STATISTICAL CORRECTIONS OF FRACTURE SAMPLING BIAS IN BOREHOLES FROM ACOUSTIC TELEVIEWER LOGS

C. Massiot[1], D. McNamara[1], B. Lewis[1], L. Price[2], G. Bignall[1]

[1] GNS Science, Wairakei Research Centre, Private Bag 2000, Taupo 3352, New Zealand.
[2] Mighty River Power Ltd., 283 Vaughan Rd, P O Box 245, Rotorua 3040, New Zealand.

c.massiot@gns.cri.nz

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ABSTRACT

Targeting structurally controlled permeability remains a challenge in high temperature geothermal fields, because of the difficulties in characterising faults and fractures and their behaviour within the reservoir. The large-scale structural framework of a reservoir is usually well defined from offsets of key marker stratigraphic units intersected by wells. Some of these large-scale faults significantly contribute to reservoir permeability. Smaller-scale structures, particularly inferred active fractures, are also of major importance for the vertical and lateral flow of fluid within fractured formations. To identify the structures directly within the formations, acoustic televiewer logs are acquired in New Zealand geothermal fields with the advent of the Acoustic Formation Imaging Technology (AFIT) tool, which is rated to 300°C. This wireline logging tool acquires a full 360° acoustic image of the inside of the borehole. Typically, fractures have different acoustic impedances from the wall-rock formation and appear as discordant features on the image, which can be systematically picked during image analysis. Each fracture has its true orientation (dip/dip direction) calculated *in-situ* taking into account image orientation and well deviation. The detailed analysis of these wireline logs provides insights on the nature, distribution, aperture and orientation of the fractures directly at the borehole wall. This information can be correlated to other logs to identify which structures may be open to fluid flow. However, fractures sub-parallel to the borehole axis will be under-sampled as fewer are intersected by the well. Here we describe a technique which we use to statistically correct for the natural bias involved when counting fractures intersected by a borehole at various angles. We demonstrate the impact that this bias can have on the structural characterisation of a fractured reservoir from acoustic televiewer images, using examples from four AFIT log intervals acquired in the Rotokawa Andesite, Rotokawa Geothermal Field (New Zealand). This correction provides a more accurate representation of the true structural character of the reservoir. The resultant, improved dataset allows for greater confidence in reservoir characterisation, future well targeting, as well as fracture and reservoir modelling.

1. INTRODUCTION

Permeability in high temperature geothermal fields is often contained within fractured zones. Therefore, having a reliable picture of the structures at all scales within the reservoir is crucial for optimising well planning and field management.

Major faults are commonly characterised by offsets of stratigraphic markers between nearby wells. However, these large fault planes may not represent the most important contribution to structural permeability. Active smaller-scale fractures can significantly contribute to fluid flow (Mclean & Mcnamara, 2011). A clear and accurate characterisation of these structures is crucial to understanding their relationship within the *in-situ* stress field, their connectivity and how this influences permeability. The first step to reach this goal relies on an accurate fracture data set, i.e. representative of their nature within the reservoir, independently from what is observed directly from the borehole walls.

Systematic analysis of high temperature acoustic televiewer image logs is, to this date, the only method of extracting direct structural information of buried reservoir lithologies in high temperature geothermal fields. Several factors contribute to interpretation bias in fracture analyses from acoustic images, the most important of which are:

- Difficulties in identifying fractures due to image quality.
- Lack of acoustic contrast between the host rock and the fracture, e.g. due to a similar alteration assemblage within the fracture and present pervasively through the host rock.
- Natural under-sampling of fractures sub-parallel to the borehole axis.

These measurement biases have to be considered before using the interpretation results for further studies, and if possible, corrected. The fact that a televiewer log is acquired along a line, i.e. the borehole, implies that fractures sub-parallel to the borehole are either missed or under-sampled. This under-sampling can be mediated to obtain a data set more representative of the fracture distribution within the reservoir and is discussed in this paper.

2. METHODOLOGY

2.1 The AFIT Tool: A High Temperature Acoustic Televiewer

The Acoustic Formation Imaging Technology (AFIT) tool is the acoustic televiewer ABI85 rated to 300°C developed by Advanced Logic Technology (ALT) and operated by Tiger Energy Services.

The AFIT tool scans the inside of the borehole wall using ultrasonic pulses emitted from a stationary transducer to a rotating mirror, generating a full 360° image (Figure 1). Pulses reflected off the borehole wall are received by the transducer and provide two types of information:

- Wave travel time provides information on borehole shape, from which calipers can be derived.

- Wave amplitude attenuation, or acoustic impedance, relates to the physical properties of the borehole wall, such as lithology, fracturing, bedding, etc.

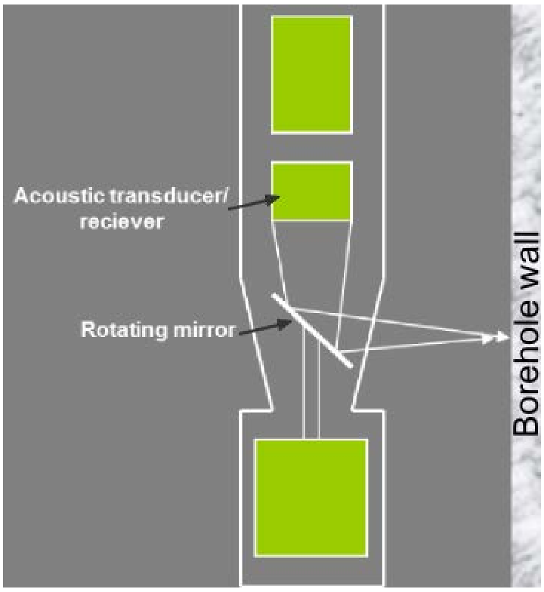

Figure 1: Schematic of the head of the AFIT tool. White arrows show pathway of acoustic pulse.

The AFIT tool contains triaxial accelerometers and magnetometers that define the orientation of the tool in the borehole. This enables calculation of the true orientation of fractures from their apparent orientation on the borehole wall, independently of the orientation of the wellbore. Unwrapped images are displayed such that 0° (N) is at the left-hand edge, 180° (S) in the centre and 360° (N) at the right-hand edge (Rider, 1996). Planar features, such as fractures or beddings, appear as sinusoids on the image. Their orientation if calculated by manually matching sinusoids onto the displayed image.

Acoustic images are now widely utilised in geothermal wells in the Taupo Volcanic Zone (TVZ) geothermal fields usinthe AFIT tool and interpreted at GNS Science (using Petris Recall^{TM} software). AFIT image log interpretation provides information on the nature, distribution, orientation and aperture of the fractures, as well as on the horizontal *in-situ* stress directions. Bedding and layering features are also assessed as they might play a role in primary (formation) permeability.

In New Zealand geothermal wells, AFIT logs are commonly acquired with a setting of 144 samples per revolution of the rotating mirror and at a vertical logging speed of 2 – 3 m/min. The measurement error associated with these acquisition parameters is ~2.5° horizontally (equivalent to ~1 cm within an 8.5 in. borehole) and ~0.5 cm vertically.

2.2 Principle of the correction of the well trajectory orientation sampling bias

A planar feature (such as a fracture) intersecting a borehole will appear as a sinusoid on the 2-D acoustic image. The amplitude of this sinusoid increases as the angle between the feature and the borehole decreases. For example, the upper fracture in Figure 2 intersects the borehole axis at ~7° and has a high amplitude sinusoid whereas the lower fracture intersects the borehole axis at an angle of ~19° and has a lower sinusoid amplitude. Fractures sub-parallel to the borehole will either not be intersected, or will be systematically under-sampled as they are less likely to be intersected by the well (Barton & Zoback, 1992). In addition, spalling from the borehole wall may occur due to the weakness of the rock at the low-angle intersection between the fracture and the borehole wall, preventing the detection of the fracture.

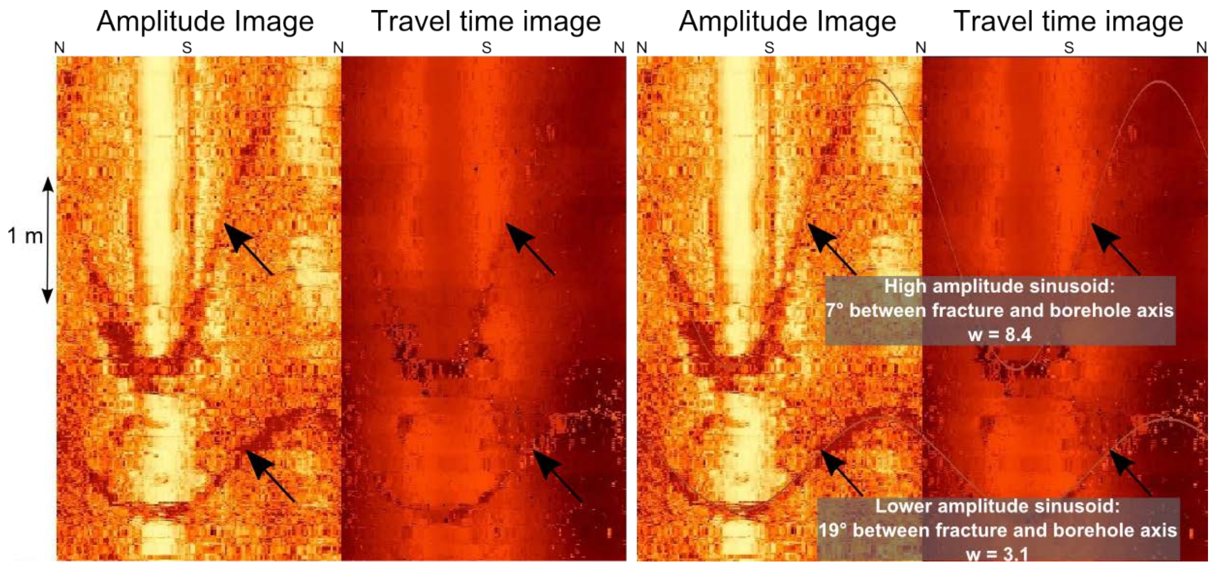

Figure 2: Acoustic images showing fractures with various angles to the borehole axis. Images on the right display interpreted sinusoids.

Statistically correcting for the under-sampling of fractures sub-parallel to the borehole is discussed by Einstein & Baecher (1983), Hudson & Priest (1983) and Terzaghi (1965). This paper describes the first ever application of this correction technique to data sets acquired in New Zealand Geothermal fields.

A statistical weight is applied to each fracture depending on its relative orientation to the borehole axis. The correction factor ‘w’ was first proposed by Terzaghi (1965) based on the acute angle (δ) between the normal plane to a fracture and the well trajectory (Equation 1):

$$w = \frac{1}{\cos\delta} \qquad (1)$$

However, w becomes very high when the fracture orientation becomes more perpendicular to the well axis trajectory (δ approaches 90°) potentially allowing a single point to dominate any given fracture density. An estimation of the w factor error (w_ε), is proposed by Yow (1987):

$$W_\varepsilon = \frac{\cos\delta}{\sin(90 - \delta - \varepsilon)} - 1 \qquad (2)$$

where ε is the error associated with the orientation measurement (angular resolution). Priest (1993) recommends a maximum allowable value for w_ε of 20%.

The w parameter is calculated for each fracture, using the well trajectory at the associated depth. The fracture information is then duplicated w times, an operation which, when performed on each fracture of the raw data set, creates a new “corrected” data set. For example in Figure 2, the upper fracture has a w of 8.4 and will be replicated 8 times in the corrected data set; the lower fracture has a w of 3.14 and will be replicated 3 times. This process therefore does not create any new fractures, but rather increases the statistical weighting of those fractures sub-parallel to the well axis.

3. CASE STUDY: ROTOKAWA GEOTHERMAL FIELD, NEW ZEALAND

The permeability within the Rotokawa Andesite is dominated by fracturing, and is an important reservoir of the Rotokawa Geothermal Field, New Zealand. The Rotokawa Andesite is highly faulted, as indicated by vertical offsets of the top of this formation between nearby wells, yet permeability is often encountered away from the major fault planes, likely associated with smaller-scale fracturing. To characterise the borehole scale structures which might be responsible for flow pathways, AFIT logs were acquired in three deviated wells (A, B and C) of the Rotokawa Geothermal Field. The Rotokawa Andesite was present in four depth intervals:

- The well axis of interval A1 has varying plunge (67-74°) (compared to the horizontal plane, fracture convention) and trends ESE to S.

- Intervals A2, B and C have constant well axes deviations, with ESE, SW and NNW trends respectively and ~65 - 70° plunge.

In the TVZ, structures commonly have high dip magnitudes, usually ≥60° (Villamor & Berryman, 2001), similar to the plunge of the studied boreholes. The dominant fracture strike orientation in the TVZ is NE-SW (Rowland & Sibson, 2004). The four studied intervals thus represent a combination of well trajectories sub-parallel (B) and sub-perpendicular (A1, A2 and C) to the main structural trend of the TVZ.

The statistical correction has been performed on the four intervals. The maximum allowed value for the weighting factor w has been determined using the methodology described in the previous section. Equation (2), using an angular resolution of the AFIT of 2.5° (ε), and a maximum allowable value for w_ε of 0.2, corresponds to an angle of δ = 84.3°. Using Equation (1) with this value of δ, we obtain the maximum value of w = 10.

The effect of the well trajectory on fracture sampling from AFIT logs is evident in Interval B where no fractures are identified within 10° of the well trajectory (Figure 3e). The presence of fractures identified with slightly higher angles to the borehole direction suggests that this absence of fractures identified sub-parallel to the borehole trajectory is due to a sampling bias rather than a natural factor. The Fischer distribution (Priest, 1993) is directly impacted: there is a very low fracture density in the vicinity of the well trajectory (i.e. within 10° dip magnitude and 10-20° dip direction). Figure 3f displays the Fischer distribution for the corrected data set. Even if no fractures are oriented parallel to the well trajectory, the high weighting (w=10) of fractures oriented near to the borehole direction is sufficient to smooth the Fischer distribution and reduce the effect of the under-sampling bias. Similar smoothing of the Fischer density is observed in interval C (Figures 3g and 3h) and A2 (Figures 3c and 3d). This effect is less evident for interval A1 (Figures 3a and 3b); indeed, the borehole has variable well trajectories, which prevented the under-sampling bias to be focused on a single direction.

Table 1 indicates the Fischer density (in % of fractures from the dataset) at the orientation of the well trajectory. The corrected data sets have significantly higher frequencies in each case, independently of the well trajectory or the main orientation of fractures identified on the log.

Table 1: Fracture density (%) of fractures with orientations sub-parallel to the hole deviation direction (raw and corrected data set).

Studied interval	Raw data set	Corrected data set
A1	2.8	5.5
A2	6.2	8.4
B	0.7	2.3
C	1.1	3.4

The correction increases the density in all dominant fracture groups identified from the acoustic image logs (Table 2). This effect is particularly noticeable in interval B, where the dominant group has a dominant strike orientation NE-SW sub-parallel to the borehole direction (Figures 3e and 3f).

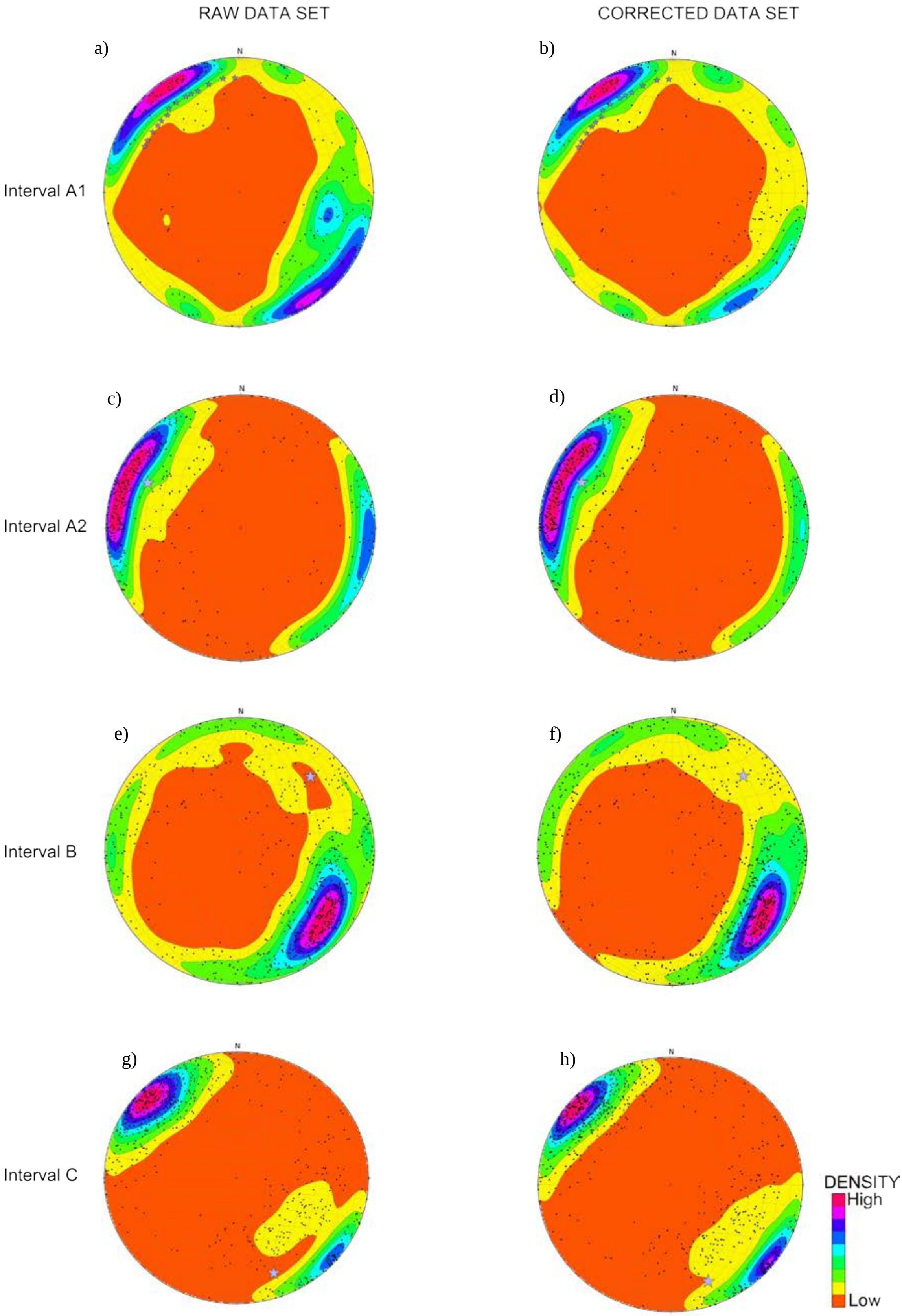

Figure 3: Lower hemisphere, equal-area stereonets of fractures identified from AFIT log analysis in the four intervals, (from top to bottom: A1, A2, B and C), using the raw (on the left) and corrected (on the right) data sets. The borehole deviation is represented by a blue star symbol.

Table 2: Fracture density (%) of the dominant fracture orientation, raw and corrected data sets.

Studied interval	Raw data set	Corrected data set
A1	12.4	16.6
A2	16	16.8
B	12.5	14
C	19.9	20.1

The A2 borehole trajectory trends ESE, sub-perpendicular to the main fracture strike. The raw data set (Figure 3e) indicates that the dominant fracture group is dipping towards ESE, in the same direction than the borehole trajectory. The borehole is therefore sub-parallel to the main orientation of fracture planes. The correction reinforces this dominant fracture orientation, by increasing the density of fractures oriented sub-parallel to the well at the expense of similar striking fractures that dip WNW (Figure 3f). This example illustrates that, even if a borehole is drilled perpendicular to the main fracture strike direction, it may still be sub-parallel to the main fracture plane orientation due to the fracture dip directions.

The correction also has an effect on subordinate fracture orientations. For example, in interval A1 (Figure 3a and 3b), the density of the subordinate group (58°/284°) oriented ~35° from the borehole axis is decreased so much after correction that it does not constitute a significant component of the corrected data set.

The orientation of the main fracture groups is not significantly modified by the correction (<5% for the four studied intervals, which for example corresponds to a variation of 04° dip magnitude and 017° dip direction in interval A2). The correction thus modifies the relative importance of the fracture groups rather than their orientation.

3. DISCUSSION AND CONCLUSION

This statistical correction of AFIT fracture data provides a more realistic representation of the fracture distribution and orientations within the reservoir, in the vicinity of the boreholes. Artificially low fracture densities sub-parallel to the borehole axis are removed. The relative importance of fracture populations is also mediated, reducing the density of fracture groups oriented sub-perpendicular to the borehole axis in favour of the under-sampled fractures sub-parallel to the borehole axis.

Correlation with other data (e.g. pressure, temperature and fluid velocity) is necessary to identify the permeable zones within a borehole. In-depth study of the fracture patterns occurring within permeable producing zones is critical to understanding the relationships between fractures and permeability. Having a fracture data set where sampling bias has been minimised reduces the risk of misinterpretation and increases the reliability of data for subsequent well planning.

The correction also provides a more accurate data set that can be utilised for fracture modeling to evaluate the structural connectivity throughout the field. A more accurate evaluation of fractures within the reservoir also reduces uncertainties on geomechanical modelling, e.g. to investigate the optimum well trajectory while maintaining borehole stability (Zoback, 2007). On-going well testing in nearby geothermal fields, together with rock mechanic experiments on TVZ reservoir rock may lead to an estimation of the stress magnitudes within the reservoir. Combined with the *in-situ* horizontal stress directions from AFIT image log analysis, a first estimate of the full stress tensor within TVZ geothermal fields may be resolved. This is a necessary step towards using geomechanical models to their full potential in the New Zealand geothermal industry. Further data acquisition will however be necessary to refine such models and to evaluate the stress variations within the geothermal fields, and across the TVZ, but will ultimately increase overall drilling success and field management.

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