From Borehole Images to Fracture Permeability and Fracturing Pressure*

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Abstract

Borehole imagers and dipole sonic tools form the ideal pair of instruments for detailed borehole image interpretation including the evaluation of structural tilt, faulting, and fracturing. In addition, the stress field (orientation and magnitude of principal stresses) can be inverted based on both analytical and FEM methods leveraging the image logs in combination with rock mechanical and formation pressure data. Borehole images can be generated from oriented high-resolution measurement of various rock parameters, such as electrical conductivity/resistivity, acoustic reflectivity, and density. Fullwave sonic can be obtained from a range of sonic tools, while rock mechanical data usually requires laboratory testing on core plugs.

This presentation will demonstrate the suitability of bore-hole image and sonic logs for geological and geomechanical studies through an integrated workflow using examples from recently drilled wells.

Reference Cited

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Agenda

1) Image logs and fracture examples
2) Semi-quantitative results from fractures
3) Stress: how do we measure it
4) Apply calculated stresses
Borehole image interpretation
Fractures
Natural and induced fractures
Fracture cluster analysis

… based on high-resolution image logs such as FMI, HMI, etc.

→ Each fracture plane is described by type, relating to STYLE, CONTINUITY and QUALITY as seen on the borehole image

→ Degree of fracturing is then described by:
  1) Density (number of planes per meter)
  2) Corrected density for borehole bias
  3) Cluster subdivision

→ Fracture porosity

→ Relative fracture permeability
Fracture cluster analysis

- Fracture Clusters
- Conductive fracture frequency
- Resistive fracture frequency
- S-N projection
- Conductive fracture strike/stereogram
- Resistive fracture strike/stereogram

56@12
52@359
61@357

Total: 68
Total: 46
Quantification of fracture aperture from BHI

Three schools: 1) Can’t be done
2) Fixed at mean value per fracture type, calib. against prod. testing
3) Luthi & Souhaite method (Geophysics, 1990) \[ W = c A R_m^b R_x^{(1-b)} \]

L-S themselves mention a long list of requirements, some of which are:
- only FMS (Static, Emex corrected – voltage current & gain)
- constant lithology (Rx) over fracture length,
- dip <45º rel.to well
- perfect image quality,
- fracs have to be planar,
- b & c are tool and environment-dependant and poorly defined
- In addition: no fracture crossing, full circumferential, edge effect, isotropic stresses …

→ Not a single fracture that does not violate some of the requirements
Quantification of fracture aperture from BHI

Limitation due to tool type, log quality, borehole quality (throat chipping), current sucking...
Quantification of fracture aperture from BHI

Manual picking of large apparent fracture apertures (correction for orientation, edge effect etc.)
Quantification of fracture aperture from BHI

Thresholding

Pollution of excess conductivity by conductive beds or artefacts
Quantification of fracture aperture from BHI

Counting of excess conductivity (fracture intersections/muddy beds)
Quantification of fracture aperture from BHI

Combined method:
Subdivision into different fracture classes with fixed mean reference apertures (calibration to core…).

Measuring excess conduct. over matrix.

Correlation of manually picked thickness to excess conductivity.

Correcting for current sucking (edge effect, throat chipping).

Distribution of calculated fracture apertures (n=2166, range 0-7mm, mean=0.4mm)
Fracture porosity

Summing up of fracture apertures per meter relative to matrix. Multiplied with a factor depending on apparent aperture & continuity.

Sanity check against Neutron Por.

... all nice, but fractures are stressed.
STRESS – How to measure it?
The test is to assume a stress field and predict the position, azimuth and angle of incidence of the resulting crack.

Induced fractures are skin-deep and only lead to mudloss when propagating into the far field with $P > S_3$. 

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Creating a Stress log along hole.
Verify stress log against reality.
Stresses on fractures

Now it is possible to calculate the stresses acting on each fracture.
Fracture permeability

as function of both normal and shear stress

… possible in combination with a geomechanical evaluation (stress tensor and rock strength data)

\[
\frac{\Delta k}{k_0} = \left[ 1 + \frac{\Delta \varepsilon}{b} \left( \frac{K_n}{E} + \frac{1}{s} \right)^{-1} + \frac{\Delta \gamma}{b} \left( \frac{K_{sh}}{G} + \frac{1}{s} \right)^{-1} \tan(u) \right]^3
\]

k \ (k_0) = Permeability (at zero stress)
s = Fracture spacing
b = Aperture
u = Shear angle
Kn, Ksh = normal and shear stiffness
E, G = Young’s and shear modulus
\Delta \varepsilon, \Delta \gamma = Normal and shear strain
Fracture behaviour away from the borehole

The shear stability of a fracture depends on shear stress relative to effective normal stress.

When it exceeds the friction coefficient of the fracture, the fracture slips and the shear stress drops.

This is an irreversible mechanism.

$k/k_0$ is stressed fracture permeability relative to unstressed state. It depends on

- fracture and stress orientation
- aperture and spacing
- fracture shear modulus
- fracture Young’s modulus
- shear dilation angle

The model is reversible also for shear as it expresses dilation instead of slip.
Fracturing pressure
Cartesian total stress $\sigma_{xx}$

Cartesian total stress $\tilde{\sigma}_{xx}$
Effect of fracturing sequence on opening pressure

1) Fracture 1 is opened at $P=60$ MPa, then propped
2) Fracture 2 is opened at $P=60$ MPa, then propped
3) Fracture 3 is opened at $P=60$ MPa, then propped

Fracture 4 does not propagate at 60 MPa due to alonghole stress increase
Conclusions

1) Geological interpretation of BHI yields semi-quantitative permeability and porosity contribution from fractures (and vugs).

2) Fracture seen in borehole is deformed by anomalous stress. Indirect methods required to predict fracture behavior in the far field.

3) Reversible model for combined shear and normal stress influence on fracture permeability exists but requires calibration.

4) The far stress field is perturbed by artificial fracturing but the effect on opening pressure and propagation direction is predictable.
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