Correcting for variations in borehole diameter in fluid velocity profiles

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ABSTRACT

Pressure-temperature-spinner (PTS) data is the most common dataset collected in geothermal wells. It provides valuable information about the well and reservoir, such as feed zone characteristics, well conditions, and well injectivity or productivity. A combination of temperature and fluid velocity profiles (calculated from spinner response) are used to accurately identify the location of feed zones in the well, and how much each feed contributes under certain conditions.

However, analysing the fluid velocity profile is often not straightforward when the borehole is heavily washed out. In this situation, the spinner data does not only reflect the actual feed zones but also the variation in borehole diameter. This interferes with feed zone interpretation, potentially providing misleading information about the well or reservoir.

Currently, to differentiate between the effects of feed zones and changing borehole diameter, reservoir engineers would look at a caliper log, which provides a physical measure of well bore diameter (if available), and visually compare the shape of it to the spinner data. This is an imprecise exercise and can fail to definitively determine whether there is a feed zone present within a washout, for example. Another current method is the spinner ratio method (Grant & Bixley, 1995), which divides one fluid velocity profile by another from a different flow rate to give a ratio. The limitations of this are: the requirement to have two high quality fluid velocity profiles, complications in aligning the datasets, and the tendency for the ratio to be very noisy.

This work therefore explores ways to explicitly remove the effects of changing diameter from the fluid velocity profile by means of applying a correction method based on caliper data. This has been recently enabled by an increase in open-hole caliper data collection. The correction method was applied to field data from three wells in Wairākei geothermal field, with significant changes to feed zone interpretation as a result of the correction.

1. INTRODUCTION

Pressure-temperature-spinner (PTS) is a standard geothermal wireline tool that typically measures thousands of pressure-temperature-spinner data points, normally over the full depth of the wellbore. Typical PTS testing programs can be for a range of well conditions: injecting (at multiple rates) then shut, discharging then shut, or just shut. In combination with other downhole measurements, such as formation imaging and calipers, PTS is used to accurately identify feed zone locations, characteristics, and contribution to the total output of the well (Massiot et al., 2017).

Downhole pressure and temperature profiles are relatively straightforward to interpret, but spinner data needs to be processed to calculate the fluid velocity profile in the well for each flow rate of the test program (Grant & Bixley, 1995). This allows identification of feed zones, where water can either exit the well (decrease in fluid velocity) or enter the well (increase in velocity). Additionally, fluid velocity is affected by changes in cross-sectional area, where velocity decreases as area increases. In this case, the area corresponds to the wellbore diameter, which can vary significantly in the production (perforated liner) section of the well.

Variation in wellbore diameter is captured using mechanical calipers, commonly the XY type in open-hole conditions prior to insertion of the liner. This measures the wellbore diameter in two dimensions, X and Y, perpendicular to the length of the wellbore. Acoustic calipers are also captured by the Acoustic Formation Imaging Tool (AFIT), a type of borehole imaging tool to image fractures in the open hole (Massiot et al., 2015). In this process the travel time of the acoustic signal as it travels between the tool and the borehole wall and back is converted into diameter.

Only open-hole caliper logs are used in this study, as these are the ones which measure the variation in wellbore diameter, not to be confused with caliper logs run after well completion/liner installation to identify scaling or casing issues. However, PTS logs can be run pre- or post-liner insertion, as both are affected by variation in wellbore diameter.

A schematic showing the changes in fluid velocity with feed zones (inflows and outflows) as well as changes in area (at top of liner, and due to washout below casing shoe) is shown in Figure 1.

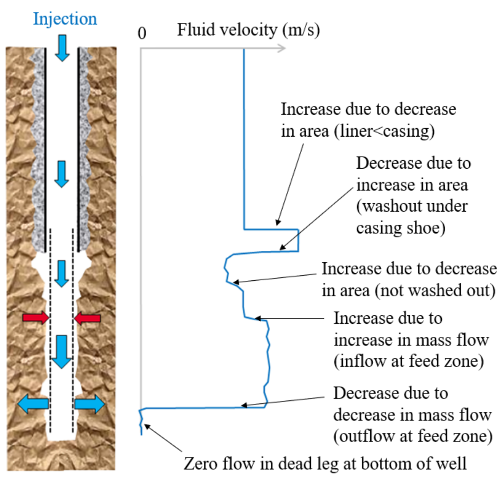

Figure 1: Schematic of change in fluid velocity due to variation in mass flow (feed zones) and borehole diameter (washouts).

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Therefore, when identifying feed zones using a fluid velocity profile, one needs to be mindful that it may also represent a change in borehole diameter. For wells with a heavily washed-out borehole, the most common practice is to view both the fluid velocity profile and caliper log side by side, visually compare them, and qualitatively reduce or ignore the extent of fluid velocity change. There have been a number of examples in Wairakei geothermal field where this exercise has proven to be imprecise, and the presence of a washout has masked the presence of a feed zone. Therefore, the aim of this work is to explore a correction method to explicitly remove the effects of changing diameter from the fluid velocity profile by applying the fundamental concept of mass flow of water in a pipeline. This will allow reservoir engineers to identify feed zones more precisely and efficiently, potentially unmask hidden feed zones and straighten out confusion at washed out sections. Knowing the exact locations of feed zones is necessary to inform the operational strategy for the well, and to assist with future well interventions.

2. BACKGROUND

2.1 Flow of water in a pipe and "mirror image"

Fluid movement in a well follows the equation for fluid mass flow in a pipe:

$$\dot{m} = \rho \times A \times V$$

Where: $\dot{m}$ is mass flow rate (kg/s), ρ is fluid density (kg/m^3), A is cross-sectional area m^2), and V is fluid velocity (m/s).

The above equation can also be expressed as volumetric flow rate Q, where $Q = \frac{\dot{m}}{\rho}$,

$$Q = A \times V$$

Where: Q is volumetric flow rate (m^3/s), A is cross-sectional area m^2), and V is fluid velocity (m/s).

Therefore, fluid velocity V in the well is affected by two main factors: a change in cross-sectional area A (borehole diameter) is inversely proportional to a change in velocity, and a change in volumetric flow rate Q is proportional to a change in velocity (flow in or out the well). This is the governing concept for correcting the fluid velocity profile.

$$V = \frac{Q}{A}$$

As a result, viewing the fluid velocity profile and caliper log side by side should create a "mirror image", where fluid velocity decreases with increasing borehole diameter and vice versa. This effect is more pronounced in washed out sections and will sometimes only be visible if the plot is zoomed in at specific depths. An example of this is shown in Figure 2. Without looking at the caliper log, it is easy to misinterpret the fluid velocity variation as being due to a feed zone, where in fact there is no fluid entering or exiting the well.

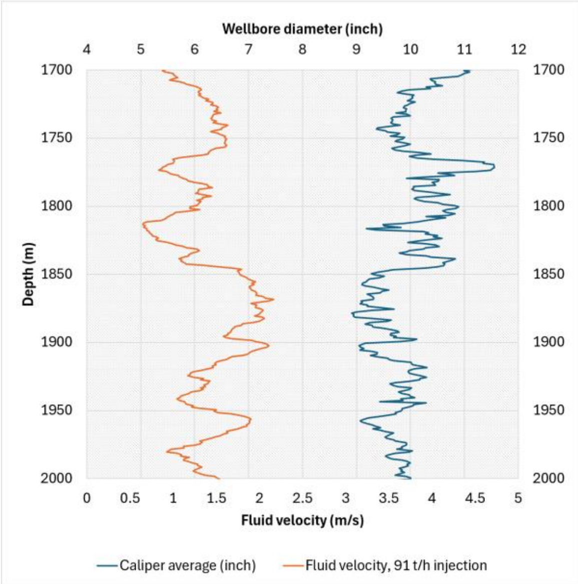

Figure 2: A "mirror image" of fluid velocity profile and caliper log. Fluid velocity decreases as borehole diameter increases, and vice versa.

2.2 Open hole calipers

While the concept of correcting fluid velocity using calipers has been around for a long time, it has been inhibited by the lack of open-hole caliper data. Only relatively recently have open-hole caliper logs become common during drilling, enabling this study. The primary purpose of carrying out an open-hole XY caliper log is for drilling purposes. Knowing the shape of the borehole helps predict and/or understand hole section issues, for example potential sticking points when running casing or liner. It is also used to calculate cement volumes for cementing stages.

Open-hole dimensions can also be measured during the process of borehole imaging using acoustic formation imaging tools (AFIT) (Massiot et al., 2015). The acoustic caliper is affected by temperature and in the past tended to drift as temperature increased towards the bottom of a well, inhibiting caliper correction methods. However, a method of correction of the acoustic caliper for temperature has been developed and so the acoustic caliper is also available for the purposes of this study.

2.3 Regional setting

There are three wells investigated in this work, all of which are located in Wairākei geothermal field, New Zealand.

WK317 is an injection well in the Otupu area drilled in 2009. It has a high degree of variation in borehole diameter, that significantly affects spinner response. Preliminary attempts were made to remove this effect using caliper data, but were only moderately successful over short intervals at the time. The interpretation defaulted back to visual comparison of the fluid velocity vs caliper log shapes. The caliper is an acoustic caliper available from the AFIT log.

WK274 and WK275 were recently drilled in 2024 as future production wells in Te Mihi area. Spinner responses from these wells are of good quality, but there was confusion when interpreting feed zones at washed out sections. Open hole

XY caliper logs are available and were initially used to visually compare the shape with the fluid velocity profile.

3. METHOD

3.1 Well and data selection

To identify the wells for this study, several criteria were used. Firstly, the wells should have an open-hole caliper log, preferably over the full depth of the production section. The caliper log results were then screened with a preference for those which had large washouts or heavily inconsistent borehole diameter.

Once a number of potential wells were identified, the choice was further narrowed down to those that had at least one injecting PTS as soon as drilling had been completed, preferably prior to the insertion of liner (open-hole PTS run).

Lastly, the potential wells were screened for those which are historically known to present difficulties when interpreting the feed zones due to the distorted spinner data. One well stood out, WK317, as this was the first well in Wairakei with a history of previous attempts to correct the spinner profile using caliper data.

Two other wells that were chosen also met all of these criteria, WK274 and WK275. These were known to have a number of washouts that caused confusion during feed zone analysis upon the completion of the well.

3.2 Data preparation and quality control

For each of these wells, the raw caliper data and measured fluid velocity data were imported into an Excel spreadsheet. The raw caliper data includes depth, X Caliper and Y Caliper (if XY caliper was used) or average caliper (if other type of caliper was used, e.g., AFIT caliper). The fluid velocity data includes depth and fluid velocity.

Both data were then plotted together, as profiles of fluid velocity and borehole diameter vs depth. This is the first step of data quality control to ensure there is enough resolution to see the "mirror image" between the caliper and fluid velocity data, as shown in Figure 2.

Additionally, it is also important to check possible sources of depth difference when viewing the "mirror image". In the case of WK317, there were noticeable features of mirror image, but with slight offset in depth between the caliper and fluid velocity data, as shown in Figure 3. There are usually two sources of error creating this inconsistency: wireline stretch issue or datum depth difference. Given that the depth difference in WK317 is up to 8.5 m, it is more likely that the error is caused by datum depth difference. Therefore, the corresponding features in the shape of fluid velocity and caliper data were lined up using an "offset plot", where the depths of one of the datasets were corrected with a constant offset value until the mirror image features matched. The corrected "mirror image" plot for WK317 is shown in Figure 3.

For WK274 and WK275, there was little difference in depth between the mirror image features, and so it is more likely that the source of error in these cases is wireline stretch. Therefore, offset plots with smaller offset subtraction were used to line up the features. The results are shown in Figure 4 and **Error! Reference source not found.**.

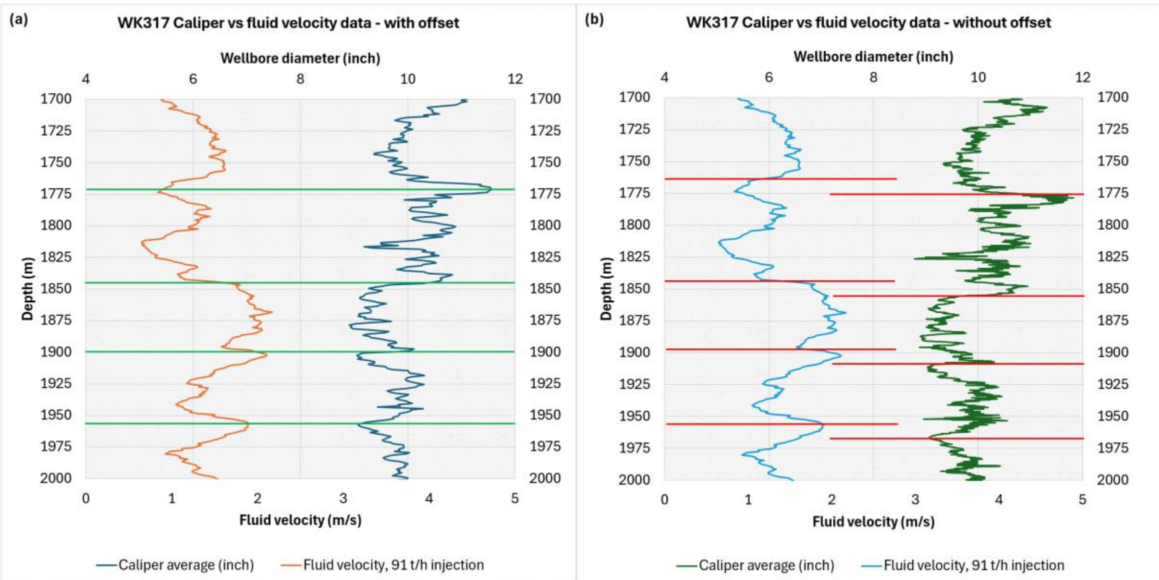

Figure 3: (a) WK317 caliper vs fluid velocity data, with offset depth of 8.5 m. The mirror image features were lined up visually by changing the offset depth. (b) WK317 caliper vs fluid velocity raw data, prior to being corrected. The mirror image features were visible but with slight offset in depths.

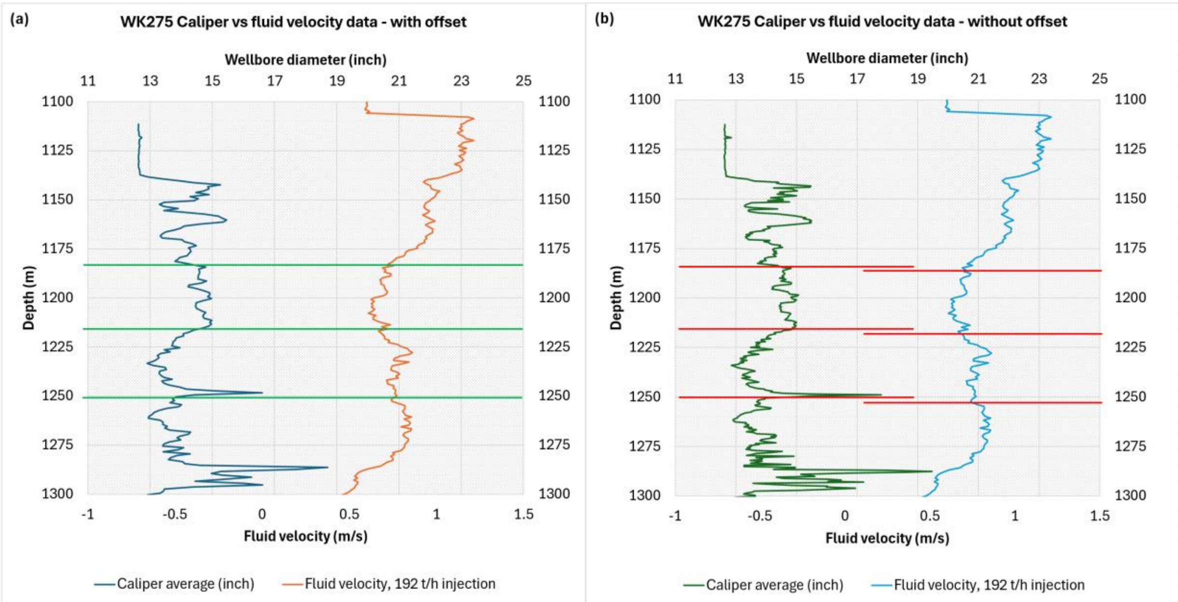

Figure 4: (a) WK275 caliper vs fluid velocity data, with offset depth of 0.65 m. The mirror image features were lined up visually by changing the offset depth. (b) WK275 caliper vs fluid velocity raw data, prior to being corrected. The mirror image features were visible but with slight offset in depths.

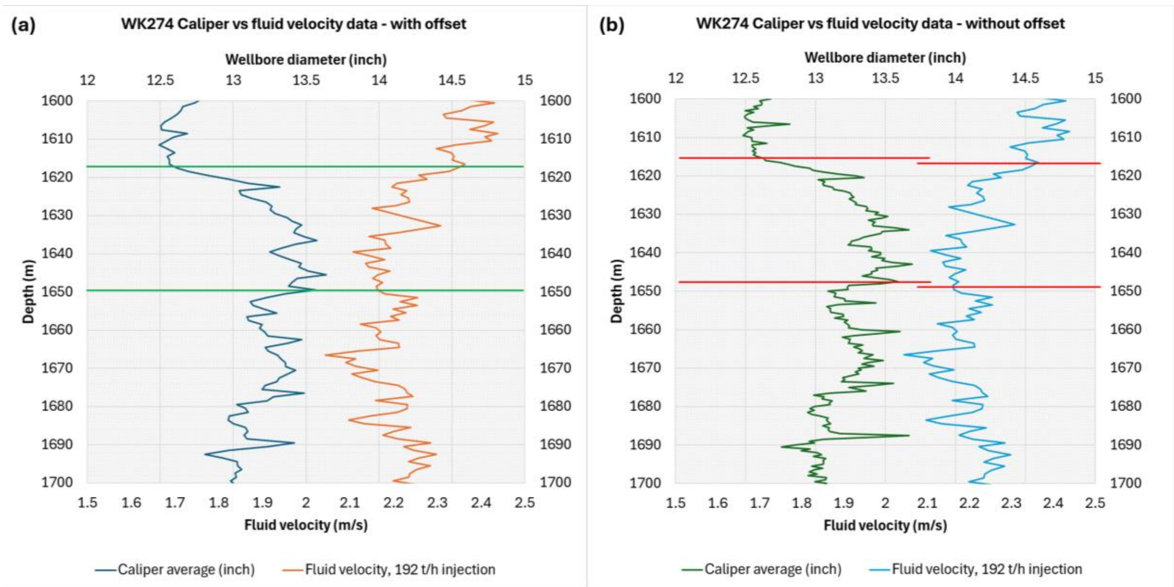

Figure 5: (a) WK274 caliper vs fluid velocity data, with offset depth of 2.5 m. The mirror image features were lined up visually by changing the offset depth. (b) WK274 caliper vs fluid velocity raw data, prior to being corrected. The mirror image features were visible but with slight offset in depths.

After ensuring that the mirror image features are all lined up correctly, the next step of quality control was applied on the caliper data itself. In practice, all boreholes are oversized, which means that all caliper data should be larger than the drill bit size. Any values recorded by the caliper cannot be less than the drill bit diameter. To check this, the caliper data was plotted alongside a constant value of the drill bit diameter across all depths. If there was any caliper value lower than the drill bit diameter, it should be excluded from analysis, leaving a gap in the caliper data at these erroneous sections. This was the case for WK317 dataset (based on an older acoustic caliper and more prone to error), where there were some erroneous data points smaller than the drill bit diameter of 8.5", as shown in Figure 6 . The caliper data for WK274 and WK275 were all larger than the drill bit size of 12", so all data points were included for analysis.

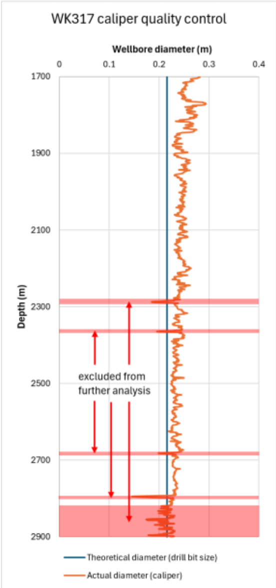

Figure 6: WK317 caliper data quality control: caliper data plotted against the drill bit size.

To sum up, the quality control process includes ensuring the presence of "mirror image" features between the caliper and fluid velocity data, lining up any depth differences, and ensuring all caliper data are larger than the drill bit diameter.

3.3 Calculating borehole oversize

The correction factor applied in this study is primarily based on cross-sectional area difference between the "theoretical" and actual borehole size. The theoretical borehole cross-sectional area is the circle area using drill bit diameter (used to drill the open hole production liner section), and the actual borehole cross-sectional area is approximated from the caliper data (Figure 7).

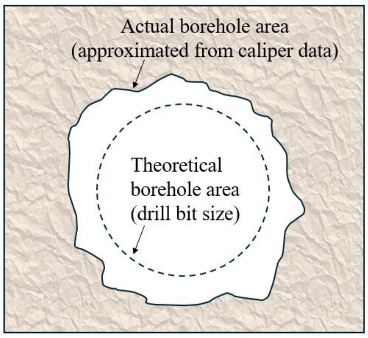

Figure 7: Definition of "theoretical" and "actual" borehole cross-sectional areas for this study.

If an XY caliper was used as in the case of WK274 & WK275, the area of an ellipse was used (Eq.1). If another type of caliper was used as in the case of WK317, the area of a circle was used, with the radius being half the average caliper value (Eq.2). This was all performed at each recorded caliper depth. The theoretical cross-sectional area is constant (calculated from drill bit size) at all depths (Eq.3).

$$Actual\ cross-sectional\ area = \frac{\pi}{4} \times X\ Cal \times Y\ Cal \quad \text{(Eq.1)}$$

Or,

$$Actual\ cross-sectional\ area = \pi \times \left(\frac{caliper\ average}{2}\right)^2 \quad \text{(Eq.2)}$$

$$Theoretical\ cross-sectional\ area = \pi \times \left(\frac{drill\ bit\ diameter}{2}\right)^2$$
(Eq.3)

The actual cross-sectional area was then divided by the theoretical cross-sectional area to give the washout ratio, as follows:

$$washout\ ratio = \frac{actual\ area}{theoretical\ area}$$

3.4 Calculating correction factor & quality control

The correction factor is based on the concept that fluid velocity is inversely proportional to cross-sectional area.

$$V = \frac{Q}{A}$$

$$Q = V \times A$$

Assuming Q is constant (maintaining the same injection rate throughout the PTS run), if the actual area (A) increases by 50% (washout ratio of 1.5), the fluid velocity (V) should decrease by a third. Similarly, if A is 100% oversize (washout ratio of 2), V should decrease by half.

$$\frac{1}{1.5}V = \frac{Q}{1.5A}$$

$$\frac{1}{2}V = \frac{Q}{2A}$$

The actual boreholes are oversized at all depths, making the measured fluid velocities slower than they would be if the borehole was the theoretical size. Therefore, the effect of removing the oversize effect is to increase the fluid velocities. For example, removing the effect of a 100% oversized (washout ratio of 2) borehole is to increase the fluid velocity by a factor of two. Similarly, removing the effect of a 200% oversized (washout ratio of 3) borehole should also triple the fluid velocity.

Therefore, the washout ratio directly translates the change in fluid velocity as a factor.

$$CF = washout\ ratio = \frac{actual\ area}{theoretical\ area}$$

This can also be explained by the concept of fluid velocity normalised to the ideal borehole diameter.

$$V_{Measured}A_{Measured} = V_{Normalised}A_{Theoretical}$$

$$V_{Normalised} = \frac{V_{Measured}A_{Measured}}{A_{Theoretical}}$$

$$washout\ ratio = \frac{A_{Measured}}{A_{Theoretical}}$$

$$V_{Normalised} = V_{Measured} \times washout\ ratio$$

The above formula was then applied across all recorded caliper depths.

3.5 Applying correction factor to the fluid velocity profile

To apply the correction factor to the fluid velocity profile correctly, the recorded caliper depths need to be matched with the recorded fluid velocity depths. To do so, a combination of Excel functions INDEX and MATCH was used to look for the calculated correction factor at the corresponding fluid velocity depths.

$$CF_{(FV)} = INDEX((\$CF_{(cal)}, MATCH\left(MIN\left(ABS\left(\$depth_{(cal)} - depth_{(FV)}, ABS\left((\$depth_{(cal)} - depth_{(FV)})\right), 0\right)\right), 1\right)$$

With:
$CF_{(FV)}$ = Correction Factor at each recorded fluid velocity depth
$\$CF_{(cal)}$ = range of correction factor calculated at each caliper depths
$\$depth_{(cal)}$ = range of caliper depths
$depth_{(FV)}$ = corresponding fluid velocity depth

However, sometimes the start and end of the recorded depth between two datasets can be different. In this case, an additional IF function can be embedded into the formula.

$$CF_{(FV)} = IF(AND(depth_{(FV)} \geq MIN(\$depth_{(cal)}), depth_{(FV)} \leq MAX(\$depth_{(cal)}), INDEX((\$CF_{(cal)}, MATCH\left(MIN\left(ABS\left(\$depth_{(cal)} - depth_{(FV)}, ABS\left((\$depth_{(cal)} - depth_{(FV)})\right), 0\right)\right), 1\right)$$

If the fluid velocity depth is outside the range of the caliper depth, then no correction factor shall be applied to the fluid velocity profile, i.e., $CF_{(FV)} = 1$.

It is important to note that the above Excel formula is only one way to match the depth. There are other ways of doing this, as long as the intention is to answer the question: given the list of correction factor calculated at each recorded caliper depth, what is the correction factor at the closest recorded fluid velocity depth?

The result of this depth-matching process can be verified by plotting together the correction factor at both caliper depth and fluid velocity depth. If both datasets match, as shown in Figure 7, then the depth matching process is considered to be successful.

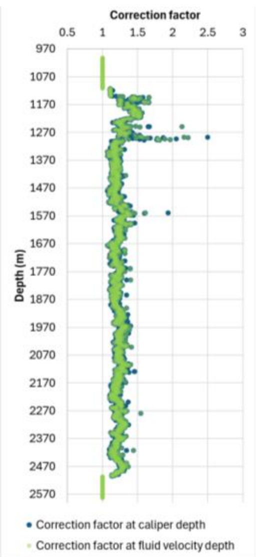

Figure 8: Correction factor depth-matching quality control. Both the correction factor at caliper depth and fluid velocity depth are plotted together to ensure both datasets match.

The correction factor can then be applied to the measured fluid velocity, by simply multiplying it across all recorded depths.

$$Corrected\ FV = Measured\ FV \times CF\ (at\ FV\ depth)$$

4. RESULTS

4.1 WK317 fluid velocity profile

The measured and corrected fluid velocity profile at 91 t/h injection rate for WK317 are shown in Figure 9. Feed zones interpretation using solely fluid velocity profiles is based on relative change in average fluid velocity between one section and another. "Section" here refers to a portion of depths where the average fluid velocity is visually constant, and this is indicated by the yellow vertical lines in Figure 9.

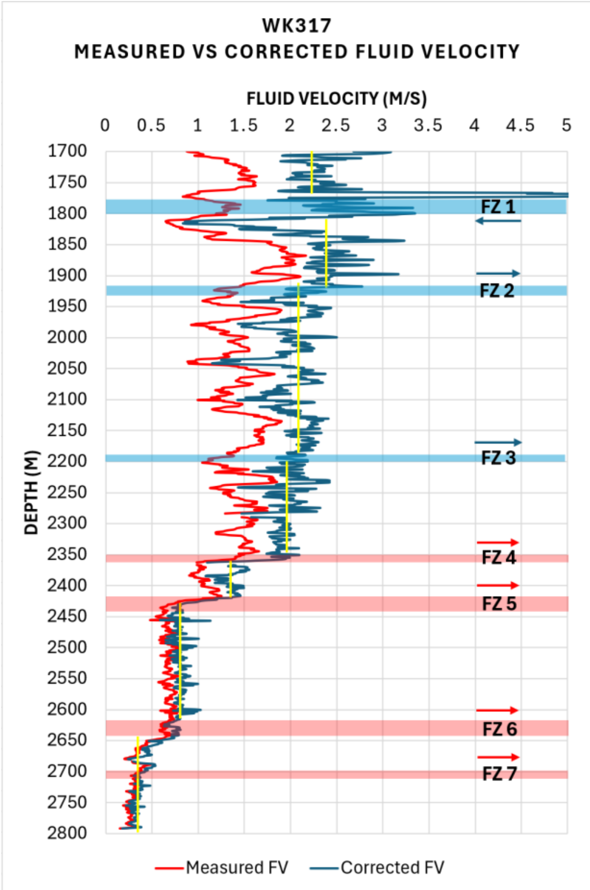

Figure 9: WK317 measured vs corrected fluid velocity at 91 t/h injection rate.

The red zones in Figure 9 are interpreted feed zones based solely on the original fluid velocity profile (without the help of PT profiles), and blue zones are newly interpreted feed zones based on the corrected fluid velocity. Arrows moving towards the plot (left) indicate inflows, and arrows pointing away from the plot (right) indicate outflows.

The original fluid velocity profile for WK317 is very noisy to begin with, and this is unfortunately still the case in the corrected fluid velocity profile. However, the corrected fluid velocity shows better separation of the different sections. Reinterpretations of feed zones enabled by the corrected fluid velocity profile are as follows:

FZ1

For example, between 1700 and 1920 m, there were several distinct spikes with over 0.5 m/s difference in the original fluid velocity profile that can be easily misinterpreted as different feed zones without the help of PT profile. In fact, the upper feed zone is only known from temperature data (sudden increase in temperature gradient), as its existence is not apparent in the original fluid velocity. The spikes in the original profile largely disappear after being corrected. While the corrected profile is noisy, there is a clear separation in the average fluid velocity before and after the inflow at 1780 m, increasing from an average fluid velocity of ~2.2 m/s to ~2.4 m/s. The corrected fluid velocity is therefore in accordance with the existence of that upper feed zone (known from temperature data), while the original was not.

FZ2 and FZ3

Between 1850 to 2350 m, there were three distinct sections in the corrected fluid velocity:

- 1850 – 1920 m section averaging at ~2.4 m/s.
- 1930 m – 2190 m averaging at ~2.1 m/s.
- 2200 m – 2340 m/s averaging at ~1.95 m/s.

This indicates the presence of small outflows at 1920 – 1930 m (FZ2) and 2190 – 2200 m (FZ3), which were not apparent in the original fluid velocity profile.

FZ5-8

There is no significant difference in the fluid velocity profiles at these depths.

4.2 WK275 fluid velocity profile

The measured and corrected fluid velocity profile at 192 t/h injection rate for WK275 are shown in Figure 10. The same colour codes as in the WK317 plot in Figure 9 are used. Grey zones in the magnified section between 1000 – 1400 m indicate that the initial interpreted feed zones are no longer valid based on the corrected fluid velocity.

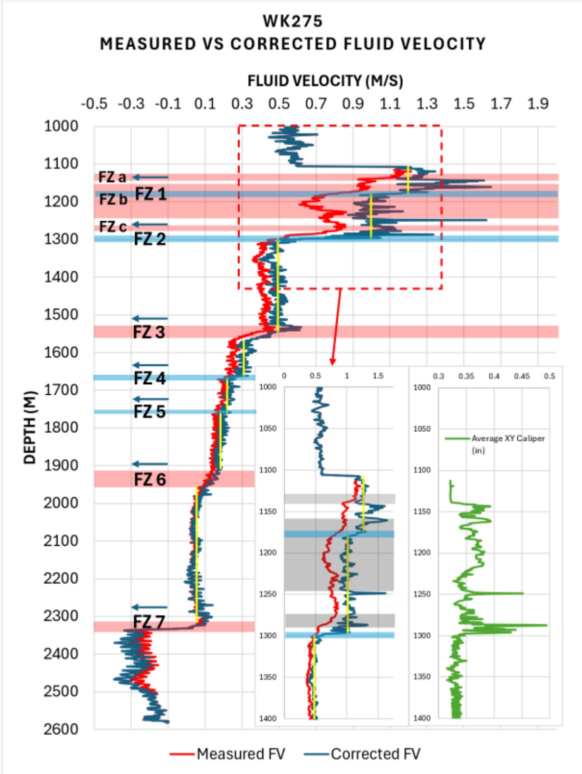

Figure 10: WK275 measured vs corrected fluid velocity at 192 t/h injection rate. The same colour codes as in Figure 9 apply.

Grey zones are interpreted feed zones based on the original PTS profile that are no longer valid after applying correction to the fluid velocity profile. The arrow pointing towards the plot indicates inflows, and arrow deviating away from the plot indicates outflows.

Sections of interest here include 1100 – 1300 m and 1550 – 1900 m.

FZ1 and FZ2

Between 1100 – 1300 m, there were initially three feed zones identified at 1130 – 1140 m (*FZ a*), 1160 – 1245 m (*FZ b*), and 1270 – 1280 m (*FZ c*). After applying the correction to the fluid velocity profile, there is a clear separation in the average fluid velocity between 1105 – 1175 m section at ~1.25 m/s and 1180 – 1300 m section at ~1 m/s. This means that instead of having three separate feed zones, with *FZ b* having a wide range of depths between 1160 – 1245 m, there are only two distinct feed zones at 1175 – 1180 m (FZ 1) and 1300 m (FZ 2). Therefore, the previously identified three feed zones are no longer valid – *FZ a* is actually not a feed (the spiky features are due to the noise in the caliper data), *FZ b* is narrowed down to FZ 1, which is more distinct at 1175 – 1180 m, and *FZ c* is corrected to be the slightly lower and more distinct FZ 2 at 1300 m. It is important to note that the top of the liner in this well is at 1100 m, hence the increase in fluid velocity is due to the change in casing diameter and not because of the presence of an inflow.

FZ4 and FZ5

Between 1550 – 1900 m, there was initially no feed zone identified. The original fluid velocity profile shows a gradual decrease across these depths, but there was no clear separation that can indicate where specifically was the fluid exiting the

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well. After being corrected, there was a better separation in the average fluid velocity between 1570 – 1670 m section at ~0.3 m/s, 1680 – 1760 m section at ~0.2 m/s, and 1780 – 1900 m at 0.15 m/s. This indicates the presence of two previously unseen small outflows at 1670 – 1680 m (FZ 4) and at 1760 – 1770 m (FZ 5).

4.3 WK274 fluid velocity profile

The measured and corrected fluid velocity profile at 192 t/h injection rate for WK274 are shown in Figure 11.

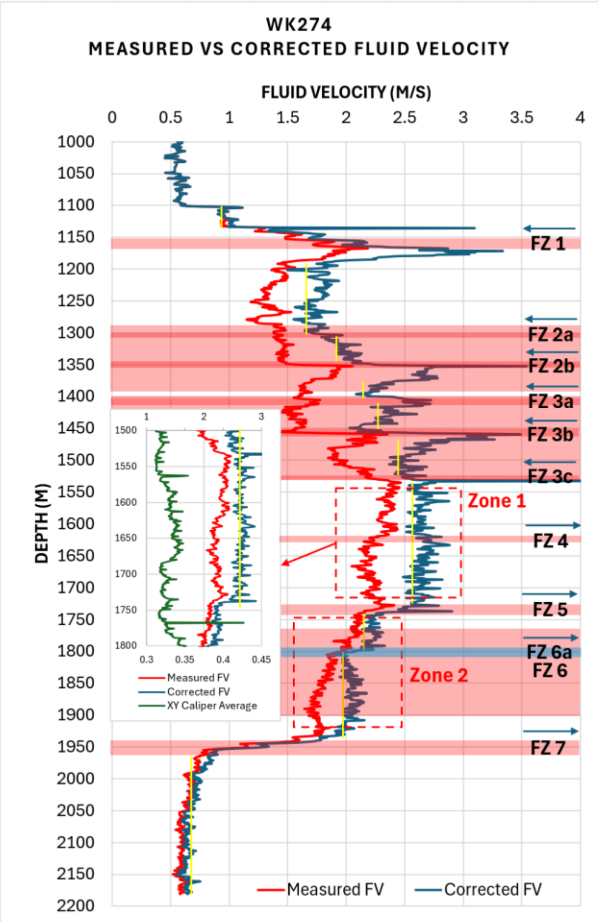

Figure 11: WK274 measured vs corrected fluid velocity at 192 t/h injection rate.The same colour codes as Figure 9 apply.

There are two sections of interest in Figure 11, between 1540 – 1720 m (Zone 1) and 1740 – 1930 m (Zone 2).

Zone 1

At 1540 – 1720 m, there was initially a clear separation in average fluid velocity between 1540 – 1600 m section and 1625 – 1720 m section in the measured profile, which could be misinterpreted as an outflow at 1600 – 1625 m without the help of PT profile. After being corrected, the average fluid velocity is relatively constant throughout the section, which does not indicate the presence of any feed. This is in line with the variation in wellbore diameter, as shown by the average of XY caliper measurements in the magnified section.

Zone 2

Between 1740 – 1930 m, the measured profile shows a gradual decrease in fluid velocity, and it was difficult to pinpoint where the fluid was exiting the well specifically. After applying the correction, there is a clear indication of where exactly the decrease in fluid velocity is located at. The average fluid velocity decreases from ~2.2 m/s at 1740 – 1800 m to ~2 m/s at 1800 – 1930 m, indicating the presence of a distinct outflow at 1800 m (FZ 6a). This was not particularly visible in the original fluid velocity profile.

5. CONCLUSION

Correcting fluid velocity profiles using caliper data is useful for revealing hidden feed zones which are masked by large variations in borehole diameter, and for refining the location of others. It can also confirm the existence and size of other feed zones. By using examples from WK317, WK275, and WK274, the following results were obtained using the correction method:

- Revealed hidden feeds when there is a large variation in wellbore diameter and therefore significant distortion of the original fluid velocity profile. This is shown as a better or clearer separation in average fluid velocity sections before and after the feed.
- Narrowed down a feed that was initially interpreted at a wide range of depths.
- Shifted the depth of a feed to a more accurate location.
- Straightened up a curvy fluid velocity profile that could be misinterpreted as permeable zones.

However, it is important to note that the correction does not necessarily make the fluid velocity profile smoother. The noise from the caliper data contributes to the noise of the original velocity profile. Therefore, when analysing the corrected fluid velocity profile, one should consider the average fluid velocity relative to different sections within the dataset (vertical lines in the profiles), rather than consider every spike as a potential feed zone. It is possible to smooth the corrected fluid velocity profile to assist with this process, however this has not been done so as not to mask the effects of the correction method, or to create confusion.

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