Temperature Prediction by Multigeophysical Inversion: Application to the IDDP-2 Well at Reykjanes, Iceland

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Keywords
Exploration, geology, geophysics, IDDP, inversion, rock physics, temperature

ABSTRACT
The target of the RN-15/IDDP-2 well at Reykjanes is geothermal resources at supercritical temperatures. The drill site has been mapped by electromagnetic and gravimetric surveys. Here, a method for subsurface temperature prediction by multigeophysical inversion is presented and demonstrated on the IDDP-2 drill site. Using resistivity from magnetotelluric inversion and density from gravity inversion, followed by Bayesian rock-physics inversion, the predrill prediction of temperature was 513± 62 oC at 5 km vertical depth along the planned well path. While-drilling updates using resistivity logs, acquired at approximately 2900m and 3450m depth, indicate that the formation temperature is most likely on the high side of the predrill estimate. The well was drilled down to approximately 4500m, and cores were taken at selected depths. The temperature predictions from geophysical data are within temperature ranges indicated by alteration minerals observed in the cores and changes in rock parameters based on well description.

1. Introduction
Supercritical water has higher enthalpy and lower viscosity compared to a two-phase liquid-vapor mixture at subcritical temperatures. The goal of the Iceland Deep Drilling Project (IDDP) is to prove the existence of a geothermal system at supercritical conditions (Friðleifsson et al., 2005). The supercritical transition is at 374 °C and 22 MPa for fresh water, and ~400 °C for brine, depending on salinity. This requires significantly deeper boreholes than conventional geothermal wells.

The first well with a supercritical target, IDDP-1, was drilled in 2008-2009 near the Krafla volcano in Northeast Iceland. The IDDP-1 well hit a shallow magma chamber, and never reached the target depth of 4-5 km. For the second well, IDDP-2, the Reykjanes geothermal field was chosen as drill site due its favorable geological conditions.
The geothermal system at the Reykjanes is located at the tip of the Reykjanes peninsula, in the southwest part of Iceland. The field situates between two active plate boundaries, in the location where the Mid-Atlantic Ridge rises from the oceanic floor. This coincides with the complex geological setting, at the same time forming a good geothermal production location. More than 30 production and injection wells have been drilled, targeting the conventional geothermal system, at depths less than 3000m, where temperature is limited by the boiling curve of water.

The drill site for IDDP-2 was chosen based on previous drilling experience, and interpretation of a 3D magnetotelluric (MT) inversion cube (Friðleifsson et al., 2014a, 2014b). It was decided to reuse well RN-15, drilled in 2004, for the upper 2500m of IDDP-2. The drilling started in August 2016, and was finished January 2017. The well was drilled to 4659 m measured depth (MD). Further details are presented by Friðleifsson and Elders (2017).

For geothermal exploration in general, it is useful to predict the depth and temperatures of potential reservoir targets. For the IDDP-2 well in particular, it is of great interest to obtain an estimate of the drilling depth needed to fulfill the main objective of the project; reaching supercritical conditions. There is no reflection-seismic data available in the area to build a structural framework. Also, limited amount of core material was recovered. Hence, subsurface information must be assessed from other types of geophysical and geological data, including well and drilling data to characterize rock units in the well.

In this paper, a multigeophysical inversion method for prediction of subsurface temperature is presented. Electric resistivity from MT inversion and density from gravity inversion were used to compute a predrill estimate of formation temperature for the IDDP-2 drilling target. Resistivity logs and core samples acquired while drilling were used to update the temperature estimate and to build a geological model. This information was subsequently passed on to the reservoir engineers for simulation of the hydrothermal system.

2. Multigeophysical inversion method

![Figure 1: Bayesian network representing the temperature dependence of geophysical model parameters and geophysical data. Here $\sigma$ is electric conductivity, $\chi$ is magnetic susceptibility, $\rho$ is density, $v_p$ is seismic P-wave velocity and $v_S$ is seismic S-wave velocity.](image)
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Hokstad et al (2016, 2017) presented a multigeophysical inversion method for estimation of radiogenic heat production in the crust. The purpose of their work was to compute basal and surface heat flow for petroleum exploration. Here, a similar approach is used for direct estimation of subsurface temperature for geothermal applications. A statistical model is constructed for the dependence of geophysical model parameters on temperature, and in turn, the dependence of geophysical data on geophysical model parameters. This can be represented as a Bayesian network, as shown in Figure 1. The first set of dependencies are given by various rock physics relations. The 2nd set of dependencies is given by differential equations, such as the Maxwell equations of electromagnetics, Newton’s law of gravity, and the elastic wave equation.

Going from the top to the bottom of the Bayesian network constitutes forward modeling, i.e., computing synthetic geophysical models and data, given a subsurface temperature distribution. More interesting is to go from the bottom to the top, performing Bayesian inversion. By inversion, we want to compute geophysical model parameters and subsurface temperature, given observed geophysical data. A pragmatic approach is taken, such that we can utilize geophysical models obtained with various geophysical inversion methods, and computed by different groups of geophysicists and service providers. Hence, we focus the Bayesian inversion on the second stage of the inversion, computing subsurface temperature from 3D geophysical models. This is effectively a rock-physics inversion.

Given the Bayesian network (Figure 1), and assuming conditional independence between the nodes not connected by arrows, the posterior probability distribution for the temperature can be written as

$$p(T|m_1, ..., m_n; \varphi) = C \prod_{i=1}^{n} p(m_i|T; \varphi) p(T), \#(1)$$

where $T$ is temperature, $m_i$ are the geophysical model parameters of interest, $C$ is the normalization constant, and $\varphi$ is porosity. The porosity can be treated as a stochastic variable (in the same way as temperature $T$), however, in the present work, the porosity is assumed to be a hyperparameter, with a given deterministic value. The prior distribution for temperature is denoted $p(T)$.

One or more geophysical parameters can be used to compute the posterior distribution. We can for instance use electric conductivity (or resistivity) alone. However, as is evident from Equation 1, the product of two (or more) likelihood functions makes the posterior distribution narrower. This implies better posterior mean and smaller variance.

Assuming Gaussian errors, the likelihood distribution for each geophysical parameter, can be written as

$$p(m_i|T; \varphi) = \frac{1}{\sqrt{2\pi |\Sigma_{e_i}|}} e^{-\frac{1}{2} [m_i - F_i(T;\varphi)]^T \Sigma_{e_i}^{-1} [m_i - F_i(T;\varphi)]}, \#(2)$$

where $F_i(T; \varphi)$ is the rock-physics relation for the dependence of model parameter $m_i$ on temperature, and $\Sigma_{e_i}$ is the corresponding error covariance. In this way, we account for the fact that the rock physics models are not perfect representations of the subsurface properties.
Equation 2 is a Gaussian distribution for model parameter $m_i$ only if the forward model $F_i(T; \varphi)$ is a linear function of $T$. This is not the case in general. In principle, we can utilize both electromagnetic data, potential-field data and seismic data. In the present work, only electric conductivity $m_1 = \sigma$ (or its inverse; resistivity) and density $m_2 = \rho$ are utilized. The corresponding rock physics relations are denoted $F_1(T; \varphi) = \sigma(T; \varphi)$ and $F_2(T; \varphi) = \rho(T; \varphi)$.

Electric conductivity (or resistivity) is the geophysical parameter that has the most direct response to temperature variations. The rock physics model for conductivity $\sigma(T; \varphi)$ was designed as a fraction-weighted parallel coupling of (1) non-porous (dry) basaltic rock, (2) clay minerals from hydrothermal alterations and (3) fractures filled with water (brine). The temperature dependence of basaltic rocks is obtained by log-linear regression of conductivity vs. inverse temperature $1000/T$ (Figure 2), using the experimental data presented by Mostafa et al. (2003). Their core measurements suggest that the temperature dependence of conductivity of dry basalt $\sigma_B(T)$ is given approximately by the sum of two Boltzmann distributions (Arrhenius equations),

$$\sigma_B(T) = \sigma_1 e^{-E_1/k_B T} + \sigma_2 e^{-E_2/k_B T}, \tag{3}$$

where $k_B$ is the Boltzmann constant, and $\sigma_j$ and $E_j$ (for j=1,2) are calibration parameters. $E_j$ play the role of activation energies for two temperature-dependent conduction mechanisms.

The conductivity of the clay is modeled using the familiar Waxman-Smits equation (Mavko et al., 2009; Usher et al., 2000). Particularly important is to account for the cation-exchange effect in smectite, at relatively shallow depth and low temperatures, below 220 °C (Karlsdóttir et al.,...
2012). The porosity of the basalt is assumed to be dominated by fractures. The fracture conductivity can be approximated by the relation published by Brace et al. (1965), with temperature-dependent water conductivity.

The rock-physics model for density $\rho(T; \varphi)$ is constructed in a similar way, using the relations presented by Hacker et al. (2003), and temperature-dependent water density in the fractures.

3. Temperature prediction for the IDDP-2 well

The drill-site selected for the IDDP-2 well was mapped by a 3D MT survey, with receivers distributed on an approximately 5x5 km$^2$ grid (Figure 3). 3D MT inversion was performed by Iceland Geosurvey (ÍSOR), using the minimum-norm (data-space Hessian) 3D MT inversion of Siripunvaraporn et al. (2005). Inversion of transient electromagnetic (TEM) data was used to obtain independent estimates of shallow resistivity, and to correct the MT data for static shifts, caused by near-surface galvanic currents. The details of the MT and TEM inversion are described by Karlsdóttir et al. (2012).

![Figure 3: Resistivity from 3D MT and TEM inversion. Horizontal slice at 5km depth (left). Vertical section in the plane of the IDDP-2 well (right). The gray line is the predrill well plan. The shallow low resistivity zone at depths less than 3 km is due to smectite from hydrothermal alteration.](image)

The shallow low-resistivity zone, at depth less than 1.5 km (Figure 3), is caused by the high cation-exchange capacity of smectite. At temperatures between 220 °C and 260 °C, chlorite with higher resistivity, becomes the dominating alteration mineral (Franzson et al., 2002). At depths
larger than 3 km, a high-resistive zone, assumed to be associated with sheeted dykes and diabase, is observed. The target of the IDDP-2 well is a zone of reduced resistivity within the high resistive zone, between 3 and 5 km depth.

Gravity surveying has been performed on the Reykjanes Peninsula for the purpose of monitoring the subsidence of the spreading ridge by time-lapse gravimetry (Guðnason et al., 2015). The most recent gravity survey, from 2014, was utilized for temperature prediction at the IDDP-2 drill site. The local gravity data was processed by complete Bouguer corrections, including terrain correction. The local data was then merged with a regional Bouguer anomaly map, to obtain sufficient aperture (15x15 km²) for 3D inversion (Figure 4).

Gravity inversion is generally ill-posed, and needs to be regularized. Therefore, a density model for the upper zone, down to approximately 2500m, was built using borehole data from the wells in the Reykjanes geothermal area. The gravity response of the upper zone was modeled and subtracted, to isolate the gravity anomaly associated with the deeper zone of interest. The residual was then inverted for density in the deeper zone, from 2500m to 7000m. A Marquardt-Levenberg type 3D inversion scheme, implemented in Matlab, was used to perform the gravity inversion (Hokstad et al., 2017).

Figure 4: Bouguer anomaly (left), covering three-times the horizontal extent of the output cube in both directions. Local gravity data from Reykjanes (circles) were merged with a regional gravity map to obtain aperture for the inversion. Vertical section from the 3D density cube from 3D gravity inversion in the plane of the IDDP-2 well (right). The gray line is the predrill well plan.

Also, a porosity vs depth trend is needed for the rock-physics inversion. Little hard information about porosity in the Reykjanes geothermal area has been published in the literature (Axelsson et
Data for the porosity is only known for the upper ca 2000 m (Franzon et al., 2002). Assuming an exponential trend (Sclater and Christie, 1980), neutron capture logs from vintage wells were used to estimate a porosity trend (Brown and Bowers, 1958). The porosity trend was calibrated such that the rock-physics model reproduced approximately the temperature-corrected (Arp’s formula) resistivity log from the RN-15 well, given measured formation temperature from the 2010 maintenance stop. The temperature-corrected resistivity log is in good agreement with the resistivity trend from 3D MT inversion (Figure 3). Also, a synthetic density log was computed and used to calibrate the absolute level of the density cube from 3D gravity inversion (Figure 4). In this way, we obtained a set of subsurface parameters $\sigma$, $\rho$ and $\phi$ consistent with the rock physics models down to 2.5 km depth (Figure 5).

The resistivity model from MT inversion (Figure 3), the density model from gravity inversion (Figure 4), and the porosity vs. depth trend (Figure 5), were input to the Bayesian inversion scheme. The prior model for temperature vs. depth was chosen close to the boiling curve down to 2.5 km depth, and then increasing with 80 °C/km. The inversion has proven to be quite robust, and the value of the prior temperature is not important. Hence, a relatively vague prior for temperature, with variance of 400 °C could be used in the Bayesian inversion.

From the multigeophysical inversion (Figure 6), the well was predicted to reach supercritical conditions ($T>400$ °C) at approximately 4 km depth. The predrill estimate for the planned TD of the well was 513 ± 62 °C at 5 km vertical depth. Reykjanes is in an active sea-floor spreading
zone, and earthquakes of magnitude 2 and less occur regularly. The earthquakes are expected to diminish in the ductile zone, starting at about 600 °C (Friðleifsson et al., 2014a). This is in fair agreement with the predrill temperature predictions. The estimated source locations of all earthquakes (prior to drilling) are above the 500 °C isotherm from the inversion (Figure 6).

The drilling of the RN-15/IDDP-2 well started in August 2016. During the drilling period, the temperature in the well was measured regularly. Also, wireline logging of resistivity, neutron capture and gamma ray was performed acquired tripping at 2900m and 3450m measured depth (MD). Cold water was used as drilling fluid. Because of the cooling effect of the injected water, the resistivity logs do not record true formation resistivity. Using measured temperatures, neutron logs, and tie to the RN-15 logs in overlapping intervals, the resistivity logs were adjusted to approximately represent the formation resistivity trend. Different correction methods were used, including empirical re-scaling, and corrections based on analytical solutions to the heat equation in cylindrical coordinates. The temperature-corrected resistivity log was used to rerun the inversion for temperature along the planned well path. The results are uncertain due to the uncertainty involved in the log corrections. However, the while-drilling updates indicate that the formation temperature is 50-100 °C higher than the predrill prediction (Figure 7).

Figure 6: Predrill prediction of temperature by multigeophysical inversion. Horizontal slice at 5km depth (left). Vertical section from the 3D temperature cube in the plane of the IDDP-2 well (right). Black lines indicate the 400 °C, 500 °C and 600 °C isotherms. The gray line is the planned well path, and the blue line is the actual well path from gyro surveying. White squares indicate source locations of earthquakes detected by the seismic array at Reykjanes.
A number of core runs were performed to collect samples of the drilled rocks. The cores were used to identify alteration minerals, and to obtain rough constraints on maximum temperatures (Zierenberg and Elders, 2016). The core runs, however, cover only very small part of the drilled well section.

The described well section and core descriptions, together with the temperature estimates from the multigeophysical inversion, were used to construct, and continuously update a geological model for the IDDP-2 borehole (Figure 8).

Combined data in the geological model supports the temperature predictions suggested by multigeophysical inversion. Several changes in rock parameters have been described to occur during the major temperature changes, most notably reaching of 400 °C and 500 °C further supporting temperature predictions made for the Reykjanes geothermal area (Figure 8).

Figure 7: Temperature predictions and measurements along the IDDP-2 well: Predrill prediction (posterior mean) from multigeophysical inversion extracted from the 3D temperature cube along the planned well path (black line). While-drilling update from inversion (blue) with uncertainty bounds (posterior variance; dotted blue lines). Temperatures measured while drilling (red). Temperature measured in January 2017 after two days of reduced water injection (magenta). Temperature measured in the RN-15 well while drilling (yellow) and during 2010 maintenance stop (green).
The drilling of the well was completed 25th January 2017. On the 3rd of January, a new temperature log was run, measuring 426 °C at ~4550 m MD (Figure 7), after only about 6 days of heating at the bottom. The kinks in the measured temperature curves are associated with high-permeability loss zones.

4. Discussion and conclusions

A method for geothermal temperature prediction was presented and demonstrated on the IDDP-2 drill site on Reykjanes. Estimated temperature is in good agreement the most recent temperature log (acquired 3. January 2017), and with geochemical indications from alteration minerals, and with changes in rock parameters. To build a 3D geological model and structural framework is difficult due to lack of reflection seismic data.

The proposed method is based on inversion of geophysical data, followed by Bayesian rock physics inversion for direct temperature estimation. The geophysical parameter that responds most directly to changes in formation temperature is electric conductivity (or resistivity). MT data are well suited due to the wide range of frequencies in the source field (i.e. the interaction between the sun and earth magnetic field). The low-frequency part of the source field is needed to image targets down to 5-6 km depth. However, due to the electromagnetic skin effect, only a low-resolution image can be obtained.

Density from gravity inversion is useful to reduce the posterior uncertainty of the method. Also a porosity vs depth trends is important input to the rock physics inversion. A relative reduction of electric resistivity and density can be caused by either increased porosity or increased temperature. Hence, there is an inherent ambiguity in the inversion. The true formation temperature is still unknown at the time of writing.
Magnetic susceptibility and seismic P-wave and S-wave velocities can also be utilized, but this was not done in the present study. The proposed method has been calibrated for and demonstrated on mid-oceanic ridge basalts (MORB). Application to other tectonic and geological settings will require recalibration of the rock physics models used in the inversion.

5. Acknowledgements

We thank numerous colleagues for discussions and advice, including: Bjørn Berger, Jostein Alvestad, Keshvad Goodarzi, Günther Kampfer, Sturla Sæther, Carsten F. Sørlie and Bjørn M. Sæther (Statoil), Guðmundur Ómar Friðleifsson and Ómar Sigurðsson (HS Orka), Ragna Karlsdóttir, Steinþór Níelsson and Tobias Weisenberger (ÍSOR), and Robert Zierenberg (UC Davis).

We thank Ragna Karlsdóttir (ÍSOR) for providing the resistivity cube from MT inversion, HS Orka for providing the gravity data, and Zuzana Alasonati Tašárová (Statoil) for doing the Bouguer corrections and merge of gravity data.

Thanks to Statoil and HS Orka for permission to publish this work.

The Iceland Deep Drilling Project (www.iddp.is) is supported by DEEPEGS (www.deepegseu).

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