Temperature Condition Modelling for well IDDP-1 in Krafla, N-Iceland

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Abstract

The transient temperature conditions near the bottom of well IDDP-1 in Krafla, which was drilled into a magma intrusion, have been simulated by some simple models addressing: (i) evolution of temperature conditions at the magma intrusion, (ii) cooling of a permeable layer above the magma due to drilling circulation losses, (iii) reheating of the permeable layer after drilling and (iv) temperature evolution during discharge testing in 2010. The modelling is quite speculative because of limited data constraints, but results indicate that the temperature conditions and evolution can be explained by the models used. The possibility that the magma was emplaced during the Krafla volcanic episode 25 – 35 years ago can neither be confirmed nor refuted, but if the intrusion is so old a thickness of at least 50 – 100 m is required. The effective thickness of the permeable layer and its equilibrium temperature, are estimated to be about 45 m and 390 – 400°C, respectively. No direct contact with the magma is needed to explain the superheated (up to 380°C) steam discharged by well IDDP-1. The situation near the bottom of the well clearly warrants further study, both through more complex modelling and with further data-constraints.

1. Introduction

This paper presents the results of modelling work performed to help understanding temperature conditions at the bottom of the IDDP-well in Krafla, which have been an issue of much interest and speculation. This involves both modelling of temperature conditions, and the temperature evolution, around the magma encountered as well as modelling of temperature changes near well-bottom during heating-up after drilling and during discharge testing of the well. Issues like the age and size of the magma intrusion, the slow warming-up of the well near well-bottom after drilling (in view of the presence of the magma) as well as the constantly increasing temperature of the super-heated steam discharged by the well, during most of the discharge period, have been of particular interest. The modelling was done through a series of simple modelling exercises, which can be linked together in a sort of unified picture, rather than through the development of a complex numerical model. For more details see Axelsson (2010) and Axelsson *et al.* (2012).

Well IDDP-1 was drilled within the Krafla caldera, at a location where the depth to an inferred magma chamber was estimated to be about 4.5 km on the basis of MT/TEM resistivity surveying. Pre-drilling was done in 2008 while the main drilling phase started in March 2009. Drilling progressed normally to about 2 km depth but then severe drilling problems started occurring. The well was side-tracked twice but a depth greater than 2104 m couldn't be reached. It slowly became clear that this was because of an unexpected magma intrusion. The well was completed by inserting a slotted liner extending from 1950 to 2080 m

depth. A 10 – 20 m volcanic glass plug (quenched magma) at the bottom of the well isolates it from the magma. The drilling operation was terminated on July 7th and the drill-rig prepared for mobilization. Cooling of the well through water circulation was continued up to August 11th 2009. Fridleifsson *et al.* (2010a) and Elders and Fridleifsson (2010) present the overall status of the IDDP-project while Hólmgeirsson *et al.* (2010) and Fridleifsson *et al.* (2010b) describe the drilling of well IDDP-1.

After the completion of the drilling operation the well was allowed to heat up until March 2010, when the first attempt at discharge testing the well was made. Continuous discharge testing started during the middle of May the same year, however, continuing for more than three months. During both of these phases a comprehensive program of data collection was in effect, including regular temperature- and pressure-logging during the heating-up period and well-head parameter monitoring during the discharge test. This paper is based on data available in late 2010. In late summer 2011 testing of well IDDP-1 started again, providing additional data.

2. The modelling problem

A simplified sketch of well IDDP-1, and the relative location of the magma intrusion and main permeable layer near the bottom of the well, as modelled in this study, is shown in Fig. 1. The figure also shows the different aspects modelled. It should be noted that both the magma intrusion and the permeable layer are assumed to be extensive layers of constant thickness, not necessarily horizontal. This conforms to the fact that most such intrusions are either kind of dikes or sills. A magma intrusion of some other shape can't be ruled out, however, which adds uncertainty to the modelling. The possibility that the magma encountered is simply the top of the Krafla magma chamber may be ruled out on the basis of data on the location of the chamber, in particular MT/TEM resistivity data and data on natural seismicity (Mortensen *et al.*, 2009).

The modelling discussed here focuses on the aspects/items listed below. Note that more relevant information for each of these is presented in the following chapter, which presents the methodology and results of modelling each aspect/item.

(i) Temperature conditions inside and around the magma intrusion and how they may have evolved since emplacement of the magma. Here the main unknowns are the time of emplacement, which may have been during the Krafla volcanic episode in 1975 – 1984 or perhaps later, and the thickness of the intrusion. Other unknowns are the temperature of the magma at the time of emplacement and its present temperature. A further uncertainty arises because the rhyolitic magma of the intrusion does not have a simple melting point temperature, but solidifies over a temperature-range controlled by the solidification of the different minerals of the magma. Finally, the temperature conditions above the magma intrusion may have evolved both through simple heat conduction and heat carried by convection.

(ii) Cooling of the permeable layer above the magma intrusion due to the circulation losses occurring during the IDDP-1 drilling operation and up to August 11, 2009. This permeable layer is assumed to correspond to the series of feed-zones associated with circulation losses between 2040 and 2075 m. Even though the loss-zones may mostly be associated with discrete fractures they are simulated by an equivalent permeable layer of a fixed thickness in this study. This reservoir layer is assumed to be separated

from the magma by an approximately 30 – 50 m thick non-permeable layer (yellow layer in Fig. 1).

(iii) Reheating of the permeable layer during the time the well was closed after August 11, 2009 (i.e. the temperature recovery of the layer as observed through repeated temperature logs). This is basically by heat flow from the rocks above and below the layer, which can be considered to be relatively unaffected by the cooling of the permeable layer.

(iv) Temperature evolution of the permeable layer during discharge of the well, based on well-head measurements during discharge testing of the well in 2010. This actually involves a complex process of boiling in the layer, because of the dramatic pressure drop during the discharge of the well, and later superheating of the steam generated. Modelling this process accurately was beyond the scope of this study so a much more simplistic approach was taken.
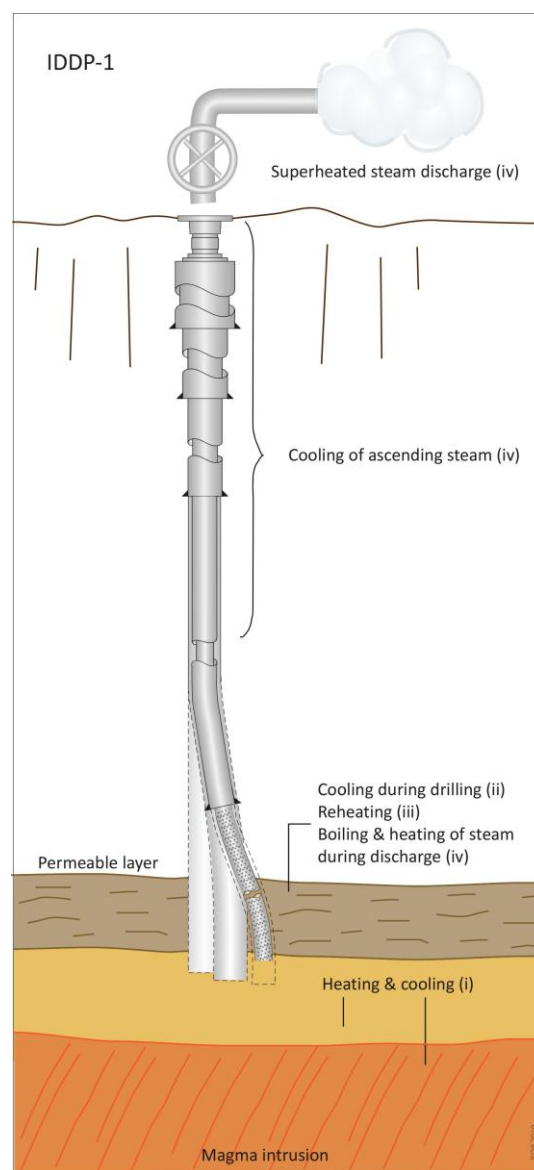

Figure 1. *A simplified sketch of the setup and different aspects considered in the simple temperature condition modelling for well IDDP-1. Markings ((i) – (iv)) refer to items in the list above. Figure not to scale.*

The purpose of the modelling was to try to understand, and explain, the overall temperature evolution, at least approximately, through the modelling exercises. The main data available to constrain the modelling are (for more details see Axelsson, 2010) data on the lithology of layers and structures intersected by the well, some preliminary results of petrological studies of samples derived from the magma (glass samples) and the surrounding rocks, data on circulation loss zones during drilling of the deepest part of the well, temperature and pressure logs measured during the wells' temperature recovery from August 2009 to March 2010 (figures 2 and 3) and discharge test data collected during the wells' main testing phase from May through August 2010. Apart from the first few days of testing the well discharged dry steam. Well-head pressure and steam temperature (Fig. 4) were measured and enthalpy estimated on basis of these two parameters. Because of the extremely high temperature most of the measurements are considered rather uncertain, however. The steam flow-rate is believed to have been in the range of 25 – 35 kg/s.
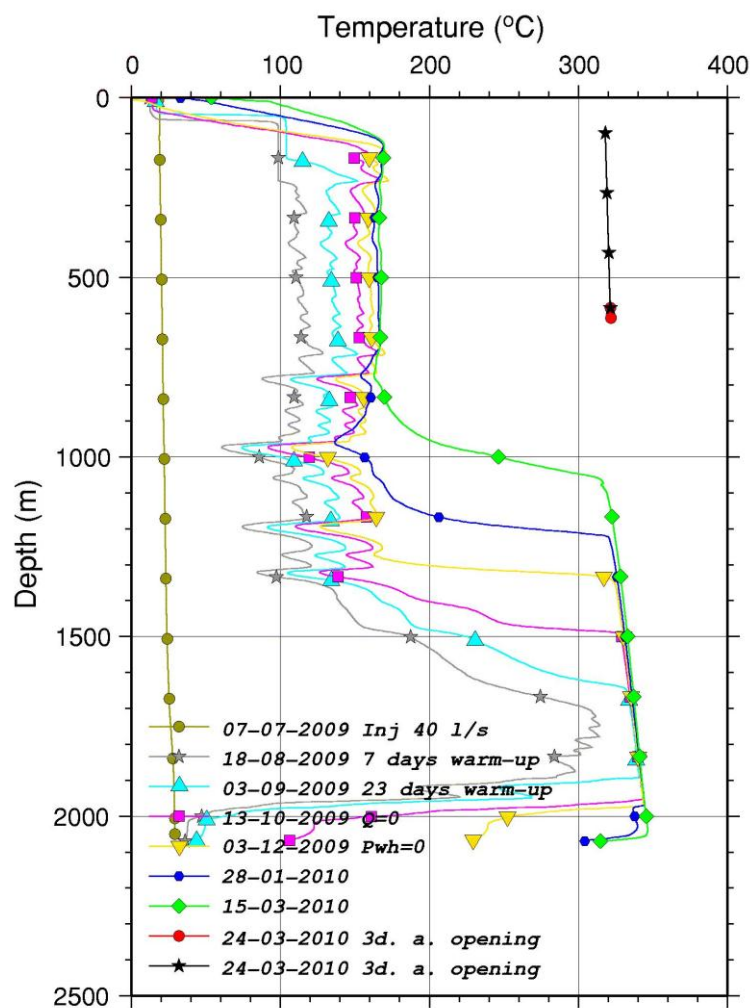

Figure 2. *Temperature logs measured during heating up of well IDDP-1 after drilling (data from the ÍSOR-database).*
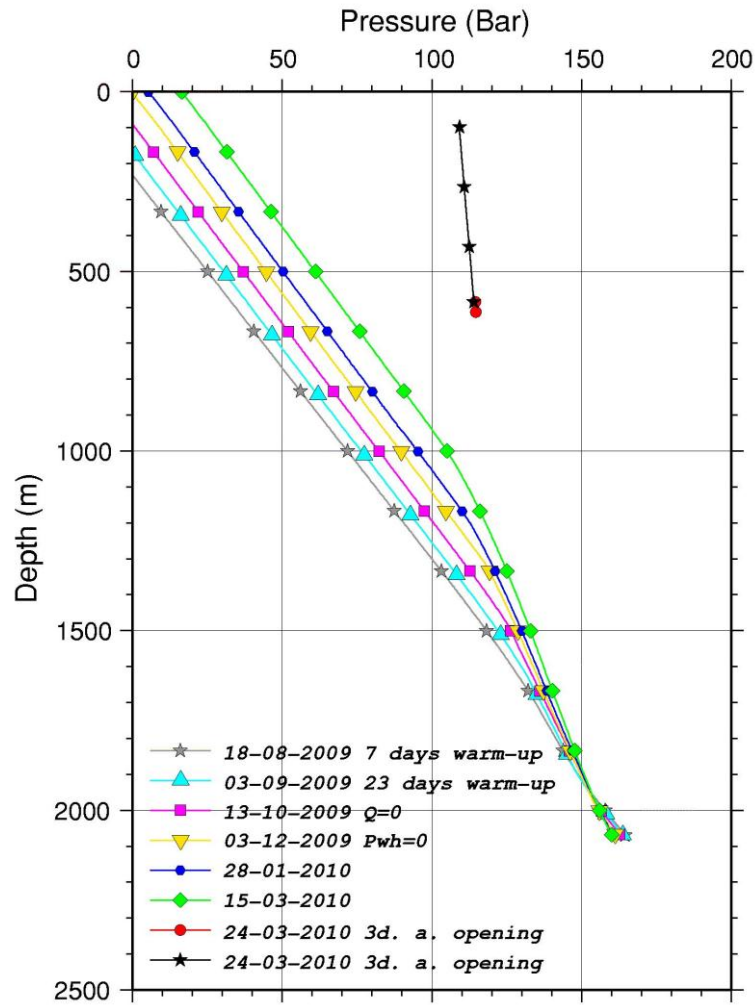
Figure 3. *Pressure logs measured during heating up of well IDDP-1 after drilling (data from the ÍSOR-database).*
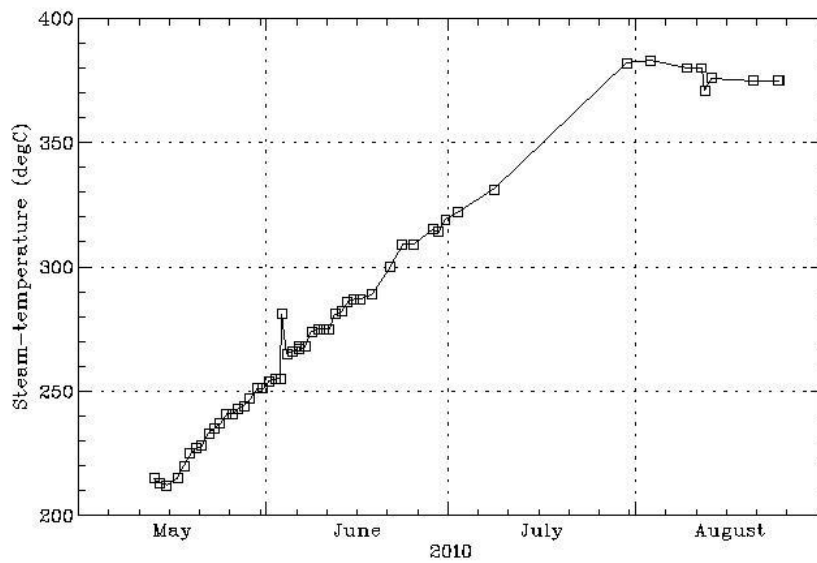

Figure 4. *Steam temperature at well-head during discharge testing of well IDDP-1 (data from the Landsvirkjun database).*

3. Simple Temperature Condition Modelling

The table below presents some of the main parameters and properties used in the modelling study presented here, along with the symbols used and numerical values assumed for them. Note that some of the parameters are estimated through the modelling study. It should be noted that the thermal properties of the magma and rock involved here are not accurately known; hence the values in the table should only be considered as approximate values.

Table 1. Parameters, symbols, properties and constants used in the simple model calculations.

Parameter	Value	Comment
Magma layer thickness, H	Unknown	
Initial (liquidus) magma temperature, T_i	~950°C	See (a) above (chapter 2)
Solidus temperature of magma, T_s	~700°C	See (a) above (chapter 2)
Present magma temperature	~850-900°C	See (a) above (chapter 2)
Initial host rock temperature, T_0	~340°C	Approximate
Latent heat of melting of magma, L_m	400,000 J/kg	Approximate
Thermal conductivity of rhyolite magma, k_m	2.0 J/m°Cs	Bagdassarov and Dingwell (1994)
Density of rhyolite magma, ρ_m	2300 kg/m^3	Bagdassarov and Dingwell (1994)
Heat capacity of rhyolite/granophyre, β_r	800 J/kg°C	Approximate
Density of solid rhyolite/granophyre, ρ_r	2700 kg/m^3	Approximate
Thermal conductivity of solid rhyolite/granophyre, k_r	1.5 J/m°Cs	Approximate
Thickness of permeable layer, h	> 35 m	See also chapter 3.3; Fig. 1
Distance separating permeable layer and magma	~30-50m	See Fig. 1
Average porosity of permeable layer, φ	0.1	Approximate
Density of liquid water in permeable layer, ρ_w	700-1000 kg/m^3	
Heat capacity of liquid water, β_w	4200 J/kg°C	
Heat capacity of 300-400°C steam, β_w	~2300 J/kg°C	At ~25 bar-g
Temp. of perm. layer before drilling, T_p	380-400°C	This analysis
Temp. of perm. layer after drilling, T_0	~25°C	Fig. 3
Density of basaltic rock, ρ_b	2900 kg/m^3	Stacey (1977)
Thermal conductivity of basalt, k_b	2.5 J/m°Cs	Stacey (1977)
Heat capacity of basalt, β_b	700 J/kg°C	Stacey (1977)

3.1 Magma Intrusion Temperature Conditions

Two models were set up to try to model the temperature evolution of the magma intrusion and its' surroundings (item (i) above), neither of which captures accurately the essence of the evolution. They should, however, provide fairly good approximations, which should aid in

understanding the issue. It should be noted that the magma in the intrusion may have originated through secondary melting of an older solid intrusion (i.e. granophyre) having come into contact with hot basaltic magma, sometime after the Krafla volcanic episode. Another model (model B) involves a magma-layer of constant thickness emplaced at a temperature well above the magmas' solidus temperature (Table 1), such that the layer doesn't solidify appreciably during the time period being considered.

One model assumes the magma has a single liquidus/solidus-temperature (not a temperature range) and that it starts solidifying right after intrusion, (model A). This model involves a magma-layer of constant thickness emplaced at a temperature near the magmas' solidus point (assumed to be approximately 850°C). The magma layer solidifies both from above and below while heating up the surrounding rock. Turcotte and Schubert (1982) present a mathematical solution for this model. The results of the modelling (Axelsson, 2010) can't be used to rule out the possibility that the magma was intruded as long ago as 30 years, since temperatures 40 – 50 m above the original magma boundary would only have risen to ~400°C (estimated temperature of permeable layer). It should be kept in mind that model A has the draw-back of assuming a single liquidus/solidus-temperature. In addition it assumes that the magma in the intrusion (sill) remains stationary as it solidifies in a symmetric manner from both above and below. It seems possible that the magma does solidify from the bottom up through a sort of convective process during which material solidifying near the top, sinks to the bottom, and liquid magma rises to the top.

Figure 5, which also presents results of calculations with model A, shows the estimated minimum thickness of such a layer, if it were still to be molten at the centre of the layer, as a function of time. In spite of the drawbacks of model A Fig. 5 should provide an approximate estimate of the minimum initial thickness of the magma intrusion as a function of age, if it were to still remain molten inside. For an age of 35 years a minimum thickness of 40 m would be required.
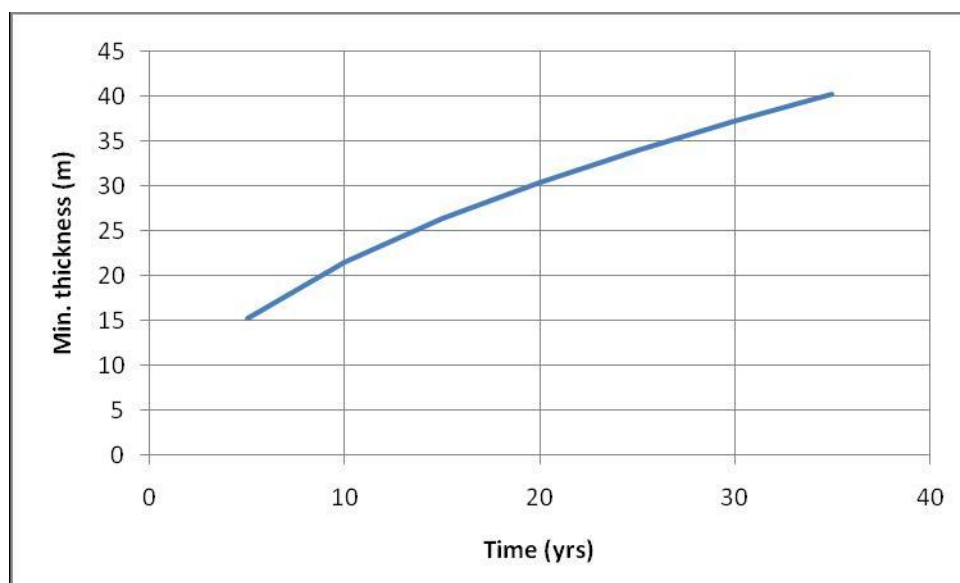

Figure 5. *Minimum thickness of the magma layer of model A, if it were still to be molten at its centre, as a function of time since its emplacement. Note that 25 – 35 years have passed since the last Krafla volcanic episode.*

Another model assumes the magma is so hot at intrusion that it doesn't solidify significantly during the time elapsed since the intrusion (model B). A solution to the associated mathematical problem can be found in Carslaw and Jaeger (1959). This situation may possibly be closer to the actual situation encountered at the bottom of the IDDP-well, since preliminary petrological results indicate that the magma, which is believed to be rhyolitic in nature, may have been as hot as 950°C or more at the time of emplacement while its' solidus temperature may only be about 700°C (Table 1). The estimated temperature conditions inside and above such a magma intrusion are shown in figures 6 and 7, at different times after emplacement, for different intrusion thickness (50 and 100 m, respectively).
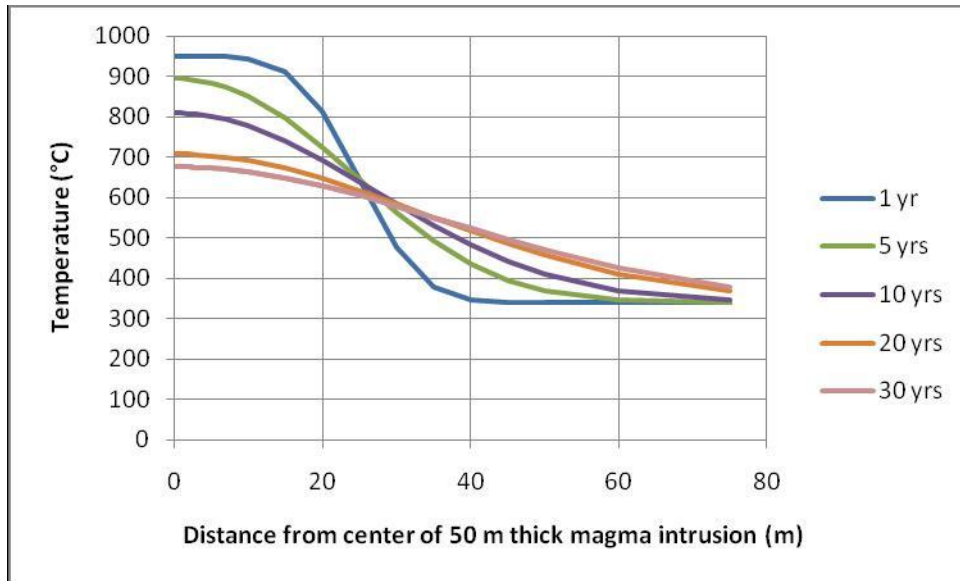

Figure 6. *Temperature conditions inside and above a 50 m thick intrusion emplaced at a temperature of 950°C in 350°C hot host rock (magma intrusion model B). Different curves apply to different times of emplacement.*
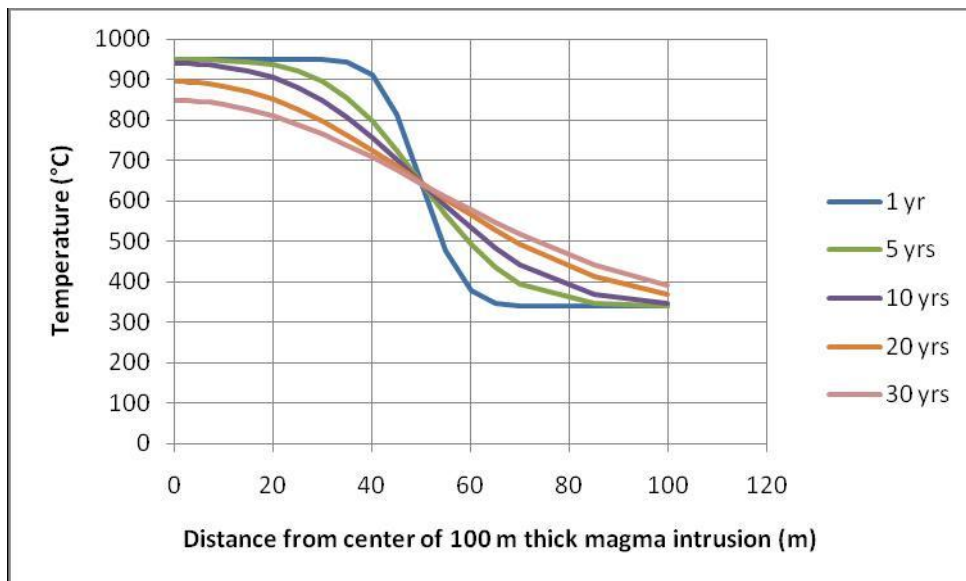

Figure 7. *Same as Fig. 6 except that intrusion is here assumed 100 m thick.*

This model is considered more realistic than model A, as already mentioned. It also conforms better with the idea of non-stationary/convective solidification of the magma mentioned above. But again the results can't be used to rule out completely the possibility that the magma was intruded during the Krafla volcanic episode. The figures predict somewhat higher temperature 30 m above the intrusion than the present temperature of about 400°C (see later), but the difference is really not any greater than the uncertainty in the model calculations. The slightly higher temperature may also indicate more efficient heat transfer in the permeable layer than by heat conduction alone, i.e. by the advection of water and steam, or even by superheated steam.

Model B can also help constrain the possible thickness of the magma intrusion. Fig. 6 shows that if the intrusion (sill) is only 50 m in thickness, its internal temperature would be way below its estimated temperature at present (Table 1) as well as being below the solidus temperature. In the case of 100 m thickness (Fig. 7) the internal temperature would still be approximately high enough.

The idea behind the thermal modelling with models A and B was to help determine whether the magma emplacement occurred during the last Krafla volcanic episode, 25 – 35 years ago, and also to help estimate how thick the intrusion could be. The main conclusion is that this can neither be confirmed nor refuted. The results from model B, however, seem to indicate that to maintain the present high internal temperature the intrusion needs to be relatively thicker than the minimum thickness indicated by model A, or at least 50 – 100 m. To rephrase this conclusion one could say that if such a thickness is considered unlikely, emplacement 25 – 35 years ago would also be unlikely. A final point worth mentioning is that both models demonstrate the extremely slow heating above the intrusion due to heat conduction alone.

3.2 Cooling due to Drilling Circulation Losses

The next item to consider (item (ii), see Chapter 2 above) is the cooling of the permeable layer between about 2040 and 2075 m depth, where most of the circulation losses occurred in the granophyric rocks near the bottom of the well. This is done by first assuming uniform cooling of a layer of constant thickness (35 m) and estimating how far into the formation the effect of the 4.5 months of circulation losses (at 30 l/s on the average) spread, i.e. up to what radial distance a cooling-front may have reached. The calculations were based on a model set up by Böðvarsson (1972), in which porous-media heat advection is assumed (heat conduction neglected because of short time-scale). Figure 8 presents the estimated cold-front radius as a function of the thickness of the permeable layer (see Table 1 for relevant properties). For the estimated thickness of 35 m the radial distance is estimated to be 76 m. Hence the estimated cooled volume equals 630,000 m^3. It should be mentioned that this approach involves a slight discrepancy because it assumes that the permeable layer is saturated with liquid water. In fact the layer is likely to have been saturated with superheated steam (see Section 3.4) instead.

This model is somewhat inaccurate as it neglects cooling of the impermeable rock above and below the layer, an inaccuracy which is not highly significant, however. It can be estimated roughly by estimating the thickness of a so-called boundary layer cooled by heat conduction from the hot impermeable rock on the outside into the permeable layer (see e.g. Turcotte and Schubert, 1982). It gives the approximate distance into the impermeable rock where the

temperature has dropped by 90%. Thus we estimate the cooled boundary layer of the impermeable rock to be about 5 m thick, on the average, on each side of the permeable layer. Thus the cooled layer effective thickness is estimated to equal approximately 45 m.
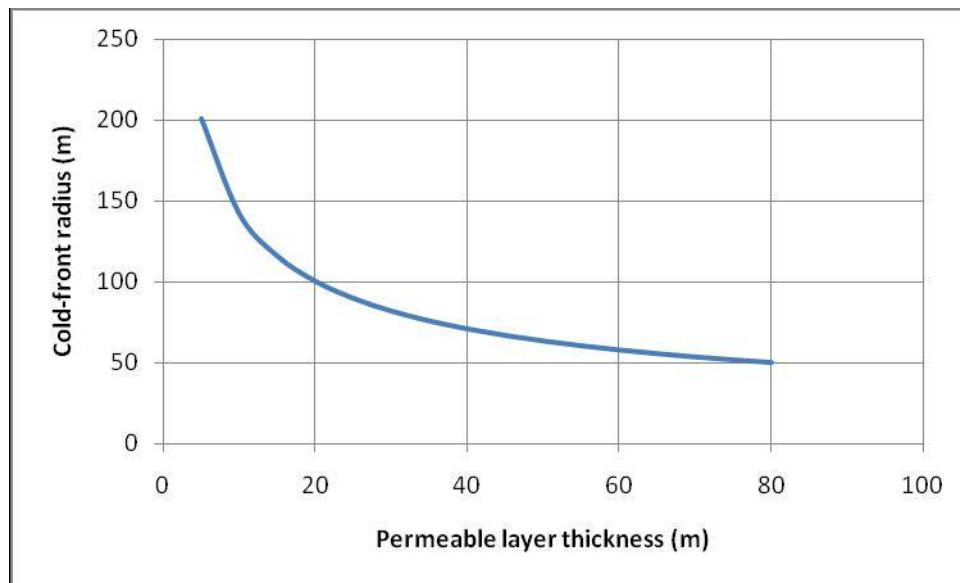

Figure 8. *Estimated radial distance to the cooling-front in the permeable layer, as a function of layer thickness, after 4.5 months of average 30 l/s circulation losses.*

3.3 Reheating after Drilling

The third item on the modelling list (item (iii), see Chapter 2) is the heating of the cooled layer during the thermal recovery of the well after drilling, as observed through temperature logging (Fig. 2). This is done by deriving a mathematical solution to the heat diffusion equation for an initially cold layer, of constant thickness, in otherwise hot rock (Axelsson, 2010). Applying the Laplace-transform method comes in handy here, but the solution can also be found in Carslaw and Jaeger (1959).

During this modelling phase the layer thickness and the undisturbed temperature of the permeable layer were adjusted until a satisfactory match between the observed data and model calculations was obtained. The results are presented in Fig. 9, which shows a very good correspondence between observed and modelled values. Note that the model assumes a 45 m thick "cooled layer", which corresponds very well with the results of Section 3.2, i.e. the fact that most of the circulation losses occurred between 2040 and 2075 m depth, approximately. To that 35 m thickness ~10 m can be added because of the 5 m cooled boundary layers on either side of the permeable layer.

3.4 Temperature Evolution during Discharge Testing

The fourth and final item on the modelling list (item (iv), see Chapter 2) is the heating up of the steam discharged by the well during the ~3.5 months of discharge testing. It should be noted that only some basic calculations have been done yet for this item, more complex modelling was beyond the scope of the present study, as already mentioned. This part of the modelling is principally based on the temperature- and pressure-log data available (figures 2 and 3) and data on the temperature of the steam discharged during the discharge testing of

well IDDP-1 (Fig. 4). Table 2 summarizes the main physical parameters of the well during three stages of the discharge test.
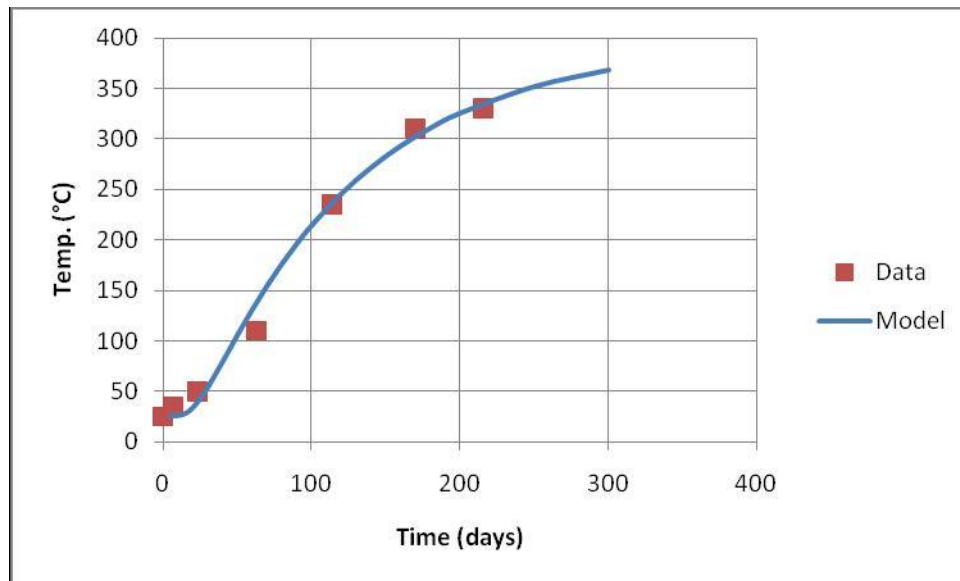

Figure 9. *Thermal recovery of well IDDP-1 after drilling, both observed (Fig. 2, at ~2070 m depth)) and simulated by a model of a cooled 45 m thick layer in a hot rock-mass (390°C). The calculated temperature is that in the centre of the layer. The 45 m layer thickness and 390°C yield the closest match between observed and calculated temperatures.*

Table 2. *Approximate physical parameters down-hole, and at well-head, for well IDDP-1 during different stages of the wells' discharge test. Down-hole conditions during discharge based on an estimated 10°C drop in steam temperature while flowing up the well (see later). The symbols T, p and h stand for temperature, pressure and enthalpy, respectively.*

	Location	T (°C)	p (bar-g)	h (kJ/kg)	Comment
At end of heating period	down-hole	345	160	1630	liquid near boiling
First days of discharge	down-hole	220	~23	2800	wet steam
	well-head	210	~19	2796	
At end of discharge	down-hole	390	~26	3217	superheated steam
	well-head	380	~22	3201	

It is clear that when the discharge test starts the feed-zones of the well between 2000 and 2100 m depth where approximately at boiling conditions. When the pressure in the well at the feed-zones drops, perhaps as low as to 20-30 bar, the feed-zones soon start yielding dry steam, and a boiling front starts propagating into the formation away from the well. At first the temperature of the steam is close to the boiling temperature at ~20 bar-g, but once the boiling/dry-steam front has propagated some distance from the well the steam flowing towards the well is heated by the rock, which is likely to be more than 150°C hotter than the steam. Thus the steam becomes superheated as it flows towards the well, and as the boiling/ dry-steam front propagates further away from the well the superheated steam picks up more heat from the rock.

Further away from the well, beyond the radius of influence of circulation loss cooling, the reservoir fluid is most likely steam at 160 bar-g and about 390°C. This would be superheated steam at an enthalpy of about 2900 kJ/kg. No direct contact with the magma is needed to explain the continuous heating of the steam up to the last month of the discharge test.

Another thing to keep in mind is that the 4.5 months of circulation losses may correspond to approximately the same mass of water as produced during the 3.5 month discharge test (less accurately known). Thus the water discharged towards the end of the discharge test may still have been mostly circulation water lost into the permeable layer. This contention may be assessed by studying the chemical composition of steam-samples collected during the discharge test. Any remaining circulation water should all have been converted to steam in-situ by now. It should be kept in mind, however, that the model proposed here may involve an oversimplification since some of the circulation water may have percolated (sunk due to gravity) to depths greater than that of the permeable layer and would, therefore, not have been recovered during the discharge.

The temperature of the steam appears to level off at about 380°C towards the end of the discharge test (Fig. 4). This is believed to indicate that the steam entering the well at this stage had reached the temperature of the formation at the feed-zone depth, when entering the well. To try to assess the inflow temperature, the cooling of the steam as it flows up the upper part of the well, which is colder than the steam, needs to be estimated. This can be done on the basis of a solution presented by Carslaw and Jaeger (1959), which equates the decline in the energy content of the ascending steam with heat-flow into the surrounding formation (Axelsson, 2010). Assuming that the steam is about 200°C hotter than the formation around the well in the top 1300 – 1500 m a cooling of the steam of the order of 15°C (±5°C) at the end of the discharge test is obtained. Thus the formation temperature appears to be close to 390 – 400°C, in good agreement with the results of modelling the heating up of the permeable layer (Section 3.3).

5. Conclusions

This paper has described the results of a series of simple modelling exercises involving the transient temperature conditions near the bottom of well IDDP-1. The modelling was broken up into the following phases:

(i)   Evolution of temperature conditions inside, and around, the magma intrusion since its emplacement.
(ii)   Cooling of a permeable layer above the magma due to circulation losses during drilling.
(iii)   Reheating of the permeable layer after drilling.
(iv)   Temperature evolution of the permeable layer, and the wells discharge, during discharge testing of the well in 2010.

It should be emphasised that the modelling is quite speculative, mostly because of limited data constraints, but the results indicate that the temperature conditions at the bottom of the IDDP well and the temperature evolution during drilling, temperature recovery and discharge can be explained by the model(s) proposed here. The main results are the following:

(1)   The possibility that the magma was emplaced during the Krafla volcanic episode 25 – 35 years ago can neither be confirmed nor refuted. If the intrusion is of that age a

thickness of at least 50 – 100 m would be required for the present high temperature to be possible, as well as a kind of "convective" solidification from below.

(2) The parameters best constrained through the modelling are considered to be the effective thickness of the permeable layer and its undisturbed temperature, about 45 m and 390 – 400°C, respectively, based on the re-heating of the layer and discharge test data.

(3) The superheated (up to 380°C) steam discharged during the output test of well IDDP-1 in 2010 is considered to have been mostly circulation water heated by the 390 – 400°C rocks of the permeable layer. No direct contact with the magma is needed to explain the high temperature obtained.

The situation near the bottom of well IDDP-1 clearly warrants further study, both because the modelling presented here was relatively simple and because further data-constraints would be highly important. More complex modelling could be applied, e.g. to model the discharge test data. Further data constraint may also be provided by additional petrological studies and chemical analyses of steam samples collected during the wells discharge.

The question whether well IDDP-1 can maintain the energy output (~15 MW$_e$), achieved during the 2010 discharge test, in the long-term, can unfortunately not be answered on basis of available data and the present modelling results. This boils down to whether "far-field" recharge into the permeable layer will be sufficient and whether large enough heat-exchange volumes and surfaces are available to heat the recharge (most likely at 340°C) to 390 – 400°C. This needs considerable further study as well as further discharge testing of the well with accurate monitoring of relevant flow parameters. It may be mentioned that carefully executed reinjection in the vicinity of the well may be the solution if the "far-field" recharge turns out not to be sufficient. This would in essence constitute a kind of EGS-operational scheme.

The work presented here was based on data available towards the end of 2010. A second flow test of the IDDP-well was started in May 2011. It started out with two brief test episodes in May and August while in late September 2011 continuous discharge testing, under restricted flow-conditions, started. This last testing phase was on-going up to the summer of 2012, apart from some brief interludes for maintenance and other activity.

The monitoring data from the second discharge test was not taken into account in the modelling study discussed here as it was collected after the completion of the study. The results of the test can be compared with the modelling results, however, in particular the results of Section 3.4. During the present discharge phase (starting late September 2011) the steam flow has been restricted to make the testing more easily manageable and has varied between 6 and 12 kg/s at a well-head pressure of about 140 bar. Surprisingly the temperature of the steam has now been drastically higher than during the first test, or between 400 and 450°C.

This high temperature of the steam discharged contradicts the results of Section 3.4, with two possible explanations coming to mind: (a) That some changes have occurred in conditions in the productive layer intersected by the well above the magma intrusion since 2010, perhaps more direct access to the thermal energy of the intrusion. (b) That the simple model used here doesn't catch the nature of the heat transfer in the permeable layer accurately enough. This reveals that the situation needs further study, including more accurate modelling, which is beyond the scope of the present study. It may be mentioned that a Horner analysis

of the temperature recovery after drilling (Fig. 11) indicates an equilibrium temperature as high as 500°C. The lower limit of the equilibrium temperature indicated by the Horner-method is close to 400°C, however, reflecting the uncertainty in the analysis.

Acknowledgements

Bibliography

Axelsson, G., 2010: Temperature condition modelling for well IDDP-1. Landsvirkjun/Iceland GeoSurvey report LV-2010/119 / ÍSOR-2010/051, 27 pp.

Axelsson, G., Th. Egilson, S.S. Gylfadóttir, 2012: Modelling of temperature conditions near the bottom of well IDDP-1 in Krafla, N-Iceland. Submitted to *Geothermics*.

Bagdassarov, N.S. and D.B. Dingwell, 1994: Thermal properties of vesicular rhyolite. *Journal Volc. Geotherm. Res.*, **60**, 179–191.

Bödvarsson, G., 1972. Thermal problems in the siting of reinjection wells. *Geothermics*, **1**, 63-66.

Carslaw, H.W. and J.C. Jaeger, 1959. *Conduction of Heat in Solids*. Second Edition, Claredon Press, Oxford, 403 pp.

Elders, W.A. and G.Ó. Fridleifsson, 2010. The science program of the Iceland Deep Drilling Project (IDDP): A study of supercritical geothermal resources. *Proceedings World Geothermal Congress 2010*, Bali, Indonesia, 25-29 April, 9 pp.

Fridleifsson, G.Ó., A. Albertsson and W.A. Elders, 2010a. Iceland Deep Drilling Project (IDDP) – 10 years later – Still an opportunity for international collaboration. *Proceedings World Geothermal Congress 2010*, Bali, Indonesia, 25-29 April, 5 pp.

Fridleifsson, G.Ó., B. Pálsson, B. Stefánsson, A. Albertsson, E. Gunnlaugsson, J. Ketilsson, R. Lamarche and P.E. Andersen, 2010b. Iceland Deep Drilling Project. The first IDDP drill hole drilled and completed in 2009. *Proceedings World Geothermal Congress 2010*, Bali, Indonesia, 25-29 April, 4 pp.

Hólmgeirsson, S., Á. Gudmundsson, B. Pálsson, H.Á. Bóasson, K. Ingason and S. Thórhallsson, 2010. Drilling operations of the first Iceland deep drilling well (IDDP). *Proceedings World Geothermal Congress 2010*, Bali, Indonesia, 25-29 April, 10 pp.

Mortensen, A.K., Á. Gudmundsson, B. Steingrímsson, F. Sigmundsson, G. Axelsson, H. Ármannsson, H. Björnsson, K. Ágústsson, K. Saemundsson, M. Ólafsson, R. Karlsdóttir, S. Halldórsdóttir and T. Hauksson, 2009. Jarðhitakerfið í Kröflu – Samantekt rannsókna á jarðhitakerfin og endurskoðað hugmyndalíkan (The Krafla geothermal system – compilation of research findings and revised conceptual model). Iceland GeoSurvey, report ÍSOR-2009/057 (in Icelandic), 209 pp + 2 maps.

Stacey, F.D., 1977. *Physics of the Earth*. John Wiley & Sons, New York, 414 pp.

Turcotte, D.L. and G. Schubert, 1982. *Geodynamics. Applications of Continuum Physics to Geological Problems*. John Wiley & Sons, New York, 450 pp.