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GEOTHERMAL WELL LOGS: THE ROLE OF SPINNER, TEMPERATURE AND PRESSURE LOGGING DURING DRILLING IN LOCATING FEED ZONES IN WELLS

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ABSTRACT

Pressure, temperature and spinner (PTS) logging is used worldwide to study geothermal wells during drilling. Temperature and spinner logs locate outflow and inflow zones in wells and the spinner log is used to quantify the flow in and out of the feed zones and determine the relative contribution of each of the feed zones to the flow pattern in the well. The pressure logs show the pressure conditions (including the water table) in the wells and give valuable information on the permeability structure around and in the vicinity of the wells and the hydrologic connection of the wells to the geothermal reservoir.

1. INTRODUCTION

The drilling of a geothermal well or borehole presents a unique opportunity; the possibility to probe the reservoir and subsurface structure in a new location. By logging pressure, temperature and flow (with a spinner tool), simultaneously in a well, valuable information is gathered about the permeability structure of the well, the temperature conditions and the pressure potential of the reservoir.

When drilling through a reasonably permeable formation, several feed zones may be intersected. As the drilling advances, deeper feed zones become part of the well. Their influence may be seen in temperature logs and as loss of circulation. The pressure in the well changes as the well deepens and more feed zones are intersected. What often occurs when several feed zones have been intersected and the well gets deeper, is that the influence of the upper feed zones become screened by the influence of larger feed zones deeper down in the well, so they are no longer visible in temperature logs. In this case the lower feed zones may be receiving most of the injected water. Regular temperature logs during drilling are therefore essential to map the permeability structure of the well.

The first indication of permeability during drilling is usually loss of circulation of drilling fluids. The depth at which the loss of circulation occurs may not correspond to depth of the feed zone since the feed zones can become blocked by drill cuttings or may not open up to flow until later, when the drill bit is situated deeper in the well.

The best method used to locate the feed zones in a geothermal well are temperature and spinner logs. The pressure logs that are run simultaneously give essential information on the pressure conditions and help to evaluate whether the pressure at a feed zone in the well is above or below the reservoir pressure, which is what determines if fluid flows out or into the well at that location.

While pressure and temperature (PT) logs are ideally done regularly during drilling, spinner logging is usually reserved for the end of drilling for a final assessment of the well's permeability structure; the feed zone locations and their relative contribution to the flow pattern in the well.

It should be noted that in this paper the drilling of the production part of a well is assumed to be done using water not drilling mud.

2. PRESSURE, TEMPERATURE AND SPINNER LOGGING DURING DRILLING

Temperature logging during drilling is important for many reasons:

- To locate the aquifers/feed zones that need to be isolated from the well with casing.
- To locate the aquifers/feed zones that the well will be producing from.
- To locate cross flow between aquifers and estimate inflow (if the inflow temperature is known).
- To estimate the participation of the various feed zones in the flow for different injection rates.
- To assess the permeability of each of the feed zones.

The injection of water or brine during drilling changes the pressure conditions in the well. Pressure logging during drilling provides an opportunity:

- To evaluate the pressure conditions, locate water table and air/gas plugs in the water column.
- To evaluate zones of over-pressure and assess blow-out risk.
- To assess the permeability in the well and determine the Injectivity Index (II).
- To assess the success of permeability stimulation efforts.

Spinner logs are usually performed when the drilling of the well is completed. The spinner runs are used to calculate fluid velocity along the well using cross plot analysis (Grant and Bixley, 1995). This analysis is further discussed in the next section.

To be able to use cross plot analysis the flow has to be logged four times with the spinner tool at each injection rate, e.g. two times down the well and two times up the well. If a measurement of the well diameter exists, the volumetric (or mass) flow can be calculated. The spinner, pressure and temperature logs give an overall assessment of the permeability of the well and give complementary information on the feed zones in the well.

For a more detailed discussion on temperature and pressure logging in wells see (Steingrímsson, 2013).

3. SPINNER LOGGING AND PROCESSING

3.1 Spinner logging

Spinner logs may be performed as a part of the step rate injection test at the end of drilling. It is best to log the spinner at medium and high injection rates. In practice this can be done by running the first series of spinner logs just before the first step of the step rate test and another series of logs at the end of the step which has the highest injection rate.

At each injection rate the tool is run up and down the well at different logging speeds, preferable four times in total. The tool speed during each run must be stable and so does the rate of injection (l/s).

3.2 Processing spinner logs

The processing of the spinner data takes place in steps.

- The first step involves a quality check of the log data and the injection history.
- If the well diameter has been measured (e.g. with a caliper log) width effects in the data can be assessed and corrected for.
- Next step includes depth correction of the data and noise and outliers are filtered out of the data.
- The fluid velocity log is then calculated.
- If a well diameter log is available (e.g. a caliper log), mass or fluid flow rate down the well may be calculated. This permits the verification of the injection rate.

These steps are further described in the following subsections.

3.3 Verification of data integrity

The spinner data is plotted against depth, see Figure 1. The logging speed is fast relative to logging speeds for other types of logs, i.e. pressure and temperature logs. Each log in a spinner log series is logged at a different logging speed than the others and the logging speed is kept as close to constant as possible during each run.

The spinner data itself is measured in rounds per minute of the impeller in the logging tool. This data is quite noisy and can contain outliers which are dealt with later in the data processing chain.

3.4 Width effects in the data

The well diameter directly affects the speed at which the fluid flows inside the well and therefore the spinner impeller rate. Fluid flow is slowed down where the well widens and inversely speeds up where the well is narrower. Therefore, the well completion needs to be considered, when evaluating the flow differences in the logs.

To correlate variations in the spinner log to changes in the width of the well, the caliper logs are plotted alongside the spinner log, see Figure 1. Changes in the diameter of the well are compared to information on location of feed zones from temperature logs, lithology or circulation losses, in order to eliminate purely geometrical effects and to isolate effects of increased or reduced flow in the well.

3.5 Depth correction

The logs are depth corrected, shifting the data up or down using the top of the liner as a reference point. As the spinner tool passes the top of the liner the well suddenly gets narrower resulting in a sharp change in flow velocity. This sharp change in velocity can be seen at around 780 m depth in both images in Figure 1. If this sharp change cannot be seen in the spinner logs, perhaps because the fluid flow is slow or the spinner logging speed is low, the data is not depth corrected.

3.6 Noise and outlier filtering

The spinner data is both noisy and tends to contain outliers. Outliers can occur e.g. when the impeller is blocked by rock chips, when there is an electrical issue in the tool or if there is a connection problem between the tool and the registration unit on the surface. To rid the data of outliers and noise a box filter and a gaussian filter are applied to the data, see Figure 2.

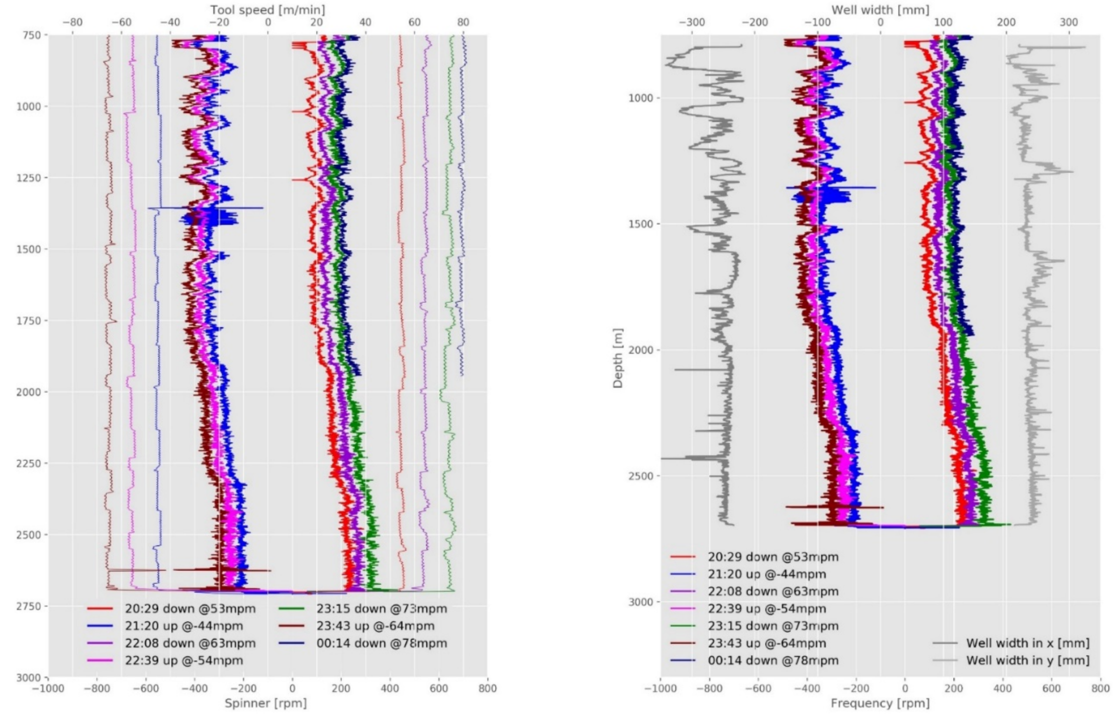


FIGURE 1: Image on the left: An example of raw spinner frequency data in rounds per minute (rpm) and the tool speed in meters per minute (denoted mpm). The log on the edges of the plot represents the logging speed, which is relatively constant for each run. The more central data in the plot is the spinner rotation log. Image on the right: An example of spinner log plotted alongside the XY-caliper log which is shown in gray. The XY-caliper log shows a measurement of the well's diameter on two perpendicular axes.

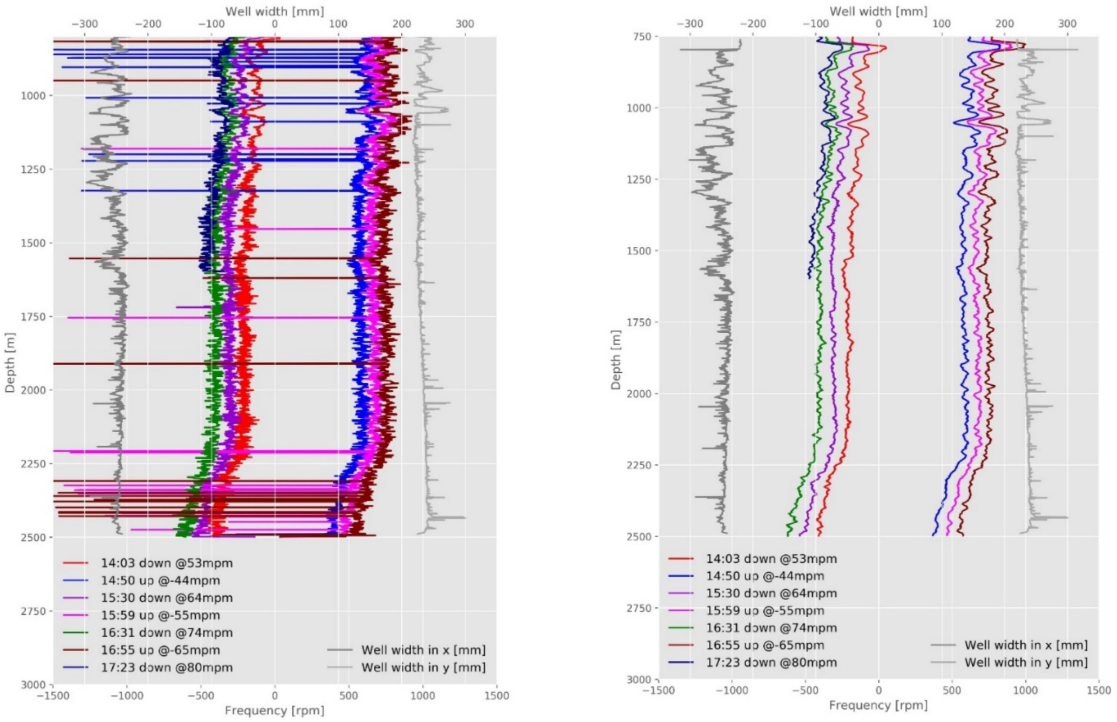


FIGURE 2: Image on the left: An example of noisy spinner logs with outliers (coloured central data). Image on the right: An example of filtered spinner log plotted next to caliper log (in gray) for the visual evaluation of the effects of the well's width on the spinner impeller rate.

3.7 Calculating the fluid velocity in a well using cross plots

The fluid velocity in the production part of the well is calculated using cross plots such as the one in Figure 3. Cross plots are generated at 1-meter intervals from production casing depth all the way down to the bottom of the well. Each plot contains data from a 4-meter long depth interval of the well, 2 meters above and 2 meters below the depth reference. The spinner data from the selected interval is plotted, with the logging speed (meters per minute, mpm) on the y-axis and the impeller rotations (in rounds per minute, rpm) on the x-axis.

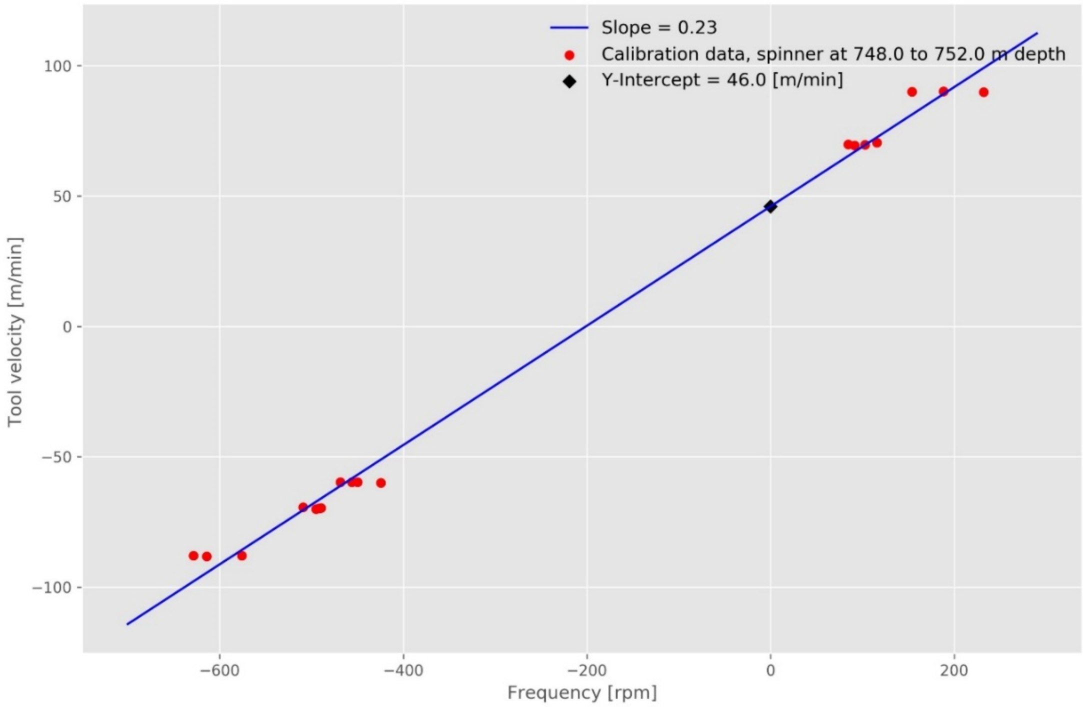


FIGURE 3: An example of a cross plot at 750 m depth. The tool velocity (in meters per minute, denoted mpm) is plotted against the impeller's frequency (in rounds per minute, denoted rpm). The datapoints (in red) in the plot are taken from a 4 m depth interval. The y-intercept (rpm=0) corresponds to the fluid velocity at this depth.

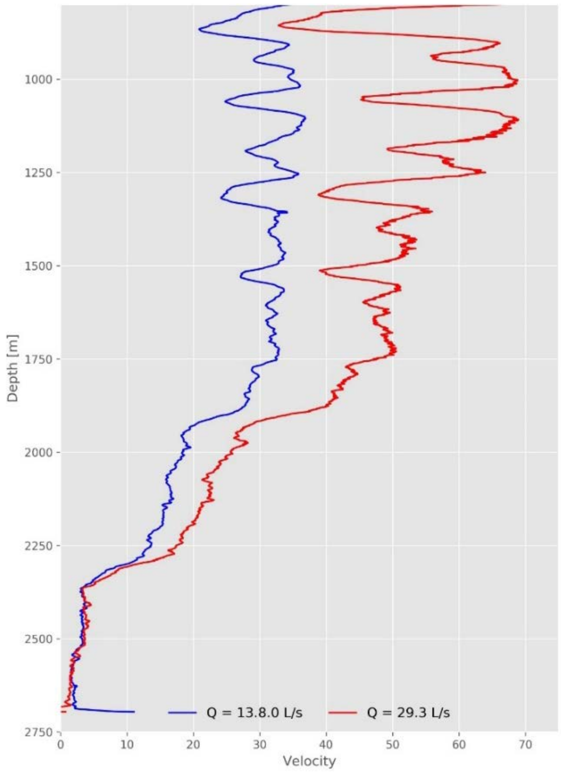
A linear regression is used to fit a line through the data points. The y-intercept of the regression line gives an estimate of the fluid velocity at the corresponding depth in the well. The idea is that where the frequency of the impeller is zero the tool is travelling at the same speed as the fluid in the well. (Grant and Bixley, 1995). These fluid velocities are then plotted against depth as a fluid velocity log, for each injection flow rate applied during the spinner logging, see Figure 4.

3.8 Calculating mass velocity

To obtain the volumetric flow rate in the well the fluid velocity is multiplied by the well´s cross-sectional area. Where the well´s diameter has been logged, using e.g. XY-caliper log, this can serve as data for estimating the cross-sectional diameter down the well. To obtain the mass flow rate in the well the volumetric flow rate must be multiplied by the density of the fluid at the relevant temperature.

3.9 Verification of injection rate

By looking at the spinner logs within the production casing of the well where the cross-sectional area is accurately determined, the fluid velocity and mass flow rate can be accurately determined too. This should match the injection rate and thus serves as a verification of the injection rate during the spinner logging.



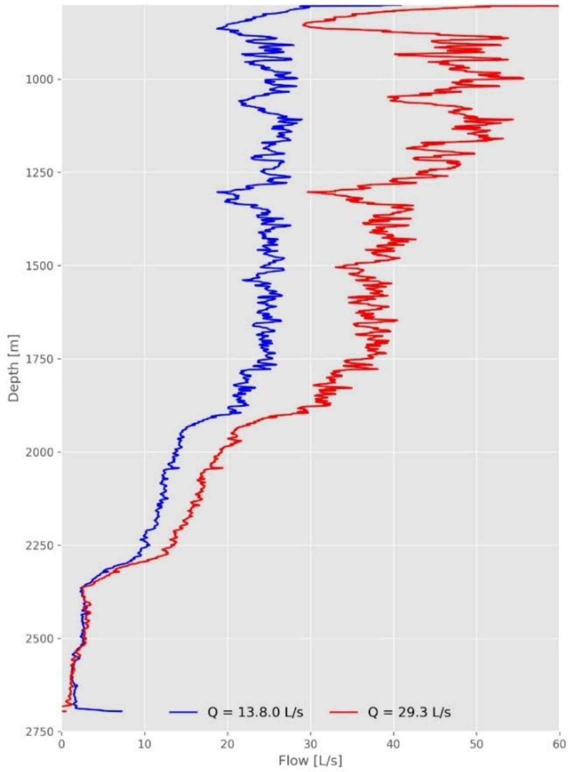


FIGURE 4: An example of fluid velocity log (image on the left) and volumetric flow log (image on the right) for two different injection rates, 13.8 and 29.3 l/s.

4. LOCATING FEED ZONES FROM SPINNER LOGS AND TEMPERATURE LOGS

4.1 Locating feed zones from spinner logs

Active feed zones are recognized by the change in fluid velocity at a certain depth, when effects due to varying diameter have been excluded. It is therefore best to use fluid velocity and/or mass flow logs to locate the feed zones in a well. Furthermore, it is beneficial to compare fluid velocities at two different injection rates, such as seen in Figure 4. The two different injection rates create different pressure conditions in the well. A feed zone located where there is little pressure difference between the well and the reservoir will not contribute to flow in the well and therefore will not be seen in velocity or mass flow logs. When the injection flow rate is changed, different pressure conditions are created in the well which may cause some feed zones to start to contribute to flow into or out of the well making them visible in fluid velocity logs. This can be seen in Figure 5, showing a pair of fluid velocity logs at two different injection rates, where the feed zones are indicated by black arrows.

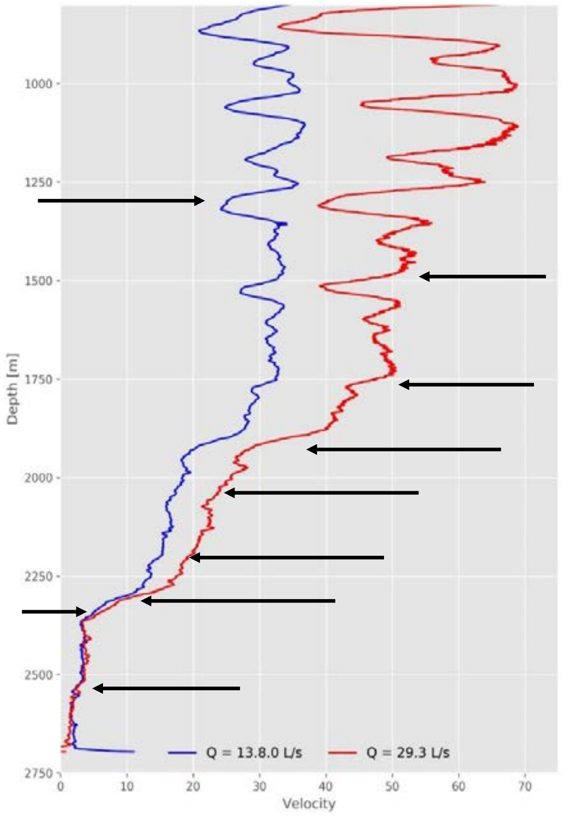


FIGURE 5: Locating feed zones in fluid velocity logs entails looking for changes in flow velocity. Here the likely feed zones have been highlighted with black arrows.

4.2 Locating feed zones from temperature logs

When temperature is logged regularly during the course of drilling of a geothermal well valuable insight into the permeability structure of the well can be gained. As the well becomes deeper, more and more feed zones are intersected by the well. As a new feed zone appears at the bottom of the well it´s influence can be seen in temperature logs but later when larger feed zones have been intersected deeper down, the feed zones higher up are not clearly seen in the temperature logs. Also, the pressure in the well where a feed zone is located may change and become similar to the reservoir pressure, under such conditions there is no flow in or out of that feed zone and feed zone will neither be seen in temperature nor spinner logs. Figure 6 shows temperature logs taken during drilling in the same well as depicted in the previous figures. Here the feed zones are detected as changes in the slopes of the temperature logs and indicated by black arrows as in Figure 5. The feed zone seen at 1300 m in the spinner logs is not seen in the temperature logs in Figure 6, most likely due to it being screened by flow.

5.3 Joint interpretation of temperature and spinner logs

Plotting the spinner and temperature data jointly can provide additional insights and certainty into feed zone locations and their estimated permeability. This is done in Figure 7 for the logs shown in Figures 5 and 6.

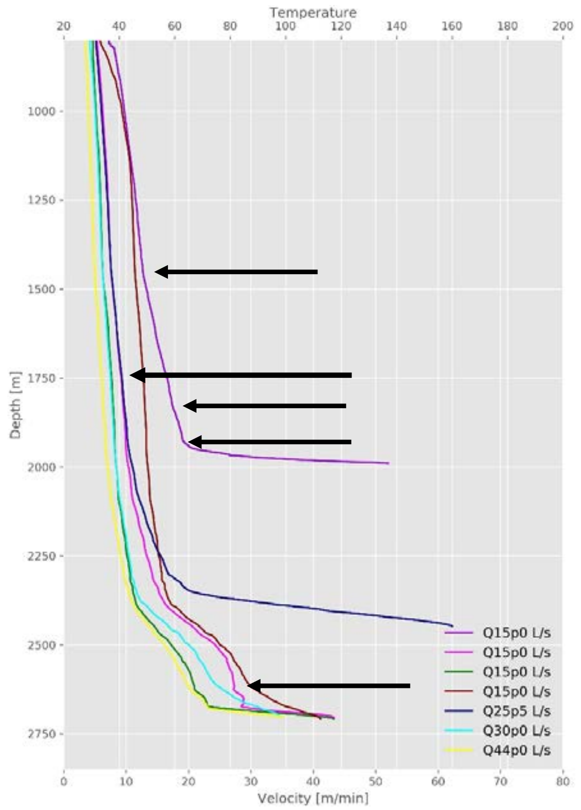


FIGURE 6: Locating feed zones in temperature logs entails looking for changes in the gradients of the temperature logs. Here the feed zones have been highlighted with black arrows.

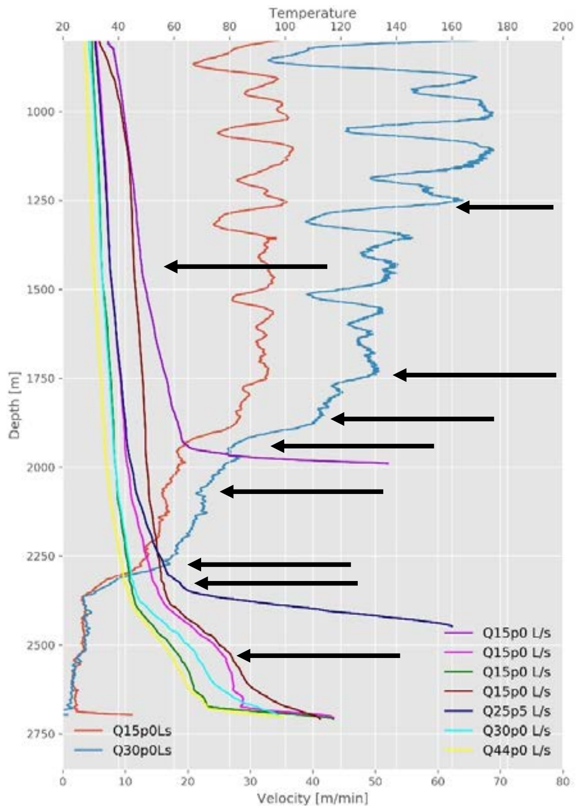


FIGURE 7: Feed zones may be located with greater certainty using logs of temperature and fluid velocity together. Here the feed zones have been highlighted with black arrows.

5.4 Creating a table of feed zones

It is best practice to summarize the interpretation of the spinner and temperature logs from a well in a table of feed zones for that well. The table should note the depths where likely feed zones were detected, an estimate of the relative size of the feed zone and what logs the feed zone was seen in. It is useful to note any drilling parameters that may have changed at the depth of the feed zone (e.g. loss of circulation, ROP) and any changes in the lithological logs that might explain the permeability of the well at that depth. The table of feed zones should summarize what is known about the permeability structure of the well and serve as a reference for further study of the reservoir and its permeability. The table of feed zones may be prepared at the end of drilling but should be updated as more relevant information becomes available, e.g. during warm-up after drilling, during flow testing of the well or later in the lifetime of the well.

REFERENCES

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Steingrímsson, B. 2013: Geothermal well logging: Temperature and pressure logs. *Papers presented at "Short Course V on Conceptual Modelling of Geothermal Systems" organized by UNU-GTP and LaGeo*, Santa Tecla, El Salvador, 16 pp.