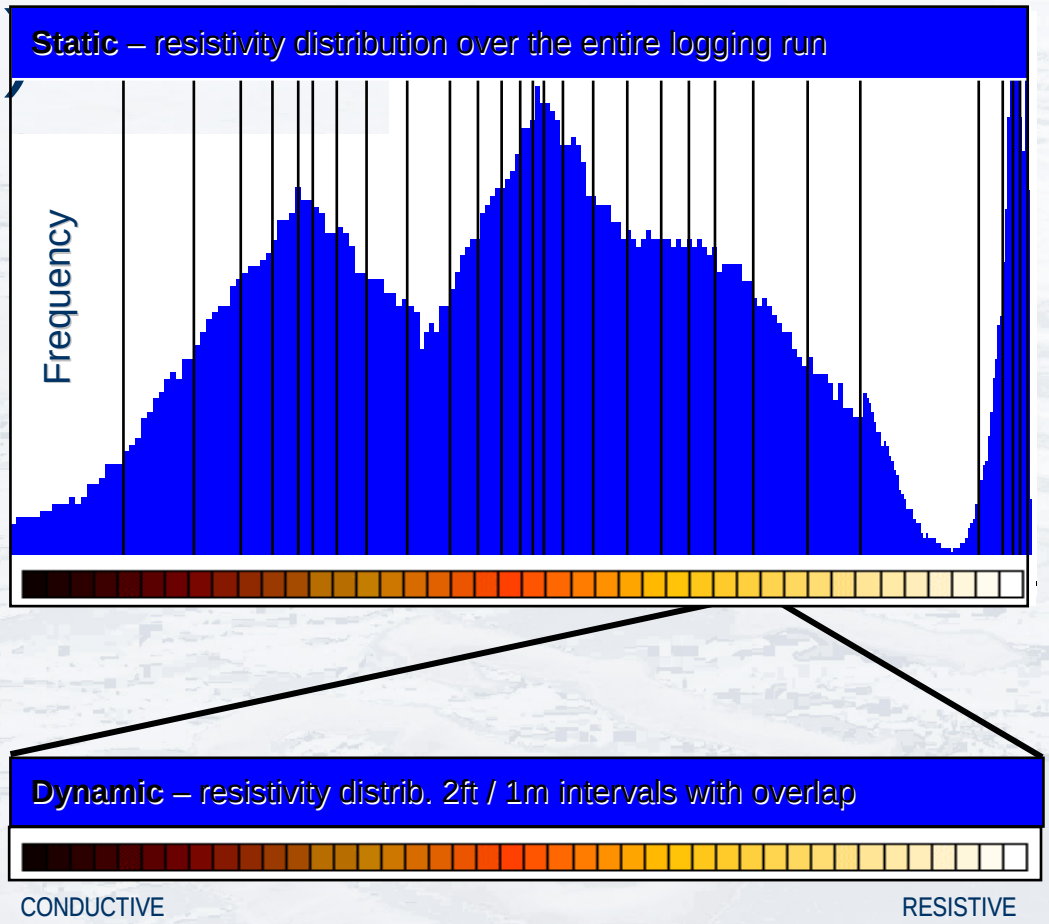


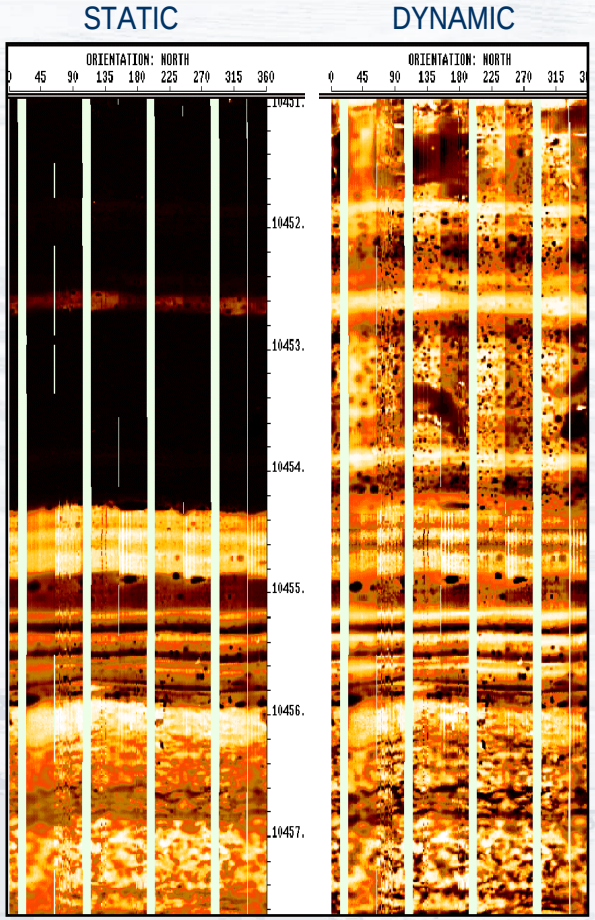
24 buttons x 8 pads = 192 resistivity curves (fast channels: colour-scaled to generate image)

Dark = conductive
Light = resistive

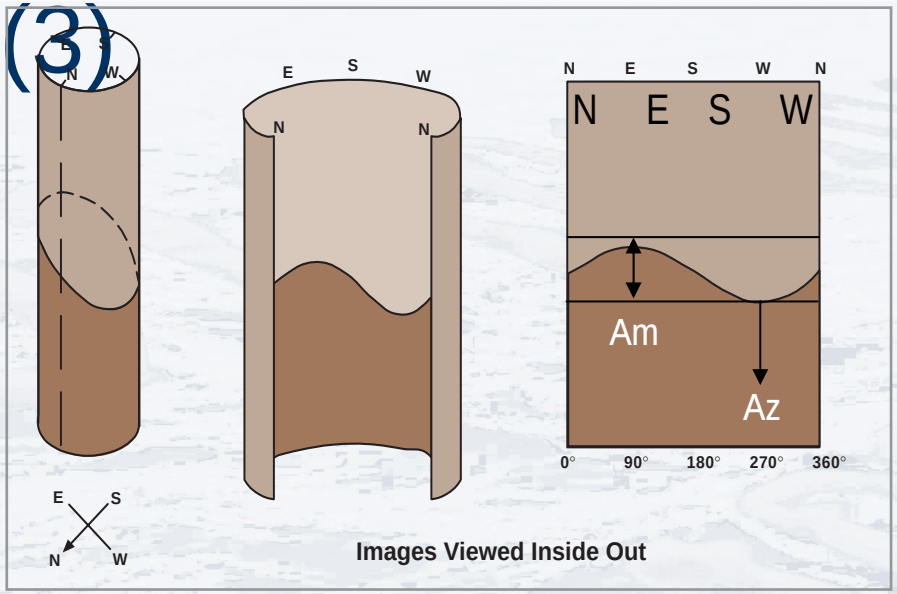


Electrical Borehole Image Processing (2)

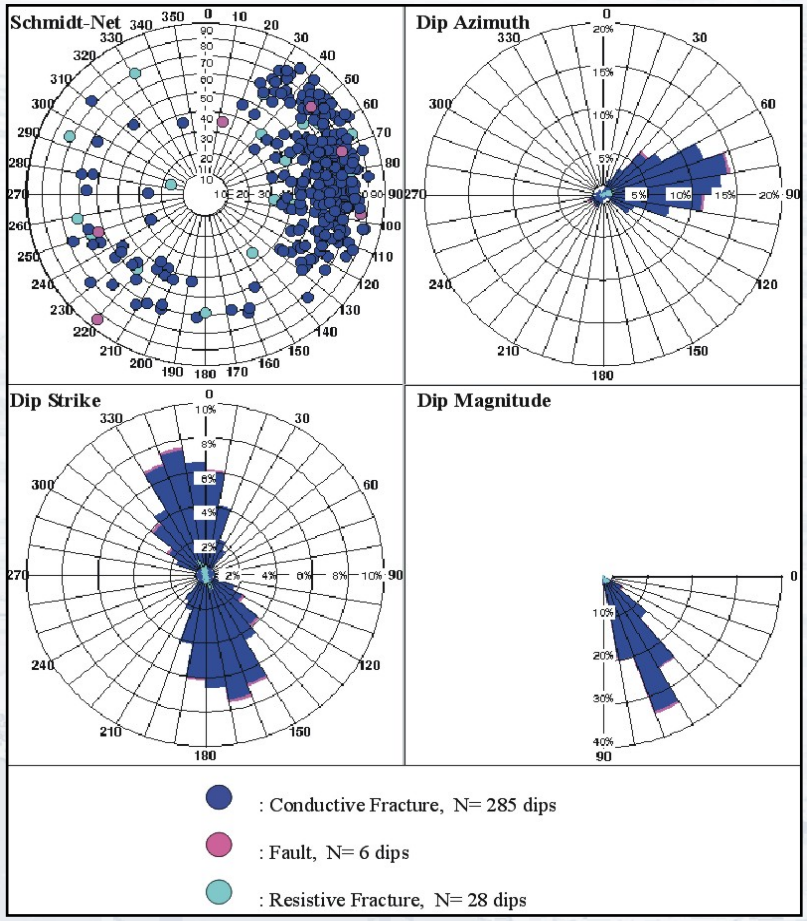




Electrical Borehole Image Processing



Planar features crossing the borehole describe a sinewave on the image
Am=dip magnitude, Az=azimuth



Natural fractures: represented by dip azimuth, strike and magnitude

Production Logging Tool

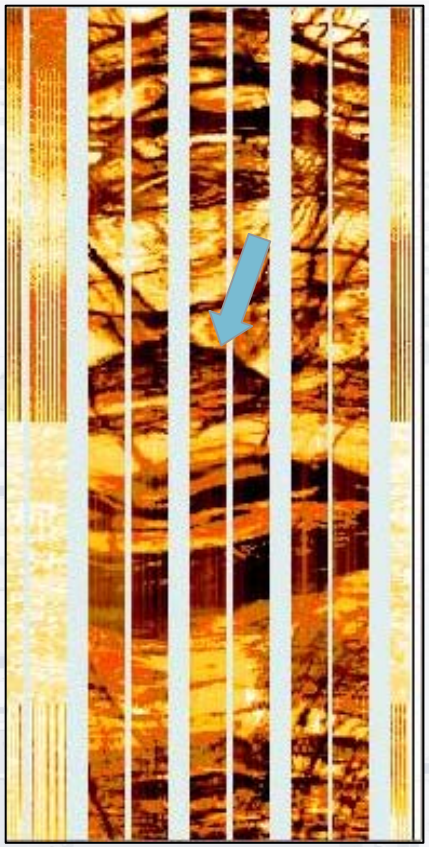
Production Logging Tool Processing

INTERPRETATION

Fracture & Fault Classification

Conductive (open) fractures

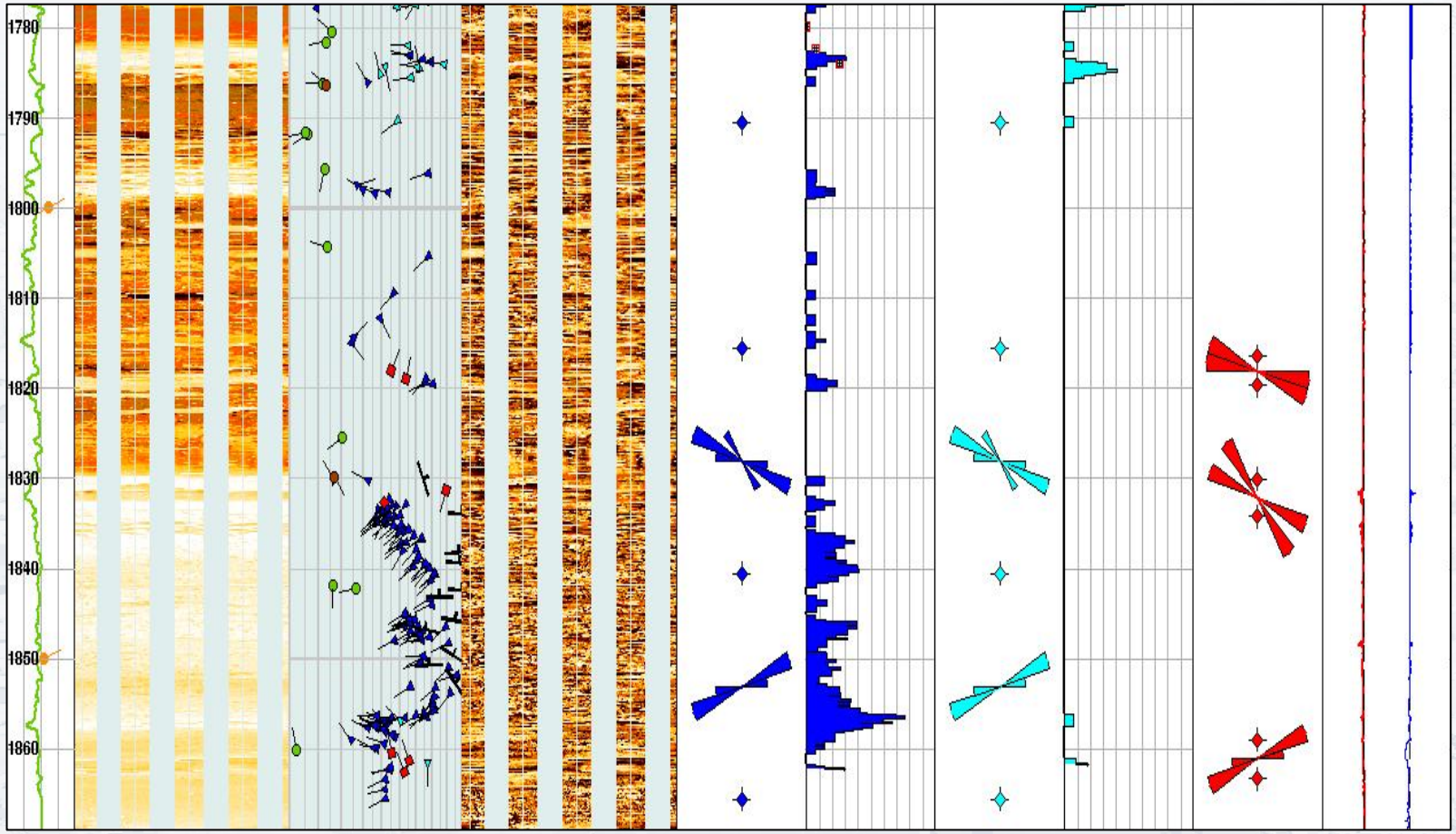
Resistive (healed) fractures



Fault (minor)

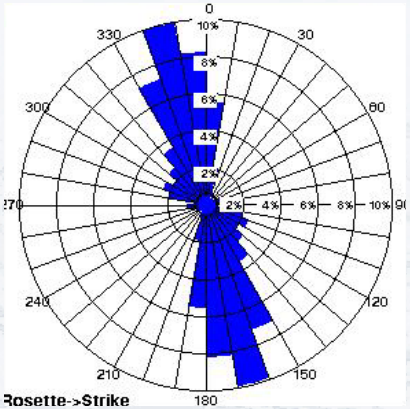
Drilling induced fractures

Fracture Distribution

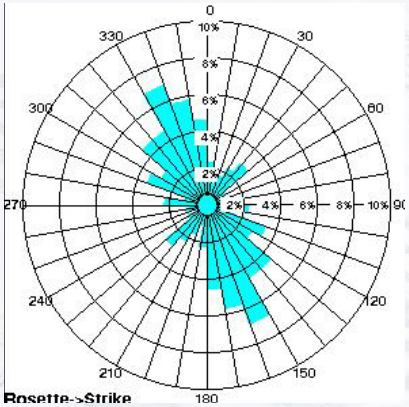


Fracture & Fault Orientation

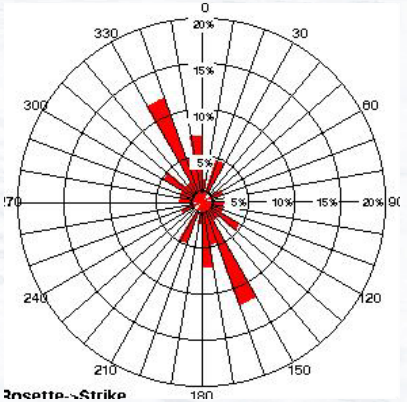
Conductive (open) fractures



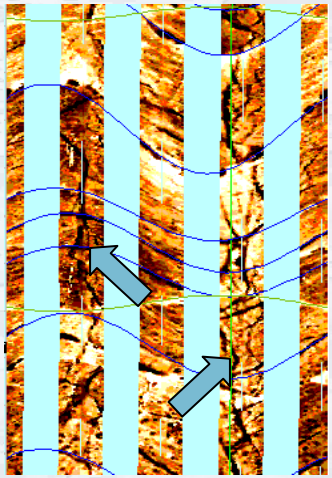
Resistive (healed) fractures

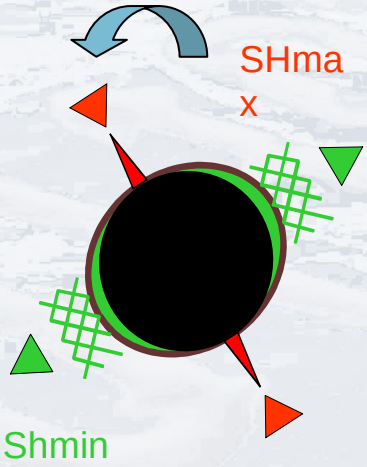


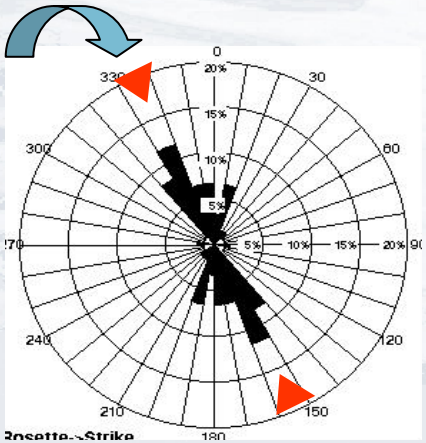
Faults



Drilling Induced fractures



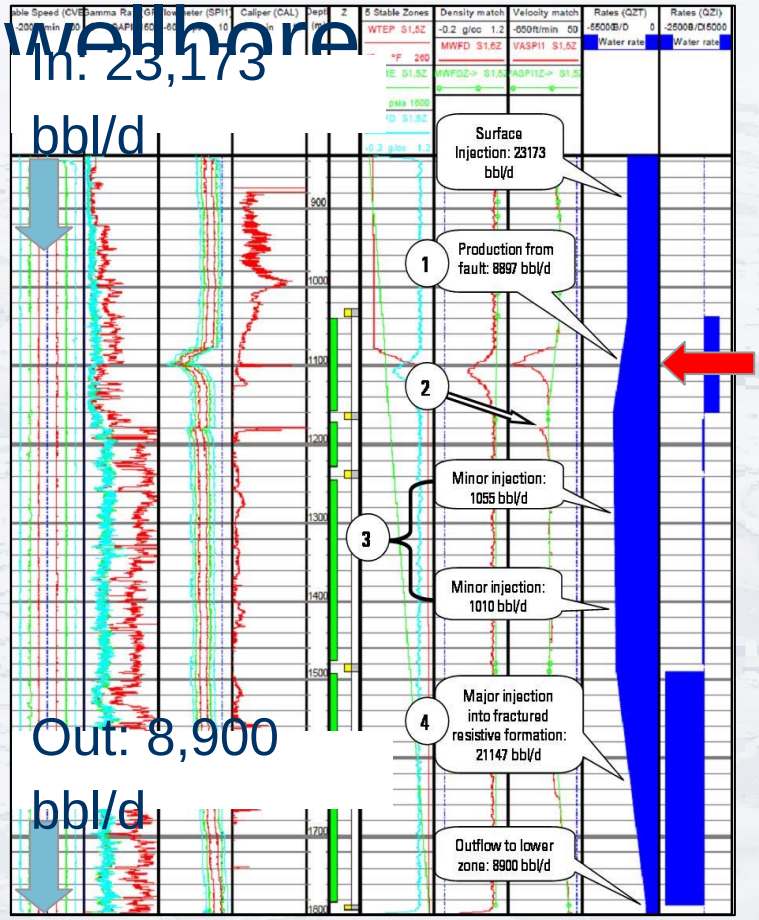


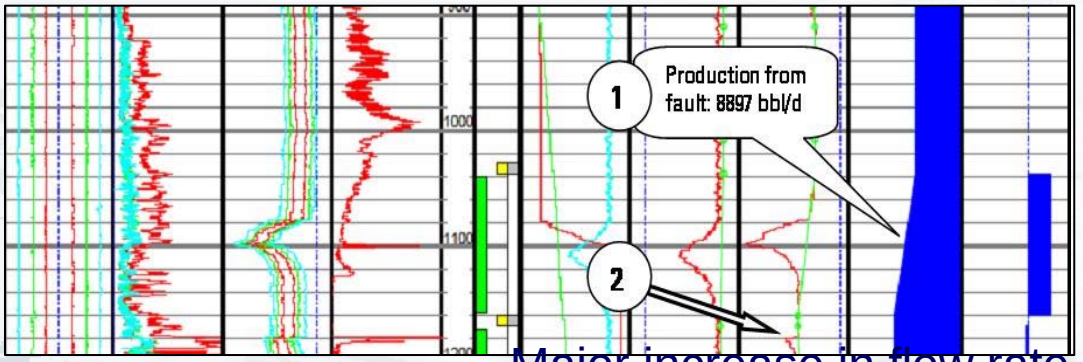


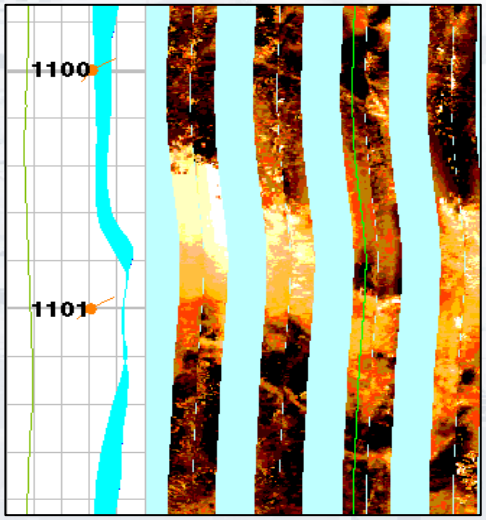
Faults and fractures all strike NNW-SSE parallel to SHmax

UPPER INTERVAL: 880-1869m
Open hole: 12.25”
Slotted liner: 9.625”

1. 1,100 m – 8,897 bbl/d flow into wellbore

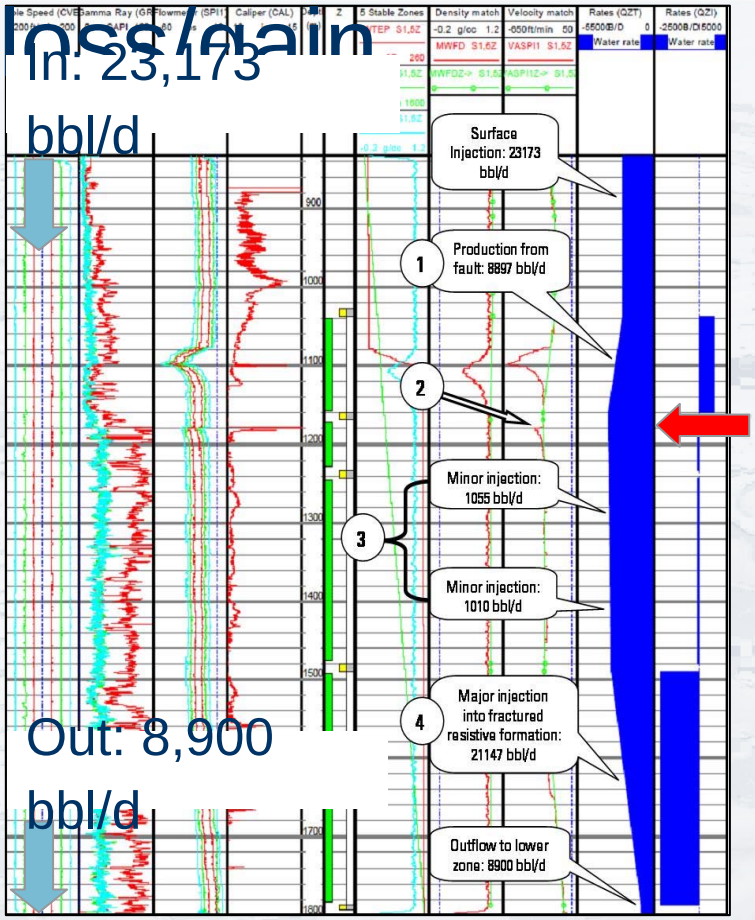


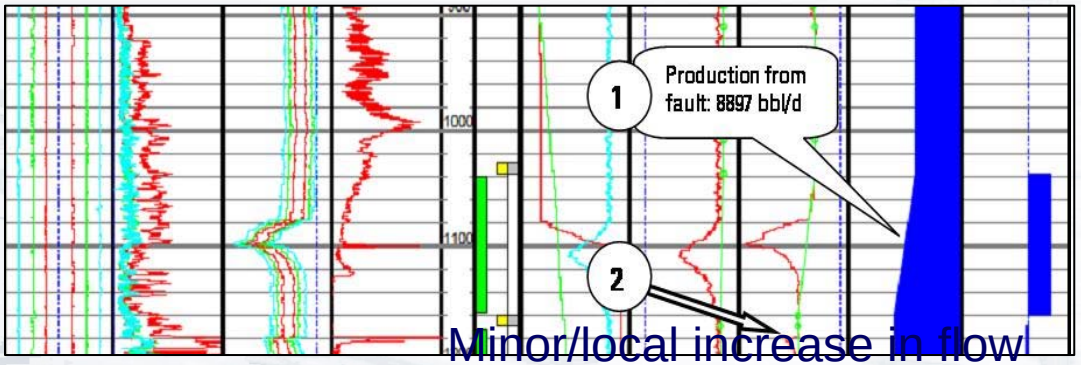


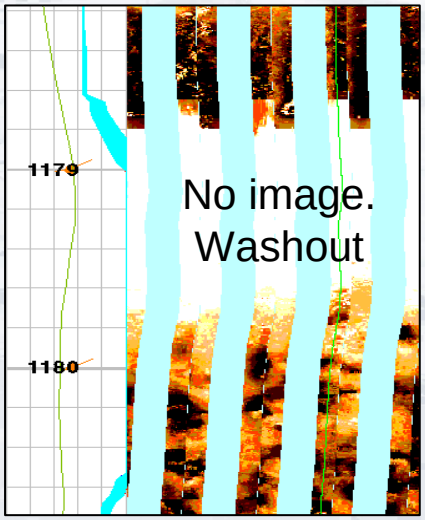


Major increase in flow rate according to spinner reading.
Corresponding temperature increase and fluid density decrease.
Flow into the borehole from the formation
is 8,897 bbl/d.
Fault observed on image.
POTENTIAL MAJOR PRODUCTION ZONE

2. 1,180 m – local anomally, no net flow

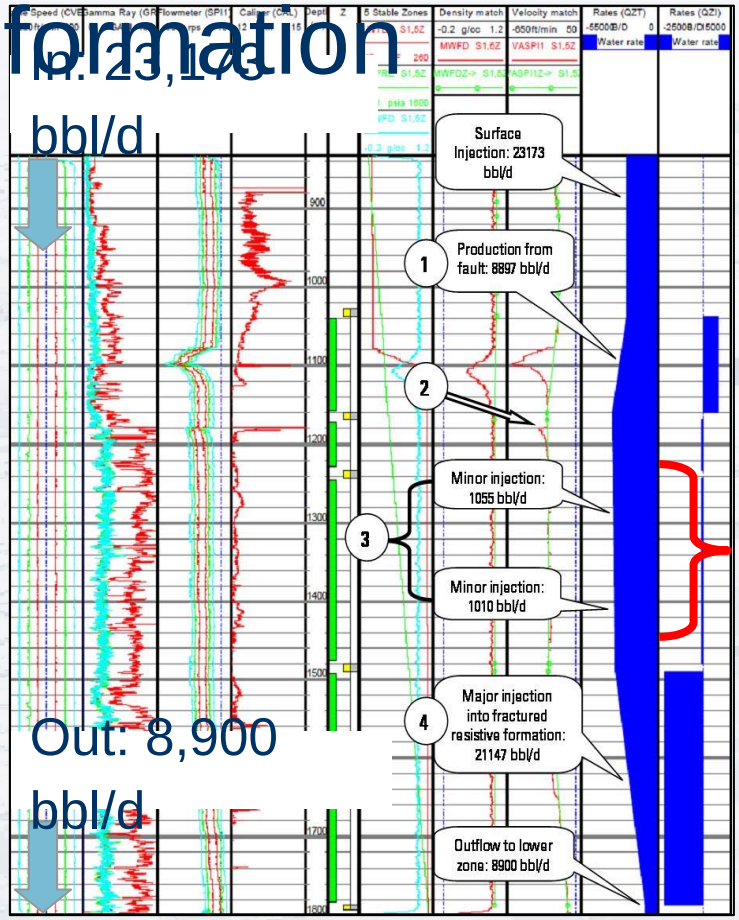


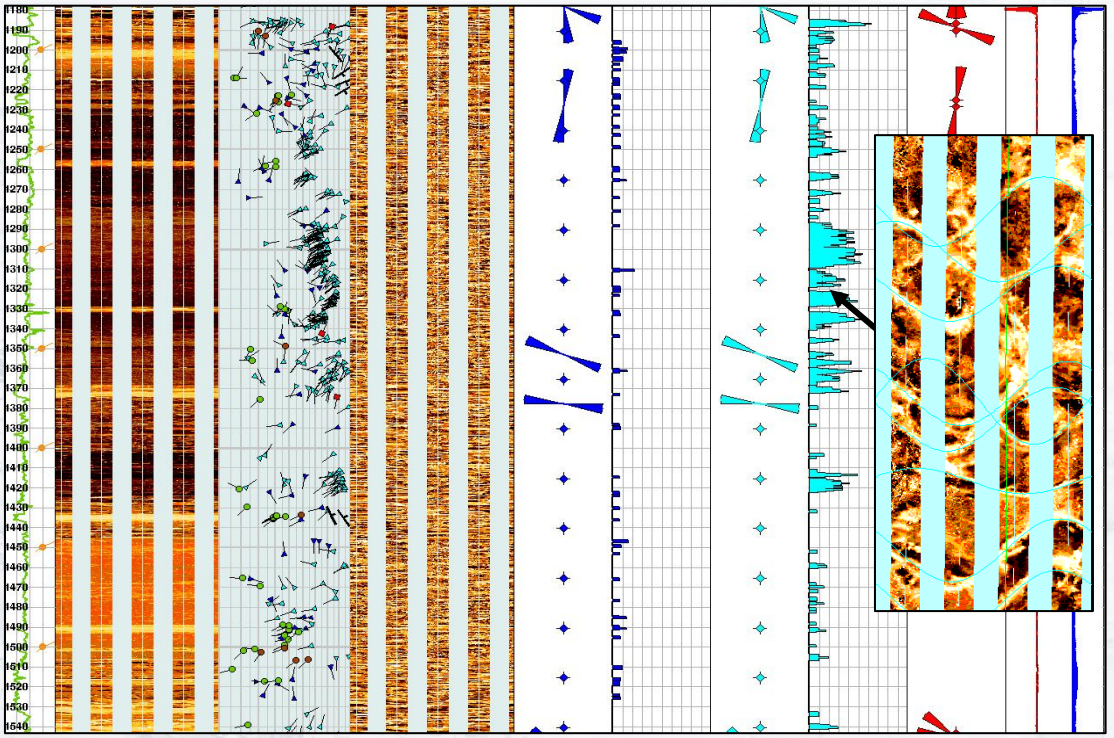




Minor/local increase in flow rate according to spinner readings, but no overall increase in flow.
No temperature increase or fluid density decrease. Major washout and change in formation lithology.
Flow disturbance associated with major washout.
NO PRODUCTION POTENTIAL

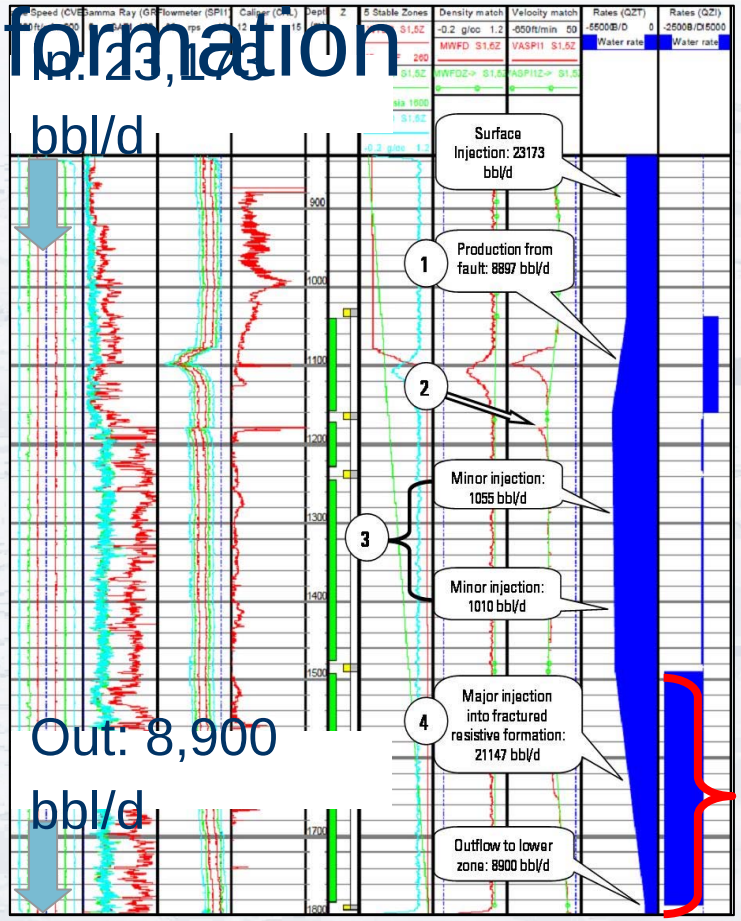
3. 1,180-1,550 m – 2,065 bbl/d flow into formation

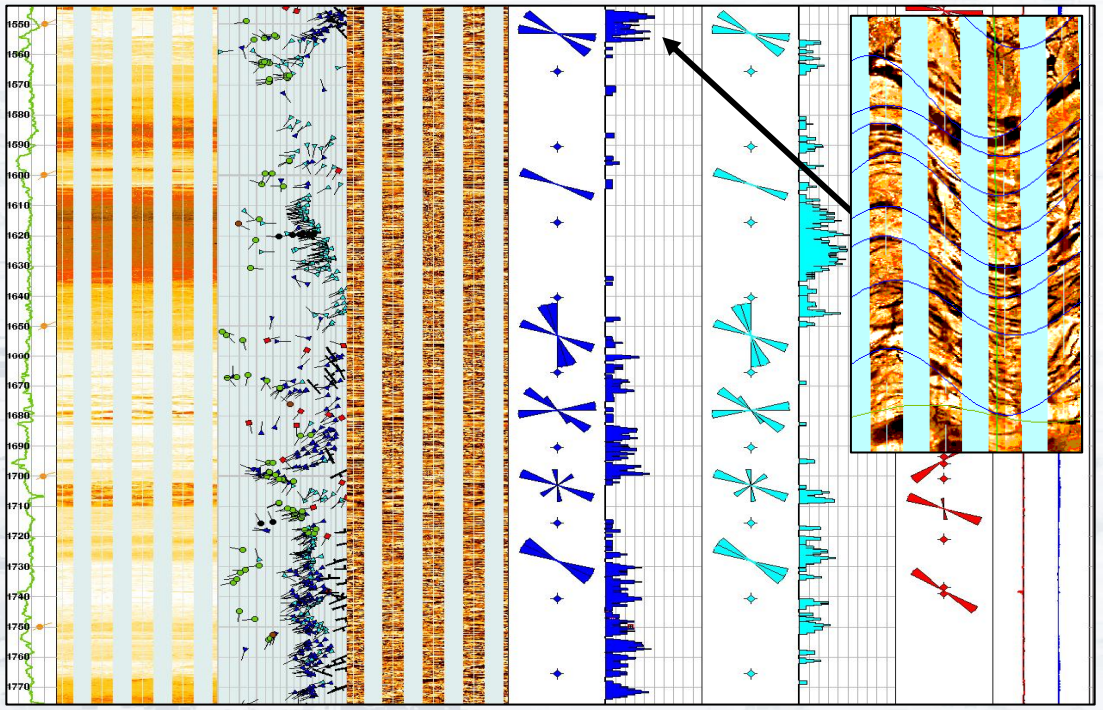




Minor 2,065 bbl/d flow into the formation. Absence of any major conductive open fractures. Dominance of resistive healed fractures. NEGLIGIBLE PRODUCTION POTENTIAL

4. 1,550-1,780 m – 21,147 bbl/d flow into formation



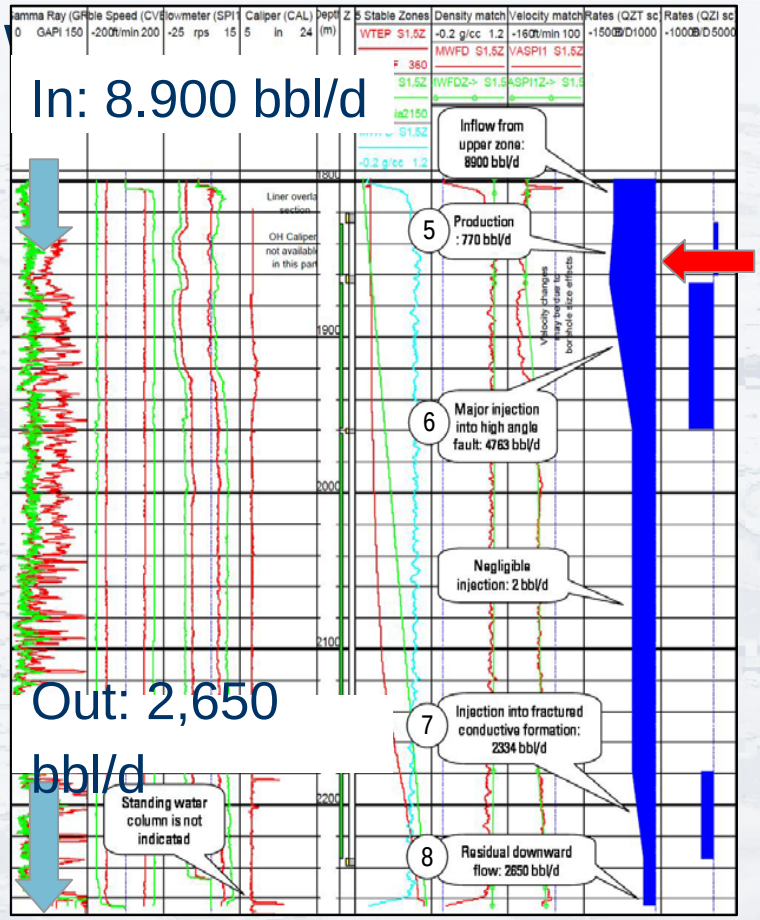


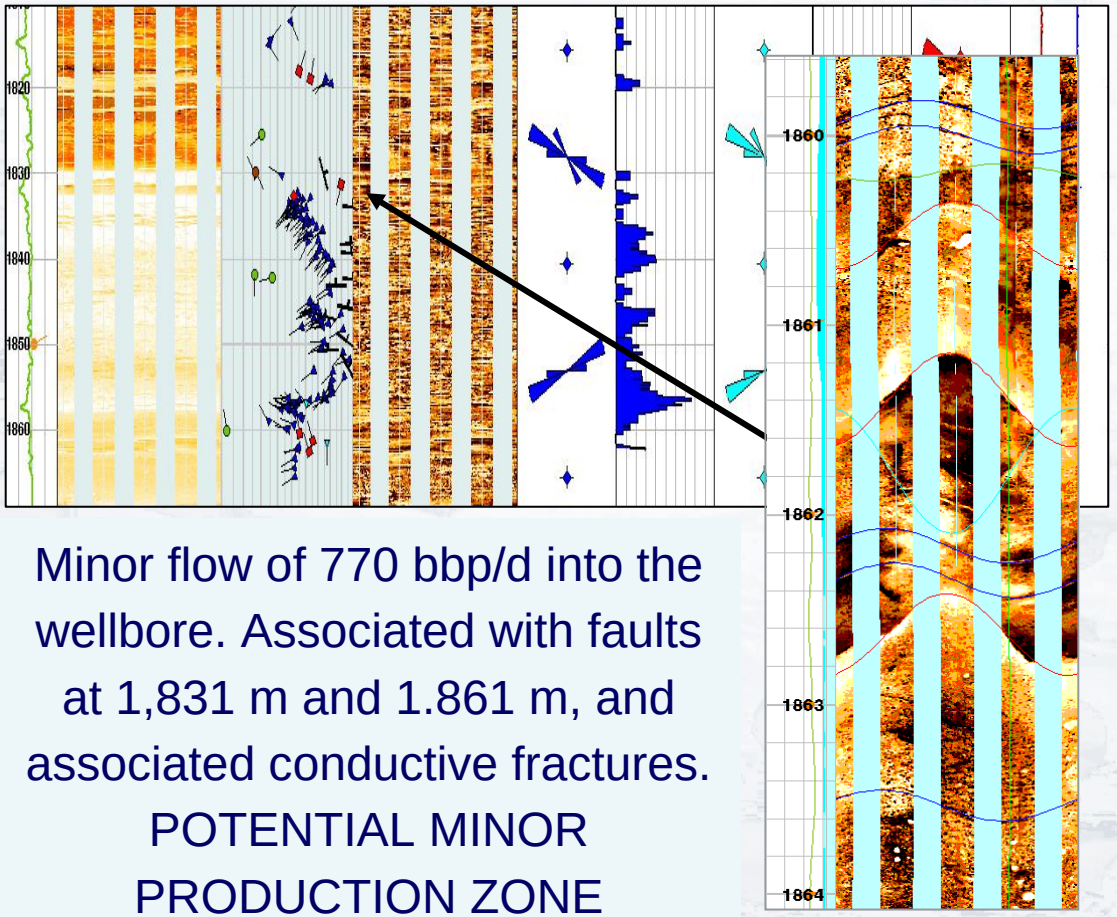
Major flow of 21,147 bbp/d into the formation associated with abundant open fractures, particularly over intervals 1,546-1,554m and 1,660-1,780m.

POTENTIAL MAJOR PRODUCTION ZONE

LOWER INTERVAL: 1880-2271m
Open hole: 8.5”
Slotted liner: 7”

5. 1,830-1,860 m – 770 bbl/d flow into

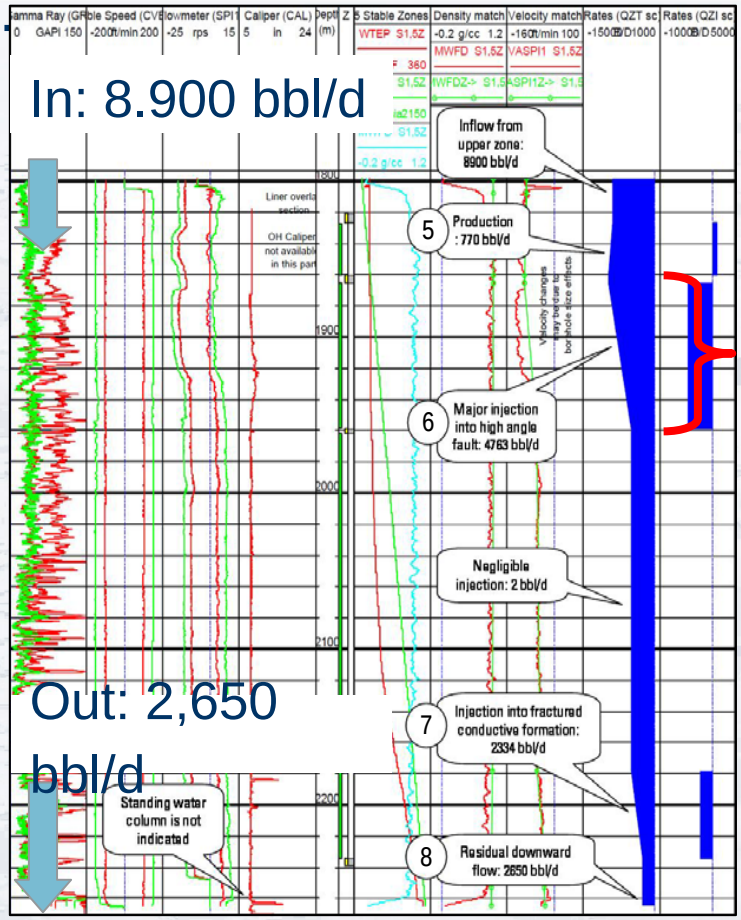


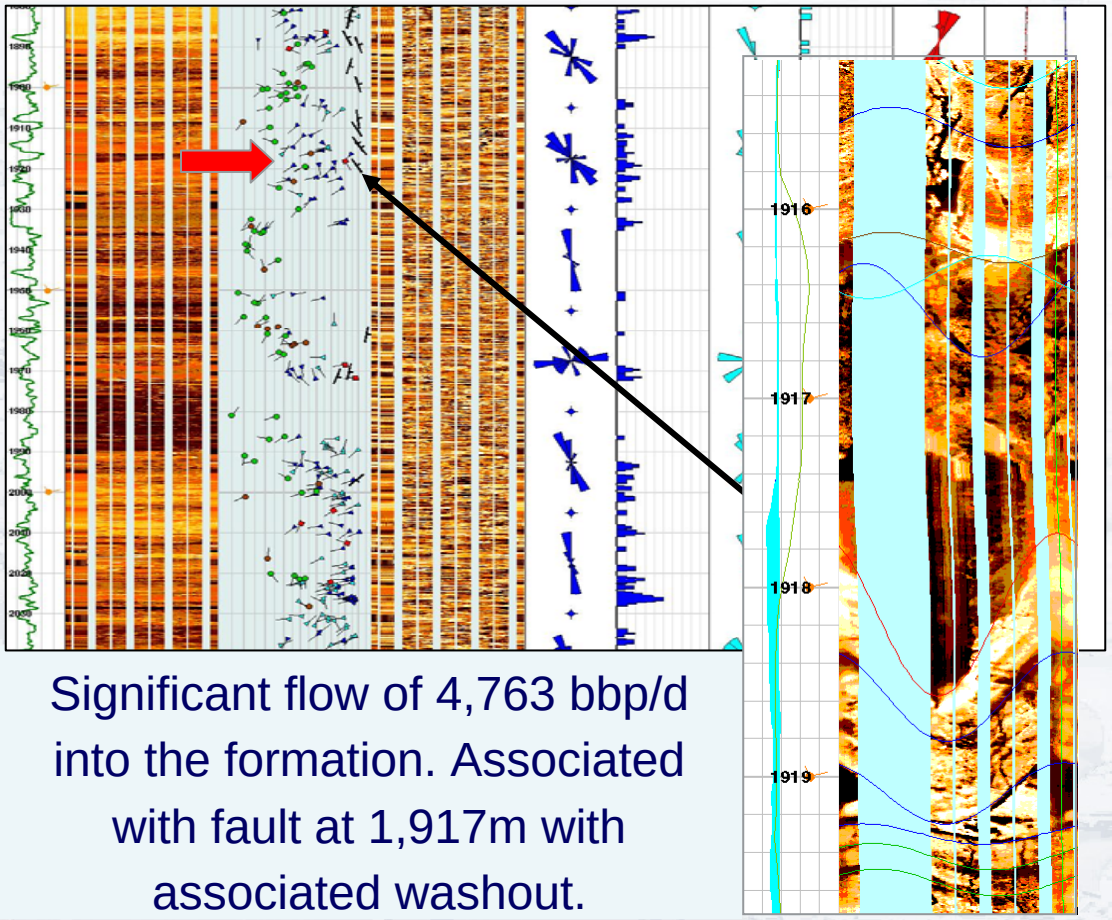


Minor flow of 770 bbp/d into the wellbore. Associated with faults at 1,831 m and 1.861 m, and associated conductive fractures.

POTENTIAL MINOR PRODUCTION ZONE

6. 1,860-1,930 m – 4,763 bbl/d flow into

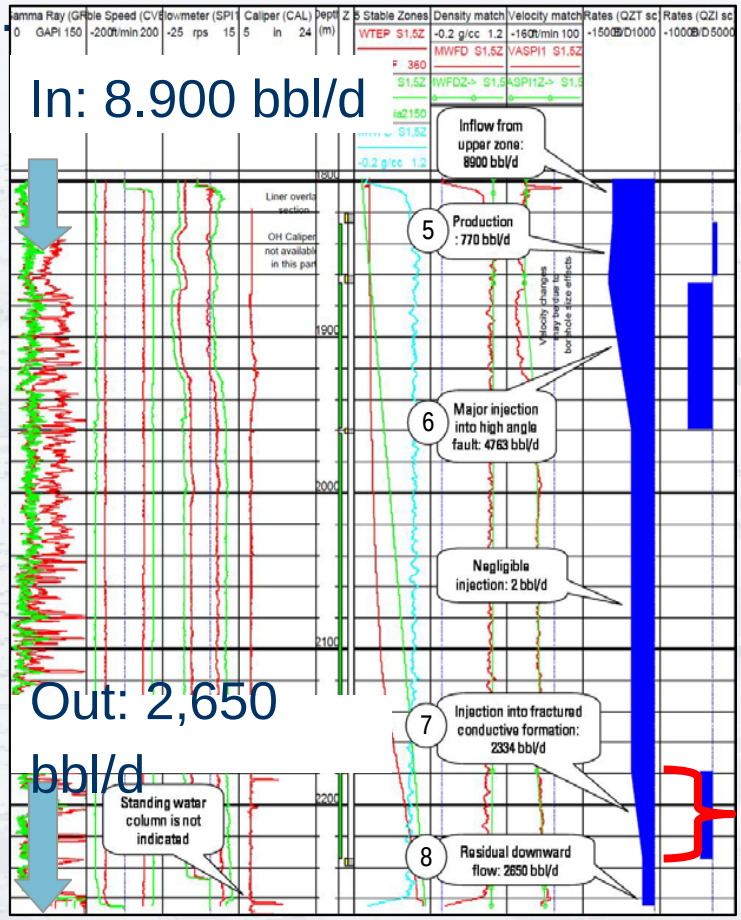


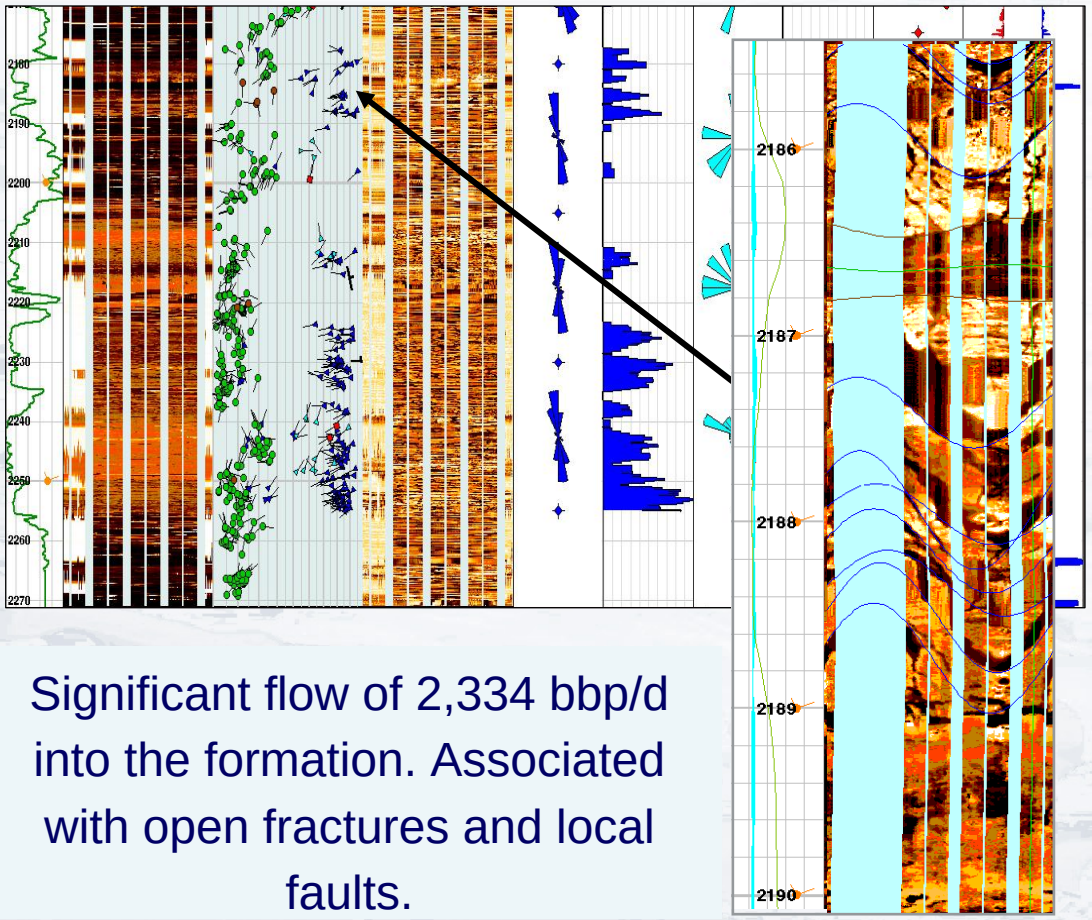


Significant flow of 4,763 bbp/d into the formation. Associated with fault at 1,917m with associated washout.

POTENTIAL MINOR PRODUCTION

7. 2,170-2,260 m – 2,334 bbl/d flow into

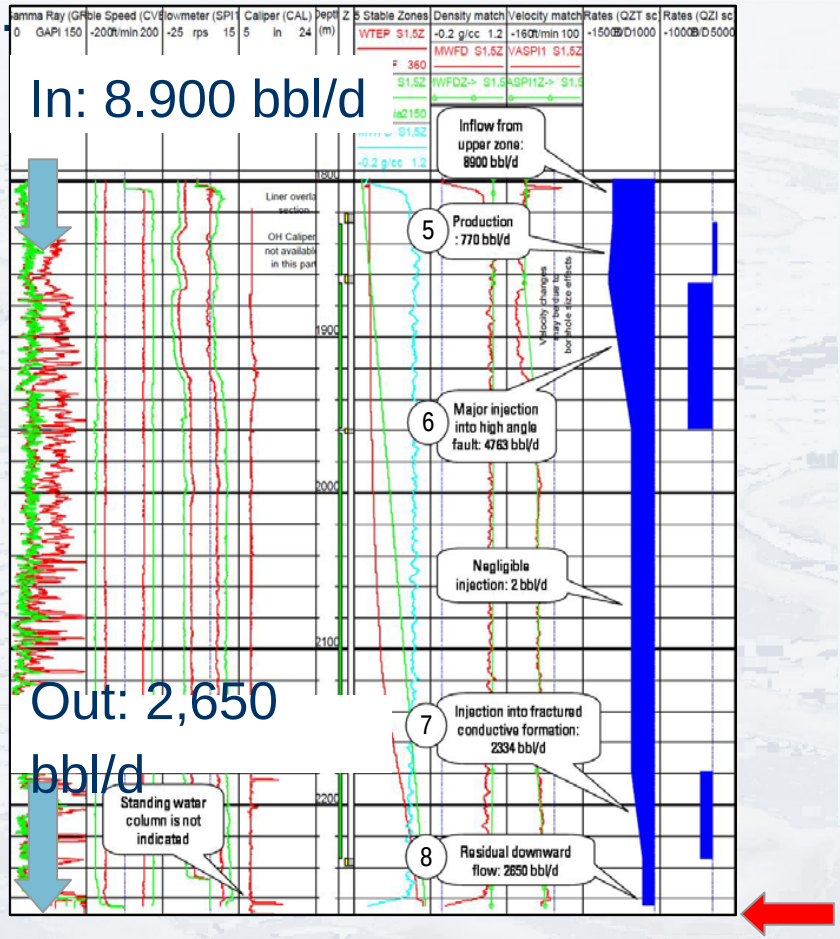




Significant flow of 2,334 bbp/d into the formation. Associated with open fractures and local faults.

POTENTIAL MINOR PRODUCTION

8. Below 2,271 m – 2,650 bbl/d flow into



2,650 bbl/d flow is calculated below the last logged depth (TD). It is possible that this represents calculation error, but the lack of a standing water column at the base of the well supports continued downward flow (into fractures?). POTENTIAL MINOR PRODUCTION

Conclusions

- Injection of cold water into geothermal wells allows acquisition of standard P&T rated logging tool data
- Electrical borehole images provide an excellent way to identify, classify, quantify & orientate fractures, faults, and borehole damage, the latter indicating stress direction
- Electrical borehole images alone do not, however, identify which fractures will or will not produce
- Integration of image data with production logging data can identify individual fractures, fracture zones and faults that will potentially produce steam