Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

How Hot Is the Deepest Part of the IDDP2 Well in Iceland?

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Keywords: DEEPEGS, IDDP2, down hole temperature, Horner plot, Iceland, Reykjanes,

ABSTRACT

The target of the RN-15/IDDP-2 well at Reykjanes is to find geothermal resources at supercritical temperatures. The well was depended from well RN-15 and drilled down to 4560 m MD (4390 m true depth) and encountered supercritical temperature. Temperature log have been run in the well during drilling, in connection to activities in the well, and during short warm up period in May 2017. During the warm up period, several temperature logs were run in the well down to the bottom of the well measuring temperature at several intervals below 3400 m depth. This data was used to estimate the formation temperature using the Horner-plot method. Even though the warm up period was relatively short, good data was acquired and the estimated temperatures are in good correlation to temperature estimated with other methods, such as modeling using surface geophysical methods. The highest temperature measured in the well was 424 °C at 4560 m MD, while the estimated temperature at that depth is around 540°C.

1. INTRODUCTION

The IDDP2/RN-15 well had been cooled more or less continuously from the deepening of RN-15 which was completed in late January 2017, except for several short periods of warm up where 4 -5 L/s was pumped into the annulus between the casing and an inner drill string extending from surface almost to the bottom of the well. Four temperature logs were run in the well using mechanical Amerada tool when the cooling was stopped in the IDDP2/RN-15 on 23rd May for six day in May 2017. Before that 60 L/s had been injected continuously into the well from 16th of May until the warm up period started. Of these 15 L/s was injected through the drill string (used to cool down the well) and 45 L/s into the annulus.

The temperature was measured at 6 to 9 different depths and the Horner plot method was used to estimate the formation temperature at five different depths. During this time the casing was cooled by pumping 5 L/s on the annulus

To estimate the formation temperature the Horner plot method was used. To use that method the time the corresponding depths were cooled had to be estimated. It was calculated from the time the drill bit reached the depths of the five points where the formation temperature was estimated. Before the warm up in May the well had been subjected to several periods of 10 days of injection followed by about five days of warm up. During these 10 days the injection was 11 – 13 L/s on the drill string and 5 – 10 L/s on the annulus. Four to five L/s was injected on the annulus during all the warm up periods to cool the casing.

The cooling time is very long compared to the warm up time making these estimations rather rough. It was estimated that the cooling was continuous and to get estimation on the accuracy of the calculations the cooling time of four months (since end of drilling in late January) was used for comparison.

2. TEMPERATURE LOGS DURING THE WARM UP IN MAY 2017

All circulation was stopped at 13:25 on May 23rd 2017 and four Amerada temperature logs were run in hole during the next six days (**Error! Reference source not found.**). As well as two continuous temperature logs from surface to the bottom of the well measured in January 2017 showing a rapid increase in temperature at about 3400 m depth, indicating that injection of cold water at wellhead cooled the well down to that depth and that water had entered the formation at that depth. The highest temperature measured in the well before the warm up in May was 424.5°C on January 3rd 2017 measured at 4560 m depth.

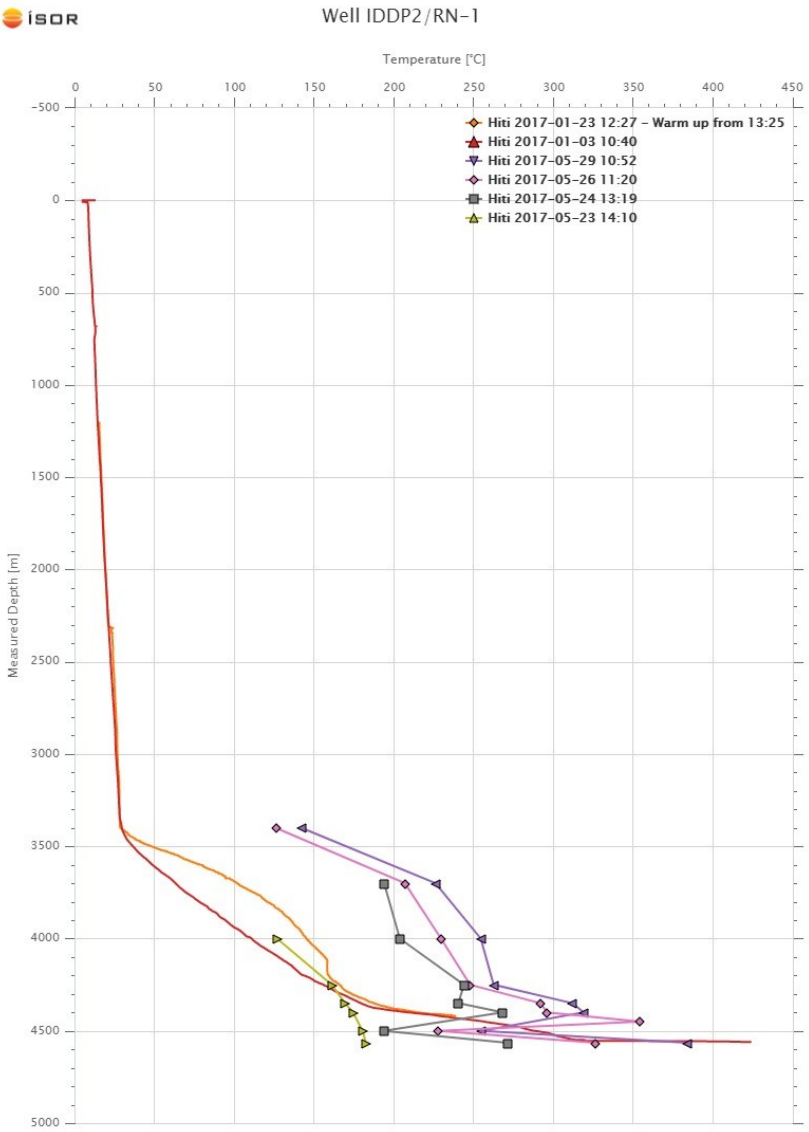

Figure 1: Temperature log in well IDDP2/RN-15 during warm up in May 2017 and two selected logs.

3. THE METHOD USED

Estimation of formation temperature is usually achieved by analytical and numerical simulation methods. Most of the analytical methods are based on the constant linear and cylindrical heat source models. Analytical methods most commonly used include the Horner-plot method. This analytical method is based on the assumption that thermal effect of drilling is a constant linear heat source. The approximate solution is given by the equation below:

$$T(t) - T_f = \frac{q}{4\pi k} ln \frac{t}{t+t_0} \quad (1)$$

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Assume that the cooling lasts for time t_0. During this time, heat is removed from the rock at constant rate q. The time passed from end of cooling period is t, the formation temperature is T_f and the temperature at any time in the well is T(t). The method is based on the assumption that the cooling is constant and then the slope of the plot where T(t) is plotted against $\ln(t/(t+t_0))$ gives the T_f when $\ln(t/(t+t_0))$ approaches zero at an infinite heat up time.

3.1 Formation temperature estimation

Even though the injection was not constant during the cooling of the well this method is used here in an attempt to get an estimate of the temperature at 4000 m, 4250, 4350, 4500 and 4565 m measured depths. Since the cooling was not continuous the formation temperature at these five depths was estimated using both the maximum cooling time, which is the time from when the drill bit reached the respective depth in question (1) and (2) the minimum cooling time which is since the end of the drilling operation late in January 2017 to the warm up in May. The minimum cooling time is therefore about four months (10,368,000 sec).

As can be seen from Figure 2 and Table 2 the estimated temperature at 4000 m depth is 343 and 355°C for the two cooling times. The estimated temperature at 4240 m depth is 356 to 363 °C (Figure 3 and Table 3). From Figure 4 and Table 4 it is estimated that the formation temperature at 4350 m depth is between 432 and 444°C. From Figure 5 and Table 5 it is estimated that the formation temperature at 4500 m depth is between 303 and 308°C. The estimated temperature at 4565 m depth is 536 to 549°C as can be seen on Figure 6 and Table 6.

The data for 4000, 4350 and 4565 m depths seem to be consistent and the true formation temperature at those depths is probably not far from these estimates as the regression coefficient of over 98% indicates. For the data at 4500 m depth the Horner plot estimate indicates much lower formation temperature than above and below. As can be seen from Figure 1 it seems to be a feed zone close to that depth. This suggests much more cooling of the formation at this zone meaning that the Horner plot method is not valid. The regression coefficient is also much lower at this depth (~85%). Figure 7 and Table 7 show the estimated formation temperatures. The data at 4250 m depth is also probably disturbed by a feed zone making the estimation of the formation temperature more uncertain as can be seen from Figure 3 and the lower regression coefficient (~90%).

Table 1. The maximum cooling time: Date when the drill rig reached each depth and the time in seconds until the warm up started on 23.05.2017 at 13:25:00.

Depth	Date	t_0 (s)
4000	17.11.2016	16,156,800
4250	28.11.2016	15,206,400
4350	8.12.2016	14,342,400
4500	12.12.2016	13,996,800
4565	16.12.2016	13,564,800

Table 2. Data for calculating the formation temperature at 4000 m depth, assuming (1) maximum cooling time since the depth was reached, 16,156,800 seconds and (2) minimum cooling time since end of drilling, four months or 10,468,000 seconds.

	Warm up at **4000 m** starts 23.5 2017 at 13:25:00				
Date	Time	Heat-up time (s)	Temperature (°C)	ln(t/(t+t0)	
				Max time	4 months
23.5.2017	15:29:00	7440	126.40	-7.689017	-7.240326
24.5.2017	14:12:00	89220	193.54	-5.209802	-4.763943
26.5.2017	12:17:00	255120	229.31	-4.16928	-3.729054
29.5.2017	11:46:00	512460	254.19	-3.487269	-3.055501
Depth reached by the drill			17.11.2016		

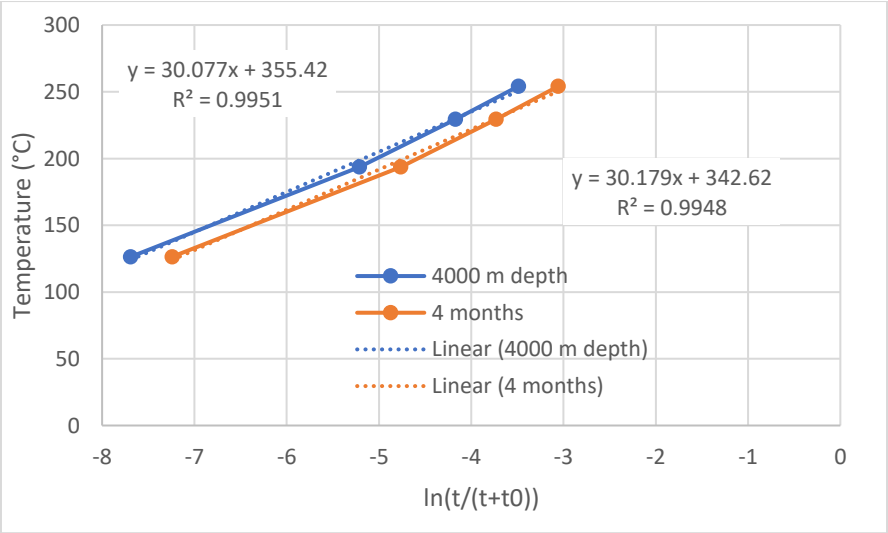

Figure 2. Horner plot for 4000 m depth for estimated cooling time (1) as the time from the drilling and (2) as the four months after drilling was completed.

Table 3. Data for calculating the formation temperature at 4250 m depth assuming (1) maximum cooling time since the depth was reached, 15,206,400seconds and (2) minimum cooling time since end of drilling, four months or 10,468,000 seconds.

	Warm up at **4250 m** starts 23.5 2017 at 13:25:00				
Date	Time	Heat-up time (s)	Temperature (°C)	ln(t/(t+t0)	
				Max time	4 months
23.5.2017	17:18	13980	168.00	-6.9927629	-6.61020
24.5.2017	15:15	93000	247.36	-5.1029694	-4.72281
26.5.2017	13:20	258900	250.66	-4.0899122	-3.71470
29.5.2017	12:39	515640	264.5	-3.41741	-3.04961
Depth reached by the drill			28.11.2016		

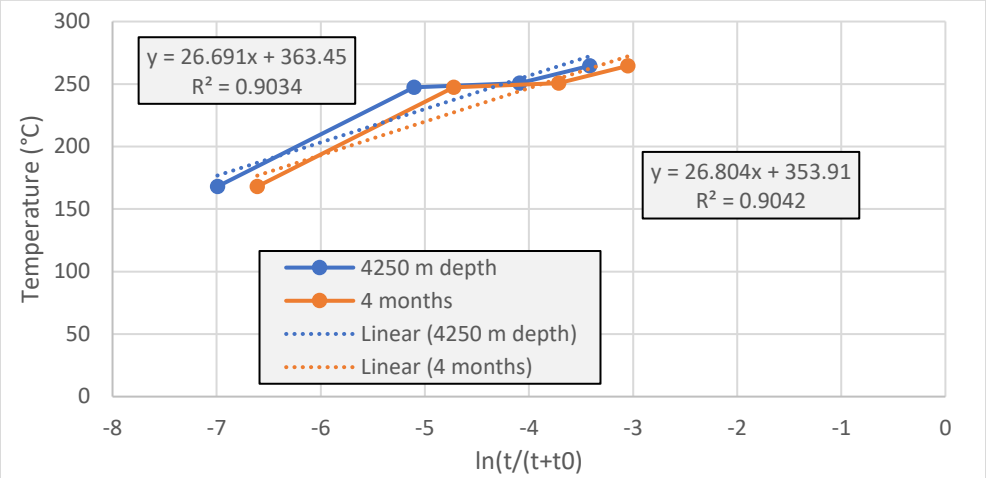

Figure 3. Horner plot for 4250 m depth for estimated cooling time (1) as the time from the drilling and (2) as the four months after drilling was completed.

Table 4. Data for calculating the formation temperature at 4350 m depth assuming (1) maximum cooling time since the depth was reached, 14,342,400 seconds and (2) minimum cooling time since end of drilling, four months or 10,468,000 seconds.

Warm up at **4350 m** starts 23.5 2017 at 13:25:00					
Date	Time	Heat-up time (s)	Temperature (°C)		ln(t/(t+t0)
				Max time	4 months
23.5.2017	16:44	11940	169.000	-7.091914	-6.76774
24.5.2017	14:42	91020	240.100	-5.066222	-4.74414
26.5.2017	12:47	256920	291.850	-4.039965	-3.72219
29.5.2017	12:07	513720	311.700	-3.364489	-3.05316
Depth reached by the drill			8.12.2016		

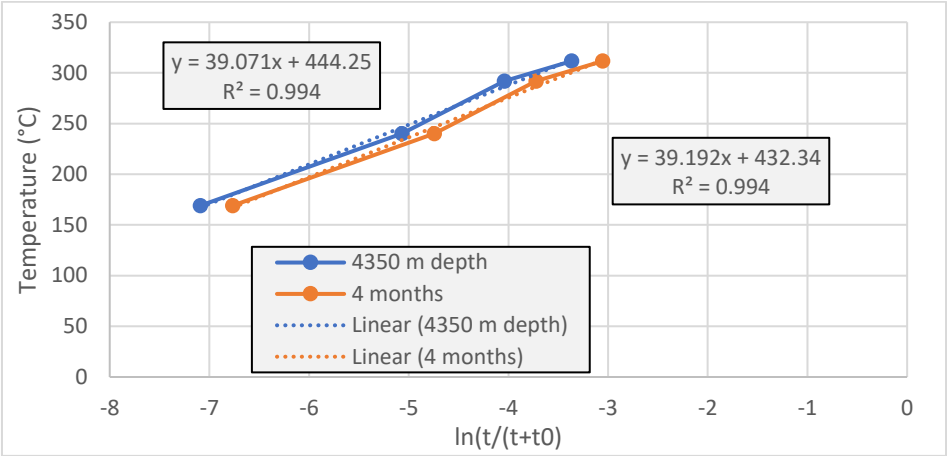

Figure 4. Horner plot for 4350 m depth for both using estimated cooling time (1) as the time from the drilling and (2) as the four months after drilling was completed.

Table 5. Data for calculating the formation temperature at 4500 m depth assuming (1) maximum cooling time since the depth was reached, 13,996,800 seconds and (2) minimum cooling time since end of drilling, four months or 10,468,000 seconds.

	Warm up at **4500 m** starts 23.5 2017 at 13:25:00				
Date	Time	Heat-up time (s)	Temperature (°C)		ln(t/(t+t0)
				Max time	4 months
23.5.2017	16:58	12780	180.100	-6.968294	-6.69983
24.5.2017	14:56	91860	193.320	-5.001717	-4.73503
26.5.2017	13:05	258000	227.640	-3.981115	-3.71810
29.5.2017	12:20	517800	254.780	-3.309265	-3.05172
Depth reached by the drill			17.11.2016		

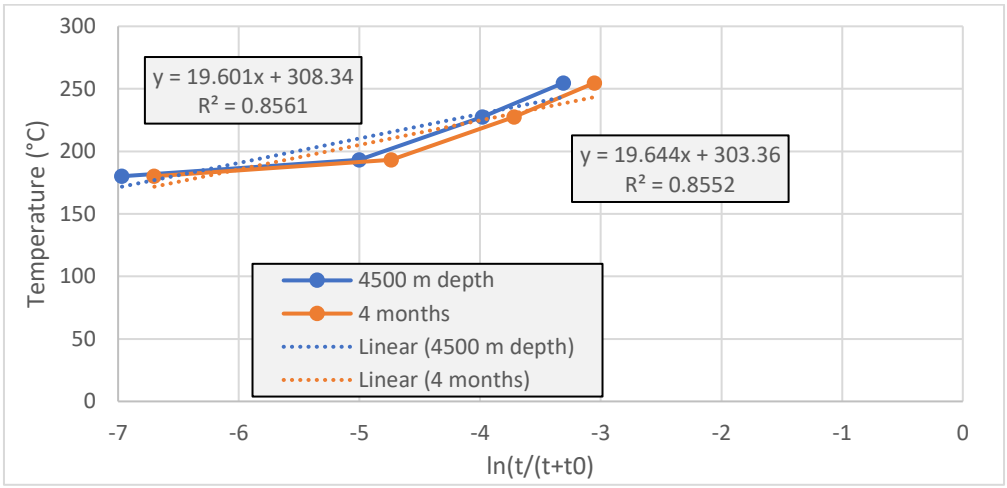

Figure 5. Horner plot for 4500 m depth for both using estimated cooling time (1) as the time from the drilling and (2) as the four months after drilling was completed.

Table 6. Data for calculating the formation temperature at 4565 m depth assuming (1) maximum cooling time since the depth was reached, 13,564,800 seconds and (2) minimum cooling time since end of drilling, four months or 10,468,000 seconds.

	Warm up at **4565 m** starts 23.5 2017 at 13:25:00				
Date	Time	Heat-up time (s)	Temperature (°C)		$\ln(t/(t+t_0)$
				Max time	4 months
23.5.2017	17:04	13140	182.1	-6.940541	-6.672085
24.5.2017	15:05	92400	271.0	-4.995895	-4.729225
26.5.2017	13:11	258360	326.3	-3.979747	-3.716739
29.5.2017	12:27	514920	383.8	-3.308479	-3.050938
Depth reached by the drill			12.12.2016		

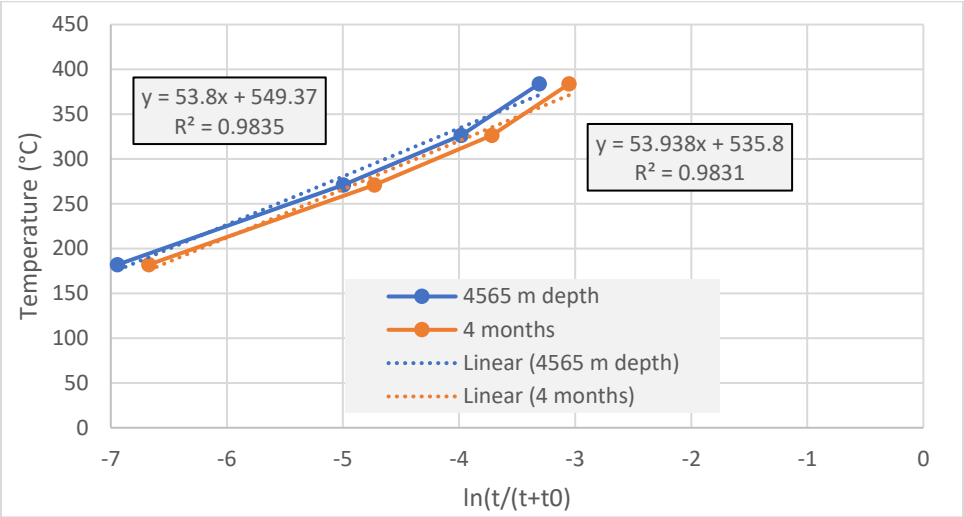

Figure 6. Horner plot for 4565 m depth for both using estimated cooling time (1) as the time from the drilling and (2) as the four months after drilling was completed.

Table 7. Estimated temperatures.

	Temperature (°C)	
Depth (m)	Min	Max
4000	343	355
4250	354	363
4350	432	444
4500	303	308
4565	536	549

4. FORMATION TEMPERATURE ESTIMATION BY OTHERS

Hokstad and Tänavsuu-Milkeviciene (2018) used resistivity from magnetotelluric inversion and density from gravity inversion, followed by Bayesian rock-physics inversion to predict the temperature at 5 km depth in the IDDP-2 well. The prediction of temperature was 513± 62 °C at 5 km vertical depth along the planned well path before drilling. During drilling, resistivity logs and core samples were used to update the temperature estimated and matched well with the predicted temperature. There has also been other unpublished work with in the DEEPEGS project using different methods to estimate the formation temoerature at depth in the IDDP2 well, with similar results.

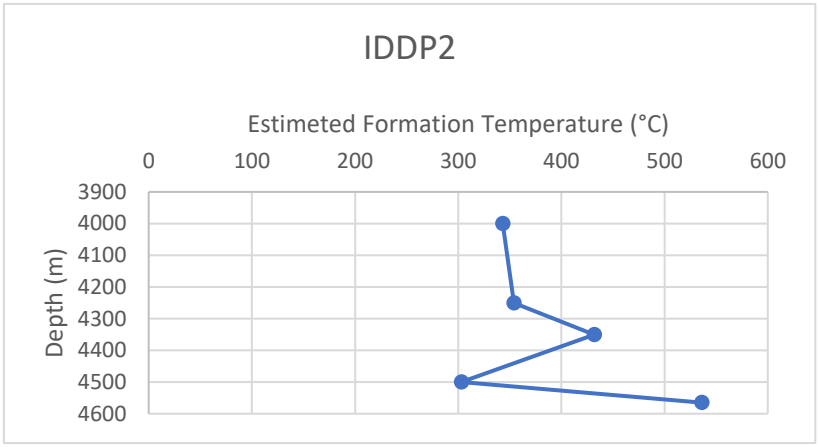

Figure 7. Estimated formation temperature in well IDDP2 based on Horner plots from data in May 2017.

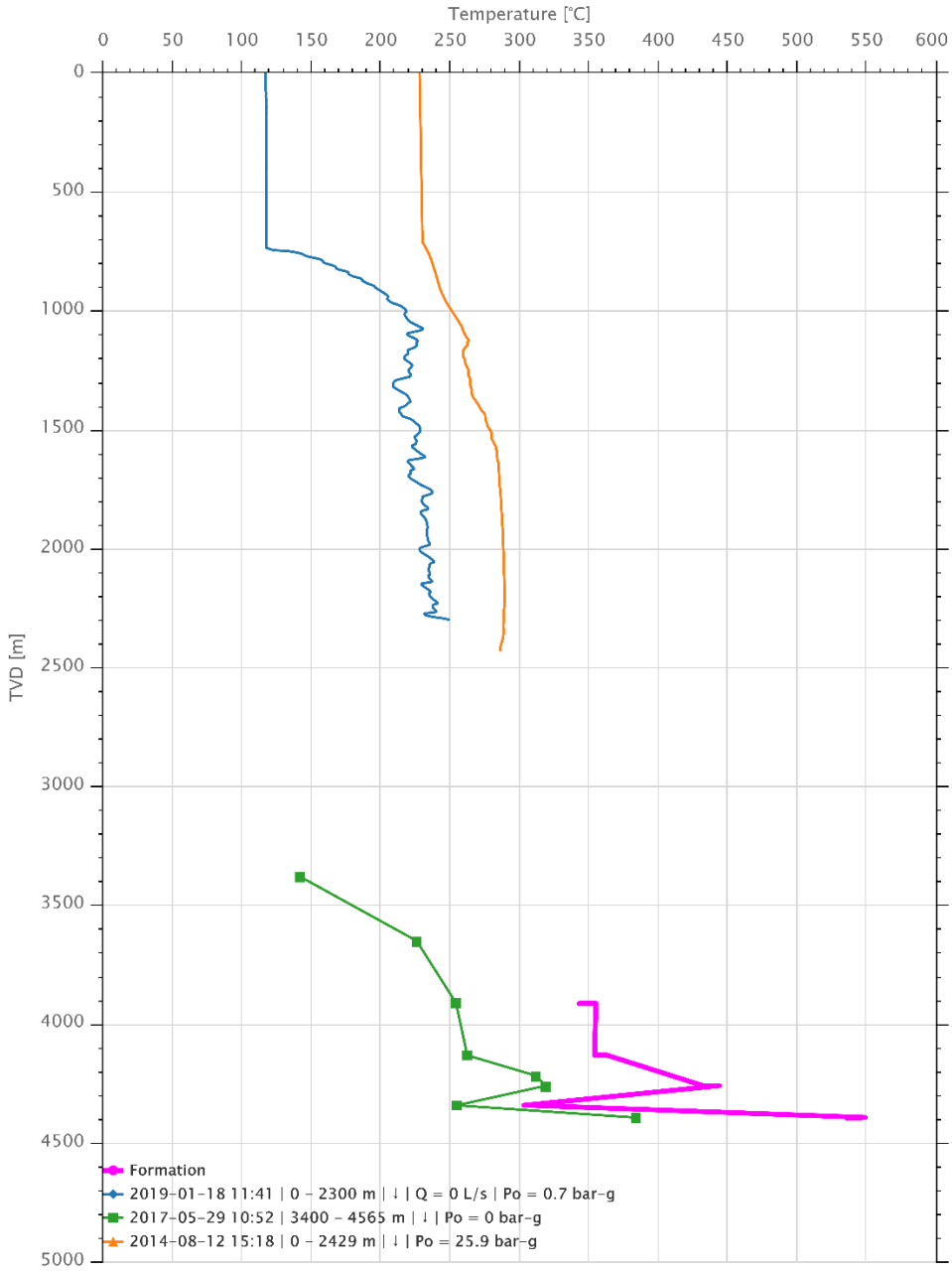

Figure 8. The last temperature log in IDDP2 (blue), The hottest temperature log from well RN-15, the deepest log in IDDP2 and the calculated formation temperature deep in the IDDP2 well based on the Horner plot method.

5. CONCLUSIONS

Cooling in well IDDP2/RN-15 was stopped for few days in May 2017 in an attempt to estimate the formation temperature below 4000 m depth. The Horner plot method was used with this data at five different depths. The result indicate temperature above 300°C in all the points and well over 500° at 4565 m depth. This method is not very accurate, but since the results are in accordance with other data these can be used as a rough estimate of the formation temperature. The Horner plots all are consentient and for 3 out of the 5 depths the regression coefficient is very high suggesting that this method is valid.

Since the cooling was not continues the formation temperature at these five depths was estimated using both the maximum cooling time, which is the time from when the drill bit reached the respective depth in question (1) and the minimum cooling time which is since the end of the drilling operation late in January 2017 to the warm up in May. The minimum cooling time is therefore about four months. This was done in an attempt to see how sensitive the Horner plot estimates were to the cooling time.

The estimated formation temperature is 343 to 363°C at 4000 and 4250 m depth, over 430°C at 4350 m depth and 536 to 549°C at the deepest point at 4565 m depth. These temperatures are in good agreement with values estimated using other methods.

REFERENCES

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