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Landsvirkjun

Þeistareykir – Well ÞG-15

Pressure, Temperature and Flow Measurements with Spinner during Discharge

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Pressure, Temperature and Flow Measurements with Spinner during Discharge

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Title:	Þeistareykir – Well ÞG-15. Pressure, Temperature and Flow Measurements with Spinner during Discharge
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Abstract:

Well ÞG-15 is a directionally drilled production well for the Þeistareykir power plant. The well discharged from October 26th 2017 and was logged with a pressure, temperature and spinner tool on January 16th 2018. These logs allow for hot inflow into the well to be located and to a certain extent quantified. Hot liquid flows (200–250°C) into the well at 1410–1440, 1670–1680 and 1770–1830 m depth and this inflow accounts for approximately three quarters of the total inflow. Below this at 1970–2020, 2050 and 2080 m cooler liquid (<200°C) enters the well accounting for about a quarter of the total inflow into the well.

Key words:

Þeistareykir, well ÞG-15, geothermal area, high temperature, pressure, temperature, feed zones, flow, spinner, Landsvirkjun, ÍSOR

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Ágrip

Hola ÞG-15 er stefnuboruð vinnsluhola fyrir Þeistareykjavirkjun. Í skýrslunni er fjallað um mælingar sem gerðar voru í holunni eftir að hún hafði verið í blæstri í tæpa þrjá mánuði. Hiti, þrýstingur og rennsli var mælt í holunni samtímis. Rennslismælingarnar voru gerðar með spinner og gefa upplýsingar um hvar flæðir inn í holuna og í hvaða hlutfallslega magni. Hitamælingarnar gefa upplýsingar um það hvort vökvinn sem flæðir inn í holuna sé í heitara eða kaldara lagi. Í holu ÞG-15 flæðir 200–250°C heitur vökvi inn í holuna á þremur svæðum; á 1410–1440 m dýpi, 1670–1680 m dýpi og 1770–1830 m dýpi. Í heildina er áætlað að þessi heiti vökvi sé um ¾ hlutar af heildarinnflæði í holuna. Neðar í holunni streymir kaldara (<200°C) vatn inn, þ.e. á 1970–2020, 2050 og 2080 m dýpi og er áætlað út frá spinner-mælingunum að þetta kalda innflæði samsvari um fjórðungi heildarinnflæðis í holuna.

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Figures

1 Introduction

Well ÞG-15 was drilled in the Þeistareykir geothermal field by Iceland Drilling (Jarðboranir) for Landsvirkjun in early 2017. Figure 1 shows the well path of ÞG-15 and the wells in the vicinity.

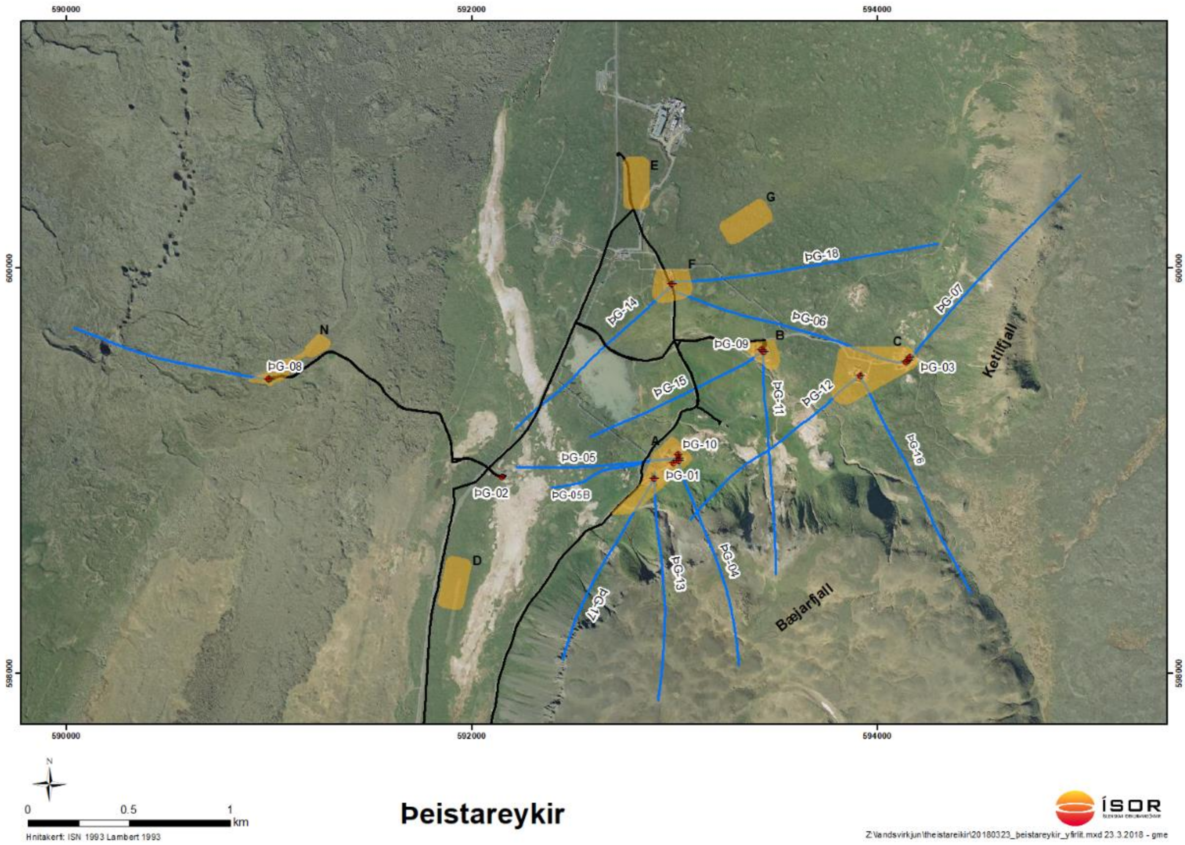

Figure 1. *The planned path (red line) and the final well path (blue line) of ÞG-15. The blue dot on the well trajectory shows the end of angle build up (EOB) at 845 m, the red dot is at 1700 m (MD) and the black dot shows the 2000 m (MD). Locations and trajectories of wells in the vicinity are also shown as blue lines.*

2 Temperature and pressure measurements

The logging took place on January 16th, 2018. The tool used was a PTS logging tool from PPS. Temperature, pressure and flow are measured simultaneously by the tool´s sensors and the impeller. The temperature and pressure logs are seen in Figures 2 and 3 respectively, where they are compared with earlier logs taken during warm-up in the well after drilling. The tool was lowered to about 300 m depth but resonance in the wellhead equipment was a concern and the well opening was narrowed (throttled) to stop the resonance, seen as a break in the light green line in Figures 2 and 3. The tool was lowered through boiling two phase fluid upflow before reaching the boiling surface at ~530 m depth where a clear break is seen in the temperature log and where the pressure log become hydrostatic as the upflow becomes single phase liquid. Below the boiling surface, the water column has a positive temperature gradient indicating that the water rising up the well is heated due to conduction through the casing as the formation outside the casing is hotter than the upflow . Inflow is seen at ~1450, 1685, 1780 and 1797 m depth. Further down in the well cooler (<200°C) inflow is observed at 1990, 2012 and 2080 m depth.

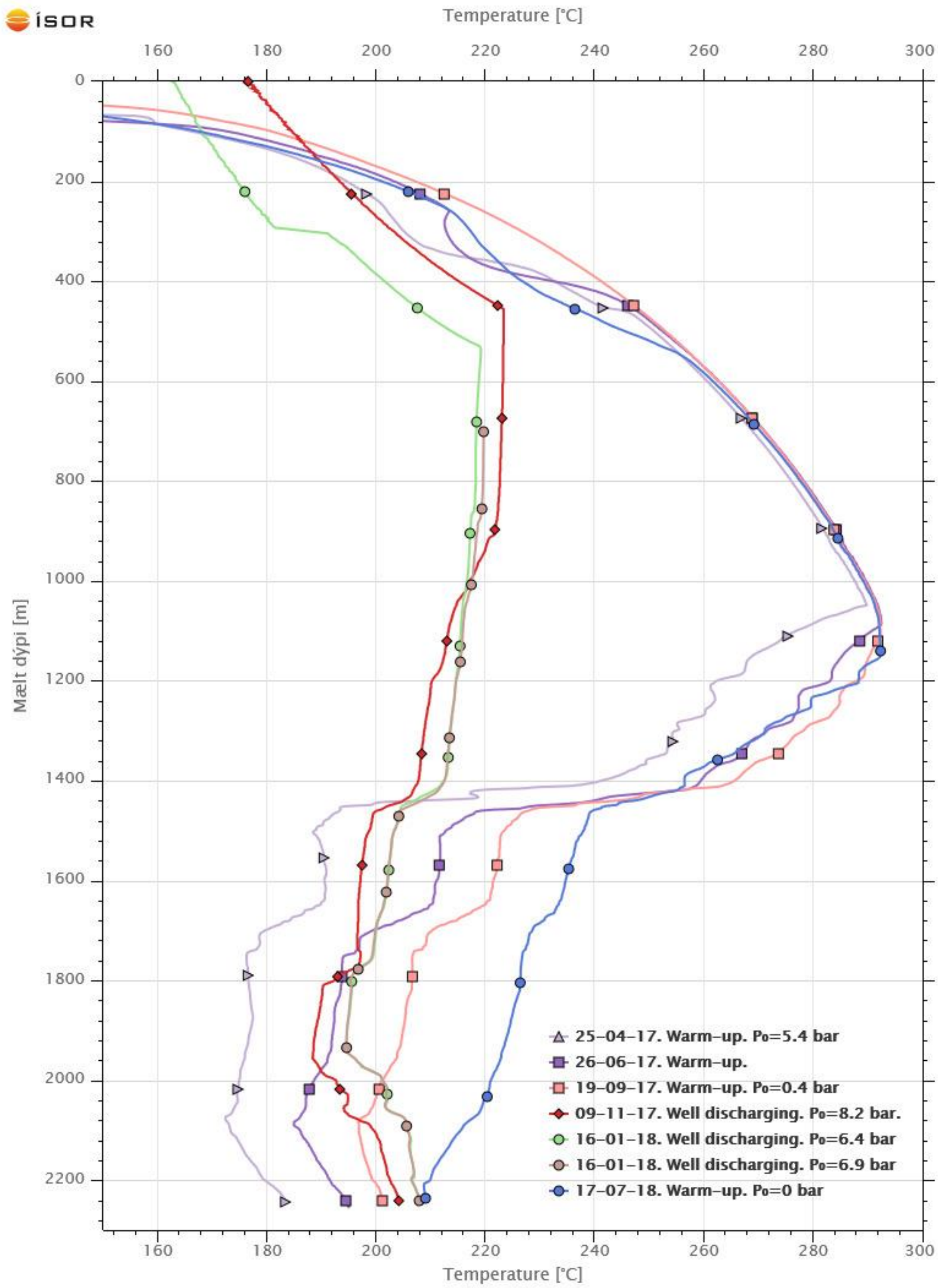

Figure 2. *The temperature logs on January 16th 2018 during discharge compared with the measurements during warm-up in the well. The dynamic logs are ordered by logging time and are seen to approximately overlap all the way down to the bottom.*

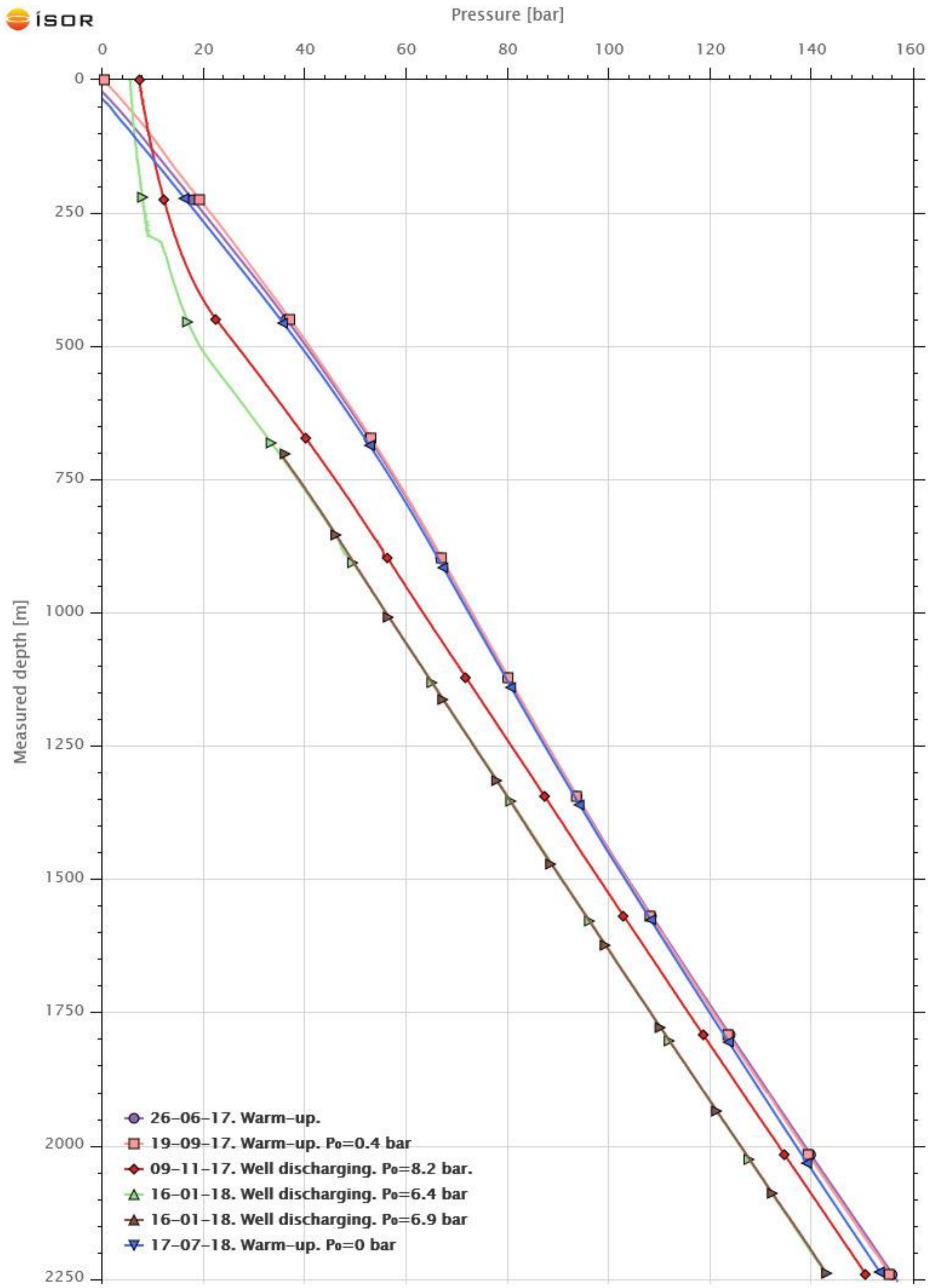

Figure 3. *The pressure logs on January 16th 2018 during discharge compared with the logs during warm-up in the well after drilling. The dynamic logs are ordered by logging time and are seen to approximately overlap all the way down to the bottom.*

3 Flow measurements with a spinner tool

3.1 Spinner log implementation and raw data

Flow rate measurements with a spinner tool were carried out in well ÞG-15 while the well was discharging on January the 16th, 2018. A spinner log involves lowering the logging tool down the hole and pulling it back up the hole at constant speed while the flow rate in the well is maintained constant by keeping the wellhead opening constant. The logging plan is seen in Table 1.

The well discharged into a large separator. The water from the separator discharged into an open pool without an apparatus to measure the flow rate. The outer conditions of the measurement were difficult. The setup of the lubricator and other logging equipment was difficult due to snow conditions and objects around the wellhead needing to be moved around. By the time the logging started, it was dark and the weather had gotten quite windy.

As the tool was lowered into the discharging well the measure of the tool´s weight pulsated which is unusual. This was likely due to outside conditions (the weather getting worse causing the wireline pulley to shake) or to the discharging from the well matching the resonance frequency of the lubricator pipe placed on the well head, which caused the pipe to shake. The resonance pulsations of the wellhead equipment caused the logging engineers to worry about the tool being lost in the well. After conferring with the clients representative and ÍSOR´s director of geothermal energy the decision was made to stop the resonance by throttling the discharge. The discharge was reduced in a stepwise manner by reducing the wells opening until the resonance stopped. The wellhead pressure was 5.4 bar at the start of the logging but after the flow was restricted the wellhead pressure increased to 6.4 bar. This change can be observed in the pressure and temperature data at 300 m depth in Figures 2 and 3. The valve controlling the opening of the well was not setup with a system to quantify how open or closed the well was.

Table 1. *The plan for the PTS logging in ÞG-15 on January 16th 2018. A negative tool speed indicates the tool being pulled out of the well.*

Start depth [MD] [m]	End depth [MD] [m]	Purpose	Tool Speed [m/min]
0	**2260**	Temp/Press	35
2260	**900**	Spinner	-45
900	**2260**	Spinner	60
2260	**900**	Spinner	-60
900	**2260**	Spinner	80
Throttle main valve to reduce flow by ~50%			
Wait 30 min for flow to stabilise.			
2260	**700**	PTS	-35
700	**800**	Spinner Calibration	40
800	**700**	Spinner Calibration	-40
700	**800**	Spinner Calibration	60
800	**700**	Spinner Calibration	-60
700	**800**	Spinner Calibration	80
800	**700**	Spinner Calibration	-80
700	**0**	Temp/Press	-35

Table 2. *An overview of the PTS logging in well ÞG-15 during discharge on January 16th 2018.*

Trip [m]	Purpose	Tool Speed [m/min]	Tool direction	P0 [bar]	Pc [bar]
-5-2244	Measurement	35	Down	5.4/6.4	
2244-915	Measurement	-40	Up	6.6	1.2
915-2240	Measurement	60	Down	6.8	1.3
2240-915	Measurement	-60	Up	6.8	1.25
915-2240	Measurement	50	Down		
2240-700	Measurement	-50	Up	6.9	1.3
720-780	Calibration	+/- 50, +/- 60, +/- 40	Up/Down		
800-0	Transfer	35	Up	7.0	1.3

Table 2 describes the contingency plan, the logging that was done when it became impossible to follow the plan in Table 1. It contains the details of the spinner runs including the tool speed and the purpose of each run of the tool.

Figure 4 shows the spinner logs on January 16th, 2018 through the depth interval from 900 to 2260 m. The rotation of the impeller is given in rounds per minute (rpm) and the speed of the logging tool is in meters per minute (mpm). The well was logged at three different speeds, all displayed as positive values on the right hand side of the impeller rotation data.

The spinner data left hand side of the graph (negative values) is measured with the tool moving upwards in the well while the data on the right (positive values) is measured downwards. The tool speed directly affects the impeller rotation. This image testifies to the fact that the measurement was taken at a constant speed and therefore there are no noteworthy effects on the data cause by variations in tool speed.

The well inner 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 speeds up where it narrows again. Thus, the well completion is important. Well ÞG-15 has a 9⅝" production casing to 917.1 m depth and a 7" liner starting at 895.3 m reaching down to the bottom of the well at 2260 m depth. The liner is perforated all the way down to the bottom.

To correlate the noise in the spinner data to the diameter variations in the well the caliper logs are plotted alongside the spinner data when the latter are being evaluated (Figure 5). Purely geometrical effects dominate variations in spinner data from the end of the production casing at 917 m and down to ~1450 m depth, while below that the noise is much less and variations better reflect increased or decreased flow. Between 1450 and 1800 m depth the shape of well is quite regular while still oval in shape as seen in the larger y-component of the width compared to the x-component. From ~1800 m down to the bottom the well is generally circular and regular in shape and therefore the variations in impeller frequency data can be entirely attributed to differences in flow velocity.

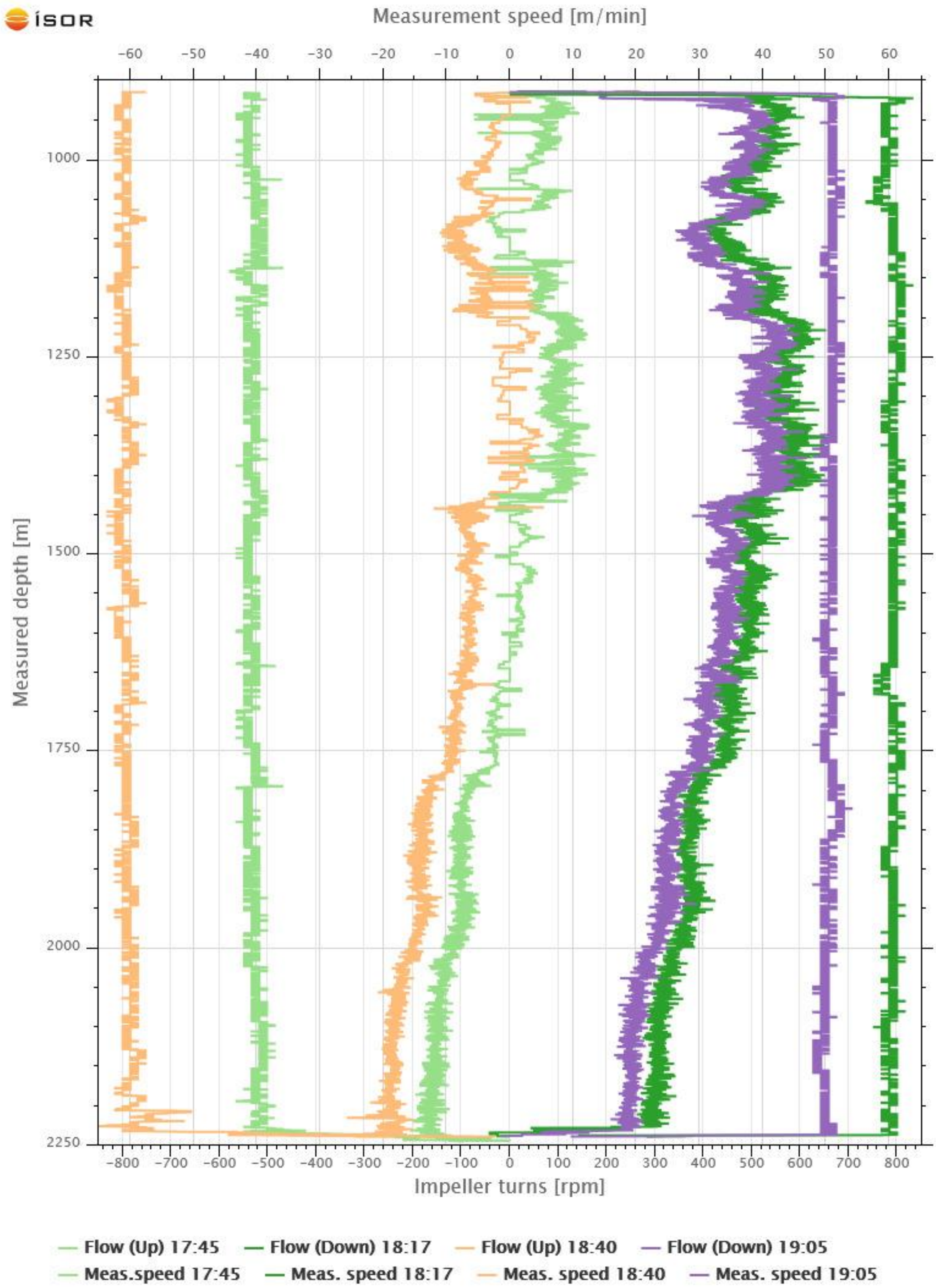

Figure 4. *Well ÞG-15. Raw spinner frequency data (in rounds per minute) and the tool speed (in meters per minute) logged on January 16th 2018, while the well was discharging. The figure shows four spinner logs, logged at different speeds from 900 to 2250 m depth. The spinner frequency is shown in the central part of the plot while the corresponding tool speeds are placed on the outer edges of the plot. The corresponding logs and tool speeds are colour coded.*

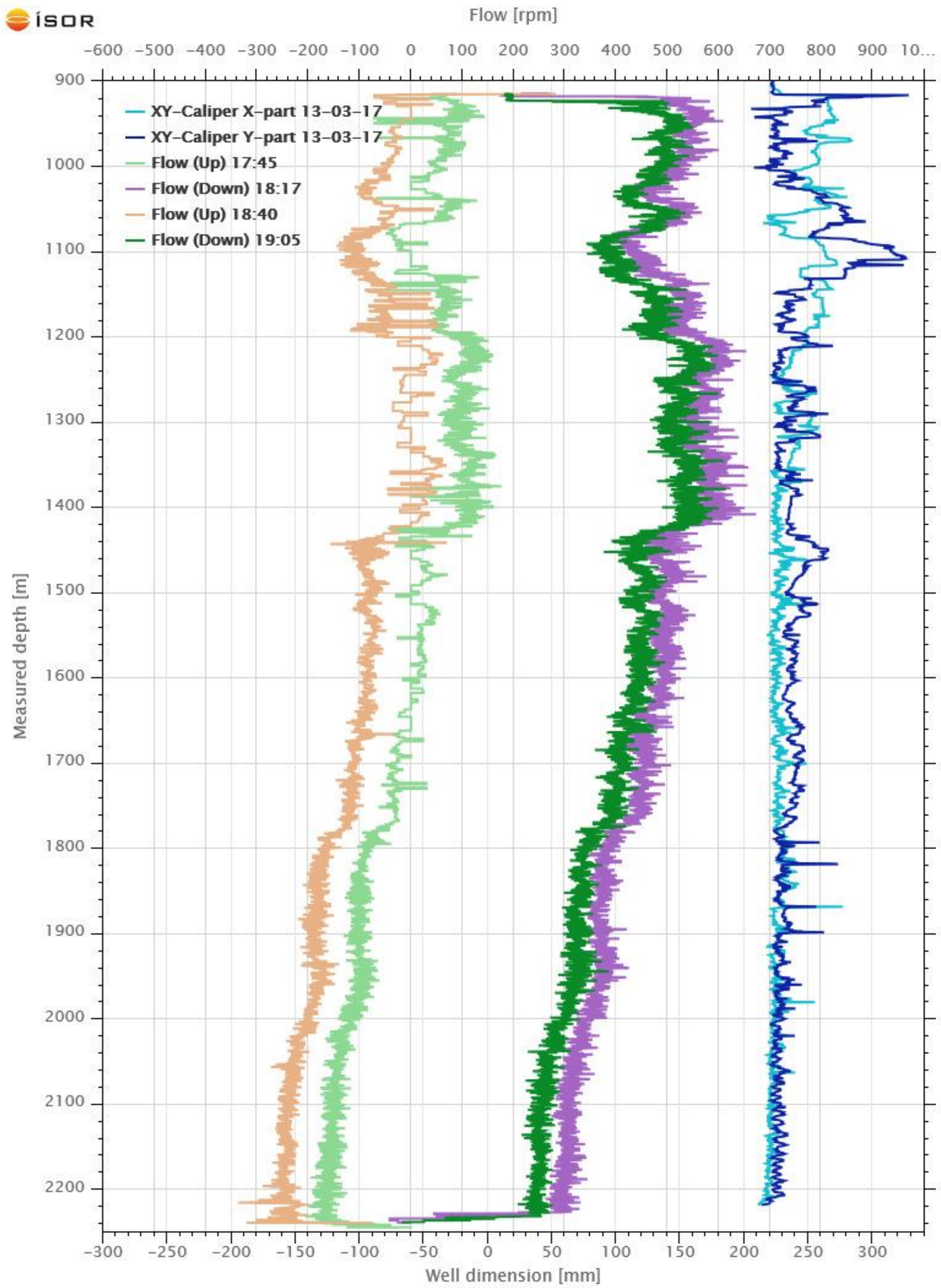

Figure 5. *Well ÞG-15. Raw spinner frequency data in rounds per minute logged during discharge on January 16th. On the right hand side of the figure the caliper log of the well, measured in mm on two axes (X and Y), is shown in light and dark blue.*

3.2 Calibrating spinner data to obtain fluid velocity and flow rate

The raw spinner data includes effects attributed to the mechanics and design of the spinner tool, the fluid viscocity in the well and to the width of the well. To obtain the fluid velocity (m/min) and flow (L/s and kg/s) the data needs to be calibrated to remove these effects from the data.

The calibration is done using cross plots, see Figure 6. This method entails creating a cross plot of data over a narrow depth interval in the well. A linear regression is used to fit a line through the data points. The intercept of the regression line, or where the frequency of the impeller is zero, gives an estimate of the fluid velocity at the corresponding depth in the well. (Grant and Bixley, 2011). At this point, the tool is assumed to be travelling at the same speed as the fluid. The velocity of the tool is related to that of the fluid according to:

$$v_{\text{fluid}} = v_{tool} - C * f_{rpm}$$

Where v_{fluid} and v_{tool} represent the fluid and tool velocities, C is the slope from the cross plot and f_{rpm} is the spinner frequency in rpm. (Grant and Bixley, 2011).

The slope of the regression line can be used to calculate the fluid velocity of each spinner log but the y-intercept of the regression line is assumed a more accurate representation of the fluid velocity at each depth interval and therefore this is used to obtain the fluid velocity during discharge in well ÞG-15.

To obtain the flow rate in the well the fluid velocity is multiplied by the well cross sectional area. The cross sectional area is assumed to be elliptical and is calculated as the product of the caliper XY measurements and π.

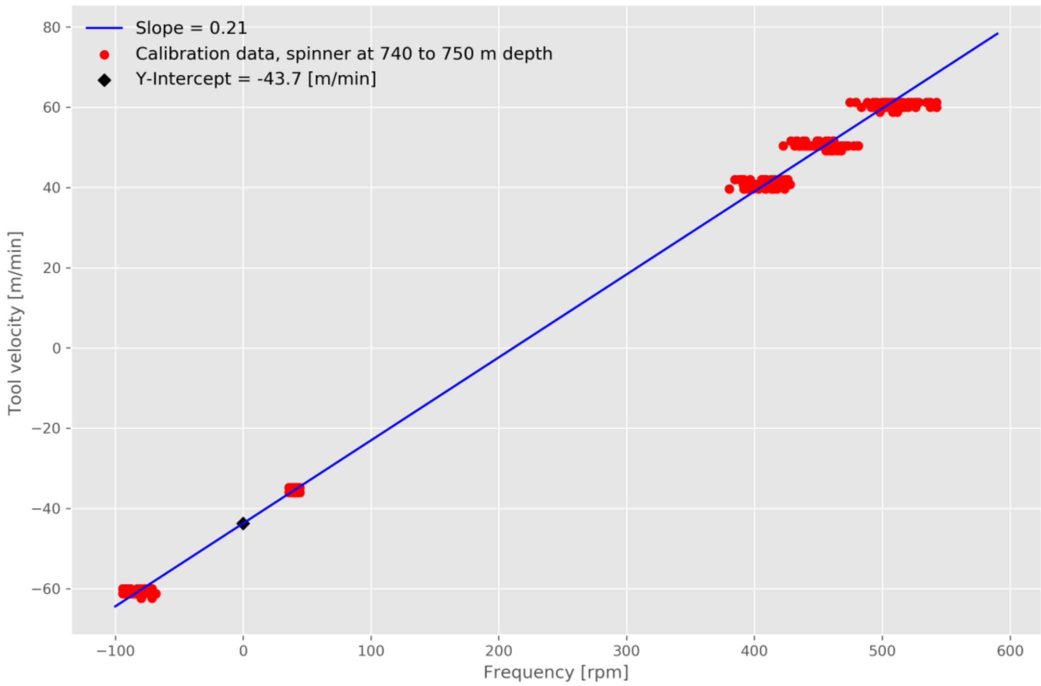

Figure 6. *An example of the cross plots used to calculate velocity in the well. The data on the plot is from logs taken during discharge over the depth interval 740–750 m. The plot shows the tool velocity plotted in meters per minute (denoted m/min) against the impeller's frequency in rounds per minute (denoted rpm) (red points). The blue line is a linear regression on the dataset. The y-intercept of the regression line represents the fluid velocity at this depth in the casing.*

3.3 Fluid velocity and flow rate

Cross plots such as the one in Figure 6 were used to obtain the velocity at 10 m depth intervals all the way down the well. The result is plotted in Figure 7.

Figure 8 shows the flowrate (in kg/s) up the well. The flow (in L/s) is calculated by multiplying the fluid velocity by the well cross sectional area (obtained from the Caliper-XY logs) and then converted into kg/s by multiplications with the density of the water from steam tables for the liquid temperature. The calculations are done at 10 m depth intervals down the well. The flow in kg/s is likely slightly overestimated, a rough estimate of the flow in the top section of the well would suggest a mass flow of around 35 kg/s. Measurements of flow from the well suggest that at wellhead pressure ~7 bar that the mass flow lies between 25 and 29 kg/s.

Changes in velocity or flow indicate zones of inflow or feed zones, see arrows and brackets in Figure 8. These changes in velocity and flow are situated at 1410–1440, 1670–1680, 1770–1830, 1970–2020, 2050 and 2080 m depth.

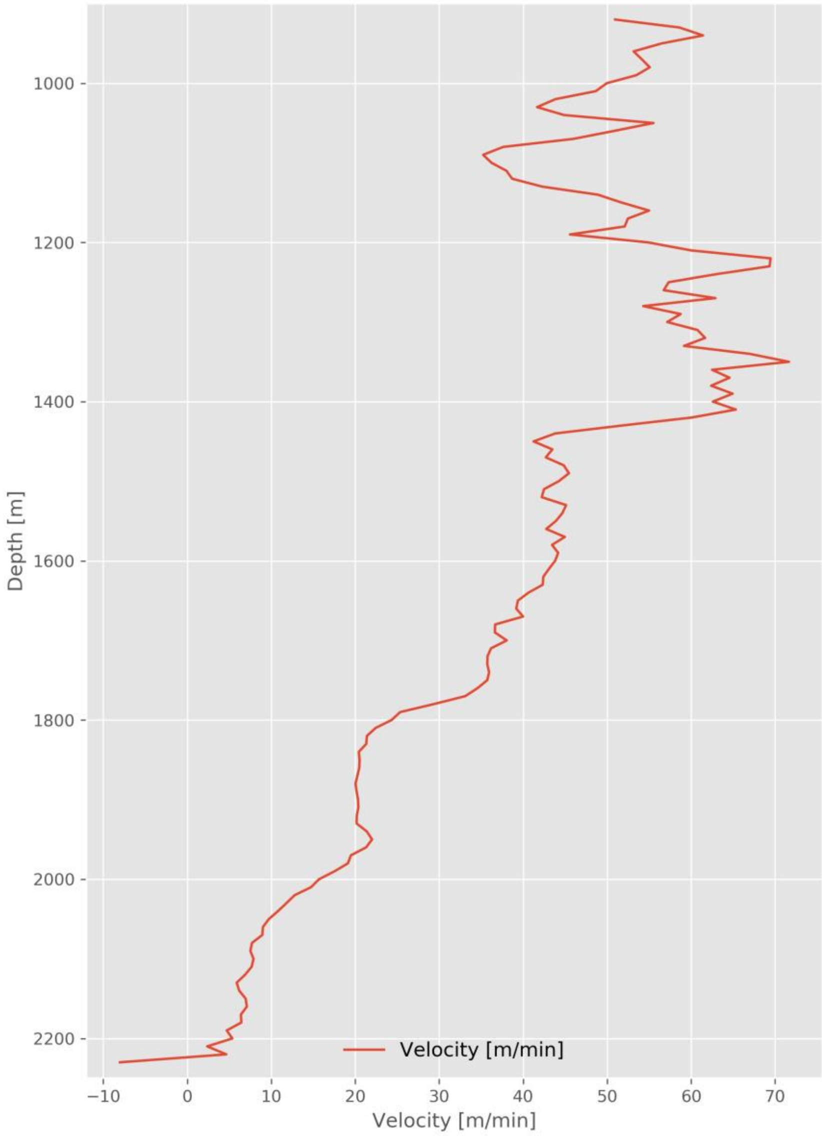

Figure 7. *The fluid velocity in m/min obtained from the intercepts of cross plots of data at 10 m intervals down the well, measured during discharge.*

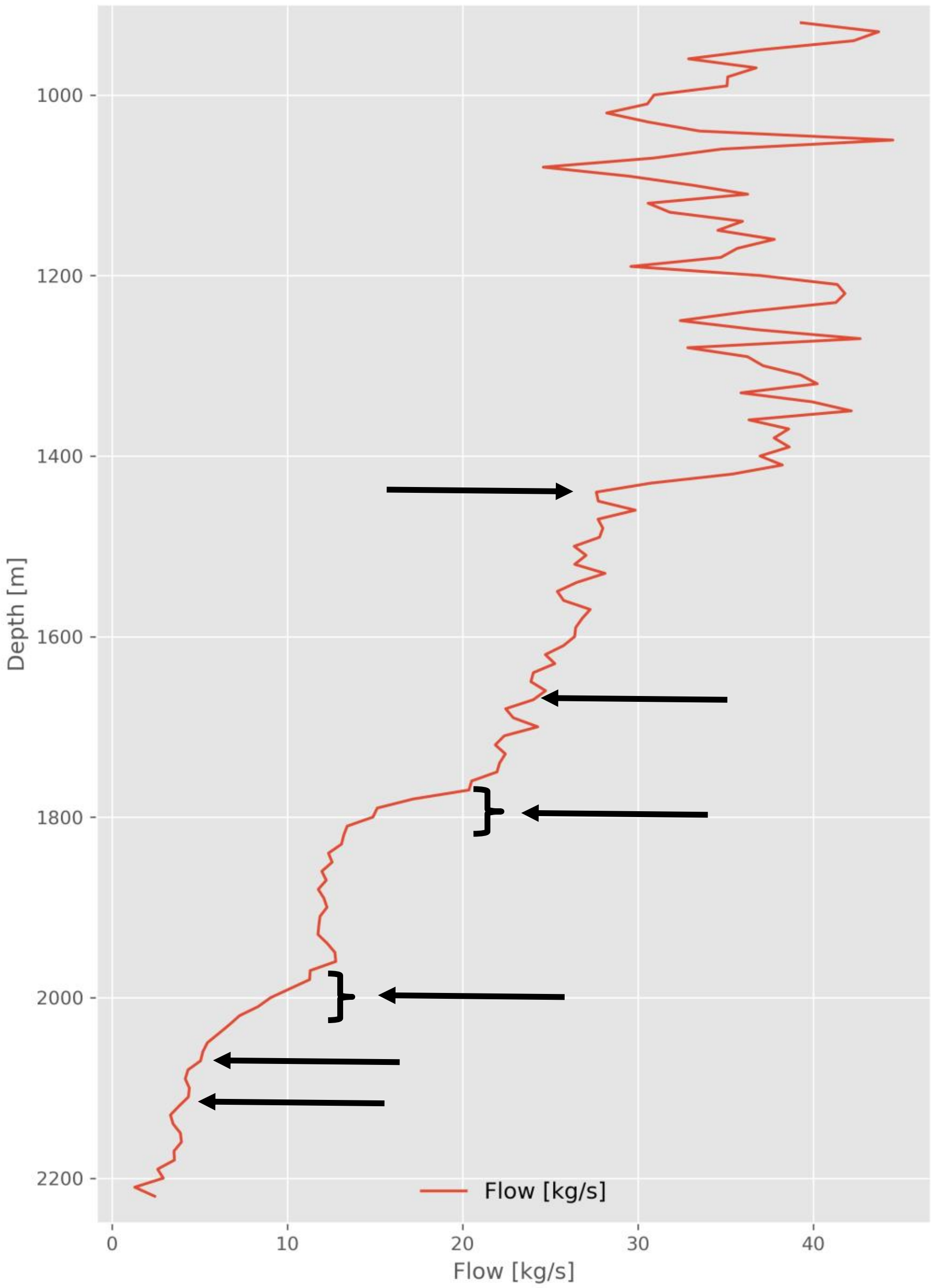

Figure 8. *The flow in ÞG-15 during discharge in kg/s. The discharge spinner data indicates inflow at 1410–1440, 1670–1680, 1770–1830, 1970–2020, 2050 and 2080 m depth.*

3.4 A comparison of spinner and temperature logs

Figure 9 shows a comparison of spinner logs during discharge and temperature logs taken discharge and during warm up. The spinner data shows zones of inflow that correspond well with steps in the temperature logs. These are at 1410–1440, 1670–1680, 1770–1830, 1970–2020, 2050 and 2080 m depth.

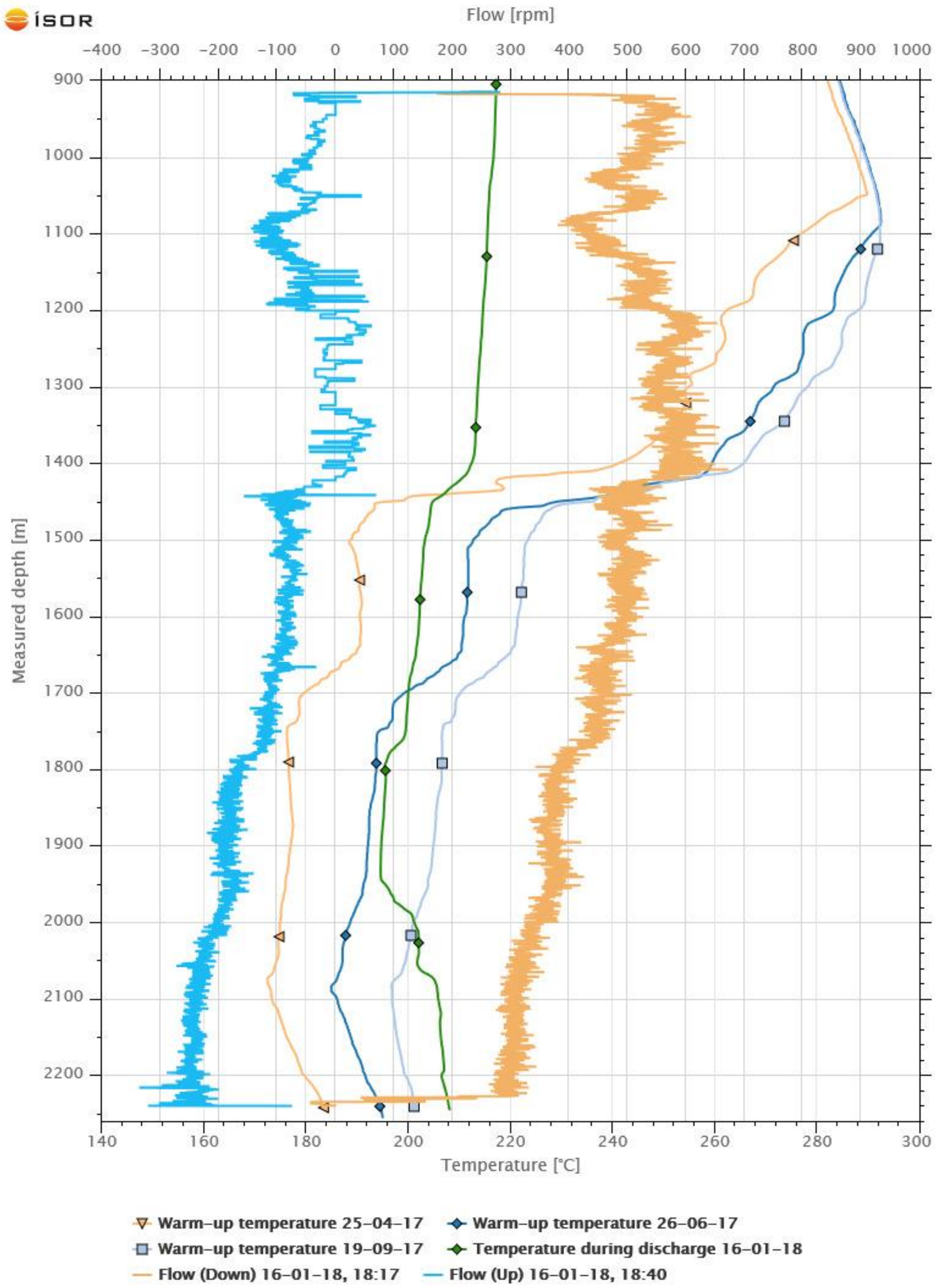

Figure 9. *A comparison of selected temperature and spinner flow measurements. The spinner logs are measured at tool speed 60 mpm and the selection of temperature logs during warm-up in the well and during discharge on January 16th 2018.*

3.5 A comparison of spinner data logged during discharge and injection

Figure 10 shows a pair of spinner logs during discharge (at 60 m/min) and another pair logged at 90 m/min during the end-of-drilling injection test, with an injection rate of 35.1 L/s. Additionally the caliper data is included in order to evaluate visually effects due to well width on the spinner data sets.

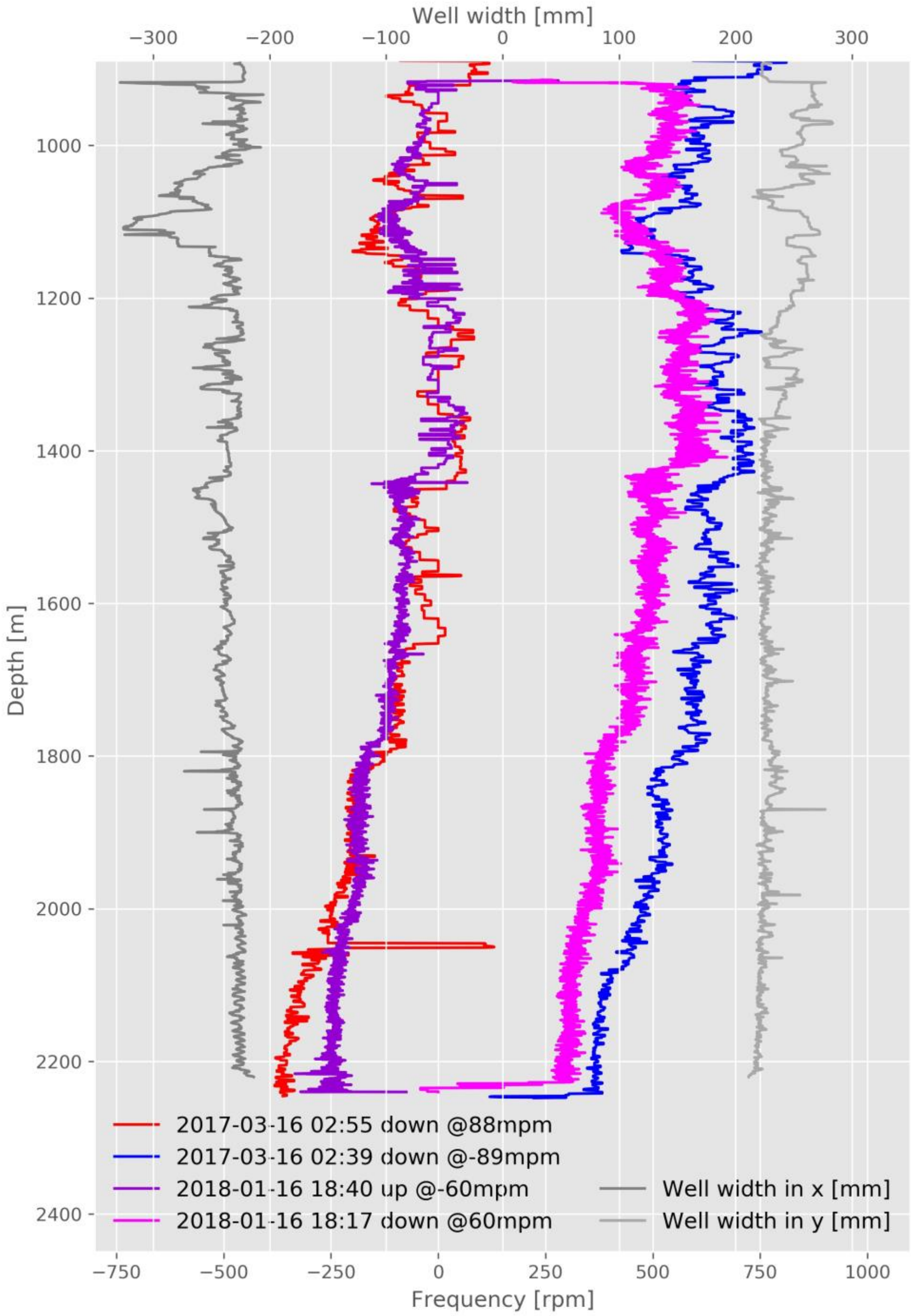

Figure 10. *A comparison of the spinner logs during discharge at a measuring speed of 60 m/min (pink and purple lines) and the spinner logs measured at 90 m/min at the injection rate 35.1 L/s. The injection logs are reversed for ease of comparison. The well width measured in mm on two axes is shown in gray and dark gray.*

The discharge spinner logs and the injection spinner logs align well. Table 4 lists the feed zones observed during injection and during discharge. Only one feed zone appears different and that is the feed zone around 1800 m depth. During injection outflow was observed at 1730 m and between 1800–1830 m while during discharge inflow appears to take place between 1770–1830 m indicating an opening of the feed zone having taken place over that depth range since drilling, probably after the well started discharging.

This compares reasonably well with the feed zones identified though the end-off-drilling logs, (see A1 in Appendix A; Sigurgeirsson et al., 2017).

Table 3. *The outflow and inflow zones identified by the spinner logs during injection on March 15th–16th 2017 and during discharge on January 16th 2018.*

Depth of outflow zones from spinner logs during injection [m]	Depth of inflow zones from spinner logs during discharge [m]
1457	1410–1440
1670	1670–1680
1730, 1800–1830	1770–1830
1980	1970–2020
	2050
2090	2080
2250?	

4 Summary and conclusions

The temperature and pressure logs show that the well contains two phase fluid flow above the boiling surface at ~530 m depth where a break is seen in the temperature log and where the pressure log become hydrostatic. Below the boiling zone the water column has a positive temperature gradient indicating that the water rising up the well is heating due to heat conduction through the casing. Inflow with temperature of 200–250°C is seen in the temperature logs at ~1450, 1685, 1780 and 1797 m depth. Further down in the well, cooler (<200°C) inflow is observed at 1990, 2012 and 2080 m depth.

The fluid velocity and flow up the well (in kg/s) were estimated from the spinner logs. The flow is probably slightly overestimated since an estimate of the flow in the top section of the well suggest a mass flow of around 35 kg/s. Measurements of flow from the well suggest that at well head pressure ~7 bar that the mass flow is between 25 and 29 kg/s.

Table 4 lists the feed zones interpreted from the dynamic logs, spinner and temperature, as well as the feed zones interpreted from the spinner logs during injection. It is worth noting that during the dynamic logs the spinner logs show flow coming into the well while during injection the spinner logs show where fluid flows down the well and exits the well at the feed zones. The inflow zones estimated from temperature and spinner data are compared in Table 4 along with the outflow zones from the spinner log taken during the injection test at the end of drilling.

A rough analysis of the changes in flow in the well indicates that the cooler inflow at the bottom of the well accounts for about a quarter of the inflow into the well (estimated from the flow in kg/s), while the inflow between 1770 and 1830 m depth accounts for around 30%. About 15% of the inflow enters the well at around 1670–1680 m depth and another 30% at around 1410–1440 m, see Table 4.

Table 4. *A summary of the feed zones interpreted from the spinner and temperature logs during discharge and for comparison the feed zones identified during the injection step test at the end of drilling are included.*

Discharge test				Injection test
Depth of inflow zones from spinner logs [m]	**Depth of inflow zones from temperature logs [m]**	**Hot or cold inflow**	**Approximate proportional inflow**	**Depth of outflow zones from spinner logs [m]**
1410–1440	~1450	>200°	~30%	1457
1670–1680	1685	>200°	~15%	1670
1770–1830	1780, 1797	>200°	~30%	1730, 1800–1830
1970–2020	1990, 2012	<200°		1980
2050		<200°	~25%	
2080	2080	<200°		2090
		?		2250?

5 References

Grant, M. A. and Bixley, P. F. (2011). *Geothermal reservoir engineering, 2nd ed.* N.Y. Academic press, 359 pp.

Sigurgeirsson, M.Á:, Guðjónsdóttir, S.R., Ásgeirsdóttir, R.S., Tryggvason, H.H., Egilson, Þ., Guðmundsdóttir, V., Gunnarsson, B.S., Vilhjálmsson, S., Ingimarsson, H., Pétursson, F. and Ingólfsson, H. (2017). *Þeistareykir – Well ÞG-15. Phase 3: Drilling for a 7" Perforated Liner down to 2260 m*. Iceland GeoSurvey, ÍSOR-2017/036, LV-2017-047.

Appendix A: Feed zones identified in well ÞG-15 at the end of drilling

For reference the table of feed zones from Sigurgeirsson et al. (2017) is included here as an appendix. The feed zones were identified using the data available at the time of the end of drilling; circulation losses, lithology, temperature and spinner logs. (Table A1). In general feed zones are ranked into three classes, from 1–3, based on their relative sizes (1–3 referring to small, medium and large respectively). Here none of the feed zones classify as large, the feed zones are considered small to moderate in size. The most permeable feeds zones were considered to be at 1455–1475, 1800–1830 and 2090 m. (Sigurgeirsson et al., 2017).

Table A1. *Feed zones in ÞG-15 evidenced by drilling data and wireline logs.*

Depth (m)	Size (1-3)	Evidenced by	Lithology/Caliper/Drilling data
950-1000	1	Temperature logs.	At 1000 m there is a boundary between lava flows. Pyrite is common and some vein fillings are seen.
1200-1230	1	Temperature logs.	At 1194 m there is a boundary between a breccia and a glassy basalt below.
Ca. 1300	1	Temperature logs.	At 1306 m there is a boundary between units of glassy basalt below (pillow lava).
1455-1475	2	Temperature logs. Spinner logs locate the feed zone at 1457 m.	Loss of circulation (LOC) increases from 12 to 23 L/s between 1449-1486 m. LOC measured 28 L/s at 1497 m. At 1460 m is a boundary between a fine-grained lava flow and a breccia below.
1650-1670	1	Temperature logs.	The cuttings are very mixed and of poor quality. The feed zone is clearly visible in Temperature logs during heating up after drilling but not during drilling.
1800-1830	2	Seen at 1830 in temperature logs but the spinner logs shows changes from 1800-1830.	1774-1810 m where a dark colored fragments are common, possibly from intrusive veins. The cuttings are mostly composed of light gray-green fragments of fine- and cryptocrystalline basalt. Fracture fillings are seen at around 1800 m.
1980	1	Spinner logs.	Total loss of circulation, no cuttings available from below 1992 m.
2090	2	Temperature logs, spinner logs.	No cuttings.
2220	1	Temperature logs,	No cuttings.
2255?	1	Temperature logs, spinner log?	No cuttings.

Appendix B: Flow measurements with spinner at the end of drilling in well ÞG-15

On March 15th 2107, spinner logs were conducted in well ÞG-15 as a part of the conventional end-of-drilling step rate injection test. The spinner tool used was a PTS Kuster tool. Details of the flow measurements with the tool are found in the table below, including the tool speed, the injection rate and the purpose of each run of the tool.

Table B1. *An overview of the spinner logging in well ÞG-15 on March 15th–16th 2017.*

Trip [m]	Purpose	Tool Speed [m/min]	Tool direction	Injection [L/s]
20-420	Measurement	50	Down	-10
~400	Calibration	+/- 40, +/- 50, +/- 60	Up/Down	-10
410-2260	Measurement	50	Down	-10
2254-870	Measurement	50	Up	-10
870-2060	Measurement	60	Down	-10
2060-2250	Transfer	-	Down	-35.1
2250-2200	Calibration	+/- 50, +/- 60, +/- 70	Up/Down	-35.1
2250-850	Measurement	90	Up	-35.1
850-2250	Measurement	90	Down	-35.1
2250-2060	Transfer	-	Up	-35.1
2060-25	Measurement	55	Up	-19.7

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