BOOK
OF PUBLICATIONS
PART 1
Acknowledgements: This document is aimed to acknowledge the scientific work achieved by DEEPEGS Team during the lifespan of the Horizon 2020 funding. It has been developed by DEEPEGS Coordinator and Project Office in close cooperation with the DEEPEGS Consortium.

Disclaimer: This book of publication is part of the DEEPEGS project dissemination work and is a published report for the final project reporting only and not for commercial use. The book of publications summarises the DEEPEGS consortium teamwork focusing on the scientific stage, covering input of scientific journal articles, proceedings and abstracts published by the consortium members in different journals and conferences in the period of 2016-2020. No part of this publication can be reproduced, sold, stored in a retrieval system or transmitted in any form or by any other means, electronic, photocopying, recording or otherwise without prior written permission of the publisher.

Any views or opinions that may be presented in this publication are solely DEEPEGS project-related and belong solely to the project owner and do not represent those of people, institutions or organizations that the owner may or may not be associated with or those part of the DEEPEGS consortium, in any professional or personal capacity unless explicitly so stated. None of the views or opinions are intended to malign any religion, ethnic group, club, organization, company, or individual.

Editors

Coordinator: Guðmundur Ómar Friðleifsson gof@iddp.is;
Project Manager: Sigurður Grétar Bogason sigurdur@georg.cluster.is;
Project Office: Alicja Wiktoria Stokłosa aws@georg.cluster.is;
Hjalti Páll Ingólfsson hpi@georg.cluster.is

Published by DEEPEGS Project Office

Design and layout by Tomasz Urban, GEORG Geothermal Research Cluster

For information, address DEEPEGS Project Office, Grensasvegur 9, 108 Reykjavik, Iceland

The DEEPEGS project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 690771.
Foreword by Coordinator

In our DEEPEGS proposal to European Union Horizon 2020, we stated that our goal with the DEEPEGS project was to demonstrate the feasibility of enhanced geothermal systems (EGS) for delivering renewable energy for the European citizens.

The testing of technologies for stimulating EGS in deep drilling in different geologies was meant to deliver new innovative solutions and models for wider deployments of EGS reservoirs, with high enough permeability for delivering significant amounts of geothermal power across Europe. Being aware of social concerns about EGS deployments in Europe, we intended to address those concerns for social acceptance in a proactive manner, where the environment, health and safety issues were prioritised. Through risk analysis and hazard mitigation plans, we meant to ensure that relevant understanding of the risks and how they can be minimised could be implemented as part of the science and technological approaches, and as a core part of the business case development.

So how did we progress?

The DEEPEGS project had selected and intended to demonstrate advanced technologies in the three types of geothermal reservoirs in different geological conditions. We intended to demonstrate the applicability of EGS for deep heat in (A) high enthalpy site in Iceland beneath existing hydrothermal field at the Reykjanes volcanic environment with expected temperatures at 5 km depth up to 500-600°C, and (B) in very deep hydrothermal reservoirs in southern France at Valence, in crystalline and sandstone environment, and Vistrenque, in limestone environment with temperatures up to 220°C. For a while, the French team dealt with Valence, but it soon became evident that the latter site would not get the social acceptance needed. Therefore, the project team sought approval to INEA to replace it with a geothermal site near Riom, in central France, which was accepted. Research and preparation at both sites continued for a while. However, things didn’t exactly go to plan; delays accumulated in getting the necessary permits for drilling and field testing, and as time passed, the DEEPEGS team was informed that none of the target fields would be greenlighted. Therefore, to proceed with the intended work, the consortium applied to INEA to substitute the two targeted fields with a geothermal site in Vendenheim, Alsace, which was accepted. The 2nd well there was drilled in 2019 and will be tested in May-June 2020 after DEEPEGS finishes. Accordingly, published data from the French sites are significantly fewer than publications from the Reykjanes demonstration site in this Book of Publications.

Deep drilling at the Reykjanes demonstration site in SW-Iceland, proceeded normally in 2016 and 2017. An existing 2.5 km deep production well, RN-15, was deepened as the IDDP-2 hole down to 4,650 m. This was followed by deep stimulation effort until July 2017. After retrieving the stimulation string from the well, damage at 2.3-2.4 km depth was discovered in the production casing. This caused an almost one-year delay in moving forward with a discharge test, which was to be followed by a pilot test for energy production and/or reinjection. These tests should have been ongoing now, at the end of the DEEPEGS project. Still, unforeseen blockage of some sort at ~780 m depth hinders the progress so we will not be able to complete the DEEPEGS project as anticipated, in a timely fashion. Despite these misgivings, the data already gathered from the Reykjanes site is plain and simply unprecedented economically and scientifically and reflected here in the Book of Publication by a considerable number of scientific publications and proceedings. The Reykjanes site met almost all the set goals in DEEPEGS, and the results will have a profound effect on the future development of deep-rooted high enthalpy geothermal systems worldwide.

Amongst the highlights are the following:

- The Reykjanes Geothermal Reservoir has almost doubled in volume due to proven deep permeability,
- Permeable supercritical system up to ~600°C hot was penetrated below 4 km depth, and
- Creation of Deep EGS systems appears to be attainable by deep drilling and by thermal contraction alone in superhot (>400°C) geothermal systems.
Avant-propos du coordinateur

Dans notre projet DEEPEGs proposé au programme européen Horizon 2020, nous annonçons que notre objectif était de démontrer la faisabilité de systèmes géothermiques améliorés (EGS) pour fournir de l'énergie renouvelable aux citoyens européens.

La mise à l'essai de technologies dédiées à la stimulation de systèmes géothermaux profonds dans différents contextes géologiques devait apporter des solutions nouvelles et des modèles innovants pour un déploiement plus large de l'exploitation des réservoirs EGS, grâce au développement d'une perméabilité suffisante qui aurait permis de fournir des quantités importantes d'énergie d'origine géothermique à travers l'Europe. Conscients des préoccupations sociales liées aux déploiements d'EGS en Europe, nous avions l'intention d'y répondre de façon proactive, en donnant la priorité aux questions environnementales, sanitaires et relatives à la sécurité des personnes et des biens. Nous voulions garantir une compréhension pertinente des risques et de la manière dont ils peuvent être minimisés grâce à une analyse et une mise en œuvre de plans d'atténuation des risques complètement intégrées dans les approches scientifiques et technologiques et au cœur du développement de l'analyse commerciale.

Et maintenant, où en sommes-nous?

Le projet DEEPEGs avait été sélectionné et visait à démontrer des technologies avancées dans trois types de réservoirs géothermiques dans différents contextes géologiques. Nous avions l'intention d'y répondre de façon proactive, en donnant la priorité aux questions environnementales, sanitaires et relatives à la sécurité des personnes et des biens. Nous voulions garantir une compréhension pertinente des risques et de la manière dont ils peuvent être minimisés grâce à une analyse et une mise en œuvre de plans d'atténuation des risques complètement intégrées dans les approches scientifiques et technologiques et au cœur du développement de l'analyse commerciale.

Le projet DEEPEGs avait été sélectionné et visait à démontrer des technologies avancées dans trois types de réservoirs géothermiques dans différents contextes géologiques. Nous avions l’intention de démontrer l’applicabilité des EGS dans des réservoirs profonds et chauds dans (A) un contexte de haute enthalpie, en Islande, sous le champ hydrothermal existant de la zone volcanique de Reykjanes, avec des températures attendues jusqu’à 500-600°C à 5 km de profondeur, et, (B) dans des réservoirs hydrothermaux profonds dans le Sud de la France à Valence, à l’interface entre le socle cristallin et les sédiments gréseux, et à Vistrenque, dans un contexte sédimentaire carbonaté, avec des températures allant jusqu’à 220°C. L’équipe française a initié les travaux sur les démonstrateurs français dès le lancement du projet; cependant, il est vite devenu évident que Vistrenque n’aurait pas l’acceptation sociale nécessaire.
à la poursuite des travaux. L’équipe projet a demandé par conséquent l’approbation de l’INEA pour remplacer Vistrenque par un site géothermique près de Riom, dans le centre de la France ; ce qui a été accepté. Les travaux de recherche et de préparation des deux sites français ont encore continué pendant un certain temps. Toutefois, les choses ne se sont pas exactement déroulées comme prévu : les retards se sont accumulés pour obtenir les permis nécessaires aux forages et aux essais, et avec le temps, l’équipe de DEEPEGS a été informée qu’aucun des champs géothermiques ciblés ne recevrait d’autorisation de forage dans les délais du projet. Par conséquent, dans l’optique de poursuivre les travaux prévus, le consortium a demandé à l’INEA de remplacer les deux sites ciblés par un autre, à Vendenheim, en Alsace ; ce qui a été accepté. Le second puits de Vendenheim a été foré en 2019 et sera testé en mai-juin 2020, après la fin du projet DEEPEGS. En conséquence, le volume de données publiées dans ce Livre des Publications sur le site français est beaucoup moins important que celui des publications relatives au démonstrateur de Reykjanes.

Le forage profond du démonstrateur de Reykjanes, dans le sud-ouest de l’Islande, s’est déroulé normalement en 2016 et 2017. Un puits de production préexistant de 2,5 km de profondeur, RN-15, a été approfondi jusqu’à 4 650 m et est devenu le forage IDDP-2. S’en est suivi la mise en œuvre de stimulations jusqu’en juillet 2017. Après avoir retiré le matériel utilisé pour la stimulation du puits, des dommages dans le tubage de production ont été découverts à une profondeur de 2,3 à 2,4 km. Cela a entraîné un retard de près d’un an dans la réalisation d’un test de décharge, qui devait être suivi d’un test pilote de production et/ou de réinjection. Ces tests auraient dû être en cours à présent que nous arrivons à la fin du projet DEEPEGS. Un blocage imprévu d’une autre origine, vers ~780 m de profondeur, entrave encore l’avancée des travaux ; nous ne pourrons donc pas achever le projet DEEPEGS comme prévu, en temps et en heure. Malgré ces soucis, les données déjà recueillies sur le site de Reykjanes sont importantes et simplement sans précédents sur le plan scientifique et économique, ce qui se reflètent ici, dans le Livre des Publications, par un nombre considérable de publications et actes de congrès scientifiques. Le site de Reykjanes a quasiment atteint tous les objectifs fixés dans DEEPEGS, et les résultats affecteront profondément le développement futur des systèmes géothermiques profonds à haute enthalpie dans le monde entier.

Parmi les faits les plus marquants, on peut retenir que :

- le réservoir géothermique du champs de Reykjanes a presque doublé de volume en raison d’une perméabilité profonde prouvée,
- un système supercritique perméable, à une température maximale de ~ 600°C, a été atteint en dessous de 4 km de profondeur,
- la création de systèmes EGS profonds dans les systèmes géothermiques superchauds (> 400 °C) apparaît réalisable grâce à un forage profond et par contraction thermique seulement.
DEEPEGS project key findings

DEEPEGS project

Number of partners: 10
Participating countries: 5
Reached audience: 10,000
Project duration: 53 months
Women vs Men workforce: 43%
Site locations: 2

Reykjanes site

Drilling operation: 168 days
Drilled depth: 4659 m
Total loss of circulation: until end
Temperature logged: 426°C
Pressure logged: 340 bar
Enthalpy of deepest fluid: 3,300 KJ/kg
Potential power output: 30MW
Lost time incident & personal injury: 0
Environmental incidents: 0

Vendenheim site

Drilling operation VDH GT1: 253 days
Drilling depth VDH GT1: 5280mD
Drilling operation VDH GT2: 282 days
Drilling depth VDH GT2: 6312mD
Temperature achieved: <225°C
Flow reached: 450 m³/h
Lost time incident & personal injury: 0
Environmental incidents: 0
CONTENTS

Scientific Papers  page 11
Conference proceedings  page 157
INDEX  page 287
Scientific Papers
The Iceland Deep Drilling Project geothermal well at Reykjaness successfully reaches its supercritical target

Guðmundur Ó. Friðleifsson and Wilfred A. Elders
IDDP-Principal Investigators
HS Orka, Iceland, and University of California, Riverside, USA

The Iceland Deep Drilling Project passed a significant milestone in the geothermal industry when its IDDP-2 well at the Reykjanes Peninsula in Iceland reached the depth of 4,659 meters on the 25th of January 2017, after 168 days of drilling. The IDDP-2 achieved its initial targets, (a) to drill deep enough to reach supercritical conditions (4 to 5 km), (b) to measure the fluid temperature and pressure, (c) to search for permeability, and (d) to recover drill cores. After only 6 days of heating, the temperature measured at the bottom of the well was ~427°C, with fluid pressure of 340 bars, and indications of permeability at depth (Figure 1), and drill cores were retrieved. It’s clear that the bottom of the well reached fluids at supercritical conditions, so that the main objective of the drilling phase of the project had been achieved.

The critical point of fresh water occurs at 374°C and 221 bars. The reservoir fluids currently produced from the Reykjanes field have the salinity of seawater which has a critical point of 406°C at 298 bars. The fluids at the bottom of the IDDP-2 well when the PT log shown in Figure 1 was measured were a mixture of injected surface water and formation fluid. Although we do not yet know the salinity of this mixture, it hard to argue that it was not at supercritical conditions during the logging operation.

The Iceland Deep Drilling Project (IDDP)

The IDDP is a long-term project by a consortium of Icelandic energy companies aimed at greatly increasing the production of usable geothermal energy by drilling deep enough to reach the supercritical conditions believed to exist beneath existing high-temperature geothermal fields in Iceland. Modeling indicates that a well producing from a supercritical geothermal
reservoir could produce an order of magnitude more usable energy than that produced by a conventional high-temperature (~300°C) geothermal well. This is because of both the higher enthalpy of supercritical fluid and its more favorable flow properties, due to its very low viscosity.

When the IDDP consortium was formed, three geothermal fields in Iceland were chosen as suitable to search for supercritical resources, Krafla in the north-east of Iceland, and Hellisheidi and Reykjanes in the south-west (Figure 3). The first attempt to drill into a supercritical reservoir was made in 2009 in the Krafla caldera, but the IDDP-1 well did not reach supercritical fluid pressures because drilling had to be suspended at a too shallow depth. This is because 900°C rhyolite magma flowed into the well at only 2,100 m depth. However, the IDDP-1 was completed with a liner set above the rhyolite intrusion. When the well was tested, it produced superheated steam at 452°C at a flow rate and pressure sufficient to generate about 35 MWe. After two years of flow testing, unfortunately repair of the surface installations was necessary, and the well had to be quenched due to failure of the master valves. This caused collapse of the well casing and abandonment of the well.

The IDDP-2

The IDDP consortium then decided to make the Reykjanes geothermal system the focus of its next attempt at drilling to supercritical conditions. HS Orka, the field operator at Reykjanes, led the drilling of the IDDP-2 well, in close collaboration with other project partners, Landsvirkjun, Orkuveita Reykjavíkur, and the National Energy Authority in Iceland, together with Statoil, the Norwegian oil and gas company. The IDDP has also received funding from the EU H2020 (DEEPEGs), and science funding from International Continental Drilling Program (ICDP) and US National Science Foundation (NSF). The drilling contractor was the Iceland Drilling Company.
The Reykjanes geothermal field lies near the southern tip of the Reykjanes Peninsula, which is the landward extension of the Mid-Atlantic Ridge. Some 34 production, injection, and observation wells supply steam to a 100 MWe power plant, from a 300°C reservoir at 1 to 2.5 km depth. It is unique among Icelandic geothermal systems in that its reservoir fluid is modified seawater, and that seawater is used to cool its steam condensers.

Figure 2 shows a conceptual model of the drilling target of the IDDP-2 well, based on the existing extensive well and geophysical data. The IDDP-2 well took advantage of an existing production well, the RN-15, which was 2,500 meters deep. This well was deepened and cased to 3,000 m depth and then deepened to the total depth of 4,659 m. The deepest existing geothermal wells at Reykjanes are about 2.5 km deep. The IDDP-2 has the deepest casing and is also the deepest well in Iceland. Figure 3 is a map showing the track of the well as actually drilled, together with the tracks of existing wells.

The IDDP-2 was drilled vertically down to 2,750 meters and below that drilled directionally to the southwest to intersect the main upflow zone of the Reykjanes system as indicated by geophysical surveys. The bottom of the well has a vertical depth of about 4,500 meters, and is situated 738 meters southwest of the well head.

Various challenges arose as the drilling progressed, there were weather delays, problems with hole stability that required frequent reaming, and the drilling assembly becoming stuck several times. Each instance was successfully solved as it happened. However, the major unsolved problem was a complete loss of circulation below 3,060 m depth, that could not be cured with lost circulation materials, or by multiple attempts to seal the loss zone with cement. As cementing was not successful, below 3180 m, drilling continued without any return of drill cuttings to the surface. Consequently, the drill cores were the only deep rock samples recovered.

In the beginning, we had difficulties recovering drill cores and overall only a total of 27.3 meters of core were retrieved in 13 attempts. These cores indicate that the IDDP-2 drilled through a basaltic sheeted dike complex that shows progressive metamorphism from greenschist, to lower amphibolite facies, consistent with hydrothermal alteration at temperatures of up to 450°C, with low water/rock ratios. The deepest core, returned from the bottom of the well is quite fresh dolerite, with minor intrusions of felsite. The main indications of hydrothermal alteration in this rock are quartz + biotite + hematite mineralization on fracture surfaces.

Another interesting aspect of the temperature log in Figure 1 is that, in addition to the major loss zone at 3,400 m, there are lesser permeable loss zones at 4,450 m and just below 4,500 m depths. After that PT logging run, a 7” perforated hanging liner was inserted to the bottom. Subsequently a 7” sacrificial casing was lowered from surface down to 1,300 m, and cemented up to the surface. Casing shoes were then drilled out and the well deepened by 6” bits, ending with 3 successive coring runs to the 4,659 m final depth. After the deepest coring run, a 3 1/2” drill string was lowered to the bottom of the hole. The aim is to enhance the permeability...
deep in the hole by pumping in cold water for several months through the 3 ½” drill string. There are already some positive indications of enhancement of injectivity. Tests made after the last coring runs showed that cold water injection increased the injectivity index from 1.7 (l/s)/bar to 3.1 (l/s)/bar. We expect that continued deep stimulation with cold water is likely to further improve the fracture permeability at depth.

While this “soft” stimulation is going on, a surface test bed, with two parallel flow lines, will be designed and constructed ready for long term flow testing. Only after these fluid handling and flow tests are concluded can we determine the nature of the formation fluids, their enthalpy and flow characteristics, and hence estimate their engineering and economic potential. The total loss of circulation below 3 km depth was unexpected, but the existence of large permeability, a kilometer deeper than the current production zones at Reykjanes, may have implications for the future development of the geothermal resource that are independent of supercritical production.

Significance of the IDDP-2

The geological environment of the Reykjanes geothermal field is of great interest to the scientific community, situated as it is on the landward extension of the Mid-Atlantic Ridge that forms part of the world-encircling system of divergent plate boundaries, or oceanic spreading centres. These are regions of frequent volcanic eruption, high heat flow, and submarine hot springs. The IDDP-2 is a unique opportunity to examine the roots of a black smoker.

In future, our demonstration that it is possible to drill into a supercritical zone could have a large impact on the economics of high-temperature geothermal resources worldwide. By extending the available economic reservoir downwards we can extend the lifetimes of existing producing fields. As higher enthalpy fluids have greater power conversion efficiencies, fewer turbines are required for a given power output. Similarly, as fewer wells are need for a given output, we can increase the productivity of a geothermal field without increasing its environmental footprint.

Iceland is fortunate in having several likely sites for such developments. Planning for drilling the IDDP-3 well at Hellisheiði is already underway, and, subject to the availability of funding, drilling could begin in 2020. However supercritical conditions are not restricted to Iceland, but should occur deep in any young volcanic-hosted geothermal system. Deep wells drilled in geothermal fields such as Kakkonda in Japan, Larderello in Italy, Los Humeros in Mexico, and The Geysers and Salton Sea in USA, have encountered temperatures above 374°C. Development of supercritical geothermal resources could be possible there and in many other volcanic areas worldwide.

More information on the IDDP can be found at www.iddp.is and www.deepegs.eu.
The Iceland Deep Drilling Project 4.5 km deep well, IDDP-2, in the seawater-recharged Reykjanes geothermal field in SW Iceland has successfully reached its supercritical target

Guðmundur Ó. Friðleifsson1, Wilfred A. Elders2, Robert A. Zierenberg3, Ari Stefánsson1, Andrew P. G. Fowler1, Tobias B. Weisenberger1, Björn S. Harðarson4, and Kiflom G. Mesfin1

1HS Orka, Svartsengi, 240 Grindavík, Iceland
2Department of Earth Sciences, University of California, Riverside, CA 92521, USA
3Department of Earth and Planetary Sciences, University of California, Davis, CA 95616, USA
4ÍSOR, Grensásvegur 9, 108 Reykjavík, Iceland

Correspondence to: Guðmundur Ó. Friðleifsson (gof@hsorka.is)

Received: 15 June 2017 – Revised: 25 August 2017 – Accepted: 4 September 2017 – Published: 30 November 2017

Abstract. The Iceland Deep Drilling Project research well RN-15/IDDP-2 at Reykjanes, Iceland, reached its target of supercritical conditions at a depth of 4.5 km in January 2017. After only 6 days of heating, the measured bottom hole temperature was 426 °C, and the fluid pressure was 34 MPa. The southern tip of the Reykjanes peninsula is the landward extension of the Mid-Atlantic Ridge in Iceland. Reykjanes is unique among Icelandic geothermal systems in that it is recharged by seawater, which has a critical point of 406 °C at 29.8 MPa. The geologic setting and fluid characteristics at Reykjanes provide a geochemical analog that allows us to investigate the roots of a mid-ocean ridge submarine black smoker hydrothermal system.

Drilling began with deepening an existing 2.5 km deep vertical production well (RN-15) to 3 km depth, followed by inclined drilling directed towards the main upflow zone of the system, for a total slant depth of 4659 m (~4.5 km vertical depth). Total circulation losses of drilling fluid were encountered below 2.5 km, which could not be cured using lost circulation blocking materials or multiple cement jobs. Accordingly, drilling continued to the total depth without return of drill cuttings. Thirteen spot coring attempts were made below 3 km depth. Rocks in the cores are basalts and dolerites with alteration ranging from upper greenschist facies to amphibolite facies, suggesting that formation temperatures at depth exceed 450 °C.

High-permeability circulation-fluid loss zones (feed points or feed zones) were detected at multiple depth levels below 3 km depth. The largest circulation losses (most permeable zones) occurred between the bottom of the casing and 3.4 km depth. Permeable zones encountered below 3.4 km accepted less than 5 % of the injected water. Currently, the project is attempting soft stimulation to increase deep permeability. While it is too early to speculate on the energy potential of this well and its economics, the IDDP-2 is a milestone in the development of geothermal resources and the study of hydrothermal systems. It is the first well that successfully encountered supercritical hydrothermal conditions, with potential high-power output, and in which on-going hydrothermal metamorphism at amphibolite facies conditions can be observed. The next step will be to carry out flow testing and fluid sampling to determine the chemical and thermodynamic properties of the formation fluids.
1 Introduction

The Iceland Deep Drilling Project (IDDP) is a long-term project (https://www.iddp.is) aimed at greatly increasing the production of usable geothermal energy by drilling deep enough to reach the supercritical conditions believed to exist beneath high-temperature geothermal fields in Iceland. When the IDDP consortium was formed in the year 2000, three geothermal fields in Iceland were chosen as suitable locations to search for supercritical resources, Krafla in the northeast of Iceland, and Hengill and Reykjanes in the southwest (Fröbliefsson et al., 2003; see Fig. 1). The first attempt to drill into a supercritical reservoir was made in 2008–2009 in the Krafla caldera (IDDP-1), but the well did not attain supercritical fluid pressures because drilling was suspended at too shallow of a depth (Elders et al., 2011). This was because drilling intercepted 900 °C rhyolite magma at a depth of only 2100 m. However, the IDDP-1 was completed with a liner set above the rhyolite intrusion. When the well was tested, it produced superheated 452 °C steam at 140 bar pressure, and had a flow rate and pressure sufficient to generate about 35 MWe. After 2 years of flow testing, repair of the surface installations was necessary, and the well had to be quenched due to failure of the master valves. Unfortunately, this caused a collapse of the well casing and the well was abandoned.

In 2013, as reported previously in this journal (Fröbliefsson et al., 2013), the IDDP began planning to drill a deep exploratory/research well, the IDDP-2, in the Reykjanes geothermal field in SW Iceland, where HS Orka generates up to 100 MWe of electric power. From a scientific perspective, this location is of great interest because the Reykjanes peninsula is the landward extension of the Mid-Atlantic Ridge (Fig. 1).

The exposed rocks in Iceland date back to about 16 Ma, the oldest rocks being exposed farthest to the west and farthest to the east, and include about 100 central volcanic complexes of different ages. In Fig. 1 we only show the active central volcanoes associated with on-going rifting at a slow spreading rate of 1.8 cm yr\(^{-1}\). The active rift systems typically show an evolution characterized by development of central volcanoes near the spreading segment centers. Central volcanoes often mature to develop rhyolitic volcanism and caldera collapse over time frames of about 1 My before drifting out of the active spreading zone and cooling down. Many of the high-temperature geothermal areas in Iceland are associated with central volcanoes, for example the Krafla volcano, which displays extensive rhyolitic volcanism and caldera collapse (e.g., Fröbliefsson et al., 2003), and which was the site of the IDDP-1 drill hole. The Reykjanes system is in an early rifting stage and has not developed into a central volcano, while the Hengill central volcano, the proposed site for IDDP-3 drilling, is considered to be in an intermediate stage of development as it has not generated large volumes of felsic rock and has yet to develop a caldera.

The drilling target for each of the IDDP sites is to reach supercritical conditions. The critical point of fresh water, which characterize the Krafla and Hengill fields, occurs at 374 °C and 22.1 MPa. The reservoir fluids currently produced from the Reykjanes field have a salinity of seawater, which has a critical point of 406 °C at 29.8 MPa (Bischoff and Rosenbauer, 1988). As described below, it is already clear that conditions at the bottom of the IDDP-2 well measured during drilling exceed the critical point of seawater. A geothermal well producing from a supercritical geothermal reservoir has the potential to generate power outputs on an order of magnitude greater than conventional high-temperature wells (at 240–340 °C) assuming the same volumetric flow rate of steam (Albertsson et al., 2003; Fröbliefsson et al., 2014a).

The Reykjanes hydrothermal resource is a two-phase geothermal system to about 1500 m depth, where temperature follows the boiling point curve with increasing depth and both liquid and vapor are present, below which the temperatures are approximately constant to about 3 km depth, with the highest recorded downhole temperature of about 320 °C (Fröbliefsson et al., 2014b). The depth to the bottom of the hydrothermal reservoir is not known, while 3 km depth has been used in reservoir modeling so far for the convection system. The primary motivation for the Reykjanes field operator to undertake such a challenging drilling operation as IDDP-2
was to address several basic questions important for the future development of the geothermal resource:

i. What is the nature and location of the base of the Reykjanes hydrothermal reservoir? Is it possibly heated by superheated steam from below?

ii. Can deeper heat sources be exploited by injecting fluid into the hot rocks beneath the current production zone?

iii. Will productive permeability be found at these great depths within the approximate center of the fault-related upflow zone?

iv. Does a hydrothermal reservoir at supercritical condition exist at 4–5 km depth under the Reykjanes well field or does it lie even deeper? Alternatively, will we be dealing with hot dry rocks at those depths?

v. What is the ultimate heat source of this saline ocean-floor-related hydrothermal system?

In December 2015, the plans for the IDDP-2 were accepted as a part of the European Union Horizon 2020 program DEEPEGS (Deployment of Deep Enhanced Geothermal Systems for Sustainable Energy Business, grant no. 690771). DEEPEGS is a major effort to speed up the development of enhanced geothermal systems within Europe and worldwide, for both high- and low-enthalpy systems.

A drill site was selected on the north side of the Reykjanes drill field (Fig. 2) making use of an existing production well RN-15 as a “well of opportunity”. In 2004, RN-15 was drilled vertically to a depth of 2500 m with a production casing cemented down to 794 m, and open hole below. The well was suitably sited within the Reykjanes geothermal system for a deepening as an inclined IDDP well, and the potential risk for affecting other production wells during the drilling and cementing operations to 3 km depth was relatively small. Therefore, after serious consideration of the economics as well, IDDP was offered the opportunity to deepen well RN-15. The well is now identified as RN-15/IDDP-2. The RN-15 was cooled down slowly, deepened with a 12 1/4′′ bit to 3000 m, and a new production casing was cemented in place. Drilling then continued with 8 1/2′′ rotary bits towards a target depth of 5 km. We planned to drill 8 1/2′′ spot cores over about 10% of the total drilling interval.

The RN-15/IDDP-2 passed a significant milestone in geothermal research by reaching a slant depth of 4659 m on 25 January 2017, after 168 days of drilling. Drilling achieved its initial targets to: (a) drill deep enough to reach supercritical conditions (4 to 5 km), (b) measure the fluid temperature and pressure, (c) search for permeable zones, and (d) recover drill cores.

2 The Reykjanes drill field

Prior to the IDDP-2, the deepest producing geothermal wells existing at Reykjanes were about 2.5 km deep. Figure 2 is a map showing the deviated track of well RN-15/IDDP-2, as it was drilled, together with the tracks of existing wells. Ver-
tactical wells are represented by dots only. Figure 3a is a simplified conceptual model of the Reykjanes drill field, showing the well RN-15/IDDP-2 directionally drilled towards 5 km depth and ending under the main drill field at temperatures anticipated to range from 400–500 °C. Figure 3b is a schematic lithological diagram (Weisenberger et al., 2017), based on lithological logs from about 34 drill holes. Below a pile of several Holocene subaerial lava flows, the rock formations are composed of shallow marine sediments and tuffs, with intervals of pillow basalt and breccia, emplaced in the last ~0.5 Ma (Friðleifsson and Richter, 2010). The dike intensity increases dramatically with increasing depth and reaches ~100% below approximately 3 km depth. This sheeted dike complex is presumably underlain by gabbroic lower crust, a model that conforms to typical “classical” ophiolite (Anonymous, 1971). Although the Reykjanes ridge is a slow spreading ridge, it is magmatically robust due to the influence of the Iceland hotspot. Enhanced magmatism results in much thicker crust (~16 km) compared to normal mid-ocean ridges (Weir et al., 2001). While the ophiolite conceptual model (Fig. 3b) has been assumed for the Reykjanes field, the RN-15/IDDP-2 well is the first to confirm the presence of a thick sheeted dike section (see below). The nature of the lower crust and the depth to any large gabbroic intrusions is unknown.

3 Drilling the RN-15/IDDP-2

The Iceland Drilling Company (IDC) began deepening well RN-15 on 11 August 2016, using the rig Thor (Þór), a Benthic 350-ton drilling rig with an electric top drive (MH PTD-500-AC). On 8 September after 29 working days, drilling to 3000 m depth was completed (Table 1). Well RN-15 had an existing 13\(\frac{3}{8}\)′′ production casing cemented from 0 to 793.8 m. An additional production casing (anchor casing) of 9\(\frac{3}{8}\)′′ (from surface to 445 m) and 9\(\frac{5}{8}\)′′ (2932.4 m) was run into the hole and cemented (see Table 1) (Weisenberger et al., 2016).

The RN-15/IDDP-2 was drilled vertically from 2500 m down to 2750 m, and below that drilled directionally to the southwest to intersect the main upflow zone of the Reykjanes system. The bottom of the well is at a vertical depth of about 4500 m, and is situated 738 m southwest of the wellhead.

Cables with eight thermocouples from Petrospec Engineering were attached to the outside of the casing string as it was run into the hole. The thermocouples were rated to tolerate up to 600 °C. They were expected to enable continuous measurement of temperatures at 341, 641, 941, 1541, 1841, 2141, 2341, and 2641 m depths. The thermocouple at 2141 m was damaged during insertion of the casing. In addition, a pressure/temperature sensor was installed at 1241 m depth, and a fiber optic cable for temperature, strain, and seismic measurements was installed by GFZ Potsdam (Geoforschung Zentrum) to 841 m depth, supported by two EU funded programs (IMAGE and GEOWELL) together with DEEPEGS, HS Orka, and Statoil. Data from these sensors were used to evaluate the progress of the cementing operation.

Reverse cementing, with ~150 m³ of cement pumped down the annulus between the casing and the borehole, was completed on 6 September, followed by two separate downhole cement bond logging trips inside the casing, which indicated that a proper cementing job had been achieved. The result is the longest production casing ever installed in any Icelandic high-temperature geothermal field.

Drilling in formations below 3000 m in the production part of the well began on 17 September (the 38th workday), and

Sci. Dril., 23, 1–12, 2017

www.sci-dril.net/23/1/2017/
Table 1. Drilling and casing depths in well RN-15 and RN-15/IDDP-2.

<table>
<thead>
<tr>
<th>ID</th>
<th>Drill rig</th>
<th>Phase</th>
<th>Depth (m)</th>
<th>Depth reference</th>
<th>Bit size</th>
<th>Casing type</th>
<th>Casing depth (m)</th>
<th>Casing-depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RN-15</td>
<td>Saga</td>
<td>Pre-drilling</td>
<td>86.5</td>
<td>Saga RF</td>
<td>26&quot;</td>
<td>22 1/2</td>
<td>84.4</td>
<td>Ground surface</td>
</tr>
<tr>
<td>RN-15</td>
<td>Jötunn</td>
<td>1. phase</td>
<td>300</td>
<td>Jötunn RF</td>
<td>21&quot;</td>
<td>18 5/8</td>
<td>292.8</td>
<td>Ground surface</td>
</tr>
<tr>
<td>RN-15</td>
<td>Jötunn</td>
<td>2. phase</td>
<td>804</td>
<td>Jötunn RF</td>
<td>17 1/2</td>
<td>13 3/8</td>
<td>793.8</td>
<td>Ground surface</td>
</tr>
<tr>
<td>RN-15</td>
<td>Jötunn</td>
<td>3. phase</td>
<td>2507</td>
<td>Jötunn RF</td>
<td>12 1/2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RN-15/IDDP-2</td>
<td>Thor</td>
<td>3. phase</td>
<td>3000</td>
<td>Thor RF</td>
<td>12 1/4</td>
<td>9 2/12</td>
<td>0–445</td>
<td>Ground surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>445–2932.4</td>
<td>Ground surface</td>
</tr>
</tbody>
</table>

Table 2. Overview of the 13 core runs attempted in well RN-15/IDDP-2 at Reykjanes. ROP is rate of penetrations.

<table>
<thead>
<tr>
<th>Core run</th>
<th>Start</th>
<th>Coring interval (m)</th>
<th>Cored length (m)</th>
<th>Drilling time (h)</th>
<th>ROP (m h(^{-1}))</th>
<th>Core recovered (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18/09/2016</td>
<td>3068.7–3074.1</td>
<td>5.4</td>
<td>7.12</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>04/10/2016</td>
<td>3177.6–3179.0</td>
<td>1.4</td>
<td>2</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>30/10/2016</td>
<td>3648.0–3648.9</td>
<td>0.9</td>
<td>5</td>
<td>0.2</td>
<td>0.52</td>
</tr>
<tr>
<td>4</td>
<td>02/11/2016</td>
<td>3648.9–3650.7</td>
<td>1.8</td>
<td>10.25</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>11/11/2016</td>
<td>3865.5–3869.8</td>
<td>4.3</td>
<td>8.5</td>
<td>0.6</td>
<td>3.85</td>
</tr>
<tr>
<td>6</td>
<td>12/11/2016</td>
<td>3869.8–3870.2</td>
<td>0.4</td>
<td>2.5</td>
<td>0.2</td>
<td>0.15</td>
</tr>
<tr>
<td>7</td>
<td>22/11/2016</td>
<td>4089.5–4090.6</td>
<td>1.1</td>
<td>2.25</td>
<td>0.5</td>
<td>0.13</td>
</tr>
<tr>
<td>8</td>
<td>28/11/2016</td>
<td>4254.6–4255.3</td>
<td>0.7</td>
<td>5.5</td>
<td>0.1</td>
<td>0.28</td>
</tr>
<tr>
<td>9</td>
<td>06/12/2016</td>
<td>4308.7–4309.9</td>
<td>1.2</td>
<td>3</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>07/12/2016</td>
<td>4309.9–4311.2</td>
<td>1.3</td>
<td>8.25</td>
<td>0.2</td>
<td>0.22</td>
</tr>
<tr>
<td>11</td>
<td>16/01/2017</td>
<td>4634.2–4642.8</td>
<td>8.6</td>
<td>1.25</td>
<td>6.9</td>
<td>7.58</td>
</tr>
<tr>
<td>12</td>
<td>17/01/2017</td>
<td>4642.8–4652.0</td>
<td>9.2</td>
<td>1</td>
<td>9.2</td>
<td>9</td>
</tr>
<tr>
<td>13</td>
<td>19/01/2017</td>
<td>4652.0–4659.0</td>
<td>7</td>
<td>0.75</td>
<td>9.3</td>
<td>5.58</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>43.3</td>
<td></td>
<td>27.31</td>
<td></td>
</tr>
<tr>
<td>Core recovery about</td>
<td></td>
<td>63 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

was concluded on 26 January 2017 (the 168th workday) at 4659 m (Fig. 4). Various challenges arose as the drilling progressed: there were weather delays, problems with hole stability that required frequent reaming, and the drilling assembly became stuck several times. These instances were successfully resolved as they happened. However, the major unsolved problem was a near-complete loss of circulation just below the 9 2/12" production casing shoe (2931 m) that could not be cured with lost circulation materials or by 12 successive attempts to seal the loss zone with cement. As cementing was not successful, drilling had to continue without any return of drill cuttings to the surface from deeper than 3200 m, except for drill cuttings that were intermittently sampled between 3000 and 3200 m depth (Weisenberger et al., 2017). Consequently, the drill cores are the only deep rock samples recovered from the well.

Figure 4 shows that after the delays attempting to condition the well by repeated cementing, the drilling itself more or less followed the scheduled path, despite several problems on the way down such as stuck drill string, weather delays, etc.

We had considerable difficulties in recovering drill cores in most of the first 10 core runs, and only a total of 27.3 m of core was retrieved in 13 attempts, or about 63 % recovery of the cored intervals (Table 2). We were using an IDDP-designed 8 1/4" coring tool, with 9.7 m long core barrel (Skinner et al., 2010), which had yielded good core recoveries in RN-17B, an inclined 8 1/4" hole from 2800 m depth, and also from three successive core runs below a 9 2/12" liner in well
RN-30 at Reykjanes from similar depth to RN-17B (Fowler et al., 2015; Fowler and Zierenberg, 2016). Table 2 gives an overview of the core recovery in 10 core runs with the IDDP 8 1/2′′ coring tool and 3 successive core runs with the 6′′ Baker Hughes tool at the bottom of IDDP-2, beneath the 7′′ liner. Prior to coring with the 6′′ tools, an 8 m deep 6′′ pilot hole was drilled with a tri-cone bit from 4626 to 4634 m to clean out the bottom fill after casing and to condition the well.

A comprehensive analysis of the poor performance of our 8 1/2′′ specially designed coring tool assembly in the IDDP-2 will appear elsewhere, but there could be several possible reasons for its poor performance. The special feature of our IDDP coring tool is its allowance for much greater water passage (up to 40 L s⁻¹) for cooling extremely hot rock formation, an order of magnitude higher flow rate than that possible using conventional coring tools. Another characteristic feature of our tool is the relatively soft coring bits, designed for single use only.

Possible reasons for the poor performance of the 8 1/2′′ coring assembly are (a) the inclination of the hole, which in-

Figure 4. Actual drilling progress of the RN-15/IDDP-2 drill hole (blue) compared to the drilling schedule (orange).
creased with increasing depth; (b) possible dog-legs in the hole, which may have damaged the relatively soft drill bits banging against the well wall on running in; (c) rapid cooling leading to thermal fracturing of the formation; and (d) the diameter of the coring tool and reamers, which exceeded the diameter of the heavy drill collars by an inch. Accordingly, the coring bottom-hole-assembly (BHA) was stiffer than the drill collar BHA alone while rotary drilling. Three stabilizers were put in the BHA above the coring tool. In some cases, the \( \frac{8\frac{1}{4}}{2} \) tri-cone bit may have been slightly under-sized, adding to the problems. We also often had to ream the hole for considerable lengths before getting to the bottom of the hole; in other cases, fill in the hole may have hindered good coring performance. We attempted to overcome the problems by shortening the core barrel from 10 to 5 m, cutting off all the stabilizers on the BHA, and using only one stabilizer above a heavy drill collar and the BHA. After that modification (in core run 4), we improved the situation considerably and retrieved 3.83 m of core in a 5 m long barrel, compared to the 0 to 0.5 m in preceding runs with the 10 m barrel. However, the situation did not improve sufficiently to satisfy our need for drill cores. Nevertheless, recovering tens of centimeters of core from depths in the field that were previously not sampled made a huge difference scientifically, compared to having no rock samples at all.

Finally, after casing the well with a 7 in perforated liner, a Baker Hughes 6 in coring tool with a PCD bit (poly crystalline diamond) resulted in very satisfying core recovery at the very bottom of the well. The immediate lesson learned is that in inclined wells, such as drilling the future we should probably use a slimmer coring assembly to the bottom of the well. The immediate lesson learned is that in

Conventional downhole geophysical logs were attained after drilling to 3000 m depth, and also when the well was 3648 m deep. Normal resistivity, neutron and natural gamma, and sonic logs were obtained from a casing depth to 3440 m. A televiwer log was attempted but had poor quality (Weisenberger et al., 2016, 2017). Close to the end of drilling, when the well was 4626 m deep, special LWD (logging while drilling) tools were hired from Weatherford International and used for the first time in Iceland. The logging suite consisted of natural gamma, temperature, pressure, and multi-frequency resistivity from casing to 4615 m. Micro-resistivity imaging was obtained to 4490 m (good quality) and acoustic velocity to 3045 m. The results will be described elsewhere. Following this, and after only 6 days of heating (3 January 2017), the temperature measured at the bottom of the well was \( \sim 426^\circ C \) with a fluid pressure of 34 MPa, and good indications of permeability at depth (at \( \sim 3400, \sim 4375, \sim 4550 \)) based on inflections in the downhole temperature profile (Fig. 5). The fluid at the bottom of the well at that time was inferred to be a mixture of injected water and formation fluids. Both the temperature and the pressure indicate that the bottom fluid was at supercritical conditions during the logging operation. Accordingly, one of the main objectives of the IDDP drilling project was achieved, i.e., to drill into supercritical fluid conditions.

In addition to the major loss zone at 3360–3380 m, there are less permeable loss zones further downhole. There are several feed points below the 2931 m casing shoe all masked by a large feed zone near 3400 m and 6 smaller feed points at 3820, 3990, 4100, 4200, 4375, and 4550 m, and possibly also at the very bottom of the well below the depth of the temperature log (Fig. 5). It is clear from the deepest drill cores that we had some open space in fractures containing pristine supercritical fluid down to the bottom of the well 4659 m.

The 7 in perforated hanging liner was inserted to the bottom after the pressure-temperature (PT) logging run of 3 January 2017. Subsequently, a 7 in sacrificial casing was lowered from the surface down to 1300 m and cemented up to the surface. Casing shoes were then drilled out and the well was deepened using 6 in. bits, ending with three successive coring runs down to the 4659 m final depth. After the deepest coring run, a 3\( \frac{1}{2} \) drill string was lowered to the bottom of the hole. The aim was to enhance the permeability deep in the hole by pumping in cold water for several months through the 3\( \frac{1}{2} \) drill string. There are already some positive indications of enhancement of injectivity. Tests made after the last coring runs showed that cold water injection increased the injectivity index from 1.7 to 3.1 L s\(^{-1}\) bar\(^{-1}\). We expect that continued deep stimulation with cold water is likely to further improve the fracture permeability at depth. While this “soft stimulation” is going on, a surface test bed, with two parallel flowlines, will be designed and constructed for long-term flow testing. Only after these fluid handling and flow tests are concluded will we be able to determine the nature of the formation fluids, their enthapy and flow characteristics, and hence estimate their engi-
neering and economic potential. The total loss of circulation below 3 km depth was unexpected but the existence of large permeability, a kilometer deeper than the current production zones at Reykjanes, may have implications for the future development of the geothermal resource that are independent of supercritical production.

5 Lithology and alteration

A detailed description of the lithologic section drilled in the IDDP-2 well is hampered by total circulation loss below ∼3200 m and is based on preliminary observations of recovered drill cores (Table 2). Despite these limitations, a relatively coherent picture of downhole lithology and hydrothermal alteration is apparent, and is generally consistent with observations from the deepest holes drilled into situ oceanic crust at fast-spreading ridges by the Deep Sea Drilling Project (DSDP)/Ocean Drilling Program (ODP)/Integrated Ocean Drilling Program (IODP), wells 504B (Costa Rica Rift, Galapagos Spreading Center) and well 1256B (Guatemala Basin, eastern tropical Pacific) (Alt et al., 1986, 2010; Anderson et al., 1982).

The upper 2500 m of the IDDP-2 well was drilled in 2004 as the former production well RN-15, which is described by Jónsson et al. (2010). Cuttings recovered during deepening of the well down to the lost circulation zone at 3200 m are described by Weisenberger et al. (2017). Here we focus on the drill core recovered at spot intervals in the depth interval between 3648 and 4659 m.

6 Primary lithology

Analysis of drill cuttings indicates that the uppermost section of RN-15 down to about 1400 m is dominantly volcanic rock with interbedded zones of basalt flows, basalt breccia, pillow lavas, and hyaloclastite. Basaltic intrusions increase in frequency downhole below ∼1400 m, and mixed intrusive and extrusive rocks continue to at least 3200 m. Variously rounded cobbles and fragments of volcanic rock derived from below the casing depth 2940 m were recovered as rubble on top of several of the cores. It is likely that many of these were derived from an enlarged eroded section of the drill hole around ∼3360 m depth, coincident with a major circulation loss zone in the well. The zone from ∼1400 to ∼3500 m depth is, therefore, interpreted as the transition zone between overlying volcanic rocks and an underlying sheeted dike complex (Fig. 6). The preliminary interpretation of the lithological structure and major alteration mineral zones identified in IDDP-2 compared to DSDP/ODP/IODP holes 504B (Costa Rica Rift, Galapagos Spreading Center) and 1256D (Guatemala Basin, eastern tropical Pacific) is presented on Fig. 6.

The shallowest cored interval extends from 3648.00 to 3648.52 m and recovered sections of three dikes separated by two chilled margins that indicate that at least the upper two dikes are half-dikes intruded by the underlying dike. Lithologic interpretation based on sparse core recovery is subject to large uncertainty, however, all of the underlying drill core can be reasonably interpreted to have come from a sheeted dike complex with no definitive evidence that they represent either coarse-grained basalt from flow interiors or thick intrusive sills or fine-grained gabbro bodies. Interpretation of the downhole geophysical logs may provide further evidence of the nature of the lithologies in-between the cored intervals as well as orientations of the contacts between intrusive units. Cores 5 and 6 recovered a relatively coarse-grained diabase with no apparent systematic grain-size variation extending from 3865.50 to 3869.95 m. Cores 11–13 provide the most continuous recovery, with four half-dikes separated by three
Figure 6. Simplified alteration and lithology logs of RN-15/IDDP-2 compared to the two deepest DSDP/ODP/IODP drill holes completed in situ oceanic crust (Hole 504B and Hole 1256D). Maximum temperature and pressure conditions are indicated. The structure of the Reykjanes geothermal system differs from 504B and 1256D in that the transition zone between the upper pillow basalt section and lower sheeted dike section is greatly expanded at Reykjanes. On a broad scale, alteration mineral sequences in the active Reykjanes system vary predictably as a function of depth in the crust and temperature. Overprinting alteration mineral sequences in rocks from Holes 504B and 1256D reflect time-integrated changes in hydrothermal conditions as rocks tectonically migrated away from active hydrothermal conditions at the spreading center. Data for DSDP/ODP/IODP holes from Alt et al. (2010); Anderson et al. (1982); and Marks et al. (2010). Data for shallower portions of Reykjanes from Marks et al. (2010); Fowler et al. (2015); and Fowler and Zierenberg (2016).

chilled margins recovered between 4634.20 and 4656.00. The thickest half-dike extends 14.4 m downhole implying a minimum thickness greater than 9 m, given the inclination of the drill hole of approximately 40° and assuming the dike is vertical.

All the recovered dikes show similar primary mineralogy with subequal concentrations of plagioclase and clinopyroxene accompanied by 3–6% titanomagnetite. The only apparent exceptions are the uppermost half-dike in core 11, which appears from hand specimen descriptions to contain ~2% euhedral green partially altered olivine crystals, and the half-dike in the lowermost 1.5 m of core 12, which is described as containing approximately 15% dark blocky clinopyroxene (2–3 mm) and 20% finer-grained beer-bottle brown orthopyroxene (~2 mm). Given that all recovered cores are overprinted by hydrothermal alteration, estimates of original mineral percentages are uncertain. Plagioclase tends to be slightly coarser-grained (3–4 mm), elongated, and more euhedral compared to clinopyroxenes, which tends to occur interstitial to the plagioclase matrix.

Irregular patches and vein-like segregations of more differentiated felsic melt are a minor component of some of the dikes and become increasingly common downcore. The first noted occurrence of these segregations is in core 5, which shows a few irregular discontinuous lighter colored veins characterized by an increased abundance of late-stage igneous plagioclase, some of which appears cloudy due to symplectic intergrowth with very fine-grained quartz. Clinopyroxene is less abundant in these veins, and some formed as thin (~1 mm) elongated prisms up to 5 mm long. All of the pyroxene in this core interval has been replaced by hydrothermal amphibole. Core 10 contains a 3 cm thick plagioclase-quartz-clinopyroxene-titanomagnetite segregation vein, where quartz occurs as coarser-grained crystal up to 2 mm in length. Rock of rhyolitic compositions, although common in other Icelandic volcanic centers such as Krafla (e.g., Jónasson, 2007), have not been observed previously at Reykjanes.

7 Alteration and hydrothermal veining

The assemblage of alteration minerals observed in cuttings from RN-15 (Jónsson et al., 2010) and the upper section of IDDP-2 above the lost circulation zone (Weisenberger et al., 2017) is consistent with the downhole prograde alteration assemblages described by Tómasson and Kristmannsdóttir (1972). Cuttings from the production reservoir of the Reykjanes field show epidote-actinolite facies alteration characterized by replacement, open-space filling veins, and vug-filling alteration minerals dominated by chlorite, epidote, actinolite, albite, and quartz.

The upper-most core samples from IDDP-2 (core 3, 3648 m) are pervasively altered and intensively veined by epidote, amphibole, plagioclase (with or without quartz) with chlorite-rich vein selvages. Igneous clinopyroxene is completely replaced by amphibole and chlorite. Igneous plagioclase shows patchy alteration to albite, epidote, and chlorite. Titanomagnetite is partially replaced by magnetite and titanite. Minor phases include pyrite, pyrrhotite, and intermediate solid solution Cu-Fe sulfide. Hydrothermal clinopyrox-
The geological environment of the Reykjanes geothermal field is of great interest to the scientific community, situated as it is on the landward extension of the Mid-Atlantic Ridge that forms part of the world-encircling system of divergent plate boundaries, or oceanic spreading centers (Elders and Friðleifsson, 2010). These are regions of frequent volcanic eruption, high heat flow, and submarine hot springs. Base-metal sulfide scales that form in drill holes and production pipes are similar to seafloor massive sulfide deposits.
Figure 8. (a) Euhedral hydrothermal biotite books, approximately 1 mm across, coating fracture surface in RN-15/IDDP-2 (4637.81 m depth). Exposed crystals were stained red by hematite during the coring operation. (b) Open-space filling quartz, up to 4 mm in length, overgrowing hydrothermal biotite (black crystals) in RN-15/IDDP-2 (4637.81 m depth). Exposed crystals were stained red by hematite during the coring operation.

(Hardardótir et al., 2012). The IDDP-2 is a unique opportunity to examine the roots of a black smoker.

In the future, our demonstration that it is possible to drill into a supercritical zone could have a large impact on the economics of high-temperature geothermal resources worldwide, wherever young volcanic rocks occur (Dobson et al., 2017). By extending the available economic reservoir downwards, we can extend the lifetimes of existing producing fields. As higher enthalpy fluids have greater power conversion efficiencies, fewer turbines are required for a given power output. Similarly, as fewer wells are needed for a given output, we can increase the productivity of a geothermal field without increasing its environmental footprint.

More information on the IDDP can be found at www.iddp.is and at www.deepegs.eu.

Data availability. Our underlying research data is partly kept at the following link: https://www.icdp-online.org/projects/world/europe/iceland/details/ and at an internal IDDP website at icdp-online for the IDDP science team only – until published.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. The IDDP-2 was funded by HS Orka, Landsvirkjun, Orkuveita Reykjavíkur, and the National Energy Authority in Iceland, together with Statoil, the Norwegian oil and gas company. The IDDP has also received funding from the EU H2020 (DEEPEGS, grant no. 690771), and science funding from ICDP and NSF. In 2005, funding for IDDP to obtain spot cores at Reykjanes and elsewhere was provided by ICDP and the US NSF (grant no. 05076725), which is greatly appreciated. Successful coring attempts exist from wells RN-17B, RN-19, RN-30, and now from RN-15/IDDP-2, Iceland.

Edited by: Tomoaki Morishita
Reviewed by: Robert O. Fournier and one anonymous referee

References


The Iceland Deep Drilling Project at Reykjanes: Drilling into the root zone of a black smoker analog

Guðmundur Ó. Friðleifsson a,⁎, Wilfred A. Elders b, Robert A. Zierenberg c, Andrew P.G. Fowler e, Tobias B. Weisenberger e, Kiflom G. Mesfin a, Ómar Sigurðsson a, Steinþór Níelsson e, Gunnlaugur Einarsson e, Finnbogi Öskarsson e, Egill Á. Guðnason e, Helga Tulinius e, Ketil Hokstad f, Gibert Benoit g, Frank Nono g,h, Didier Loggia g, Fleurice Parat g, Sarah B. Cichy g, i, David Escobedo g, David Mainprice g

a HS Orka, Svartsengi, 240 Grindavík, Iceland
b Dept. of Earth Sciences, University of California, Riverside, CA 92521, USA
c Dept. of Earth and Planetary Sciences, University of California, Davis, CA 95616, USA
d Department of Earth Sciences, University of Minnesota, Minneapolis, USA
e ÍSOR, Grensásvegur 9, 108 Reykjavík, Iceland
f Statoil Research Centre, Trondheim, Norway
g Géosciences Montpellier, Université de Montpellier, France
h Université de Pau, France
i University of Potsdam and GFZ, Potsdam, Germany

ARTICLE INFO

Article history:
Received 28 November 2017
Accepted 23 August 2018
Available online xxxx

Keywords:
IDDP
Reykjanes
Supercritical fluids
Deep drilling
Black smokers
Geothermal

ABSTRACT

The aim of the Iceland Deep Drilling Project is to drill into supercritical geothermal systems and examine their economic potential. The exploratory well IDDP-2 was drilled in the Reykjanes geothermal field on SW Iceland, on the landward extension of the Mid-Atlantic Ridge. The Reykjanes geothermal field produces from a ~380 °C reservoir at 1 to 2.5 km depth and is unusual because it is recharged by seawater. The well was cased to 3000 m depth, and then angled towards the main up-flow zone of the system, to a total slant depth of 4659 m (~4500 m vertical depth). Based on alteration mineral assemblages, joint inversion of wireline logging, and rate of heating measurements, the bottom hole temperature is estimated to be about 535 °C. The major problem encountered during drilling was the total loss of circulation below 3 km depth and continuing to the final depth. Drilling continued without recovering drill cuttings, consequently spot coring provided the only deep rock samples from the well. These cores are characteristic of a basaltic sheeted dike complex, with hydrothermal alteration mineral assemblages that range from greenschist to amphibolite facies, hornblende hornfels, and pyroxene hornfels, allowing the opportunity to investigate water-rock interaction in the active roots of an analog of a submarine hydrothermal system. As they have not yet been sampled, the composition of the deep fluids at Reykjanes is unknown at present. Cold water is currently being injected with the aim of enhancing permeability at depth, before allowing the well to heat up prior to flow tests planned for early 2019. The well has at least two fluid feed zones, a dominant one at 3.4 km depth and a second smaller one at 4.5 km. Extensive geophysical surveys of the Reykjanes Peninsula completed recently allow correlation of geophysical signals with rocks properties and in-situ conditions in the subsurface. Earthquake activity monitored with a local seismic network during drilling the IDDP-2 drilling detected abundant small earthquakes (ML ≤ 2) within the depth range of 3–5 km. A zone at 3–5 km depth below the producing geothermal field that was generally aseismic prior to drilling, but became seismically active during the drilling. The drilling of the IDDP-2 has achieved number of scientific and engineering firsts. It is the deepest and hottest drill hole so far sited on an active mid-ocean spreading center. It penetrated an active supercritical hydrothermal environment at depths analogous to those postulated as the high temperature reaction zones feeding black smoker systems.

© 2018 Elsevier B.V. All rights reserved.

1. Introduction

The aim of the Iceland Deep Drilling Project (IDDP) is to explore the feasibility, technology, and economics of producing supercritical
geothermal resources. The IDDP-2 well was recently completed at Reykjanes in SW-Iceland on the landward extension of the Mid-Atlantic Ridge (Fig. 1), and the project was successful in reaching its immediate objective of demonstrating that it is possible to drill a supercritical geothermal well (Friðleifsson and Elders, 2017; Friðleifsson et al., 2017). Flow tests are planned for 2019 to determine the potential energy output of the well where we hope to demonstrate that a new, potentially very large and more economic geothermal resource will become available. This paper provides an overview of the motivation and background of the IDDP, describes new results from, and future plans for the IDDP-2 well, and discusses both its scientific and geothermal implications.

Iceland is the largest land mass astride an oceanic spreading center because it also is the surface expression of a mantle hotspot that produces a very high flux of basaltic magma (Fig. 1). High temperature reactions between seawater and basalt at Reykjanes provide a unique opportunity to explore physical conditions that control hydrothermal fluid composition in the roots of submarine black smoker systems that occur along much of mid-ocean ridge spreading systems, including the Reykjanes Ridge (Palgan et al., 2017). The chemical composition of the Reykjanes geothermal fluids is similar to those of black smokers and the fluids precipitate base-metal sulfide deposits similar to black smoker chimneys (Harðardóttir et al., 2012, 2013). The most significant difference between typical black smoker vents and the Reykjanes geothermal system is the pressure difference at the surface, which results in subsurface boiling and deposition of metals at Reykjanes in contrast to chimney formation by cooling during mixing with seawater on the seafloor. A more important comparison is to the temperature and pressure conditions at which high temperature water-rock reaction sets the composition of the geothermal fluids. Our drilling results confirm that supercritical temperatures are attained below Reykjanes at pressures and depths below sea level comparable to the base of the sheeted dike

Fig. 1. The location of Iceland on the Mid-Atlantic Ridge. The arrows show the spreading directions on the Reykjanes ridge to the south and the Kolbeinsey Ridge to the north. Iceland’s neovolcanic zone with its active central volcanoes hosts the three high temperature systems of Reykjanes, Nesjavellir (in the Hengill Volcano), and Krafá, that were chosen as suitable for IDDP deep drilling.

section below typical MOR vent systems. The IDDP-2 is therefore able to explore the roots of a black smoker analog without the technical challenges that have precluded seafloor drilling into this scientifically significant environment.

A major milestone for the IDDP was completion of well IDDP-2 at Reykjanes on January 25, 2017 to a slant depth of 4659 m from the rig floor (Weisenberger et al., 2017). The upper part of the well is vertical (Jonsson et al., 2010) but it was directionally drilled to the southwest from about 2750 m to the final depth. The true vertical depth from ground surface is close to 4500 m. This appears to be the first geothermal production well worldwide to successfully reach supercritical conditions. Some preliminary results from IDDP-2 have already been described in several conference reports and papers (e.g., Fridleifsson and Elders, 2017; Fridleifsson et al., 2017; Zierenberg et al., 2017; Stefansson et al., 2017; Hokstad and Tanavsuu-Milkkeiciene, 2017).

The Iceland Deep Drilling Project (IDDP) was organized and funded by a consortium consisting of three Icelandic energy companies (HS Orka, Landsvirkjun and Orkveita Reykjavikur), together with Orkustofnun (the Energy Authority of Iceland), and later with additional funding from Statoil. The idea of deep drilling to reach supercritical conditions was introduced at the 2000 World Geothermal Congress where it attracted interest from the international geothermal and scientific community (Fridleifsson and Albertsson, 2006; Elders et al., 2001). A three-part IDDP Feasibility Report was produced in 2003, outlining Geoscience Objectives and Site Selection criteria (Fridleifsson et al., 2003), Drilling Technology (Thórhallsson et al., 2003), and Fluid Handling and Evaluation (Albertsson et al., 2003). Modeling studies suggest that producing superheated steam from a hydrothermal reservoir with relevant temperatures, but also hydrostatic pressures found at depth, requires reaching supercritical conditions. Some preliminary results from IDDP-2 have already been described in several conference reports and papers (e.g., Fridleifsson and Elders, 2017; Fridleifsson et al., 2017; Zierenberg et al., 2017; Stefansson et al., 2017; Hokstad and Tanavsuu-Milkkeiciene, 2017).

2. Supercritical geothermal resources

The critical point for pure water, where the distinction between liquid, vapor, and steam disappears, is at 374 °C and 22.1 MPa (Fig. 2A). This is relevant to the root zone of typical black smokers which have 3.5% salt, approximates seawater. Before the IDDP-2 was drilled, Fridriksson et al. (2015) considered possible fluid scenarios for the well, depending on the pressure/temperature regime encountered at depth. Three different methods to estimate the temperature at 5 km depth yielded 382 °C, 441 °C and 550 °C (1, 2 and 3 in Fig. 2B). In each case the source fluid was assumed to be in equilibrium with quartz. For simplicity other fluid-mineral equilibria were disregarded. The three models resulted in very different fluids with different production properties; the first being subcritical single-phase fluid similar to the currently produced fluids in Reykjanes, only hotter and with higher silica scaling potential; the second is either superheated steam or a mixture of low salinity vapor (~3.5 wt%) and brine, similar to what has been observed in some ocean-floor black smokers (Cournou et al., 2009); and the third case is superheated steam similar to what was observed in IDDP-1 (Armansson et al., 2014), which has significant concentrations of silica and HCl. Given the temperature gradients anticipated in the IDDP-2, cases 2 and 3 appeared to be most applicable, and both would have enlarged potential for silica scaling.

3. The IDDP-1

In 2005 a plan for drilling the first IDDP well at Reykjanes was proposed by deepening RN-17, an existing production well, to a depth of 4–5 km to make certain of reaching a supercritical environment (Fig. 3). The Reykjanes geothermal field is unique in Iceland in that, because it is situated on a narrow peninsula, seawater recharges its reservoir and is the medium of pressure regulation. However, this plan could not be realized. Before deepening could begin, the uncased 3 km deep well collapsed during a flow test, and unfortunately attempts in 2006 to recondition RN-17 for deepening failed. For various reasons IDDP then moved to the Krafla caldera, in NE Iceland, to drill the IDDP-1, in 2008–2009. Given the geothermal gradients known to depths of ~2 km at Krafla, supercritical conditions should exist at 4–5 km depths. This attempt at drilling to supercritical in the IDDP-1 was unsuccessful as the borehole penetrated a nearly aphyric rhyolite magma at ~900 °C, at only 2100 m depth, but with fluid pressures well below the critical point of the low salinity meteoric water-sourced fluids (Elders et al., 2011; Zierenberg et al., 2012). The IDDP-1 was completed with a slotted production liner set above the rhyolite magma, where there was good permeability. In subsequent long-term flow tests, IDDP produced superheated steam with a wellhead temperature of 452 °C at a flow rate and enthalpy sufficient to generate about 35 MWe. When flowing this was the world’s hottest production well, but, after two years of successful production tests, repair of the surface installations became necessary, resulting in the need to quench the well. This caused collapse of the well casing and ultimately abandonment of the well. The IDDP-1 well is described in 14 papers in a special issue of Geothermics, volume 49, 2014, accessible through Science Direct (http://iddp.is/2014/01/15/geothermics-special-issue-on-iddp-january-2014/).

4. The Reykjanes geothermal field

The field operator Hitaveita Suðurnesja (now HS Orka), drilled its first well in 1999 followed by 15 additional wells before commissioning a 100 MWe power plant in 2006. Since then, ten more wells have been
Reykjanes are shown on the geological map in Fig. 3. Reports, are available of 2791 m depth. A step out well, RN-36, was then completed in March 2018, at a slant depth of 2381 m. The well provides constraints on the subsurface geological and geophysical conditions of the geothermal field. The locations of all wells at Reykjanes are shown on the geological map in Fig. 3. Reports, are available for each of the wells drilled in the past 20 years. These include the drilling operations, flow testing results, downright P-T logging, wellhead fluid sampling and chemical monitoring. Much of these data are incorporated into a Petrel model at ISOR (the Iceland Geosurvey). Figs. 3, 4, and 5 are selected from that database, showing the surface geology (Fig. 3), temperature profiles with depth, (Fig. 4) and a cross-section showing the hydrothermal alteration pattern (Fig. 5). While some of this information may be upgraded with time (e.g., earthquakes in different periods and fluid chemistry), other data have more permanent value (e.g., hydrothermal alteration zonation and subsurface lithology).

A detailed report on the surface geology and the structural characteristics of the Reykjanes area is presented in another contribution submitted to this volume (Saemundsson et al., 2018). In brief, the hydrothermal up-flow zone and surface hydrothermal activity at Reykjanes is centered within the Late glacial hyaloclastite ridges (Tindar in Fig. 3) and early Holocene eruptive fissures (Fig. 3). The subsurface lithology to about 2.5 km depth in the Reykjanes field has been described in numerous contributions (e.g., Björnsson et al., 1972; Franzson et al., 2002; Friðleifsson et al., 2003, 2014; Marks et al., 2010). The lower resistivity down to about 2 km depth is characterized by subglacial and submarine hyaloclastite tuffs and sediments at shallower levels, and pillow basalts and breccias at deeper levels. Below about 1.5 km depth the intrusive rock intensity, in the form of basaltic dikes and sheets, increases dramatically in some wells, while pillow basalts and shallow marine deposits are found at depths in others, e.g., in spot cores from RN-17B. The presence of shallow marine deposits at depth records the subsidence of the central part of the rift zone. Friðleifsson and Richter (2010) estimated the average subsidence rate of the Reykjanes strata to about 6 mm/year for half a million years, which is comparable with Vadon and Sigmundsson’s (1997) calculations from Satellite Radar Interferometry over a 3 years period 1992–1995. Subsidence and rifting are continuing as evidenced by major (>-5M) seismic events, that occur at intervals of several decades, and by the presence of Holocene normal faults with throws of several tens of meter (Saemundsson et al., 2018). The major seismic events affect both the hydrothermal field and its overlying fumaroles. Apparently, this seismic activity temporarily enhances fracture permeability within the reservoir.

These temperature profiles provide insight into fluid convection in the currently producing upper portion of the Reykjanes hydrothermal system down to about 2.5 km, below the original water table (located at 400–500 m depth). Exceptions are temperature profiles in two wells located outside and to the west of the main up-flow zone, wells RN-16 and RN-29. RN-16 has a conductive character to the base, and RN-29 the temperatures increase conductively to about 1.5 km but show convective behavior deeper in the well. Temperature profiles for wells RN-17B and RN-30 indicate fluid convection within the production field, and conductive heating in the lowermost 1 km of the wells (Fig. 4). The lowermost 1 km of RN-17B and RN-30 extend outside of the main up-flow zone southwards and southeastward, respectively (Fig. 3).

Fig. 5 is a cross section across the middle of the Reykjanes well field based on drill hole and geophysical data. The resistivity model used is from Karlsdóttir et al. (2012). Wells RN-29 and RN-16 are furthest to the left (west) in this section, while most productive wells cluster in the center of the cross section. The inclined well IDDP-2 (colored pink) enters the field of view below 3 km depth, stretching down to about 4.5 km depth, inside a lower resistivity (green colored) field which is surrounded by higher resistivity (blue colored) resistivity field. The lower resistivity green column, targeted by the IDDP-2 well, is interpreted as a hotter, and apparently more permeable, up-flow zone lying below the overlying production field, shown by lighter green, yellow and red resistivity regions of lower resistivity. Three paleo-temperature surfaces are defined by connecting the first appearance of hydrothermal alteration index minerals between wells, which rise to the shallowest depths within the center of the well field (Fig. 5). The hydrothermal index minerals are quartz, epidote and actinolite, which precipitate in voids and fractures from geothermal fluids at temperatures above 180 °C, 230 °C and 280 °C respectively (Kristmannsdóttir, 1979).

5. Fluid chemistry of the Reykjanes system

The geothermal fluid in the Reykjanes geothermal system is derived from the heating of cold seawater, modified by reactions with basalt and the precipitation of alteration minerals, and possible additions of magmatic gases from intrusions beneath the geothermal reservoir (Arnórsson, 1978). The pre-production chloride content of the reservoir fluid matches that of local seawater (19,200 mg/kg, Fig. 6), and sodium is near seawater concentrations, although some Na is lost to albitionization of feldspars. Important deviations from seawater composition for other non-volatiles include increased concentrations of silica, potassium, and calcium, all of which can be explained by basalt dissolution and equilibration with secondary minerals. There are also decreased concentrations of sulfate and magnesium due to precipitation of secondary minerals such as anhydrite and magnesium phyllosilicates (Arnórsson, 1978).

Elevated concentrations of CO2 and other volatiles relative to seawater can be attributed to basalt dissolution and direct input from cooling intrusions below the geothermal reservoir. The concentration of the
Semi-volatile element boron is also higher in the Reykjanes well fluids than in seawater. Figure 7 shows the reservoir chloride concentration plotted against the concentration of boron, along with lines representing the average Cl/B ratio in the Reykjanes fluids, local seawater (Cl/B mass ratio 4510; Bjarnason, 1995), and Icelandic basalt (Cl/B molal ratio in tholeiites 25–50; Arnórsson and Andrésdóttir, 1995).
The Cl/B ratio in the Reykjanes fluids is very homogeneous and lies between the ratios for seawater and basalt. This may be due either to rock dissolution or to the addition of B-rich magmatic gas. Thermodynamic calculations indicate that the concentrations of the reactive gases H₂S and H₂ are controlled by temperature dependent equilibria with minerals; possibly anhydrite, wollastonite, magnetite, quartz, and pyrite. N₂ and Ar on the other hand, appear to be controlled by the solubility of these gases in water (Óskarsson and Galecka, 2017). At the onset of production, excess N₂ and He, possibly of magmatic origin, appear to have accumulated in the reservoir, but samples collected in 2013 showed that the concentrations of these gases had decreased drastically since 2007 (Óskarsson et al., 2015b).

The only observation that contradicts the seawater origin theory is low ratio of deuterium in the hydrothermal fluids. The oxygen isotopes in the fluid vary from ~1 to 2‰, with an average value near seawater (Pope et al., 2009). In contrast, geothermal solutions at Reykjanes have ΔD ranging from ~15 to ~25‰ (relative to SMOW), whereas seawater has ΔD ≈ 0‰, as do most seafloor hydrothermal fluids (Shanks et al., 2001). Pope et al. (2009) suggested that the low deuterium values could be explained by isotope exchange between seawater and hydrothermal secondary minerals (epidote, chlorite, smectite) formed under pre-Holocene conditions when the geothermal fluids at Reykjanes were likely of meteoric origin, in a system that was probably fed by glacial meltwater. This hypothesis is supported by studies on fluid inclusions in drill cuttings from Reykjanes which have suggested that a low- to high-salinity transition has taken place in the reservoir since the last glaciation (Franzson et al., 2002). However, in their modeling Pope et al. (2009) assumed that the Reykjanes reservoir is a closed system and that the residence time of water must be very long in order that isotopic equilibrium to be reached. With elevated fluid recharge rates due to production, the fluids should have a shorter time to reach isotopic equilibrium and therefore would be predicted to become less depleted in deuterium with time. This has not been observed during the first 10 years of production (Óskarsson and Galecka, 2017), in which fluid is estimated to have been extracted from about 1.2 km³ of rock (Axelsson et al., 2015).

Geothermal monitoring in Reykjanes has been ongoing since the first discharge of well RN-8 in 1970, but little changes were noticed before the commissioning of the 100 MW power plant in 2006. Since 2006, the geochemical monitoring has been more frequent, and some changes in the reservoir fluid composition have been observed. In the first years of production an increase was observed in the concentrations of most solutes, including Cl (Fig. 6). These changes were most prominent in wells producing from the SW part of the production field (Fig. 3). The data for the 26th and 29th of May show considerable cooling at the 4500 m loss zone, indicating that the cold-water injection or “soft” stimulation has been successful in increasing permeability in this supercritical zone. It is clear from the temperature profile shown in Fig. 8A that these measurements were made when the well was far from thermal equilibrium. At that time, 40 L/s cold surface water was being injected to cool and control the well. We could therefore expect that when thermal recovery is complete the maximum temperature would certainly exceed 426 °C.

In late May 2017, a second week-long heating-up experiment was carried out. Four successive temperature logs were measured, this time using a Kuster bimetal logging tool calibrated over the range from 120 °C to 440 °C (Fig. 8B). During these measurements approximately 5 L/s of cold water was being injected down the annulus between the well and the 7” stimulation liner string. The data for the 26th and 29th of May show considerable cooling at the 4500 m loss zone, indicating that the cold-water injection or “soft” stimulation has been successful in increasing permeability in this supercritical zone. The purple stars in Fig. 8B show calculated equilibrium formation temperatures (FT), using the Horner method (Horner, 1951), at several logging points on the warm-up T-logs. The highest temperature estimate is 535 °C at approximately 4615 m slant depth. For comparison, Fig. 8B also shows the boiling point versus depth curve (BDP) for seawater assuming a water table at 450 m depth.
(green line), and a temperature gradient extrapolated from measurements of RN-15 (pink line) prior to deepening (Friðriksson et al., 2015). Hokstad and Tänavsuu-Milkeviciene (2017) have also estimated the formation temperature by a Bayesian inversion of multigeophysical data.

Their FT-inversion pre-drilling estimate is represented in Fig. 8B by the black line that ends at 470 °C at 4600 m depth. Hokstad then used logging data collected during drilling of the RN-15/IDDP-2 well, for a new joint inversion that suggests still higher formation temperatures of 535 °C (±50 °C) at 4500 m (Fig. 9), similar to the temperature estimated using the Horner method at that depth.

Since drilling the IDDP-2 ended, the well has been controlled and permeability stimulation attempted by injecting cold fresh water at rates of 5–10 L/s. However, late in 2017 a problem within the production casing was detected. Deploying logging tools is now prevented by a constriction in the 9 5/8″ production casing between 2307 and 2380 m depth. As repair of this constriction would be difficult and expensive, the current consensus is to carry out flow tests without a repair of the casing. Cold water injection was continued until early August 2018 when injection of hot water began. This will be followed by a gradual warm-up period in preparation for long-term flow tests in early 2019. This should allow sampling of the deep supercritical formation fluids, and more tightly constrain the actual formation temperatures.

7. Seismic activity during the IDDP-2 drilling

Seismic activity in Reykjanes is variable over time, with scattered activity and occasional short-term earthquake swarms. Since the beginning of 2013, a dense local seismic network of seven seismic stations with an average spacing of ~0.5 km has been in operation around the Reykjanes geothermal field. In addition, on-line data from four seismic stations in the regional seismic network of Iceland (the SIL network) are available. Seismic activity was closely monitored during the IDDP-2 drilling from the 12th of August 2016 to the 25th of January 2017. During this period 650 earthquakes occurred in the Reykjanes area and more than 200 of them were located within ~1 km of the RN-15/IDDP-2 wellhead (Fig. 10).

Scattered earthquake activity was ongoing during drilling, with a maximum daily rate of 12 earthquakes occurring on the 15th of October 2016. Comparison of hypocentral depths with daily reports on the drilling progress, starting at 3 km depth, indicates that induced earthquakes seem to follow the drill bit with time. Earthquake activity mainly occurred within the depth range where drilling activity took place, i.e. 3–5 km (Fig. 11).

The brittle-ductile boundary at Reykjanes is generally believed to occur at 5.5–6 km depth (Guðnason et al., 2015), but earlier observations from the local seismic network also revealed an aseismic body between 3 and 6 km depth beneath the center of the production field of Reykjanes (Fig. 9). The apparent size of this aseismic body was reduced somewhat by including older data from the national network. However, the uppermost part of this inferred aseismic body, from 3 to 5 km depth, became seismically active during the deep drilling (Guðnason et al., 2016). A possible explanation for the absence of natural earthquakes in this body is that its temperature is very close to the brittle-ductile boundary for normal strain rates. Presumably, the introduction of cold water into the zone of total circulation below 3.0 km depth increased the strain rate sufficiently to induce seismicity. This opens the possibilities to put better constraints on the temperature of the brittle-ductile boundary of basaltic crust in general.

Fig. 9. Temperature prediction based on multi-geophysical inversion and data collected during drilling (from Hokstad and Tiniasvuo-Milkeviciene, 2017). Black lines indicate 400 °C, 500 °C and 600 °C isotherms with increasing depth. The blue line is the actual path of the IDDP-2 well. White squares indicate the focal points of earthquakes detected by the seismic array at Reykjanes prior to drilling. Earthquakes are sparse at temperatures above ~550 °C, and few were detected below ~3 in the fluid up-flow zone prior to drilling. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

8. IDDP drill cores at Reykjanes

Studies of drill cuttings recovered from Reykjanes geothermal wells have provided important insights into the complexities of fluid evolution and temperature fluctuations in the production zone of the Reykjanes system (Franzson et al., 2002; Fröllifsson et al., 2003, 2005; Marks et al., 2010, 2011, 2015). However, drill cuttings are not ideal samples because recovery is biased towards more resistant alteration minerals, mixing occurs over significant depth intervals, and drill cuttings from greater depths are commonly of smaller grain size than those from shallower levels. (Fowler and Zierenberg, 2016a). Although taking drill cores while drilling a production well is expensive in terms of rig time, study of drill cores is highly preferable to studying
drill cuttings from deep levels in a geothermal system, especially when petrological and petrophysical data are important.

There were no drill cores available from the Reykjanes field until the IDDP began operations there. In preparation for deep drilling, cores were taken from the upper 3 km of the field, firstly to test a custom-made 10 m-long IDDP coring assembly, designed with extra cooling, and custom-made PCD drill bits designed to operate at high-temperatures, and, secondly, to learn more about the petrology and petrophysics of the upper 3 km of the field that would not be sampled while drilling the IDDP-2. Fig. 12 shows the location of wells from which the IDDP obtained drill cores, RN-17B, RN-19, RN-30 and IDDP-2.

RN-19 is a vertical well located on the edge of the main geothermal production area (Fig. 12). A 2.7 m long core was drilled in April 2005.
from a depth of 2245 m at an in-situ temperature of 275 °C. The core is composed of coarse crystalline dolerite coming from a sheeted dike complex (Friðleifsson et al., 2005; Mortensen et al., 2006; Friðleifsson and Richter, 2010). The RN-19 core is the coarsest-grained and least altered sample of basaltic intrusive rock recovered from Reykjanes to date, with plagioclase and clinopyroxene phenocrysts in the size range 2–3 mm (Fig. 13C). Fowler and Zierenberg (2016a) showed that the RN-19 core belongs to the trace element depleted basalt category of Gee et al. (1998), a rock type typically associated with picritic basalts that are found in ~2% of surface exposures on the Reykjanes Peninsula (Jakobsson et al., 1978).

RN-17B is an inclined hole side tracked to the south southwest from the RN-17 well pad, with an inclination of about 35° from vertical starting at depth of 933 m (Fig. 12). A 9.3 m core was drilled in RN-17B in November 2008, at a starting downhole depth of 2798.5 m (true vertical depth ~2560 m) and an in-situ temperature of 345 °C. The core is composed of a series of basalt pillows, hyaloclastite, lithic breccia (examples in Fig. 13A and B), and volcanic sandstone units (Friðleifsson et al., 2005; Friðleifsson and Richter, 2010; Fowler et al., 2015; Helgadóttir et al., 2009). The rocks recovered from RN-17B share many characteristics of axial volcanic ridge deposits observed offshore along the submarine Reykjanes Ridge (Fowler et al., 2015). The presence of shell fragments replaced by epidote indicates some of the RN-17B sedimentary material was derived from relatively shallow water. This suggests that this formation has experienced a high rate of subsidence (Friðleifsson and Richter, 2010). The concentration of relatively immobile trace elements indicates that these rocks are related to the trace element enriched category of Gee et al. (1998), similar to the tholeiitic lava flows that cover most of the Reykjanes Peninsula. The pattern of alteration-induced gains and losses of elements recorded...
in the RN-17B core, relative to an unaltered precursor, suggests emplacement on the seafloor and passive alteration by seawater, followed by subsidence, burial, and alteration at progressively higher temperature conditions (Fowler and Zierenberg, 2016b).

RN-30 is also inclined at depth at an angle of ~35° heading southeast and was drilled from the same well pad as well RN-17 (Sigurgeirsson et al., 2011). A total of 22.5 m of core was drilled from three sequential intervals in May 2011, from a starting downhole depth of 2510 m (true vertical depth ~2250 m) and an in-situ temperature of 345 °C. The cores are composed of a series of fine- to coarse-grained dolerite intrusions of basaltic composition (example in Fig. 13F), interpreted to come from a sheeted dike complex (Fowler and Zierenberg, 2016b). The location of RN-30 rocks immediately below the Skálafell shield volcano suggests at least some of the intrusions may be feeder dikes for that edifice, but confirmation studies are needed. It is interesting that at least two of the dikes recovered in RN-30 fall into Gee et al. (1998) trace element and was drilled from the same well pad as well RN-17 (Sigurgeirsson et al., 2011). A total of 22.5 m of core was drilled from three sequential intervals in May 2011, from a starting downhole depth of 2510 m (true vertical depth ~2250 m) and an in-situ temperature of 345 °C. The cores are composed of a series of fine- to coarse-grained dolerite intrusions of basaltic composition (example in Fig. 13F), interpreted to come from a sheeted dike complex (Fowler and Zierenberg, 2016b). The location of RN-30 rocks immediately below the Skálafell shield volcano suggests at least some of the intrusions may be feeder dikes for that edifice, but confirmation studies are needed. It is interesting that at least two of the dikes recovered in RN-30 fall into Gee et al. (1998) trace element and was drilled from the same well pad as well RN-17 (Sigurgeirsson et al., 2011). A total of 22.5 m of core was drilled from three sequential intervals in May 2011, from a starting downhole depth of 2510 m (true vertical depth ~2250 m) and an in-situ temperature of 345 °C. The cores are composed of a series of fine- to coarse-grained dolerite intrusions of basaltic composition (example in Fig. 13F), interpreted to come from a sheeted dike complex (Fowler and Zierenberg, 2016b). The location of RN-30 rocks immediately below the Skálafell shield volcano suggests at least some of the intrusions may be feeder dikes for that edifice, but confirmation studies are needed. It is interesting that at least two of the dikes recovered in RN-30 fall into Gee et al. (1998) trace element.

Rocks in the RN-17B core are variably altered to greenschist and amphibolite facies mineral assemblages (Fowler et al., 2015). Prominent epido-+ pyrite veins with actinolite and chlorite selvages are common in RN-17B. Temperature/salinity relationships of fluid inclusions suggest portions of epido-+ pyrite veins formed from modern geothermal conditions, while others suggest a temperature spike in the past possibly related to adjacent intrusion of a dike. The interiors of crystalline clasts and basalt pillows are largely replaced with chlorite, and incipient amphibole is actinolitic in composition relative to more pervasive hornblende amphibole in glassy clast exteriors and replacing glassy hyaloclastite fragments (Fig. 14E and F). Plagioclase laths retain their igneous texture, but many have calcite (up to An0), compositions, and coupled with hornblende amphibole compositions, indicating incipient amphibolite grade alteration. The disequilibrium assemblage of greenschist and amphibole grade indicator minerals suggest the RN-17B rocks may be actively transitioning to an amphibole grade assemblage at the in-situ temperature owing to subsidence to higher P-T conditions. The bulk rock composition, secondary mineralization, and fluid inclusion petrography of RN-17B rocks suggest a complex history of fluctuating P-T conditions and fluid composition (Fowler et al., 2015; Fowler and Zierenberg, 2016a). Alternatively, the disequilibrium secondary mineral assemblage may reflect periodic spikes in the local temperature environment in response to adjacent diking events that promote the formation of amphibolite grade minerals.

9. Hydrothermal alteration

A series of indicator minerals and rock textures that occur at progressively higher temperatures have been recognized previously in Icelandic geothermal systems, in part facilitated by IDDP drilling (Tomasson and Kristmannsdottir, 1972; Schimming and Frohlich, 1991; Lonker et al., 1993; Marks et al., 2010). Successive alteration minerals that appear with increasing temperatures in the Reykjanes system include: mixed-layer smectite–chlorite, chlorite, mixed layer chlorite–illite, epidote–actinolite, amphibole, and pyroxene (Marks et al., 2010; Zierenberg et al., 2017). At the most extreme conditions, interpreted to be related to diking events, drill cuttings are recrystallized with granoblastic textures and secondary clinoxyroxe and ortho pyroxene formed at temperatures in excess of 925 °C (Marks et al., 2011; Schillingman et al., 2014). Of the IDDP cores, dolerite in the RN-19 core is the least altered rock with fresh igneous clinoxyroxe, plagioclase, and magnetite (Fig. 14A and B). Localized alteration is confined to replacement of late-stage interstitial melt and clinoxyroxe rims chlorite–actinolite which also occurs as rare thin, discontinuous veins (Fowler and Zierenberg, 2016b).

Alteration of RN-30 dolerite in the RN-19 core is the least altered rock with fresh igneous clinoxyroxe, plagioclase, and magnetite (Fig. 14A and B). Localized alteration is confined to replacement of late-stage interstitial melt and clinoxyroxe rims chlorite–actinolite which also occurs as rare thin, discontinuous veins (Fowler and Zierenberg, 2016b).

In the oldest RN-30 dikes (age based on chilled dike margin relationships), there are sparse epidote + quartz in vugs and the core is cut by wispy epidote veins. Rocks in the RN-17B core are variably altered to greenschist and amphibolite facies mineral assemblages (Fowler et al., 2015). Prominent epidote + pyrite veins with actinolite and chlorite selvages are common in RN-17B. Temperature/salinity relationships of fluid inclusions suggest portions of epido-+ pyrite veins formed from modern geothermal conditions, while others suggest a temperature spike in the past possibly related to adjacent intrusion of a dike. The interiors of crystalline clasts and basalt pillows are largely replaced with chlorite, and incipient amphibole is actinolitic in composition relative to more pervasive hornblende amphibole in glassy clast exteriors and replacing glassy hyaloclastite fragments (Fig. 14E and F). Plagioclase laths retain their igneous texture, but many have calcite (up to An0), compositions, and coupled with hornblende amphibole compositions, indicating incipient amphibolite grade alteration. The disequilibrium assemblage of greenschist and amphibole grade indicator minerals suggest the RN-17B rocks may be actively transitioning to an amphibole grade assemblage at the in-situ temperature owing to subsidence to higher P-T conditions. The bulk rock composition, secondary mineralization, and fluid inclusion petrography of RN-17B rocks suggest a complex history of fluctuating P-T conditions and fluid composition (Fowler et al., 2015; Fowler and Zierenberg, 2016a). Alternatively, the disequilibrium secondary mineral assemblage may reflect periodic spikes in the local temperature environment in response to adjacent diking events that promotes the formation of amphibolite grade minerals.

10. IDDP-2 drill cores

Because of the total loss of circulation in the IDDP-2 well below 3200 m depth, the spot cores are the only rock samples available from deeper than 3.1 km (Table 1). Coring proved difficult in these conditions with the equipment available, and although thirteen coring attempts were made, coring in total 43.3 m, only 27.3 m of cores were recovered. The IDDP-2 cores include a series of dolerite dikes with chilled margins (Fig. 13G) interpreted to come from a sheeted dike complex (Zierenberg et al., 2017). Many of the rocks that sloughed onto the cores from unknown depths above drilling intervals include dolerites, basalts, and a few hyaloclastite and volcanic sandstone/siltstones with alteration similar to the RN-17B and RN-30 cores. The core samples recovered from IDDP-2 differ from those in the other Reykjanes wells in the alteration style and extent of alteration (see below), and uniquely include felsic segregation patches of the last melt fraction that form thin plagiogranite vein dikes in core 10 and below (Fig. 13I). IDDP-2 drill cores 10–13 recovered the first examples of felsic intrusive rocks on the Reykjanes peninsula; southwest of Hengill, a major volcanic complex to the north (Fig. 1).

Although many of the core samples show pervasive alteration, cross cutting veins are relatively uncommon and open space filling veins are nearly absent. Alteration assemblages show that the rocks have not completely attained an equilibrium mineral assemblage reflective of the current P-T conditions. These rocks record a complex history of response to adjacent dike emplacement and variable hydrothermal conditions. Further study promises to reveal insights into the longevity and transient conditions near the roots of hydrothermal circulation.

Dolerite alteration and vein mineralogy in the shallowest IDDP-2 cores (i.e. core 3; Fig. 14G & H) bears many similarities to that in the RN-17B core. The shallowest IDDP-2 rocks are extensively veined by epidote, amphibole, plagioclase ± quartz with chlorite-rich vein selvages (Fig. 13 G). Igneous clinoxyroxe is completely replaced with actinolite/hornblende ± chlorite, and plagioclase has secondary calcic domains and appears dusty with abundant secondary mineral and fluid inclusions (Fig. 14G and H). The presence of hornblende and calcic plagioclase is an indication that the rocks have reached P-T conditions of the amphibole alteration facies, but the rocks have not reached equilibrium, possibly reflecting prograde expansion of the hydrothermal system and/or subsidence of these rocks to higher T, P conditions (Zierenberg et al., 2017). Fluid inclusion and alteration mineral paragenetic studies are ongoing to determine the range of P-T conditions and fluid compositions that IDDP-2 cores have experienced.

In contrast to shallower IDDP cores, chlorite and epidote are absent from core 5 and below (i.e. below ~3865 m), thus, amphibolite grade P-T conditions prevail. In most of the cores, igneous clinoxyroxe is
Fig. 14. Plane polarized light (ppl) and back scattered electron (BSE) images of secondary alteration in IDDP core samples. See text for descriptions.

pervasively to completely altered to amphibole. Actinolite persists at depth, but hornblende becomes increasingly abundant downhill. At the bottom of the hole (Core 11–13), hornblende alteration is accompanied by secondary clinopyroxene and orthopyroxene. Plagioclase retains its original igneous textures and normally appears to be little altered. Albitionation of plagioclase is minor to absent in the deeper cores, but the plagioclase is often cloudy due to an abundance of vapor-rich fluid inclusions and the compositions show a wide range from andesine to anorthite. The dominant vein minerals are amphibole and calcic plagioclase, which can occur separately or together. Plagioclase rich veins may contain minor amounts of quartz, but quartz is absent from most hydrothermal veins cutting dolerite, but is locally abundant in replacement veins in and adjacent to the plagiogranite segregation patches and veins (Fig. 14). Although most of the cores show pervasive alteration, cross-cutting veins are volumetrically a very minor component of the rock. The veins tend to be thin (1–4 mm), irregular and discontinuous and lack evidence filling of open space, consistent with formation in the brittle/ductile transition zone. Trace amounts of hydrothermal biotite is noted as shallow as Core 8 (4254 m) and become more abundant at depth.

The most continuous core recovery was achieved at the bottom of the hole from 4634 to 4659 m. Most of the dikes in this section show pervasive alteration of igneous biotite to hornblende, which is locally intergrown with secondary clinopyroxene and orthopyroxene. Hydrothermal biotite is less abundant than amphibole, but it is intergrown with hornblende and secondary pyroxene in the deeper cores.

There is patchy development of recrystallized granoblastic textures clinopyroxene, which is locally intergrown with hydrothermal orthopyroxene + hornblende (Fig. 14). These patches record hydrothermal alteration at the transition from magmatic to hydrothermal conditions. Plagioclase segregation veins are more common in the deepest cores. The shallower veins are dominantly intermediate plagioclase and quartz with minor clinopyroxene, most of which has been altered to hornblende. The deepest felsic veins also have minor amounts of igneous biotite, which has higher F and Cl content compared to hyaloclastites where the permeability has migrated away from the spreading center. At the bottom of the hole from 4634 to 4659 m. Most of the dikes in this section show pervasive alteration of igneous biotite to hornblende, which is locally intergrown with secondary clinopyroxene and orthopyroxene. Hydrothermal biotite is less abundant than amphibole, but it is intergrown with hornblende and secondary pyroxene in the deeper cores.

The alteration of the deeper Reykjanes rocks is remarkably like that of hydrothermally altered oceanic crust (Fig. 15; Marks et al., 2010; Fowler et al., 2015; Fowler and Zierenberg, 2016b; Zierenberg et al., 2017). The IDDP core samples thus provide a unique opportunity to investigate water-rock reaction processes actively occurring in the roots of such submarine ‘black smoker’ hydrothermal systems. This has not previously been possible because the drill cores obtained by ocean drilling were recovered from older crust that can be overprinted with generations of subsequent low temperature alteration as oceanic crust migrated away from the spreading center.

Although drilling the IDDP-2 was significantly more expensive and technically challenging than drilling a conventional geothermal production well, it was significantly less so than drilling an active mid-ocean ridge at sea from a dynamically positioned drill ship.

11. Petrophysical properties of IDDP core samples from the Reykjanes geothermal field

Reliable data on the physical properties of rocks is of major interest for a realistic interpretation of geophysical and wireline log measurements necessary for predicting reservoir potential. This is particularly the case when considering supercritical reservoirs, whose conditions of pressure and temperature are difficult to replicate at the laboratory scale. Up to now, laboratory petrophysical investigations at high temperature and pressure have been restricted largely to dry conditions and did not account for the effect of a pore fluid pressure on the physical properties of rocks. For technical reasons, experimental set-ups with flow of pore fluid flow have been restricted to ~250 °C (e.g. Kristjánsson et al., 2010). Recent technical developments have allowed measurement of some physical properties, such as electrical conductivity and permeability, under pore fluid pressure, confining pressure and temperature that are expected deep in geothermal reservoirs, under supercritical conditions (e.g. Kummerow and Raab, 2015; Nono et al., 2017) and up to magmatic conditions. We are now able to investigate the physical behavior of samples under in-situ conditions at the laboratory scale, including samples from all of the Reykjanes drill cores. Intensive geophysical surveys of this area offer an excellent opportunity to compare small scale investigations to large scale geophysics, leading to a better understanding of geophysical signals in terms of rocks properties and in-situ conditions.

Several core samples from wells RN-17B, RN-19, RN-30 and IDDP-2 were made available for petrophysical investigations at the Laboratoire Geosciences Montpellier (Table 2). They were mostly dolerites, except for one hyaloclastite (RN-17B), and all display high temperature alteration. Mineralogy was determined by XRD and SEM analysis. Conventional petrophysical characterization at ambient conditions was performed on several mini-cores (25.4 mm in diameter) subsampled from the larger drill cores. To characterize the pore space topology, triple weight, mercury and helium porosities, and sonic velocities, permeability, and electrical parameters, such as formation factor and surface conductivity, were determined. Dolerites display a low porosity, mostly resulting from inter- or intra-granular fractures, while hyaloclastites display a high porosity and behave macroscopically as a granular medium. The high level of micro-fracturing in dolerites may have been induced during drilling operations, i.e. rapid mineral contraction during cooling, and is mostly observed on samples from IDDP-2. A subset of the mini-cores was selected for measurements at high-temperature and high-pressure in a gas pressure apparatus (Paternak Press) at Geosciences Montpellier. Major results are summarized in Table 2 (From Escobedo et al., 2017; Nono et al., 2016a,b and Nono et al., 2017).

To investigate the effect of pressure and temperature on the pore network, permeability was measured with argon as a pore fluid, to avoid fluid-rock interactions. Pore pressure was fixed at 20 MPa, while confining pressure and temperature were varied from room conditions to 150 MPa and 800 °C, respectively. Measurements indicate that the permeabilities of dolerite strongly decreases with increasing confining pressure and reach very low values at reservoir conditions (10⁻¹⁵–10⁻²⁰ m² s⁻¹), as expected for micro-cracked crystalline rocks where micro-cracks close with pressure, while it remains nearly constant for the hyaloclastites where the permeability is about 10⁻¹⁵–10⁻₁³ m² s⁻¹. Increasing temperature does not modify the permeability significantly, except for the RN-19 sample where an irreversible increase by two orders of magnitude is
observed in the range of 200–400 °C. In hyaloclastite, temperature has no effect on permeability up to 800 °C.

Acoustic velocities (P-waves), measured up to 300 MPa using the time of flight method, display similar results: they increase nonlinearly in dolerite up to 200 MPa, while they remain constant in hyaloclastites, showing a weak effect of pressure. P-waves velocities at 100 MPa of confining pressure are given in Table 2. Acoustic properties at high temperature are currently being investigated at the Geosciences Montpellier laboratory. Electrical conductivities were measured under dry and saturated conditions (Nono et al., 2017) to highlight the role of fluids on electrical conductivity up to supercritical conditions. Under saturated conditions, the electrical conductivities were measured at different fluid salinities, in order to mimic the variability of geothermal fluids and to investigate the respective contribution of pore fluid conductivity and interfacial conductivity due to fluid-rock electrical charge exchanges (electrical double layer). Results at typical P-T conditions of supercritical reservoirs are given in Table 2 for fluid of near sea-water salinities, like the Reykjanes geothermal reservoir fluids. The measurements at 400 °C highlight the clear differences between electrical conductivity of dry rocks and saturated rocks, saturated rocks being more conductive by one to two orders of magnitude relative to dry rocks. This indicates it may be possible to detect the electrical signature of supercritical fluids in the Icelandic crust. Under these conditions, it was found that surface conduction dominates the electrical conductivity of rock samples. Additional measurements will be performed on the IDDP-2 core samples, where electrical conductivity and permeability are still lacking. Specific behaviors, such as the increase of permeability in some dolerites due to thermal effects, as well as the role of surface contribution to conductivity and fluid-rock interaction at high temperature need more investigations to better characterize the physical properties of rocks at supercritical conditions.
The Reykjanes ridge is the portion of the Mid-Atlantic Ridge (MAR) that extends onshore in southwest Iceland, where the subaerial location of the Reykjanes Peninsula allows investigation of the deep structure of the volcanic/hydrothermal system of a slow spreading mid-ocean ridge. However, the enhanced magma productivity from the Iceland hotspot has produced thicker crust at the Reykjanes ridge than is typical for the Mid-Atlantic Ridge. Our understanding of the structure of oceanic crust has produced thicker crust at the Reykjanes ridge than is typical for fast spreading centers. The deep drill holes completed in in situ oceanic crust are Holes 504B and 1256D, near the fast spreading Mid-Atlantic Ridge. Our understanding of the structure of oceanic crust has produced thicker crust at the Reykjanes ridge than is typical for fast spreading centers.

The IDDP drill cores therefore provide an unprecedented opportunity to investigate water-rock reactions occurring in the active roots of the volcanic/sheeted dike transition than that occurring at fast-spreading centers, such as that observed in Holes 504B and 1256D (Fig. 15). Crustal age is another key difference between Reykjanes and rocks sampled in Holes 504B and 1256D. The crust at Reykjanes is actively forming and its rocks are certainly younger than 1 Ma, whereas Hole 504B and 1256D were completed in 5.9 and 15 Ma old crust and had maximum in situ temperatures of only 165 °C and 67.5 °C respectively (Becker et al., 1989; Teagle et al., 2006). The implication is that the older, colder rocks sampled in Holes 504B and 1256D have migrated away from the spreading center and have a longer and more complex record of integrated alteration-induced geochemical changes, including both higher temperatures near axial hydrothermal and lower-temperature off-axial processes. These characteristics are particularly useful for estimating bulk elemental fluxes between oceans and oceanic crust (e.g., Laverne et al., 2001; Bach et al., 2003). However, due to overprinting by subsequent low-temperature alteration processes, these off-axis processes obscure the high temperature alteration and geochemical exchange actively occurring in the hydrothermal root-zone at the ridge axis.

The IDDP drill cores therefore provide an unprecedented opportunity to investigate water-rock reactions occurring in the active roots of an analog of a submarine 'black smoker' hydrothermal system; one that is free of overprinting by lower-temperature alteration. Rocks at supercritical temperatures from an active hydrothermal environment have not previously been sampled. The IDDP-2 rock samples, and down hole data record supercritical conditions that lack adequate physical and thermodynamic data to be rigorously described using theoretical models. Initial studies reveal the deep hydrothermal system is a dynamic environment with more variability in physical and chemical conditions than simple conceptual models of an environment with fixed physical properties would predict. Despite low intrinsic permeability and modest amounts of fracturing, the rocks are pervasively altered, likely due to the properties of supercritical fluids such as low viscosity that facilitate extensive water-rock interaction.

Even under the extreme active hydrothermal P-T conditions deep in the IDDP-2, disequilibrium greenschist/amphibolite alteration assemblages occur over a large depth range as sampled in the RN-17B and in shallow IDDP-2 drill cores. We hypothesize that this may reflect progression of the hydrothermal system, due to repeated dike intrusions and crustal subsidence that expand the P-T regime into the stability fields of minerals of the amphibolite and higher metamorphic facies. IDDP-2 rocks also have styles of alteration not previously predicted for hydrothermal root zones, e.g., the occurrence of hydrothermal biotite, that appears to be related to the occurrence of K-rich brine formed from phase separation (Zierenberg et al., 2017). Traces of this brine were captured in drill core pore space that are the focus of ongoing studies that may provide the first direct fluid samples that will allow us to characterize downhole fluids in the IDDP-2, an onshore analog of the root zone of a submarine black smoker.

### 12.2. Implications for the development of geothermal resources

As discussed above, the deep geologic environment of the Reykjanes geothermal system is of great interest to the scientific community, situated as it is on the landward extension of the Mid Atlantic Ridge (Elders and Fridleifsson, 2010) and provides easier access to geochemical process occurring under seafloor spreading centers worldwide. However, in the future, the IDDP’s demonstration that it is possible to drill into supercritical conditions could also have a large impact on improving the economics of geothermal resources worldwide. The potential advantages of the approach of accessing hotter and deeper geothermal resources include: (1) Improvement in the ratio of drilling costs to power output per well. Although deeper wells would be more expensive, this should be offset by much higher power output per well. (2) Improvement in the power output of existing geothermal fields without increasing their environmental footprints. (3) Improvement in the lifetime of existing geothermal fields by increasing the size of the producible resource by extending it downwards. (4) Accessing a deeper, hotter, environment for fluid injection. (5) Improvement in the economics of geothermal power production. Higher-enthalpy aqueous working fluids in a turbine have a higher heat-to-power efficiency and therefore should potentially yield more favorable economics. Higher temperatures of the working fluid result in higher power efficiency and therefore should potentially yield more favorable economics. Higher temperatures of the working fluid result in higher power efficiency and therefore should potentially yield more favorable economics.

---

**Table 2**

Mineralogical and petrophysical properties of mini-cores from different drill holes in Reykjanes Peninsula. Permeability and electrical properties are given at in-situ conditions corresponding to supercritical conditions. Electrical properties are given for samples saturated with a brine that is free of overprinting by lower-temperature alteration. Rocks at supercritical temperatures from an active hydrothermal environment have not previously been sampled. The IDDP-2 rock samples, and down hole data record supercritical conditions that lack adequate physical and thermodynamic data to be rigorously described using theoretical models. Initial studies reveal the deep hydrothermal system is a dynamic environment with more variability in physical and chemical conditions than simple conceptual models of an environment with fixed physical properties would predict. Despite low intrinsic permeability and modest amounts of fracturing, the rocks are pervasively altered, likely due to the properties of supercritical fluids such as low viscosity that facilitate extensive water-rock interaction.

<table>
<thead>
<tr>
<th>Sample (core number)</th>
<th>RN-19 (2)</th>
<th>RN-30 (1)</th>
<th>RN-17B (2)</th>
<th>RN-15-IDDP2 (12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>2245</td>
<td>2510</td>
<td>2798</td>
<td>12 samples ranging from 3638 to 4054 m</td>
</tr>
<tr>
<td>Rock type</td>
<td>Dolerite</td>
<td>Dolerite</td>
<td>Hyaloclastite</td>
<td>Dolerites</td>
</tr>
<tr>
<td>Is-o-sat T(°C)</td>
<td>320</td>
<td>350</td>
<td>350</td>
<td>350–450</td>
</tr>
<tr>
<td>From XRD (when content &gt; 5%)</td>
<td>Plagioclase, augite, arfvedsonite, chrome</td>
<td>Plagioclase, augite, actinolite, amazonite</td>
<td>Epidote, albitite</td>
<td>Plagioclase (38–55%)–amphibole</td>
</tr>
<tr>
<td>Porosity (%) at room conditions (std. dev.)</td>
<td>2.9 (0.4)</td>
<td>3.3 (0.4)</td>
<td>0.3–4.5 × 10⁻¹⁰</td>
<td>TBD</td>
</tr>
<tr>
<td>Permeability at Pp = 100 MPa &amp; T = 400 °C</td>
<td>3.2 × 10⁻¹⁰</td>
<td>1.6 × 10⁻¹⁰</td>
<td>TBD</td>
<td>1–3%</td>
</tr>
<tr>
<td>and Pp = 20 MPa (m² · s⁻¹)</td>
<td>10⁻¹⁴</td>
<td>10⁻¹⁴</td>
<td>TBD</td>
<td>10⁻¹⁴ S (sample PP2 at 4649.25 m)</td>
</tr>
<tr>
<td>Dry electrical conductivity at Pp = 100 MPa &amp; T = 400 °C (5 s · m⁻¹)</td>
<td>0.057 ± 0.05</td>
<td>0.51 ± 0.05</td>
<td>0.2 ± 0.05</td>
<td>TBD</td>
</tr>
<tr>
<td>T = 400 °C (5 s · m⁻¹)</td>
<td>0.057 ± 0.05</td>
<td>0.51 ± 0.05</td>
<td>0.2 ± 0.05</td>
<td>TBD</td>
</tr>
<tr>
<td>MPa, S = 400 °C and Pp = 30 MPa</td>
<td>5863 ± 100</td>
<td>5863 ± 100</td>
<td>5060 ± 100</td>
<td></td>
</tr>
<tr>
<td>P-wave velocity at Pp = 100 MPa (m · s⁻¹)</td>
<td>4900 ± 100</td>
<td>4900 ± 100</td>
<td>5060 ± 100</td>
<td></td>
</tr>
</tbody>
</table>

exergy (i.e., availability of maximum electrical power production potential for a given flow rate).

Recent numerical simulations of magma-heated, saline, hydrothermal systems indicate that the first-order control on the dynamics and efficiency of heat and mass transfer is phase separation near the intrusion (Scott et al., 2017). Above deep intrusions emplaced at ~4 km depth, where fluid pressure is ~30 MPa, phase separation occurs by condensation of hypersaline brine from a saline intermediate-density fluid. The fraction of brine remains small, and advective and vapor-dominated mass and heat fluxes are therefore maximized for exploitation of supercritical geothermal resources. Thus, the Reykjanes system, although saline, is an attractive target to test utilization of supercritical geothermal resources. If successful, the long-term flow tests now being planned for the IDDP-2, will supply useful information on the technology and economics of the production of useful energy from supercritical geothermal systems. Iceland is fortunate in having several likely sites for such developments. Planning for drilling the IDDP-3 well at Hellisheiði is already underway, and, subject to the availability of funding, drilling could begin as early as 2021–2022.

However, supercritical conditions are not restricted to Iceland, but should occur deep in any young volcanic-hosted geothermal system. Deep wells drilled in geothermal fields such as Kakkioda in NE Japan (Muraoka et al., 1998), Larderello in Italy (Bertini et al., 1980), Los Humeros in Mexico (Gutiérrez-Negrín and Izquierdo-Montalvo, 2010), and Salton Sea in USA (Kasperger et al., 2016) have all encountered temperatures above 374 °C. Development of supercritical geothermal resources could be possible there and in many other volcanic areas worldwide. For example, in Japan the Japanese Beyond the Biflue Project (BBP) is an ambitious EGS project to extract geothermal energy from ~500 °C geothermies (Muraoka et al., 2014). Another possibility, when the technology and economics in the future permit, is to produce useful energy directly from the worldwide submarine mid-ocean ridge systems (Elders, 2015). Vents discharges supercritical water on the sea floor have been directly observed at 5° S on the Mid-Atlantic Ridge (Koshchinsky et al., 2008).

13. Summary and conclusions

The IDDP-2 is the deepest and hottest geothermal production well in Iceland and has demonstrated, for the first time, that it is possible to drill into supercritical conditions. The actual temperature in the formation is expected to exceed the measured 426 °C reported during drilling, and likely reach above 535 °C at 4.5 km depth. The well drilled through rocks like those of the mid-ocean spreading centers, but with a thicker section of sheeted dikes due to a greater input of basal magma from the Icelandic hotspot. Fracture permeability exists even in the supercritical part of the well and has been enhanced by injecting cold water. Although the deeper rocks have very low porosity and sparse fractures, they are pervasively altered to amphibole- and pyroxene-bearing mineral assemblages, suggesting high fluid/rock ratios through the medium of low viscosity supercritical water. The uppermost part of a previously postulated aseismic body, from 3 to 5 km depth below the drill field, became seismically active during the deep drilling. A possible explanation for the previous lack of natural earthquakes in this body is that the body is at temperatures very close to the brittle-ductile boundary for normal strain rates, but injection of cold water during drilling induced fracturing. Drill cores obtained from the IDDP-2 permit, for the first time, investigation of high temperature alteration during the transition from magmatic to hydrothermal conditions and the physical behavior of such rocks under in-situ conditions. Intensive geophysical surveys of the Reykjanes peninsula area offer the opportunity of comparing small scale investigations to large scale geophysics, allowing for a better understanding of geophysical signals in terms of rocks properties and in situ conditions. Various scenarios have been suggested for the deep fluid chemistry of well IDDP-2, but the composition will remain unknown until flow tests allow fluid sampling and analysis. The next step is to allow the well to warm-up and perform flow tests and fluid sampling. Designing the wellhead equipment, flow line and preparation for flow testing is underway. If that step is successful, it will have significant technical and economic implications for the geothermal industry worldwide, wherever supercritical conditions exist at drillable depth.

Acknowledgements

The IDDP-2 was funded by HS Orka, Landsvirkjun, Orkveita Reykjavíkur, and the National Energy Authority (Orkustofnun) in Iceland, together with Statoil (Equinor), the Norwegian Oil and Gas Company. The IDDP has also received funding from the EU H2020 (DEEPEGs, grant no. 690771). Funding for IDDP to obtain spot cores at Reykjanes and elsewhere was provided by ICDP and the US NSF (grant no. 0507625). EU FP7 project IMAGE (grant number No. 608553) supported petrophysical studies of cores. The authors also thank two anonymous reviewers for their contributions to the improvement of this paper.

References


Geology and structure of the Reykjanes volcanic system, Iceland

Kristján Sæmundsson a, Magnús Á. Sigurgeirsson a, Guðmundur Ómar Friðleifsson b

Keywords:
Geothermal systems
Faulting
Segmented volcanic systems
Volcanic systems

A B S T R A C T

The Reykjanes Peninsula is a trans-tensional plate boundary with several volcanic systems from the centers of which fissure swarms extend to the NE and SW. The fissure swarms accommodate the extensional component, whereas north-south trending strike-slip faults accommodate the transform component. The fissure swarms release stress during volcanic-tectonic episodes that occur at intervals of several hundred years. Stress is released by the strike-slip faults by microearthquake swarms at intervals of a few decades. The fissure swarms are segmented along their trend. The segments include a volcanic center with a clustering of fissure eruptions and extensional faults. A proximal zone of 20–40 km follows were faults become dominant with distance from the center. Linear anomalies of a high geothermal gradient extend further still, into the marginal area of Early Quaternary to Miocene rocks indicating dyke propagation for another 30–40 km beyond visible faults. The Reykjanes volcanic center is nested in a 5–6 km wide rift zone with boundary faults of just over 20 m visible throw. Volcanic production keeps pace with extension and subsidence to fill the rift. The last three volcano-tectonic episodes occurred at Reykjanes in the 13th century, about 2000 years ago and about 3200 years ago. The lavas from these three fissure eruptions cover ~2/3 of Reykjanes by area, largely smoothing over faults of the rift floor. During the Weichselian glacial maximum the ice margin may have reached 75–100 km beyond Reykjanes. It had become ice free 14,500 years ago. There is evidence of at least 10 eruptions on the Reykjanes volcanic system since, of which the first ones were of lava shield type. A similar eruption frequency may have prevailed at Reykjanes during its postglacial time interval.

There are three volcanic fissure zones within the Reykjanes center. The middle zone of 1.5 km² hosts the main geothermal resource of the system. Recently the western zone proved to host an exploitable resource also. It may be restricted to a narrow zone of dykes. The reservoir temperatures of these two lie in the range 280–310°C. The eastern zone has not proved productive so far. It has erupted olivine rich shield lavas on most of its trace whereas the others have erupted slightly evolved tholeiite. Feed zones in the main production zone have been correlated partly with the axis of the eastern two tindars. They cluster also in near horizontal intervals which may suggest that density controlled offshoots also play a role.

© 2018 Elsevier B.V. All rights reserved.
2. Reykjanes in the context of the geology of Iceland

Volcanic systems are the building blocks of spreading zones. The rate of spreading has been defined at 18.6 mm/y for the Iceland area from the ocean floor reversal pattern (DeMets et al., 1994), and at 18–20 mm/y for a 9 year period from GPS measurements of extension across Iceland’s combined Western and Eastern Volcanic Zones (LaFemina et al., 2005). That rate of spreading viewed against the volcanic production rate (Jakobsson, 1972) and a lifetime of individual volcanic systems of at least 500 ky, creates a pile of extrusive rocks. Such piles are at least 5 km thick forming units of elongated, lenticular shape (Gibson and Piper, 1972). A preferred zone of magmatic upwelling produces crustal temporal or long term magma storage from which dykes are expelled upwards and laterally, perpendicular to minimum compression to form dyke swarms and crater rows. The latter extend rarely over 50 km from the magmatic center, but faults and open fissures – the surface marks of dykes (Walker, 1965) – continue far beyond. Observed and documented rift zone examples are the Krafla Fires of 1975–1984 (Einarsson, 1991) and Bárðarbunga 2014–2015 (Sigmundsson et al., 2015). Most volcanic systems run subparallel with the plate boundary to form volcanic rift zones, however trans-tensional zones such as the Reykjanes Peninsula are different. Northeast of the Peninsula the dykes of its volcanic systems invade into the flank of Early Quaternary and Tertiary age. This has proved of a major economic benefit in producing low to medium temperature geothermal systems on their distal segments. Walker (1974) recognized this kind of relationship in East Iceland where dyke swarms extend across lava isochrones up to 5 million years older than the central volcano where they originated. Transform faulting offsets 8 million year old rocks by at least 100 km laterally along the Tjörnes Fracture Zone (TFZ) in North-Iceland (Hjartarson and Sæmundsson, 2014). A second apparently much younger transform fault zone occurs in South Iceland (SISZ). There a true transform fault has not developed, but rather a zone of conjugate N–S and ENE–WSW strike-slip faults indicating left lateral slip. This system continues along the Reykjanes Peninsula with only the N–S component well developed at the surface (Hreinsdóttir et al., 2001). A narrow epicentral zone is manifested at 4–5 km depth along the Peninsula, connecting to the SISZ in the east.

3. The Reykjanes Peninsula

The Reykjanes Peninsula connects towards the east to the Hengill volcanic system, the southernmost volcanic system in Iceland’s Western volcanic spreading zone. Magnetic anomalies zigzag along the Reykjanes Peninsula, with a reasonably well defined boundary between rocks of Matuyama and Brunhes age (Fig. 2). A large part of the reverse Matuyama epoch series is overlapped by Brunhes rocks, most of them non-tilted lava shields and their flow foot breccias of postglacial and interglacial age. Six boreholes have been drilled into such rocks in the northwest of the Peninsula. Some of these passed through a minimum thickness of 100–200 m fresh rock. Shells dated from sediment immediately below flow foot breccias at 70–80 m depth in the boreholes
Fig. 2. Aeromagnetic map of Reykjanes Peninsula (Kristjánsson and Jónsson, 1989). The spreading direction has been added and the volcanic systems are outlined. They show up with normal magnetization about as far as their eruptive segments reach Red dots mark boreholes in the dominantly reversely magnetized Matuyama border zone north of Reykjanes. Rocks of normal magnetization of Brunhes epoch age overlap a substantial part of the reversely magnetized Matuyama anomaly. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. Three volcanic and rifting episodes have occurred on the Reykjanes Peninsula in the past 4000 years. The Hengill volcanic system is included for comparison. A non-volcanic rifting episode occurred there in 1789 CE. This system is usually considered as belonging to Iceland’s Western volcanic zone. The numbers between the shaded segments represent the time intervals between the volcanic intervals (Sæmundsson and Sigurgeirsson, 2013). The up-slope time trend from east to west underlines the time sequence of the volcanic episodes jumping successively at intervals of 100–200 years.

Please cite this article as: K. Sæmundsson, M.A. Sigurgeirsson and G.O. Friðleifsson, Geology and structure of the Reykjanes volcanic system, Iceland, Journal of Volcanology and Geothermal Research, https://doi.org/10.1016/j.jvolgeores.2018.11.022
farthest east and southwest yielded an age of about 14,500 years, i.e. Bölling-Alleröd interstadial (Sæmundsson, 2019).

The plate boundary as defined from earthquake epicenters runs N80°E along the western part of the Peninsula passing through three central volcanic complexes. From west to east these are: Reykjanes, Svartsengi, and Krysúvik. Krysúvik is the only one of those on the Peninsula with features common to most central volcanoes, such as segments of arcuate crater rows and tindars, circular geophysical anomalies (resistivity and gravity), alternating inflation-deflation periods (Michalczewska et al., 2012) and gabbroic ejecta from volcanic-hydrothermal explosion craters (Johnston-Lavis, 1895; Jónsson, 1978). Acid rocks have not been found in any of the Peninsula’s centers but Hengill nearest to it in the east has them (Sæmundsson et al., 2016). Only Krysúvik has erupted large volumes of evolved tholeiite. As regards to volcanic production from fissure eruptions, the Brennisteinsfjöll system next east to Krysúvik has been most productive considering the areal extent of lavas produced during the past 7000 years. Comparing further back in time is problematic. As for age assessment, tephra layers older than 6100 y BP are poorly preserved in the soils of the western part of the Reykjanes Peninsula except locally. A number of radiocarbon ages have been acquired. For the oldest postglacial members of the lava succession the poorly defined time transgressive character of ice melt poses a problem.

On the Reykjanes Peninsula periods of rifting and volcanism occur at intervals of 800–1000 years alternating with periods of only transcurrent movement manifested as earthquake episodes occurring at intervals of a few tens of years (Einarsson, 1991). The volcanic activity affects one system at a time jumping successively from east to west with the jumps spaced 100–200 years apart (Fig. 3).

Postglacial volcanism started with the eruption of small volume picritic lavas. Voluminous olivine tholeiite lava shields followed, each about 150 km² by area, of which the two westernmost were dated to about 14,500 y BP (Sæmundsson, 2019). Fissure volcanism became dominant from then on. Shield volcanism fell into two periods, the first occurred during the deglaciation and includes four major shields. The second period began 7000–8000 y BP with a shield of about 100 km², the only postglacial shield of the Krýsuvík volcanic system.

Fig. 4. Volcanic systems of the Reykjanes Peninsula have a core area (1) from which extend volcanic and open fissures (2). Further away, non-volcanic fissures continue (3). The underlying dyke swarms continue into Early Quaternary (green) and Pliocene-Miocene (blue) formations. There they bring about geothermal convection systems where hot springs and still further away tepid springs occur (4), but there is clear evidence from linear anomalies of ultrahigh near surface geothermal gradient that the dykes propagate much further to the NE producing vertical permeability (5). A number of geothermal systems have been detected in the (5) segment settings lacking visible surface manifestations. The distribution and trend of those is shown as red lines on the map. A volcanic system, Fagradalsfjall, is indicated between Svartsengi and Krysúvik. It is made up of tuyas, short tindars and a number of small postglacial lavas, all of picrite and olivine tholeiite composition (Sæmundsson et al., 2016). We name it Fagradalsfjall from the dominant tuya. A NE-SW fissure swarm and a geothermal field are lacking. This and the primitive rocks suggest an embryonic stage for it.
was followed by six more shields at about 1000 year intervals, the last about 900 CE. These shields were small and occurred on the Brennisteinsfjöll volcanic system (Sæmundsson et al., 2016).

Tephrochronology based on eight distinctive ash layers and a number of C-14 datings allow a fairly detailed record of volcanic activity on the Peninsula for the last 4500 years (Fig. 3). It occurred episodically during active periods lasting a few hundred years. The active periods were separated by commonly 800–1000 volcanically quiescent years (Fig. 3). For the western half of the Peninsula the tephra fall from a near shore eruption off Reykjanes dated at 6100 BP might provide a marker for viewing the volcanic history approximately back to that datum. This tephra most likely had its origin on then a near sea platform southwest of Skilafljót where tephra mounds project through the last Skilafljót lavas (Fig. 7). For the first 7000 years of postglacial time five C-14 dates and local tephra falls from maars in Krýsuvík provide for time constraints for volcanic activity during early postglacial time (Sæmundsson and Fridleifsson, 2018, in prep.).

The volcanic systems of the Reykjanes Peninsula are segmented along their trend (Fig. 4). The central area is marked by maximum volcanic production. It hosts a high temperature geothermal system that is kept active as volcanic high temperature geothermal systems generally are, by repeated magma intrusions nesting in their roots. This has been demonstrated repeatedly in deeply eroded central volcanic complexes. An impressive example (much used for demonstration purposes) with twelve separable intrusive phases was studied by Fridleifsson (1983) in SE-Iceland. In the center and on the first 10–15 km of the associated fissure swarms faults, open fissures, crater rows and tindars abound. Tectonic faults and fissures continue far beyond the eruptive segment with variable throws and widths depending on the age of the surface rock but volcanic manifestations are rare if any. The dykes apparently continue at depth even farther than the segment of faults and fissures. This is concluded from a surface expression, which is at best visible as lines of hot springs but otherwise lacking surface expressions, but show up as linear anomalies of ultrahigh geothermal gradient (Sæmundsson, 2011, 2013). The maxima commonly show values 3–4 times higher than the regional average.

On this basis the farthest type of segment has been traced for about 50 km in case of the Krýsuvík and Svartsengi dyke swarms (Sæmundsson, 2013). They create vertical permeability in otherwise low permeability rocks of the plateau-basalt series, and allow for convective geothermal systems (85 °–140 °C) to form. These provide a significant proportion of SW-Iceland’s population with hot water for domestic use.

The transform tectonics are represented by N–S right lateral strike-slip fractures, irregularly distributed along the Reykjanes Peninsula. Geodetic measurements of surface deformation on the Reykjanes Peninsula indicate dominantly left lateral strike slip (Árnadóttir et al., 2008). The seismic imprint of the fracture zone at depth is discontinuous. Microearthquake swarms registered over the last 40 years gradually extend the trace of the plate boundary and fill into the gap. The focal depths define a narrow zone above 5 km depth (Fig. 5) which seems to be a steady state feature. The length of the en échelon strike-slip fracture arrays is commonly 3–5 km. The slip is mostly horizontal and opening of the individual cracks is rarely over 1 m. Conjugate left lateral ENE–WSW faults are lacking on the Reykjanes Peninsula. They do occur within the South Iceland seismic zone (SISZ) east of it, but are rare (Einarsson, 2010). The N–S fractures host an exploitable geothermal convection system above 1000 m depth in the SISZ. At Reykjanes, where tested, the same have proved poor producers below the casing depth of about 1000 m.
4. The Reykjanes volcanic system

The Reykjanes volcanic system is at least 45 km in length of which 30 km are on land. The core area is nested within a 5–6 km broad rift structure at the very SW tip of the Peninsula. Its border faults are well defined with a visible throw of 20 m on the NW in a 14,500 BP lava shield and over 20 m visible in lavas of ~8000 BP on the SE. The SE margin of the system is defined by a row of lava shields and tuyas. Among the shields in the row there is the aforementioned 14,500 year old shield of about 150 km². Its lava and crater bound Reykjanes on the north (Fig. 7). In the center of the rift the shield lava has subsided about 80 m (Sigurgeirsson, 2014). This rate of subsidence is of the same order as found for the period 1992–1995 at 6.5 mm/y by Vadon and Sigmundsson (1997), and by Friðleifsson and Richter (2010) on the basis of depth of burial of cored supramarine strata. Direct distance measurements across the Reykjanes fissure swarm for a four year period (1968–1972) (Fig. 5) showed that a combination of left-lateral and extensional movement of 9 mm/y occurred (Brander et al., 1976). Hreinsdóttir et al. (2001) and Sigmundsson (2006) reported horizontal mainly strike-slip movement of 8 mm/y from GPS measurements for the Reykjanes Peninsula over a 5 year period (1993–1998). The Reykjanes volcanic system has well defined fissure swarms towards the NE and SW. Crater rows and tindars reach 15 km NE from the core area and faults and open fissures another 10 km before disappearing below sea level. The topographic expression of the system extends 15 km SW from the shore. It is clearly offset east relative to the “Eldey volcanic system” next to it (Fig. 6).

The others farther east do not show up as clearly in the sea floor topography beyond the shore as does Reykjanes (Fig. 2). A broad shoal southwest of Svartsengi which is next to the east probably marks a fissure swarm (Fig. 6, east border) and Brennisteinsfjöll may possess an offshore fissure swarm also, with a vague expression on the magnetic map (Fig. 2). Only faults of the one next to Reykjanes, i.e. the Svartsengi-system, extend visibly down to the shore (Sæmundsson et al., 2016). Faults and non-eruptive fissures are likely to occur offshore.

Considering the spreading direction we estimate that of the total spreading of 1.8 cm/y for the Iceland area, about half may be taken up by Reykjanes and its southwestern fissure swarm, with the other half by the fissure swarm of the Eldey volcanic system to the west and by indistinctive offshore fissure swarms to the east. This would mean that during the 14,500 years of postglacial volcanism of Reykjanes it might have widened about 120 m, including perhaps >10 volcano-tectonic episodes. Extension would be accommodated by dykes, normal border faults and intra-rift fissure swarms towards the east. This would mean that during the 14,500 years of postglacial volcanism of Reykjanes it might have widened about 120 m, including perhaps >10 volcano-tectonic episodes. Extension would be accommodated by dykes, normal border faults and intra-rift fissures and faults with their near vertical downward continuation until substituted by dykes. A common feature of rift related NE-SW trending faults and eruptive fissures of the Reykjanes volcanic system is their segmentation. The segments are arranged en echelon. Both left and right stepping occurs on the same fault lines and crater rows, best seen in case of the longest ones (Nakamura, 1970; Jenness and Clifton, 2009; Sæmundsson and Einarsson, 2014;
Sæmundsson et al., 2016). There occur in the eruption center of the Reykjanes volcanic system two late Pleistocene segmented volcanic ridges, one of tindar, the other partly of tuya type. Of over 10 postglacial fissure eruptions in and around the Reykjanes center only the three youngest are preserved almost wholly on shore. All are distinctly segmented. The eastern border of the Reykjanes system is sharply defined by a NE-SW row of three lava shields and three pillow lava mounds, all composed of picrite and olivine tholeiite. These primitive type basalts were erupted during a stage of rapid ice melting and isostatic rebound 15,000–14,500 years ago (Norddahl et al., 2008). Picrite and voluminous olivine tholeiite lava shields formed all along the Reykjanes Peninsula in the wake of ice melting. Gee et al. (1998) suggested that rapid isostatic fluctuations at the end of the Weichselian reduced residence times for parental magmas. Sigvaldason (2002) pointed out that a high rate of volcanic production on the Peninsula was associated with isostatic uplift as found for the Northern Volcanic Zone as well.

Of the volcanic systems of the Reykjanes Peninsula only the Reykjanes volcanic system has developed a single master fault along large segments on its NW border. The largest segments have names, so the southwesternmost of Kinn [Fig. 7] followed by three prominent segments farther northeast up to the outskirts of Reykjavík. Large throws (hundreds of meters) bound the Western Volcanic Zone on the NW from Hengill to the northeast (Sæmundsson, 1992). The walls of these faults are almost vertical for the maximum of little over 30 m of measurable throw or depth in case of open fissures. There has been speculation about the inclination of the faults below the depth of exposure. On the one hand the fault planes have been shown listric all along although the rock is brittle (Nakamura, 1970). On the other hand they
are shown vertical near the surface, and then becoming inclined at 70° (Gudmundsson, 1992). In a Mid- to Early-Pleistocene rock succession in SE-Iceland Tentler and Mazzoli (2005) found examples of dykes continuing upwards as normal faults. This is perhaps the most likely downward continuation of the rift zone faults. It conforms with direct observation of the fault zones of the Reykjanes Peninsula continuing far to the northeast from where eruption fissures end (Fig. 4). Walker (1965) concluded that the faults at Thingvellir in the Western Volcanic Zone were the surface expression of dykes.

4.1. The Reykjanes center

Reykjanes marks the focus of volcanic production in the system with its geothermal steam field of 1.5 km², probably an expression of an intrusive complex at upper crustal level, underneath it. Reykjanes is located in a transition zone where spreading of the Iceland area shifts from the trans-tensional zone of the Reykjanes Peninsula to the predominantly spreading zone of the Reykjanes Ridge. The bending of the seismic zone towards SW to the tip of Reykjanes (Fig. 5) indicates the transitional character of the Reykjanes volcanic system. The surface geology of Reykjanes can be traced back in time only into the Weichselian glacial stage. Absolute datings of glacial age rocks from the Reykjanes Peninsula have been done on a group of transitionally to reversely magnetized lavas topping subglacially erupted mounds of hyaloclastite belonging to the Fagradalsfjall volcanic system (Fig. 2). The rock of these is olivine tholeiite. A first group of samples dated by K–Ar yielded ages averaging around 40 ka suggesting a correlation with the Laschamp reverse excursion (Levi et al., 1990). A second group of samples dated by Ar–Ar and U–Th produced ages around 94 ka (Jicha et al., 2011) nearest to the Blake excursion.

4.2. Tindars

The oldest volcanic units of Reykjanes are two NE–SW trending tindars in the center of the Reykjanes rift zone, each about 2.5 km in length. The western tindar is discontinuous, consisting of pillow lava, hyaloclastite tuff and breccia. Drilling has shown this unit to form the topmost part of an over 300 m thick series of mostly hyaloclastite breccia underneath the western part of Reykjanes (Sigurgeirsson, 2014). It probably makes up a large part of the Weichselian member of the volcanic succession. Empirical data and modelling indicate a Late Glacial Maximum (LGM) glacial extension at 24–21 ka reaching 75,100 km² southwest beyond Reykjanes (Norddahl et al., 2008; Hjartarson and Eríndóttir, 2015). From 15 to 14 ka ice recession left the western Reykjanes Peninsula ice free with a glacier cover on its central and eastern volcanic ranges. The ice thickness at the formation of the Valahnúkur tindar may be estimated from the preserved fluctuating transition zone of pillow lava to hyaloclastite. For comparison the transition level within tindars of similar composition in the Western Volcanic Zone indicate a minimum intraglacial lake depth of at least 200 m for the transition from pillow lava to hyaloclastite (Jones, 1970). At Reykjanes the 300 m hyaloclastite group is followed downwards by over 2000 m of mainly pillow lava. It is interlayered by lavas around 1460 m depth (IDDP core data from well RN-36, 2017 HS-Orka affiliation) and sediment with hydrothermally altered shell mounds at 2500 m in a core from well RN-17 B (Friðleifsson et al., 2014). This is in line with the build up of the Reykjanes volcanic sequence near sea level for most of the time, as illustrated for Iceland by the Pálmason (1980) model of crustal evolution.

The eastern tindar is almost continuous for most of its length. It consists of hyaloclastite breccia and tuff, overlain by a cogenetic eroded
4.3.4. Group 4

Group 4 (Stampar) includes three eruptions of the Western fissure zone. The first is known from three small outcrops, distributed from SW to NE over 4.5 km. What remains are a tuff bed, the topmost part of which is exposed at low tide and scoria craters inland half buried by younger flows. The age of this eruption was estimated 3500–4000 y BP on the basis of tephorochronology (Sigurgeirsson, 1992). The youngest two lavas cover the western half of Reykjanes. They were erupted on 7 km and 4 km long crater rows, one about 2000 y BP the other in the 13th century. Their name, Stampar, refers to tub like craters on the younger of the two. Craters of both and their feeder dykes are exposed in section in the southwestern sea cliff. Also remnants of ash rings from these eruptions are preserved, one offshore in the tuff pillar of Karl (51 m), the other in the coastal cliff opposite. The ash from these was blown NE across Reykjanes (Fig. 8). These two youngest lavas smoothed over underlying faults. Such are now visible only in the SW sea cliff and as secondary lava pillars in line with the general fault trend. As to the progress of the 13th century eruptions, contemporary annals give some information. They report intermittent eruptions
from 2011 CE to 1240 of both tephra and lava. The most widespread tephra is the so-called “medieval tephra” formed in an offshore eruption in 1226 CE (Fig. 8). This is in close agreement with the geological evidence (Sigurgeirsson, 1992) of which Fig. 9 also gives a vivid picture. The 13th century episode affected both the Reykjanes and Svartsengi volcanic systems, of which the last eruptive phase occurred on the Svartsengi system after 1226 CE with the largest flows of the episode erupted most likely in 1240.

5. Faulting

On Reykjanes three zones of active NE–SW dip-slip faults, open fissures and crater rows occur. The western zone is covered by two lavas, one about 800 years old the other about 2000 years old. Faults have not been visibly reactivated since on the lava surface, but they are seen below the youngest lava in the southwest sea cliff cutting the older flow. Also feeder dykes of the two youngest Stampar crater rows are exposed in the sea cliff. The Gunnur and Skálafell flows of about 3000–3200 y BP have been broken up only moderately by the western branch of the Valbjargagjá fault. The branches of that fault unite in the southwest with a displacement of over 10 m in Skálafell shield lava of group 2. The western branch of Valbjargagjá marks the oblique southwest continuation of the Gunnur crater row. It has the most varied thermal activity of Reykjanes associated with it. The vertical displacement of the fault across the 3200 y BP lava is insignificant and the horizontal displacement is < 1 m.

The lava plateau NE of Skálafell is heavily broken up by faults (Fig. 7). There are two main normal faults trending N45°E. They split up towards the NE into several branches trending N20°E with a dominant dip-slip component also. The two westernmost branches have a strike-slip component as well. The displacement is observable 1–3 m for the dip-slip but not so for the strike-slip one. It is right lateral though and probably of the same order as the dip-slip judging from the size and moderate shattering of their push-ups.

5.1. Geothermal field

As with other centers of active volcanic systems in Iceland, Reykjanes hosts a geothermal high temperature system. It is located within the eastern rift zone of Reykjanes with an area of 1.5 km² of active surface manifestations (Fig. 10). Most of the thermal field is between 10 and 20 m above sea level. Fumaroles, and mud pools dominate in a central area of about 1 km² with hot ground and weak steam emanations around it. These occur mainly towards the northeast and south in the Gunnur- and Skálafell-lavas of 3000–3200 y BP. Cold clayey alteration extends northeast all along Rauðhólar. The most varied types of activity occur along branches of the Valbjargagjá fault including temporarily active geysers depositing silica. They were active in the 20th century, and were last reactivated following an earthquake swarm in 1967. In 2008 a powerful blow up occurred issuing steam and mud. It was active until 2014, then ceased and a new exit formed lower down on a common fissure, this time issuing both a thick steam column and some 10 L/s of sea water. A subsidence bowl, generally a corollary of production began to form during the stage of drilling and well testing (Keiding et al., 2010). It developed an elliptic shape of 6–7 km long axis and 26 cm depth centered

---

**Fig. 10.** Location of the Reykjanes geothermal field in relation to its middle fissure zone. The colorful central part shows the result of a soil temperature survey made 50 years ago (Jonasson, 1968). The production area is plume like, coinciding neatly with the area of elevated soil temperature. The reservoir temperature is in the range 280–310 °C in feed zones, mainly in depth ranges around 1700 and 2200 m. The geothermal field is flushed on the exit by a non-convective rise in temperature to ~320 °C on level with the reservoir interval. A recently completed borehole in the Stampar fissure zone revealed an exploitable resource of the same character there also, possibly restricted to a part of the zone of feeder dykes. A low in reservoir and alteration temperature separates the two production zones (Friðleifsson et al., 2014).

---

Please cite this article as: K. Sæmundsson, M.Á. Sigurgeirsson and G.O. Friðleifsson, Geology and structure of the Reykjanes volcanic system, Iceland, Journal of Volcanology and Geothermal Research, https://doi.org/10.1016/j.jvolgeores.2018.11.022
on the main production focus southwest of Rauðhólar (Parks et al., 2018). Production from the geothermal system comes from feed zones below 1000 m (Fig. 11). They have not been ascribed convincingly to specific faults or dykes, except the dyke system of the Rauðhólar tindar and recently also to dykes of the Stampar zone. There are indications of aquifers at level intervals in the production part of the drilled section. The feed zones could be strata-bound but are more likely related to sheets. Such tend to form when rising magma has reached up to a density level equal to its own, but before gas begins to exsolve. The middle of three feed zone levels is at 1600–1800 m depth, below which dyke intensity increases markedly relative to the upper section (ÍSOR affiliated borehole data).

The Stampar and Skálafell fissure zones lack geothermal surface manifestations. They proved for the most part hotter than the main reservoir underneath the active geothermal field indicating non-convective character. Directional boreholes on the east margin (RN-20b and RN-30) were unproductive, despite intersecting two prominent faults including the Skálafell feeder dyke system. In the western, Stampar fissure zone a productive interval was recently discovered.

6. Conclusions

The most prominent structural features of the Reykjanes Peninsula are its crater rows, tindars, normal faults and open fissures of NE–SW trend. These group into discrete volcanic systems. Less prominent N–S arrays of faults of clearly right-lateral strike slip displacement were discovered later. However, the present day seismicity of the Peninsula is restricted to the latter.

The Reykjanes volcanic system is dominated by the NE–SW structural features with eruptive fissures clustering to define its volcanic center on the very SW-tip of the Peninsula. Countless faults and open fissures emanate from it to the NE. Only two oblique-slip N20°E faults occur. They are on the east margin of the Reykjanes center. Their slip displacements are at least an order of magnitude less than the throws of the normal faults.

The Reykjanes volcanic system is one of constructional build up and subsidence. The dip-slip faults have rarely measurable throws of over 20 m being banked up by or even levelled out by lavas of eruptive episodes occurring every 1000 years on average. Drill
cores from the volcanic center of the Reykjanes geothermal area have revealed lava flows down to 1450–1500 m and shell moulds down to 2500 m. The current rate of tectonic subsidence has been defined at about 6.5 mm/year.

A geothermal power plant has been in operation at Reykjanes since 2006. Fluid extraction has produced a maximum subsidence of 26 cm at a center of 6 × 4 km size bowl. Mapping and dating of the volcanism of the Reykjanes Peninsula has been under way by the authors. A fairly clear picture is emerging for the past 4500 years for the individual volcanic systems of the Peninsula. It includes the Hengill volcanic system which is intermediate between the Reykjanes Peninsula and the Western Peninsula. The volcanic pattern shows about 500 year periodicity of volcanism which pass along the Peninsula from east to west. The transform tectonics apparently rules the stage in the volcanically quiet intervals.

The last volcanic crisis of the Reykjanes Peninsula occurred in the 13th century. It involved the Reykjanes and Svartsengi volcanic systems. The progress of the Reykjanes episode could be traced in detail by comparing written and geological sources. In included a number of eruptive events from 1190 to 1226 CE. For a detailed study were dated ashes produced by near shore phreatic eruptions. The Reykjanes episode was followed by the eruption of three fissure eruptions on the Svartsengi volcanic system next to the east. Some geologists include Svartsengi with the Reykjanes volcanic system. A narrowing between the subsidence bowls from fluid production of the geothermal reservoir of the two indicates a poor connection between them. The Svartsengi volcanic episode occurred probably in 1240 CE. Its three separate lava flows are underlain by the main ash of the Reykjanes episode of 1226 CE. An age succession has not been defined.

An important aspect of the fissure swarms of the Reykjanes Peninsula is the far reach of the dyke swarms into the Early- to Late-Pleistocene tuya and tindar type volcanoes and a number of near surface thermal anomalies of high gradient have, when drilled into, revealed otherwise hidden geothermal systems of tens of meters deep. The abnormally high thermal gradient manifest in boreholes a few about 300 m of the surface. Thermal conduction above produces information and man-made subsidence around geothermal systems on the Reykjanes Peninsula. J. Volcanol. Geotherm. Res. 194, 139–148.


References


Please cite this article as: K. Sæmundsson, M.Á. Sigurgeirsson and G.Ó. Friðleifsson, Geology and structure of the Reykjanes volcanic system, Iceland, Journal of Volcanology and Geothermal Research, https://doi.org/10.1016/j.jvolgeores.2018.11.022
Monitoring geothermal reservoir developments with the Controlled-Source Electro-Magnetic method — A calibration study on the Reykjanes geothermal field

M. Darnet 1,*, P. Wawrzyniak 2, N. Coppo 2, S. Nielsson 2, E. Schill 3, G.Ó. Fríðleifsson 4

1 BRGM, 3 Av. Claude Guillemin, Orleans 45060, France
2 Íðóskur Orkurannsoknir/Iceland GeoSurvey, Grensengar 9, Reykjavík 108, Iceland
3 KIT, Institut für Nukleare Entsorgung, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
4 HS Orka, Svartsengi, Grindavík 240, Iceland

ABSTRACT

Surface geophysical monitoring techniques are important tools for geothermal reservoir management as they provide unique information on the reservoir development away from boreholes. For magmatic environments, electromagnetic (EM) methods are attractive monitoring tools as they allow to characterize the reservoir and hence potentially monitor changes related to fluid injection/production. Indeed, the electrical resistivity of reservoir rocks is highly dependent on the volume, chemistry and phase of the in-situ geothermal brine (e.g. liquid, vapor, supercritical).

Passive EM techniques (e.g. magnetotellurics or MT) are traditionally used for geothermal exploration and a few recent studies have demonstrated its potential for monitoring reservoir development. One of the main challenges is though the presence of cultural noise and/or variability of the Earth magnetic field that can obfuscate the EM signals of interest. We have investigated the benefits and drawbacks of active EM surveying (Controlled-Source EM or CSEM) to tackle this challenge, first with a synthetic study and subsequently with an actual time-lapse survey acquired in 2016 and 2017 over the Reykjanes geothermal field in Iceland before (baseline) and after (monitor) the thermal stimulation of the supercritical RN-15/IDDP-2 geothermal well.

The synthetic study showed that for geothermal fields having a resistivity structure similar to the Reykjanes field (i.e. a conductive caprock overlying a more resistive higher temperature reservoir), CSEM and MT measurements can both detect resistivity changes within the deep resistive reservoir, provided that measurement errors are small. Variations in many survey parameters (e.g. errors in receiver position/orientation, differences in recording devices, variations of near surface conditions, external noise) can create significant time-lapse CSEM measurement errors. Our actual time-lapse survey showed that when similar CSEM equipment is used during the baseline surveys and systematically d-GPS positioned, the remaining key parameter controlling the survey repeatability is the level of external noise. Since the influence of external noise on CSEM data can be artificially reduced (e.g. by increasing the transmitter dipolar moment), it offers the possibility to adapt the survey design to increase the chance of detecting the time-lapse signals of interest. On the contrary, little control is possible on the MT signal to noise ratio and hence repeatability.

The time-lapse EM survey acquired over the Reykjanes geothermal reservoir showed indeed that a high CSEM survey repeatability can be achieved with electric field measurements (within a few percent) but that time-lapse MT survey is a challenging task because of the high level of cultural noise in this industrialized environment. To assess the quality of our CSEM dataset, we inverted the data and confronted the resulting resistivity model with the resistivity logged in the RN-15/IDDP-2 well. We obtained a good match up to 2-3 km depth, i.e. enough to image the caprock and the liquid-dominated reservoir but not deep enough to image the reservoir in supercritical conditions. To obtain such an image, we had to jointly invert legacy MT...
data with our CSEM data. On the monitoring aspects, the analysis of changes in electric fields did not allow to identify any CSEM signal related to the thermal stimulation of the RN-15/IDDP-2 well. One possible explanation is the weakness of the time-lapse CSEM signal compared to the acquired CSEM survey repeatability as a result of a limited resistivity change over a limited volume within the reservoir. Future reservoir developments in the supercritical reservoir (e.g. hydraulic stimulation, long-term fluid circulation) will most likely generate stronger resistivity variations over a larger volume than during the thermal stimulation of the well. This calibration study provides the basic information for deciding when and how an EM monitor survey must be performed for the monitoring of the Reykjanes geothermal reservoir but also for the definition of the monitoring strategy of similar high-enthalpy geothermal reservoirs.

1. Introduction

The DEEPEGS project is exploring the technical and economic feasibility of producing supercritical geothermal resources. The RN-15/IDDP-2 well is located in the Reykjanes saline geothermal system in South-West Iceland, on the landward extension of the Mid-Atlantic Ridge. The drilling of the wellbore RN-15/IDDP-2 began in August 2016 and the well was completed at a depth of 4659 m MD (Measured Depth, 4.5 km vertical depth) in January 2017. Supercritical conditions were encountered at the bottom (measured temperature: 426 °C, but estimated around 500–530 °C; 340 bar pressure; Friðleifsson et al., 2017; Stefanson et al., 2017). Stimulations in the form of cold-water injection (mainly thermal stimulations) have been performed to connect the wellbore to existing hydraulic pathways, i.e. pre-existing natural fracture network, in order to improve the productivity of the well and hence increase the chance of harnessing the energy contained in the super-critical fluid (Reinsch et al., 2017). The implementation of geophysical field monitoring methods was required to characterize the impact of such stimulation on its environment, in particular 1) prior to the operation to obtain a reference state unrelated to the field development and 2) during and after the stimulation operation to evaluate its impact on the geothermal reservoir development.

Among the geophysical methods applicable on high enthalpy geothermal systems, the electromagnetic (EM) methods are of prime importance as they offer the unique opportunity to characterize some of the key ingredients of an economically exploitable geothermal system, like the presence of geothermal fluids; the geometry of the permeable reservoir and associated impermeable clay cap and its temperature (Spichak and Manzella, 2009; Munoz, 2014). Indeed, the lower temperature (<230 °C) smectite clay alteration products are more electrically conductive than their higher temperature (>230 °C) chlorite-epidote clay counterparts due to loosely bound cations in smectite (Leroy and Revié, 2004; Munoz, 2014; KristinSDóttir et al., 2010). In addition, the presence of in-situ geothermal brine in the pore space usually lowers significantly the electrical resistivity of the medium (Arche et al., 1942). Similarly, the increase of temperature generally lowers the rock electrical resistivity, through an increase of the fluid and surface conductivity (KristinSDóttir et al., 2010). At higher temperatures and above the brine critical point, the combination of lower viscosity reduction, thermal expansion and decrease of the dielectric constant results in a sharp decrease in the brine conductivity (Kummerow and Raab, 2015). Laboratory experiments on synthetic Reykjanes geothermal brine showed that its conductivity indeed decrease by a factor 5 to 7 when crossing the critical point around 405 °C (Reinsch, 2010). For geothermal systems like Reykjanes, it is therefore expected that the rock resistivity strongly varies with depth with a shallow conductive clay cap (smectite rich, temperature <230 °C) overlain by a more resistive high temperature medium (chlorite/epidote rich, temperature >230 °C), subsequently possibly even more resistive when crossing the critical point (chlorite/epidote rich material with supercritical fluid, temperature >405 °C). Such a sensitivity of the rock electrical resistivity makes it a parameter of choice to characterize the reservoir geometry and hence potentially monitor changes related to fluid injection/production.

Electromagnetic monitoring is becoming increasingly popular, including magnetotelluric (MT) monitoring of hydraulic stimulation of enhanced geothermal reservoirs (Peacock et al., 2013; Didana et al., 2017; Thiel, 2017; Abdellettah et al., 2018), MT monitoring of hydraulic fracturing of tight hydrocarbon reservoirs (Orange et al., 2009; Rees et al., 2016a,b,c), DC resistivity and Controlled-Source Electromagnetic (CSEM) monitoring of CO2-sequestration scenarios (Streich et al., 2010; Börner et al., 2015a,b; Streich, 2016), and CSEM monitoring of heavy oil recovery using a borehole-surface configuration (Tietze et al., 2015). One of the main challenges of passive EM monitoring (MT) remains the variability of the Earth magnetic field variations that may lead to poor signal to noise data and hence unreliable MT recordings at the times of interest (Abdellettah et al., 2018). In addition, industrial activities can sometimes generate low frequency EM noise that can obfuscate the MT signals of interest (Streich et al., 2013).

To increase the signal to noise and hence reliability of EM monitoring techniques, we propose to complement passive MT monitoring experiments with active CSEM surveys to compensate for the occasional weakness of MT signal in specific frequency bands (e.g. dead band) and/or the presence of strong cultural noise. Indeed, active surveying allows to control and hence potentially increase the signal to noise ratio of acquired data at any point in time (e.g. by increasing the transmitter strength and/or increasing the recording times). In addition, the CSEM source configuration can be such that it provides additional information on the resistivity structure at depth that MT data cannot necessarily resolve. For instance, a horizontal electric dipole is often used for direct targeting of thin resistive layers, due to its superior sensitivity to resistors compared to MT (Constable and Weiss, 2006; Wiedelt, 2007; Constable et al., 2009; Commer and Newman, 2009). To test and validate this approach in actual field conditions, we undertook to design and acquire a time-lapse MT and CSEM survey over the Reykjanes geothermal field to assess its ability to characterize and monitor the thermal stimulation of the DEEPEGS/IDDP-2 supercritical reservoir, and more generally, any types of natural and/or forced fluid circulations in geothermal systems (e.g. hydraulic, thermal, acid stimulations; geothermal fluid production; produced fluid re-injection). In this paper, after briefly describing the Reykjanes geothermal field, we will first discuss with a synthetic study the benefits of acquiring CSEM data in addition to MT data for resistivity mapping and monitoring. We will then describe how we have designed, acquired, processed and inverted the time-lapse CSEM/MT surveys in order to obtain a reliable and highly-repeatable EM dataset on this reservoir. We will then conclude with an attempt to identify time-lapse resistivity changes and discuss the remaining challenges towards reliable resistivity monitoring of such high-enthalpy geothermal reservoir development.

2. Reykjanes geothermal field

The Reykjanes geothermal system is located at the tip of the Reykjanes peninsula, SW-Iceland (Fig. 1) at the landward extension...
of the Reykjanes Ridge. The heat source of the Reykjanes geothermal field is not known but interpreted to be dykes, thin sills or a sheeted dyke complex. A brittle-ductile transition is estimated at 5.5–6 km depth which marks the bottom of potential permeability and therefore the base of the hydrothermal system (Gudnason and Flovenz, 2015). Based on geothermal manifestations on surface the aerial extent of the Reykjanes geothermal field is estimated to be 1–1.5 km² (Björnsson et al., 1970) on surface but with greater lateral extent at depths based on resistivity surveys (Karlsdottir and Vilhjalmsdottir, 2014). The reservoir fluid is of seawater origin but affected by boiling and fluid-rock interaction (e.g. Tömsson and Kristmannsdóttir, 1972; Arnórsson, 1995; Óskarsson et al., 2015).

Before the production started from the Reykjanes field in 2006, the geothermal reservoir was liquid dominated. Production has caused a pressure draw-down in the centre of the field and therefore a steam cap has formed above 1000–1100 m depth in the reservoir (Gudmundsdottir, 2015).

The reservoir has been in operation for power production since May 2006, when the Reykjanes power plant started generation of 100 MW with two 50 MW steam turbines. Installed power capacity is 175 MW from the two geothermal power plants at Svartsengi, 75 MW, and Reykjanes, 100 MW. In addition, 150 MW thermal energy is generated for district heating and supplies fresh water to the municipalities at the Reykjanes peninsula. Average production from the reservoir at about 2 km depth is 500 kg/s of 220 °C geothermal fluid at 22 bar Well Head Pressure.

3. CSEM and MT sensitivity study

3.1. Reykjanes conceptual resistivity model

In order to study the sensitivity of the CSEM and MT methods for the characterization and monitoring of high-enthalpy geothermal reservoir, we have first designed a simplified 1D resistivity model of the Reykjanes reservoir based on the existing conceptual geological models (Flovenz et al., 1985; Kristinsdóttir et al., 2010; Khodayar et al., 2016), resistivity logs (Fig. 2) and MT soundings (Karlsdóttr and Vilhjálmsdottir, 2016). It consists in a relatively unaltered and hence resistive (100 Ωm) layer overlying a more conductive (1 Ωm) smectite-zeolite rich zone (Fig. 3); then, follows a more resistive (30 Ωm) chlorite-epidote rich zone within supercritical conditions are met (at 4 km depth in RN-15/IDDP-2 well). At this point, only a handful of studies have measured in laboratory conditions the behavior of the rock electrical resistivity but it is likely that it increases due to the drop of the brine electrical conductivity (Reinsch, 2016; Nono et al., 2018). A factor three increase of the resistivity on different Icelandic rock samples has been observed (Reinsch, 2016), most likely caused by the combination of lower viscosity reduction, thermal expansion and decrease of the dielectric constant (Kummerow and Raab, 2015; Nono et al., 2018). We therefore assumed that the chlorite-epidote rich zone in supercritical conditions is three times more resistive than the chlorite-epidote rich zone (i.e. 100 Ωm). Depths of the different interfaces have been defined based on the existing conceptual geological models of the Reykjanes geothermal field and well data. To study the sensitivity of the CSEM and MT methods to resistivity changes at the reservoir depth, we assumed that its resistivity drops by a factor three over a 1 km thick section at 4 km depth, simulating a change of geothermal fluid from supercritical to liquid due thermal cooling, as expected during the thermal stimulation of the RN-15/IDDP-2 well.

3.2. MT sensitivity study

We have first computed the MT impedance tensor on the aforementioned 1D resistivity models and subsequently calculated the detectability D of a time lapse MT signal between two surveys A and B as (Ogaya et al., 2016; Thiell, 2017):

\[
D_{MT} = \frac{|\mu_n - \mu_s|}{\sqrt{\Delta \mu_4 + \Delta \mu_2}}
\]

where \(\mu_n\) is the MT apparent resistivity (1Ωm) and \(\epsilon\) is the measurement error (1Ωm). Frequencies are logarithmically distributed from 0.001 Hz until 100 Hz. Fig. 4 displays the apparent resistivity curves for the simplified 1D resistivity model of the Reykjanes geothermal field (Fig. 3) as well as the detectability D of the signal caused by the 100 Ωm to 30 Ωm resistivity drop at 4 km depth. Here, we assumed a 1% measurement error on the apparent resistivities on the base and monitor surveys (Ogaya et al., 2016). Detectability is maximum at low frequencies (<0.1 Hz) and tops around 5.

3.3. CSEM sensitivity study

Similarly to the MT case, we have first computed the CSEM impedance tensor on the aforementioned 1D resistivity models based on the CSAMT formulation (Zonge et al., 1991) and subsequently calculated the detectability D of a time lapse CSEM signal between two surveys A and B as:

\[
D_{CSEM} = \frac{|\mu_n - \mu_s|}{\sqrt{\Delta \mu_4 + \Delta \mu_2}}
\]

where \(\mu_n\) is the CSEM apparent resistivity (1Ωm) and \(\epsilon\) is the measurement error (1Ωm). CSEM fundamental frequencies range from 1/32 s until 32 Hz and increase by a factor 4, as typically used during CSEM field surveys (Coppo et al., 2016). We also calculated the CSEM response for the first four odd harmonics of the aforementioned fundamental frequencies to obtain a well sampled spectrum from 1/32 s until 100 Hz. Fig. 4 displays the CSEM apparent resistivity curves for the simplified 1D resistivity model of the Reykjanes geothermal field (Fig. 3) as well as the CSEM detectability D of the signal caused by the 100 Ωm to 30 Ωm resistivity drop at 4 km depth. Here also, we assumed a 1% error on apparent resistivities as observed on our actual measurements (see next section). Detectability is high at low frequencies (<1 Hz) and long transmitter-receiver offset (10 km). Detectability tops around 10 at intermediate frequencies (0.1 –1 Hz) i.e. in the transition zone between the far and near-field CSEM response (Zonge et al., 1991).

3.4. MT vs CSEM sensitivity

The CSEM and MT detectability computed on the simplified 1D resistivity model of the Reykjanes geothermal field (Fig. 4) shows that for a similar noise level over the whole frequency band, the sensitivity to a resistivity change within the resistive reservoir is likely to be higher on CSEM data than on MT data, most likely due to the superior sensitivity of the CSEM technique to resistors compared to MT (Constable and Weiss, 2006; Weidelt, 2007; Constable et al., 2009; Commer and Newman, 2009). In addition, the use of a CSEM transmitter allows to control and hence potentially decrease the measurement error on apparent resistivities. This provides an unique opportunity to increase the detectability and hence sensitivity of the EM monitoring method to resistivity changes at the reservoir level (Siripunvaraporn et al., 2018).

4. Reykjanes time lapse EM surveys

4.1. Survey design

A pre-survey modelling study was performed to define the best CSEM transmitter configuration as well as the appropriate set of frequencies. An a-priori 2.5D resistivity model (i.e. 3D model with one
axis of symmetry) was designed based on the aforementioned conceptual 1D resistivity model of the Reykjanes geothermal reservoir (Fig. 4). Here also, we made the assumption that the injection of cold water during the thermal stimulation of the RN-15/IDDP-2 well is lowering the resistivity of the stimulated zone and hence it is getting three times more conductive than the initial state (dropping from 100 $\Omega$m to 30 $\Omega$m). It is challenging to predict the size of the stimulated zone but for simplicity and as a reference case, we assumed that a 1 km thick supercritical reservoir section is affected and that it extends laterally over 3 km (Fig. 4).

We subsequently modelled the CSEM response of this model using the MARE2DEM finite-element code developed by Key and Ovall (2011). To do so, we assumed that a horizontal electric dipole transmits a CSEM signal at different frequencies (from 1/32 s until 2 Hz) into a grid of 500 m-spaced receivers. Since CSEM impedance are not directly measured in the field, we focused on electric and magnetic field measurements. Furthermore, we looked into electric field measurements rather the magnetic fields due to their higher sensitivity to resistive anomalies when transmitted by a horizontal electric dipole (Grayver et al., 2014). We first computed the amplitudes of the major axis of the polarization ellipse (PE) of the horizontal electric field as function of the CSEM frequency and position of the receivers, before and after the stimulation, and subsequently derived the detectability of the time-lapse CSEM signal using Eq. (2), where the amplitudes of the electric field is used instead of apparent resistivities. We assumed that measurement errors range from 0.1% to 10% of the total electric field, as typically observed in actual surveys (see next section). The time-lapse signal is maximal at long transmitter-receiver offsets (>5 km) and low frequencies (<2 Hz). Also, the longer the offset, the stronger the anomaly is. Detectable time-lapse signals (i.e. D much greater than 1) require measurement errors in the 1% range or less, highlighting the need for very high repeatability time-lapse CSEM surveys in order to be able to sense such a change. As a consequence, we designed the time-lapse CSEM surveys over the Reykjanes reservoir such that long-offset (>5 km) and low-frequency (<2 Hz) signals could be measured with a high degree of repeatability. This posed a real challenge due to logistical constrains on the narrow Reykjanes peninsula and expected high-level of EM noise related to the presence of the geothermal plants.

4.2. Time-lapse EM data acquisition

Time-lapse CSEM surveys have been acquired in September 2016, while drilling of RN-15/IDDP-2 well and in August 2017, after the thermal stimulation of the well. It used a double orthogonal horizontal electric dipole for the transmitter (Fig. 1), 3 km north of the geothermal field providing two polarizations called POL1 (900 m-long dipole between E1 and E2) and POL2 (900 m-long dipole between E2 and E3). Its position is such that the mid-point of the longest transmitter-receiver offsets (7 km) is located in the vicinity of the target of interest and such that injection electrodes can be installed in conductive superficial material (here, a swamp) to ensure a good electrical coupling of the transmitter with the ground. In the end, we managed to inject repeatedly a current of about 30 A at 560 V with a Metronix TXM22 during both baseline and monitor CSEM surveys. This signal was successfully picked up by all our CSEM stations deployed over the Reykjanes peninsula (Fig. 1). To adequately characterize the subsurface, a broad band set of CSEM frequencies (from 1/32 s up to 1024 Hz) was acquired with a minimum set of 50 cycles at low-frequencies to ensure proper stacking of any random noise.
ARTICLE IN PRESS

M. Darnet et al. / Journal of Volcanology and Geothermal Research xxx (xxxx) xxx–xxx

The waveforms were seven square waves of fundamental frequencies ranging from 1/32 s up to 128 Hz increasing with a factor 4. A total number of 22 CSEM recording stations were deployed during the baseline and monitor surveys. They were Metronix ADU07 acquisition systems, MF507 or MF506 magnetic coils and two orthogonal 100 m long electric dipoles oriented North-South and East-West. MT data have been acquired with the same equipment during the night shifts of the baseline survey i.e. when the CSEM transmitter was off.

**Fig. 2.** Logged resistivity in the RN-15, subsequently DEEPEGS/IDDP-2 well (solid gray line) and Cation Exchange Capacity (square) measured in laboratory conditions from cuttings, a function of the depth below surface (modified from Reinsch, 2016).

Given the results of the baseline MT survey (see section MT analysis), MT stations were only deployed a couple of hours during the monitor survey, not long enough on the ground to provide reliable low-frequency MT data. Finally, Transient EM (TEM) soundings using a 50 m-wide square loop acting as a transmitter and receiver and transmitting an alternating on/off 4A current have been acquired to characterize the near surface resistivity (<200 m) and to perform static shift corrections, if necessary (see next section). All recording equipment (electrodes, magnetometers, recording units) have been positioned with a differential GPS with a centimeter accuracy and replaced at the same position during the monitor survey to minimize positioning errors. When possible, electrodes and magnetometers have been put back in the same holes into the ground. Similarly, the transmitter electrodes and cables have been dGPS positioned and re-installed at the same position during the monitor survey.

4.3. MT analysis

4.3.1. MT data processing

The magnetotelluric method studies the transfer function (hereafter TF), in frequency domain, between the natural electric $E$ and the magnetic field $H$, recorded at ground surface (Cagniard, 1953; Vozoff, 1972), also called the impedance tensor $Z$. The MT impedance contains information about the geo-electric structure for the subsurface. The MT theory is based on the hypothesis of plane wave sources and stationarity of the signals.

Assuming one station location, a fixed frequency $f$, a $e_i$ vector ($N$ corresponds to the number of Fourier coefficients obtained from successive and overlapping subdivision of time series) of horizontal electric field Fourier transform along direction $i$ and a $2 \times N$ vector of magnetic field $b$ (two horizontal directions), both quantities are linked by the following equation

$$e_i = b \cdot z_i + \epsilon$$  \hspace{1cm} (3)

where $z_i$ is the magnetotelluric impedance associated with the direction of the electric field (vector of dimension 2, $z_i = [z_{ix}, z_{iy}]$) and $\epsilon$ is a vector of random errors.

Eq. (3) can be solved using ordinary least-square estimates (Sims et al., 1971), but often furnishes biased estimates due to local correlated noise between $e$ and $b$. To overcome this bias, the remote reference method, (hereafter RR) consists in introducing magnetic field data from one (Goubau et al., 1978) or several (Chave and Thomson, 2004) distant MT station in order to filter noise impact in

---

Please cite this article as: M. Darnet et al., Monitoring geothermal reservoir developments with the Controlled-Source Electro-Magnetic..., Journal of Volcanology and Geothermal Research (2018), https://doi.org/10.1016/j.jvolgeores.2018.08.015
Fig. 4. a) MT and b) CSEM apparent resistivity curves for the simplified 1D resistivity model of the Reykjanes geothermal field with a 100 km (initial state) and 30 km (stimulated) thick layer at 4 km depth. c) MT and d) CSEM detectability of the 100 km to 30 km resistivity change over 1 km at 4 km depth. Offsets between the CSEM transmitter and receivers are displayed on the figure.

The least square estimate, provided the RR site and the local station are not contaminated by correlated noise.

Chave and Thomson (2004) introduced the two-stage implementation of the remote reference method. Considering a set of remote reference horizontal magnetic field reunited in one vector \( Q \) (size \( px^2 \)), the local magnetic field is linked to \( Q \) by

\[
b = Q \cdot W + \epsilon
\]

\[
\hat{b} = Q \cdot \hat{W}
\]

The two-stage RR method consists in replacing \( b \) in Eq. (3) by \( \hat{b} \) and solve the system. Unfortunately, due to non-stationarity of the MT signals and transient noise to signal fluctuations, the simple least-square solution

Fig. 5. Detectability of the time-lapse CSEM signal on the amplitudes of the electric field calculated on the Reykjanes 2.5D resistivity model (Fig. 4) as a function of the distance from the electric dipole transmitter and for different measurement errors (0.1% (top left), 1% (top right) and 10% (bottom left) of the total electric field). On each panel, each curve corresponds to a different transmitter frequency (see legend for the actual frequencies). Stimulated zone extends from 3000 to 6000 m offset from the transmitter.

Please cite this article as: M. Darnet et al., Monitoring geothermal reservoir developments with the Controlled-Source Electro-Magnetic..., Journal of Volcanology and Geothermal Research (2018), https://doi.org/10.1016/j.jvolgeores.2018.08.015
leads to unreliable estimates. In order to overcome these problems, robust methods were introduced in the 80s. Two principal robust methods are commonly used to estimate the MT transfer function (Chave and Jones, 2012).

The first is the M-estimator, a robust TF estimator, designed to minimize the influence of data associated to large electric field residuals in the regression (Chave and Thomson, 1985). M-estimator TFs provides a good protection against strong data residuals but are still highly sensitive to extreme values in the magnetic field (predictor), i.e. the so called leverage points. The second method is the bounded influence estimator (Chave and Thomson, 2004), which consists in a variation of the M-estimator where the diagonal weighting matrix is enhanced to provide protection against leverage points. In this paper, we use the RAZORback Python library (Smai and Wawrzyniak, 2018) to perform two-stage multiple remote reference bounded influence processing.

### 4.3.2. MT results

Seven stations were used for MT acquisition during the baseline survey (see Fig. 1). Each MT station dataset consists in 1 h of recordings at 4096 Hz sampling frequency and at least 12 h at 512 Hz. A distant simultaneous MT station, located 80 km away, was used as a reference (hereafter site 100).

MT sounding consistency quality assessment was performed using apparent resistivity and phase curves inter-comparison between single site and combinations of remote reference results. Phase tensor consistency analysis was performed, as advocated by Booker (2014): “Smooth variation of the phase tensor with period and position is a strong indicator of data consistency”.

In order to asses the quality of the MT data in the [1 mHz – 128 Hz] band, we show the normalized phase tensor (hereafter PT), i.e. the phase tensor with longer axis $\phi_{\max}$ normalized to 1, is displayed for all frequency and RR combination. Ellipses are filled with a color bar indexed either on their ellipticity value (left panel on Fig. 6) or their $\beta$ angle (right panel, same figures). Low values of ellipticity diagnose a 1D medium (Bibby et al., 2005) while $\beta$ angles absolute values below 3° diagnoses a 2D medium (Booker, 2014).

In any remote reference combination (indexed by vertical scale ticks on Fig. 6), discontinuous PT behavior are observed for 4 soundings (sites 9, 10, 11, and 24), leading to rejection of those data for interpretation. Site 13 displays a smoother and coherent behavior in SS mode.

### 4.4. CSEM data processing

Considering a transmitter injecting a square wave electric current at a frequency $f_0$ and a set of synchronous EM receivers recording the horizontal components of the electromagnetic field, CSEM data processing consist in estimating frequency domain transfer functions between the receiver’s 4 components of the horizontal electromagnetic field $(Ex, Ey, Hz, Hx)$ and the transmitter injected current $I$ along each chosen direction of injection.

$$\frac{Ex}{I} = \frac{TEy}{THx} = \frac{THy}{TEx}$$

TF estimation is performed on the harmonics of the injected frequency $f_0$. The CSEM TF estimation problem (Eq. (6)) is simpler than the MT one as i) it reduces to TF estimation between one input $I$ and one output $y$ (any component of the EM field) and ii) the input $I$ is stationary (no leverage points are expected).

In practice, we estimated CSEM TFs using both simple least-square (hereafter LS) and M-estimator (hereafter ME) techniques, as advocated by Streich et al. (2013), using the RAZORBACK library (Smai and Wawrzyniak, 2018). In our case, both LS and ME converges to similar results and therefore LS results have been used.

In addition, an estimation of the ambient noise is performed around each frequency $f_0$. It is computed as the quadratic mean of all Fourier Transform coefficients contained in the interval $f_0 - 0.1 f_0 ; f_0 + 1.0 f_0$ and is considered an estimate of the noise to signal ratio.

### 4.5. MT and CSEM static shift corrections

Shallow lateral changes of resistivity and topographic features can create charge accumulations at the surface of these inhomogeneities and shift electric field measurements up or down by a factor independent of frequency but phase remains unaffected (Zonge et al., 1991). To correct for such effects on CSEM and MT data, we shifted the MT apparent resistivity and CSEM amplitude curves by a factor such that high frequency data ($>100$ Hz) match the response from a 1D resistivity model built from the 1D inversion of the co-located TDEM sounding. In the end, only the few CSEM/MT stations located close to the geothermal alteration zone outcropping at surface required such corrections.

### 5. Reykjanes time-lapse CSEM survey repeatability

In this section, we aim at establishing the accuracy at which time-lapse CSEM measurements can be repeated over a period time of several months and what the key parameters that influence it. We focused our attention on the electric field measurements rather than the magnetic fields due to their higher sensitivity to resistive anomalies when transmitted by a horizontal electric dipole (Grayver et al., 2014).

#### 5.1. Influence of CSEM recording equipment and transmitter

To assess the influence of the transmitter and recording equipment on the CSEM survey repeatability, we have performed a CSEM experiment where a 1 Hz square is transmitted continuously with a 200 m-long horizontal electric dipole and recorded with a set of four ADU07 acquisition systems measuring the horizontal electric field at the same location i.e. all electrodes buried in the same pit. Transmitting and recording electric dipoles are separated by 500 m and an in inline configuration (parallel dipoles). We then uninstalled and reinstalled a few hours later the electrodes at the same location and...
M. Darnet et al. / Journal of Volcanology and Geothermal Research xxx (xxxx) xxx–xxx

ARTICLE IN PRESS

Fig. 6. Multiple remote reference two-stage bounded influence processing results. Comparison of normalized phase tensor (PT) for each possible combination of remote reference. PT are filled with color bar indexed on their ellipticity value (left panel) and their $\psi$ angle value (right panel).

compared the repeatability of the electric field measurements. To compensate for the variability of the injected current at the transmitter due to changes of the electrical coupling of the injection electrodes with time (i.e. caused by heating of the ground), the electric fields have been normalized by the injected current measured at the transmitter. We then define the repeatability $R$ of electric field measurements as:

$$R_{AB} = \frac{|E_B - E_A|}{(E_A + E_B)/2}$$ (7)

where $E$ is the amplitude of the electric field normalized by the transmitter dipolar moment (V/Am$^2$), $A$ and $B$ refer to the baseline and monitor surveys, respectively. All measurements fall within a 0.1% repeatability range, demonstrating that the influence of the CSEM recording system (electrodes, cables, connectors and recording device) on the repeatability of time-lapse electric field measurements is small.

5.2. Influence of near surface

To assess the influence of the heterogeneity of the near surface on the CSEM survey repeatability, we have performed a test where the CSEM signal is recorded simultaneously at the same site (site 18) with two different recording devices. For that purpose, the orientation of the two orthogonal 100 m-long electric dipoles of the first station have rotated by 45° compared to the second station in order to sample different near surface terrain. The amplitudes and phases of the PE major axis of the horizontal electric field as a function of the CSEM fundamental frequencies and associated first fifth odd harmonics are shown on Fig. 8. It is clear that measurements agreed with each other within a few percent. We have therefore also displayed the relative variation or repeatability $R$ (Eq. (7)) of the amplitudes of the major PE axis between the N0 and N45 stations. For the phases, we simply calculated phase differences. Within the 1 and 100 Hz band, the electric field measurements agreed within 1% (except at 50 Hz due to the presence of cultural noise). Above 100 Hz, electric field measurements deviate up to about 5%, possibly caused by increased levels of external noise (50 Hz harmonics and other types of cultural noise generated by the nearby industrial activities). Similarly below 1 Hz, the repeatability is poorer (3–4%) most likely caused by an increased level of external noise, here of magnetotelluric origin as evidenced by the low signal to noise ratio of the lowest frequency (1/32 s). Similar conclusions hold for the phase of the electric field with less than 1° repeatability between 1 and 100 Hz.

Please cite this article as: M. Darnet et al., Monitoring geothermal reservoir developments with the Controlled-Source Electro-Magnetic..., Journal of Volcanology and Geothermal Research (2018), https://doi.org/10.1016/j.jvolgeores.2018.08.015
and 2–3° below 1 Hz and above 100 Hz. We therefore conclude that the heterogeneity of the near surface has a limited influence on the survey repeatability and definitely much less than external noise.

5.3. Influence of external noise

To assess the influence of external noise on the CSEM survey repeatability, we have installed station 18 twice three days apart,

Fig. 7. MT soundings for Single Site (blue curves) and maximum number of remote reference processing for sites 00, 13 and 15 (red curves). Apparent resistivity curves $\rho_{xy}$ and $\rho_{yx}$ and phases $\phi_{xy}$ and $\phi_{yx}$ are shown in continuous lines, components $xx$ and $yy$ in dashed lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
while the CSEM transmitter was kept unchanged. The amplitude and phase of the PE major axis of the horizontal electric field as well as their repeatability is shown on Fig. 9. Between 0.1 Hz and 10 Hz, repeatability is within 2–3%, occasionally less than 1%, and 2–3%, while the CSEM transmitter was kept unchanged. The amplitude and phase of the PE major axis of the horizontal electric field as well as their repeatability is shown on Fig. 9. Between 0.1 Hz and 10 Hz, repeatability is within 2–3%, occasionally less than 1%, and 2–3%, occasionally less than 1%, for the amplitudes and phases, respectively. At higher frequencies (>10 Hz), the presence of external noise (e.g. 50 Hz and harmonics) degrades the repeatability (5–10% and 5–10° for the amplitudes and phases, respectively). Similarly, at low frequencies (<0.1 Hz), the presence of low frequency MT signals degrades the repeatability (>10% and >10° for the amplitudes and phases, respectively). These observations highlight again the prime influence of external EM noise on CSEM survey repeatability.

5.4. Overall time-lapse CSEM survey repeatability

To assess whether the aforementioned influence of external noise on survey repeatability holds for longer periods of time and between time-lapse surveys, we have compared the amplitude and phase variations of the PE major axis of the horizontal electric field at station 18 between the baseline and monitor surveys (Fig. 10). Over the whole frequency band, repeatability is within 2–3% and 2–3% for the amplitudes and phases, respectively but the presence of strong external noise on the baseline or monitor surveys on some specific frequencies degrades the repeatability again significantly the repeatability up to 10% and 10° for the amplitudes and phases, respectively. Although weather was humid during the baseline and dry during the monitor survey, the change of the top soil water saturation and hence resistivity seems to have a limited influence on survey repeatability.

Interestingly, similar conclusions hold for the entire time-lapse dataset. Indeed, when comparing the repeatability of the amplitudes and phases of the PE major axis of the horizontal electric field with the baseline and monitor signal to noise ratio (Fig. 11), the trend is a clear decrease of the repeatability R with increasing signal to noise ratio i.e. with decreasing level of external noise. Since the frequencies of interest for deep reservoir monitoring are low, we have limited our analysis to frequencies less than 10 Hz. This observation demonstrates that for our time-lapse CSEM procedure, the signal to external noise ratio of the repeated EM measurements is the most important parameter to control in order to achieve a good survey repeatability. Contrary to MT monitoring experiments where the practitioner has limited control on the source strength and hence on the achievable survey repeatability, the CSEM signal to noise ratio can be controlled and increased at will by simply increasing the transmitter dipolar moment (e.g. longer electric dipole transmitter and/or stronger power generator) and/or recording signals for longer periods of time to increase the chance of stacking-out random external noise.

6. Reykjanes spatial and time-lapse CSEM results

In this section, we have first performed an inversion CSEM and MT data to confront and validate the CSEM and MT results with the logged resistivities in the RN-15/IDDP-2 well. For this calibration, we only inverted stations along a profile running from the transmitter and crossing the producing geothermal reservoir (Fig. 1). For the inversion, we used the 2.5D MARE2DEM inversion code (Key, 2016). We subsequently attempted to identify a time-lapse CSEM signal by analyzing CSEM amplitude and phase changes of the electric field between the baseline and monitor surveys.

6.1. 2.5D CSEM and MT inversions

6.1.1. CSEM inversion

We inverted the amplitudes of the PE major axis of the horizontal electric field from seven CSEM stations located in the vicinity of the selected profile (stations 05, 09, 14, 18, 22 and 24). Inverted frequencies were 1/32 s, 1/8 s, 1/2 s, 2 Hz, 8 Hz, 32 Hz and associated first firth odd harmonics up to 50 Hz. Both POL1 and POL2 transmitter polarizations were inverted. Data from either the baseline or monitor
survey were used depending on their signal to noise ratio. We limited the frequency band on the high side to 50 Hz due to the presence of strong external noise (e.g. 50 Hz and harmonics, industrial noise). The starting model of the CSEM inversion was a homogeneous 2 Ωm half-space. Numerical simulations of the impact of the land/ocean interface showed that stations nearby the coast may be affected by the presence of the conductive sea over a large frequency band but since the area of interest (RN-15/IDDP-2 well) is located far away from the coast (at least 2 km), we did not include it. Future 3D inversions will however require to include such an interface and will be the scope of a subsequent paper.

To assess the convergence of the inversion and quality of the data fit, we calculated RMS misfits based on measurement errors (Key, 2016). Measurement errors have been estimated from the external...
noise levels calculated at the processing stage. The target misfit is set to 1 and we consider the data fit to be satisfactory when misfits are small (as close as possible to unity) and have been significantly reduced during the inversion process (typically several units). Here, initial misfits were in the 10–20 range and dropped into the 2–5 range after 15 iterations, leading a satisfactory data fit over the whole frequency band (Fig. 12). Only station 14 has a RMS misfit great than 10, most likely due to a remaining static effect as evidenced by the similar shapes of the modelled and observed amplitude curves. To compensate for that, a second-stage static shift correction would be necessary and the inversion re-run but since misfits are already small for most of the stations, we did not perform this additional step.

The resulting resistivity model as well as the average resistivities logged in the RN-15/IDDP-2 well are displayed on the top of Fig. 13. The shallow conductive smectite-rich caprock is well imaged in the vicinity of the RN-15/IDDP-2 well, with a resistivity (\(<3\) \(\Omega\)m) and thickness (approximately 1200 m) in good agreement with the logged values. The underlying more resistive chlorite/epidote rich layer is also imaged but deeper than 2 km, the recovered resistivities are too low (20/10m vs 50/100m in the well). To explain this discrepancy, we have computed the Jacobian or sensitivity matrix at the last iteration of the inversion (Fig. 14). Higher values indicate areas where the dataset is highly sensitive to a change in resistivity. The sensitivity of the CSEM setup is clearly non-uniform with the highest sensitivity towards the mid-point between the CSEM transmitter and receiver grid (around 3 km from the transmitter) i.e. in the vicinity of the RN15/IDDP-2 well (located at 3.7 km distance from the transmitter), confirming that the transmitter and receiver layout is adequate for imaging resistivity variations in this area. It however also shows that the sensitivity at 4/5 km depth is low (at least two orders of magnitudes less than in the first 1.5 km), possibly explaining why the resistivity values recovered from the CSEM inversion are too low compared to the logged ones. Finally, Fig. 14 also shows that the CSEM sensitivity is poor underneath the transmitter and the most distant receivers (distances greater than 5 km from the transmitter). These low sensitivity areas explain most likely the unexpected absence of the conductive layer at large distances from the transmitter (greater than RX18) and its unexpected thickening at negative distances from the transmitter. Similarly, at shallow depth (\(<1.5\) km) between the transmitter and first receiver (RX05), artefacts may be present due to the low sensitivity of the CSEM setup. This illustrates the difficulty of imaging complex resistivity variations with only CSEM transmitter and the need for multiple transmitter positions to obtain a more homogeneous sensitivity matrix.

Fig. 11. Repeatability R of the amplitudes of the major PE axis of the horizontal electric fields between the baseline and monitor surveys as a function of the combined baseline and monitor signal to noise (S/N) ratios on their amplitudes. Only CSEM fundamental frequencies and associated first fifth odd harmonics less than 10 Hz are displayed.

Fig. 12. Observed (dots) and modelled (solid lines) after 2.5D inversion of the amplitudes of the major axis of the polarization ellipses of the horizontal electric field as a function of the CSEM frequencies for POL1 (red/magenta) and POL2 (blue/cyan) transmitter polarizations for stations 05, 09, 14, 18, 22 and 24. Each panel corresponds to a different CSEM receiver along the inversion line. Measurement errors are displayed as vertical bars. Thin and thick solid modelled curves corresponds to the CSEM only and joint CSEM and MT inversions, respectively. [For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.]

Please cite this article as: M. Darnet et al., Monitoring geothermal reservoir developments with the Controlled-Source Electro-Magnetic..., Journal of Volcanology and Geothermal Research (2018), https://doi.org/10.1016/j.jvolgeores.2018.08.015
6.1.2. Joint CSEM and MT inversion

To compensate for the low sensitivity at depth of our CSEM setup, additional constraints (e.g. structural, petrophysical) and/or datasets (e.g. MT, resistivity logs) may be necessary (Scholl et al., 2010). In an attempt to increase the resolution of the resistivity image at depths greater than 2/3 km, we have looked into the possibility of jointly inverting CSEM and MT over the area of interest (Abubakar et al., 2011). Since our MT dataset is of poor quality, we used the legacy MT dataset collected over the Reykjanes geothermal field instead (Karlsdóttir and Vilhjálmsson, 2016).

We first inverted the apparent resistivities and phases of the non-diagonal components of the MT impedance tensor for seven
MT stations nearby our CSEM stations along the profile of interest (Fig. 1). Frequencies range from 0.001 Hz until 100 Hz. Final RMS misfits are close to unity, providing a satisfactory data match (Fig. 15). The resulting resistivity model as well as the average resistivities logged in the RN-15/IDDP-2 well are displayed in the middle of Fig. 13. Here also, the shallow conductive smectite-rich caprock is well imaged with inverted resistivities (<5 Ωm) in good agreement with the logged values. Nevertheless, the depth of the base of this conductive layer does not match well with the well observations (a few hundreds of meters difference). Contrary to the CSEM inversion, the underlying more resistive chlorite/epidote rich layer is well imaged with highly resistive layers (up to 100 Ωm at 5 km depth).

To take advantage of both CSEM and MT datasets, we have jointly inverted the amplitudes of the electric field for the CSEM stations 05, 09, 14, 18, 22 and 24 with the apparent resistivities and phases of the non-diagonal components of the MT impedance tensor for MT stations 77, 76, 74, 78, 79, 70 and 139. CSEM and MT data fit are displayed on Figs. 12 and 15. Overall, misfits are small and similar to the CSEM only and MT only cases, providing a satisfactory match.
data fit. However, RMS misfits are slightly larger than the standalone cases, simply due to the fact that additional constraints have been introduced in the inversion process by the addition of new data. The resulting resistivity model as well as the average resistivities logged in the RN15/IDDP2 well are displayed at the bottom of Fig. 13. Interestingly, both the shallow conductive smectite-rich caprock and the underlying resistive chlorite/epidote rich layer are now well imaged and in good agreement with the logged values. Furthermore, the depth of transition zone between the caprock and the deeper and more resistive material fits now very well with the well observations. This good match demonstrates the validity of CSEM and MT measurements for estimating and hence monitoring resistivity variations within the Reykjanes geothermal reservoir.

6.2. Time-lapse CSEM signals

In order to identify time-lapse signals in our dataset related to the thermal stimulation of the RN-15/IDDP2 well, we have calculated the amplitude and phase change of the polarization ellipse of the horizontal electric field between the monitor and baseline CSEM surveys as a function of frequency. Vertical bars indicate the estimated time-lapse amplitude measurement error.

Fig. 16. Relative amplitude change of the major axis of the polarization ellipse of the horizontal electric field for the stations 09, 14, 18, 19, 22 and 24 between the monitor and baseline CSEM surveys as a function of frequency. Vertical bars indicate the estimated time-lapse amplitude measurement error.

Fig. 17. Detectability of the CSEM time-lapse signal based on the amplitudes of the electric field at 10 km offset from the transmitter as function of the width of the stimulated area and measurement errors for the 2.5D Reykjanes resistivity model (Fig. 4). Measurement errors are expressed as a percentage of the total electric field.

7. Results and discussion

7.1. Time-lapse CSEM signals related to the RN-15/IDDP-2 thermal stimulation

Despite the high degree repeatability of the CSEM measurements between the Reykjanes baseline and monitor (a few percent on the amplitude of the electric field), no clear and consistent time-lapse anomaly related to the RN-15/IDDP-2 thermal stimulation has been identified. A most likely explanation is related to the weakness of the time-lapse CSEM signals in comparison to the achieved repeatability. To demonstrate this, we have calculated the detectability of time-lapse CSEM signals based on electric field amplitudes as a function of the size of the stimulated zone (here, width) and measurements errors for the 2.5D Reykjanes conceptual model (Fig. 17). It clearly

Please cite this article as: M. Darnet et al., Monitoring geothermal reservoir developments with the Controlled-Source Electro-Magnetic..., Journal of Volcanology and Geothermal Research (2018), https://doi.org/10.1016/j.jvolgeores.2018.08.015
shows that the amplitude of the time-lapse signal is strongly related to the volume of the stimulated area (here, its width as its height is kept fixed at 1 km). For the repeatability achieved during the actual Reykjanes time-lapse survey (a few percent), it indicates that a time-lapse signal can be observed (D greater than 1) only if the stimulated area is larger than 500 m in width. During the drilling of RN-15/IDDP-2 well, high-permeability circulation-fluid loss zones were detected below 3 km depth to bottom. The largest one occurred at around 3.4 km depth with permeable zones encountered below 3.4 km accepting less than 5% of the injected water. It is therefore likely that most of the fluid injected during the thermal stimulation leaked into this zone between 3 and 3.4 km depth. Since the total volume of injected cold water was roughly 100,000 m³ in one month and the porosity of the in-situ rock is low (a few percent), the lateral extent of the stimulated zone does not exceed a couple of hundreds meters and most likely well below the detectability threshold achieved for our actual survey. To pick such a small signal up, even more repeatable measurements would be required (less than a percent, Fig. 17) or alternatively, a more sensitive CSEM layout would need to be deployed (e.g. a borehole to surface CSEM configuration, Tietze et al., 2015). Our CSEM time-lapse analysis is based on the amplitude and phase of the electric phase measurements but it is possible that other parameters are actually more sensitive to resistivity changes than the raw electric field measurements, like the distortion (Rees et al., 2016c) or phase tensor (Booker, 2014). The computation of such parameters have however to be adapted to the CSEM case and will be the scope of a subsequent paper.

7.2. CSEM and MT imaging and monitoring of high-enthalpy geothermal reservoir

The resistivity structure of the Reykjanes geothermal field (conductive caprock overlying a more resistive high temperature reservoir) is very generic for any high-enthalpy geothermal reservoirs (Flóvenz et al., 1985; Kristinsdóttir et al., 2010; Khodayar et al., 2016) and conclusions drawn on this particular example are therefore applicable to many other geothermal fields. The CSEM calibration survey performed here shows such data provides reliable data for the imaging and monitoring of high-enthalpy geothermal reservoir. The main benefit relies on the high signal to noise ratios that can be achieved despite the presence of high levels of cultural noise. At this stage, the main drawback is caused by the limited depth of penetration (2–3 km depth), most likely caused by the combination of a thick conductive and hence attenuating caprock, and the limited dipolar moment of the transmitter. Greater depths of penetration can surely be achieved using more powerful transmitters (e.g. longer dipole, higher currents) as well as more powerful transmitters (e.g. higher dipole, higher currents) as recently developed for offshore CSEM systems (Hansen et al., 2017). In addition, the resistivity of the overburden has to be taken into account as more resistive overburdens can often lead to greater depths of penetration (3–4 km) with similar CSEM systems (Coppo et al., 2016).

As shown on the Reykjanes example, MT data provides a good alternative to increase the depth of investigation (>2–3 km) when CSEM data is of limited use. For monitoring purposes, the challenge is however to obtain a highly repeatable MT dataset (Abdel fattah et al., 2018). Continuous MT and CSEM monitoring surely provides a good way to control the quality of the measurements by correlating them with subsurface phenomena but it also represents a huge logistical challenge for long term monitoring. Indeed, numerical simulations (Fig. 18, Orange et al., 2009; Wirianto et al., 2010; Thiel, 2017) show that only resistivity changes happening over a significant reservoir volume (e.g. after long periods of fluid injection/production) may lead to detectable EM signals. Time-lapse MT measurements alleviate this logistical constraint but as shown with our particular example, significant efforts have to be made to ensure sufficient data quality during both baseline and monitor MT surveys, especially when performed in highly industrialized areas with high levels of electromagnetic noise.

8. Conclusions

Monitoring resistivity changes associated to fluid movement in deep high-enthalpy geothermal reservoirs from the surface generally requires measuring small variations in EM fields and therefore high survey repeatability. This poses a real challenge in highly industrialized areas like geothermal plants, as it usually generates spatially variable and broad frequency band EM noise that can obfuscate the EM signals of interest and alter the survey repeatability, especially when using natural MT signals. Controlled-Source EM surveying may be an attractive option as the use of an transmitter allows to control and hence influence the signal repeatability. We have investigated the benefits and drawbacks of such an option in actual field conditions by acquiring a time-lapse CSEM survey over the Reykjanes geothermal field. Careful survey planning and execution allows to reduce the large number of parameters influencing survey repeatability to the level of external noise of the baseline and monitor surveys. As it can be artificially influenced, it offers the possibility to adapt the survey design to increase the chance of detecting the time-lapse signals of interest. On the contrary, little control is possible on the MT signal to noise ratio and hence repeatability. The time-lapse EM survey acquired over the Reykjanes geothermal reservoir provides the basic information for deciding when and how an EM monitor survey must be performed for the monitoring of the Reykjanes reservoir but also for the definition of the monitoring strategy of similar high-enthalpy geothermal reservoirs.

Monitoring high-enthalpy geothermal reservoir development with CSEM and/or MT techniques is still at its infancy but we believe that by careful survey design and by applying dedicated data acquisition, processing and imaging techniques, sufficient data repeatability can be achieved to monitor resistivity changes associated to fluid movements in the deep geothermal reservoir.

Acknowledgments

The IDDP-2 was funded by HS Orka, Landsvirkjun, Orkuveita Reykjavíkur, and the National Energy Authority in Iceland, together with StatOil, the Norwegian oil and gas company. The IDDP-2 project and our project have also received funding from the DEEPGS project, European Union’s HORIZON 2020 research and innovation program under grant agreement No 690771. We would like to thank HS-ORKA for providing access to the MT dataset over the Reykjanes geothermal field. We are also very grateful to Steinthor Nielsson, Stephan Audun Stefansson from the Iceland Geosurvey (ISOR) for their logistical support during the EM surveys. We would like also to thank Eva Schill, Nadine Haaf from the Karlsruhe Institute of Technology, Germany, Mariane Peter-Borie, Florent Beaubois and Esteban Pineda for their invaluable help during the field work.

References


Please cite this article as: M. Darnet et al., Monitoring geothermal reservoir developments with the Controlled-Source Electro-Magnetic,... Journal of Volcanology and Geothermal Research (2018), https://doi.org/10.1016/j.jvolgeores.2018.08.015


Borehole damaging under thermo-mechanical loading in the RN-15/IDDP-2 deep well: towards validation of numerical modeling using logging images

M. Peter-Borie1*, A. Loschetter1, I. A. Merciu2, G. Kampfer2 and O. Sigurdsson3

Abstract
A wider exploitation of deep geothermal reservoir requires the development of Enhanced Geothermal System technology. In this context, drilling and stimulation of high-enthalpy geothermal wells raise technical challenges. Understanding and predicting the rock behavior near a deep geothermal wellbore are decisive to implement stimulation strategies to reach the couple temperature/flowrate target. Numerical modeling can contribute to enhanced stimulation processes thanks to a better understanding of impact of stress release, pressure changes and rock cooling in the near-wellbore area. In this paper, we use Discrete Element Method (code PFC2D, © Itasca Consulting Group), and more specifically bonded-particle model to capture the thermo-mechanical processes at metric scale. The application case corresponds to the beginning of thermal stimulation at Reykjanes in well RN-15/IDDP-2 (Iceland, IDDP-2 project and H2020 project DEEPEGS). A cold fluid is injected at a depth of 4.5 km where the rock temperature is above 430 °C and the well pressure is around 34 MPa. Since we have site-specific data and logging images after drilling, we attempt to link the simulations with the reality. The numerical results are confronted with incipient interpretation of logging images and with analytical solution to go towards validation of the modeling approach. Numerical results show breakouts and thermally and/or mechanically induced fractures consistent with the analytical solutions. Moreover, the sensitivity analysis on uncertain parameters yields important clues regarding some logging features as, for example, asymmetric damaging or caving.

Keywords: EGS (Enhanced Geothermal System), Borehole, Thermal stimulation, Fracture initiation, DEM (Discrete Element Model), PFC2D, LWD, Borehole logging images

© The Author(s) 2018. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.
Background

EGS (enhanced/engineered geothermal system) constitutes a potential renewable energy technology to produce heat and electricity from geothermal reservoirs deficient in fluid or in permeability. In most cases, reaching an economically viable temperature target requires drilling down to several kilometers depth, where the permeability of the system is generally naturally low. The implementation of stimulation strategies is then necessary to increase the injectivity or the productivity of the wells (Tester et al. 2006). The deployment of such EGS method in a wide range of geological contexts is still a technical challenge, and the number of projects in operation is currently limited. According to EGEC (2017), concerning EGS, three electricity plants (Insheim and Landau in Germany, Soultz-sous-Forêts in France; the reservoir temperatures are, respectively, > 160 °C, 160 °C and > 180 °C; Lu 2018) and one heat plant (Rittershoffen in France, the reservoir temperature is 177 °C; Baujard et al. 2017) are now in operation, with a further ten plants under development.

In this context, the EU-funded H2020 DEEPEGS (Deployment of DEEP Enhanced Geothermal Systems for sustainable energy business) project aims at demonstrating the feasibility of EGS in high-enthalpy reservoirs (temperature up to 550 °C, with an Icelandic demonstrator) and in deep hydrothermal reservoirs (temperatures around 200 °C, with French demonstrators), to deliver new innovative solutions and models for wider deployments of EGS. The first demonstrator deployed in the frame of the DEEPEGS project is located in the Reykjanes geothermal system in southwest Iceland. The deepening of the wellbore RN-15 from 2500 m depth (RN-15/IDDP-2) began in August 2016 and the well is completed at a depth of 4659 m MD (measured depth, ~ 4.5 km vertical depth) in January 2017 (temperature around 500–530 °C) (Friðleifsson et al. 2017; Friðleifsson and Elders 2017a, b; Stefanson et al. 2017). RN-15/IDDP-2 provides information about the deep geology and the deep rock behavior in the Icelandic context. Notably, borehole images provide a unique view of the geological structure of the Icelandic crust. To improve the productivity of the well (estimated injectivity index around 1.7 L s⁻¹ bar⁻¹ at the end of drilling), stimulations in the form of cold-water injection (mainly thermal stimulations) have been performed to connect the wellbore to existing hydraulic pathways, i.e., pre-existing natural fracture network.

Understanding all the processes that lead to fracture initiation in the EGS near-wellbore remains challenging due to the high temperatures. In this context, numerical modeling contributes to improve our understanding and it allows for predictions in the future. The objective of this article is to propose a physical modeling approach contributing to the understanding of phenomena occurring in the wellbore vicinity during drilling and EGS operations. We focus on the thermo-mechanical processes induced by the rock cooling. The choice of the numerical method is based on assumptions drawn from onsite information. The results are compared with results from analytical equations and with observations made during drilling to critically discuss the numerical results and go towards validation of the chosen approach.

In this paper, after briefly describing the geological and geothermal context, we first present data and borehole images from well RN-15/IDDP-2. Then we describe the numerical modeling tool, based on the Discrete Element Method (DEM), and the chosen setup for the numerical simulations. Numerical results show breakouts and thermally
and/or mechanically induced fractures consistent with the analytical solutions and with observations made during drilling. We finish with words of conclusion and with discussion on the experienced limitations and perspectives.

**Geological knowledge**

**Regional data**
The in situ geological, mechanical and thermal conditions are little known in the deep part of the Reykjanes field. The deepest well in this area was shallower than 3 km before drilling the IDDP-2 well. Besides, geophysical methods are limited for investigations at several kilometers depth. We summarize below the information concerning the regional geology, the regional stress state and the rock behavior.

**Geology**
The Reykjanes geothermal system is located at the tip of the Reykjanes peninsula, SW Iceland (Fig. 1a) at the landward extension of the Reykjanes Ridge. From the surface to around 2.5 km depth, the lithology consists of sub-aerial basaltic lavas and to a lesser
degree of hyaloclastites. Below, typical sheeted dyke complex of an ophiolite is assumed to take place, including a swarm of tectonic fractures and faults. These intrusive rocks are assumed to overlay a lower gabbroic crust (Pálmason 1970; Gudmundsson 2000; Foulger et al. 2003; Karson 2016; Stefanson et al. 2017; Friðleifsson and Elders 2017b).

Regional stress state
The in situ stress field is poorly characterized in the deep part of the Reykjanes field. The World Stress Map (Heidbach et al. 2008, 2016) indicates that the stress regime varies by short distances around Reykjanes. Most data (e.g., Ziegler et al. 2016 in the vicinity of wellbore RN-15/IDDP-2) consist of principal stress directions, with no indication of the stress magnitudes. It is not even certain that the vertical direction is a principal stress axis (Keiding and Lund 2009; Kristjánsdóttir 2013). Pieces of information concerning the orientation and magnitude of principal stresses were found in Keiding and Lund (2009), Batir et al. (2012), and Kristjánsdóttir (2013) but the characterization of in situ stress at such depth in this complex area remains very uncertain.

Rock behavior
Foulger et al. (2003) suggest that the brittle–ductile transition occurs deeper than the targeted depth considering gabbro-like rocks and the geothermal gradient. The analysis of earthquake swarms indicates that the brittle–ductile boundary is at 5.5–6 km depth under Reykjanes (Khodayar et al. 2017), thus below the considered depth. Observations from core retrieved between 4643 and 4652 m MD show fractures, which are supposed to be open and fluid-filled downhole, indicated by precipitations on the fracture surface. For that reason, we only assume brittle formation behavior in the presented study.

Site-specific data acquired during drilling operations
The drilling of IDDP-2 provides new knowledge concerning the rock composition, the rock properties and the in situ temperature at depth.

Rock composition
In-depth logging and coring lend credibility to the thesis of sheeted dyke complex. Cores retrieved from 4 km depth show mainly rocks with fine-grained igneous texture: micro-gabbro/dolerite to fine-grained basaltic intrusive (cf. Fig. 1c), with heterogeneous grain size (Friðleifsson et al. 2017). The mineral composition was assessed (see “Numerical settings and scenarios” section) and the porosity is found to be very low (matrix porosity between 3.6 and 0.1%—Claudia Kruber, Equinor internal report in progress).

Rock properties
Knowing the rock mineralogy and an estimate of the in situ temperature range, we can use results of Keshavarz (2009) to confirm the assumption of brittle rock behavior. His experimental results indeed show that the physical and mechanical properties of this gabbro remain on the same trend up to the critical temperature of 600 °C, thus sufficiently above the estimated formation temperature in the IDDP-2 well.
Rock temperature
At the end of drilling, the fluid temperature measured at 4560 m MD of IDDP-2 was 426 °C (Friðleifsson et al. 2017), after the deepest part of the well had the possibility to warm up for 6 days. It should be noted that this measurement is probably an underestimation of the in situ formation temperature since extensive cooling occurred during drilling the well. The in situ formation temperature was estimated in the range 536–549 °C, based on warm-up measurements and a Horner plot at 4565 m MD (Tulinius 2017).

Borehole response to drilling
During drilling, shear and tensile rock failures may threaten wellbore stability. We mainly distinguish between shear failure-induced breakouts and drilling-induced fractures (opening mode fractures) as the two main sets of mechanical instabilities when drilling with overly low and overly high mud weights, respectively. Breakouts are aligned with the minimum horizontal stress whereas drilling-induced fractures are aligned with the maximum horizontal stress in a vertical well. In the present case, severe mud losses were observed during drilling, leading to the conclusion that the pressure in the well exceeded the minimum compressive hoop stress around the wellbore, inducing a drilling-induced fracture or opening a pre-existing fracture. Since the volumes of mud loss are high, it is very likely due to leakage into a naturally existing fracture network (swarm of fractures of the sheeted dyke complex). Either the well directly crossed such a discontinuity, or induced damages connected the wellbore and natural discontinuities. Logging images (see next section) give insight into possible damages in the wellbore. It should be noted that as a consequence of the total mud loss, it was not possible to influence the well pressure. The pressure measured at the bottom of the well after completing the drilling operations was 34 MPa (thus below the hydrostatic pressure expected at such depths, around 45 MPa) and is supposed to represent an equilibrium between gain and loss from the formation along the whole open section which intersects several fracture zones of different productivity and injectivity, respectively. The low pressure, however, can also result from the change in density as the formation water is heated up to above-supercritical reservoir conditions.

Logging images
Borehole images recorded during drilling campaign of IDDP-2 well provide a unique view into the geological structure of the Icelandic crust.

For a selected IDDP-2 drilled interval from 2940 to 3410 m MD in a 21.6-cm (8.5 in.) hole, two sets of images are available for our exemplification: ultrasonic images and electrical microimages (Stefanson et al. 2017) with no caliper measurement available. Ultrasonic amplitude images are collected using wireline standard televviewer ABI 43 (ALT advanced logic technology 2018) from 9 5/8 in. (24.5 cm) casing shoe at 2940 m MD down to 3410 m MD. Electrical microimages are collected using Logging While Drilling SineWave™ Micro-Imager Tool (Weatherford International logging while
drilling SinWave (2018) images from 9 5/8 in (24.5 cm) casing shoe at 2940 m MD to 4513 m MD (Friðleifsson et al. 2017; Friðleifsson and Elders 2017a, b; Stefanson et al. 2017).

Ultrasonic amplitude image data are affected by poor centralization and lack of measurement references at surface (Stefanson et al. 2017). The eccentricization of the sensor affects heavily the reflection coefficients that may be extracted from the amplitude envelope and post-processing artifacts are present on the images in the form of vertical shades. Further processing on ultrasonic amplitude images is limited due to challenging acquisition conditions.

Electrical microimages are affected by the high resistivity of the formation and the general raw values are accumulating towards 0 mA and exhibit sandy texture in dynamic normalization window which is further corrected by applying a median filter.

As a large data integration effort is ongoing at the time of this publication, we are selecting representative image examples for the scope of numerical simulation validation with intervals where both ultrasonic and electrical microimages are recorded and refraining from an in-depth evaluation of logging results.

Qualitative analysis of recorded images reveals a feature-rich borehole with clear evidence of vertical drilling-induced features and petals in both static and dynamic normalization window especially on ultrasonic amplitude images (Fig. 2) (Menger 1994; Deltombe and Schepers 2001; Holl and Barton 2015). The borehole breakouts manifest themselves largely in images with a clear 180° opposite directions (Fig. 2). Tensile fractures and other drilling-induced fractures manifest themselves at about 90° azimuth with respect to observable large breakouts forming rib-like structures which may emerge in larger petals—centerline features visible especially on the ultrasonic image towards the bottom of exemplified image, see Figs. 2 and 3 (Davatzes and Hickman 2005; Tingay et al. 2008; Rajabi et al. 2016). A closer look into lateral extension of the breakout manifestation in electrical microimage compared with ultrasonic image shows that the aperture extracted from the electrical microimage is three orders larger than the aperture observed on ultrasonic images. Furthermore, we chose an exemplification interval where the eccentricization of ultrasonic images is not very prominent and display the images side by side (3 times 360°) to eliminate visual obstruction at azimuths 0° and 360°. Images are displayed in Fig. 4 and reveal aggressive hole damages with petal features which can be observed along the well especially in ultrasonic images. These observations, corroborated with core sample analyses (Zierenberg et al. 2017) and inverse multigeophysical inversion (Hokstad and Tanavasuu-Milkeviciene 2017), lead to hypothesizing a mechanism of fracturing which is driven by temperature, low pressure and intersections with vertical sheeted dyke structure. The scope of the current article is to investigate further the initial fracture mechanism based on thermomechanical stress mechanism.

(See figure on next page.)

**Fig. 2** Example of electrical microimage and ultrasonic image from RN-15/DDP-2 wells with associated preliminary feature extractions (courtesy of Equinor and HS Orka). Observe large variation on azimuthal breakouts picking given by angular extension of the feature on the given images. Vertical white stripe on the ultrasonic image is an artifact from tool eccentricization, which adds to complexity of analysis.
Legend for handpicked features sketch:
- Planar features in Electric Microimage respective ultrasonic
- Borehole breakouts
- Drilling induced tensile fracture
Numerical simulations

Observation-driven modeling

Based on data and observations, the following main assumptions are held:

- The rock matrix has brittle elasto-plastic material properties.
- The porosity of the matrix is below 3%. As a consequence, it is considered reasonable to neglect the poroelastic effects (referring to the poroelasticity theory, this would mean assuming a zero Biot coefficient, which can be supported in such a situation, see Fjar et al. (2008), sections 1.3, 2.9 and 6.2; subsequently effective stresses are simplified and assumed as total stresses).
- The hole stability is ensured mainly by the rock matrix rigidity, with little influence from fluid pressure in the fractures of the surrounding rock.
- The rock has a fine-grained texture, with heterogeneous grain size and different mineral grain composition.
The stress state has a strong influence on the failure initiation and propagation, but we lack quantitative data to make solid assumptions. Hence, it was decided to work with a series of possible scenarios for the stress state (see "Numerical approach" section).

Logging images reveal numerous features, between other breakouts and induced fractures. From the drilling operation without any return of fluid to surface (for depths beyond around 3300 m) we can assume that the pressure in the wellbore during drilling was very close to the pressure in the fluid-filled fracture systems intersected by the well. With this limited hydraulic pressure in the well, it is not expected to observe drilling-induced fractures in conventional wells. A possible explanation for this observation is cooling-induced fracture (e.g., Yan et al. 2014). In such high-temperature environments, cooling of the rock necessarily occurs during drilling operations (even before dedicated thermal stimulation). In the following, we provide insight into the initial fracture mechanism based on thermomechanical stress mechanism.
The role of the thermal stimulation is often unclear, and determining which mechanisms lead to observed injectivity increase is still challenging (Flores et al. 2005; Grant et al. 2013; Héðinsdóttir 2014). Covell (2016) shows that thermal stimulation is driven by thermal contraction caused by the significant temperature difference between cold injection fluid and hot reservoir rock. The involved mechanisms lead to opening pre-existing discontinuities (contraction of discontinuity walls) or creating new ones. The thermal solicitation induces differential strains at the origin of thermo-mechanical stresses. When these stresses exceed the mechanical resistance of the rock, micro-cracks and failures could appear. Strains at the origin of this process can be mainly due to two causes: on the one hand, a thermal gradient in the rock mass, on the other hand, the heterogeneity of the grain contraction in the rock matrix. Because of this heterogeneity, two adjacent minerals can contract at different rates and this can generate uneven strains at the grain boundary (Wanne and Young 2008). In addition, petrographic characteristics (including grain size, grain shape, packing density, packing proximity, degree of interlocking, type of contacts and mineralogical composition) are known to affect mechanical properties (Ulusay et al. 1994). A critical review concerning DEM and its application to borehole stability was proposed by Kang et al. (2009). Santarelli et al. (1992) were among the first to study borehole stability using DEM. Yamamoto et al. (2002) used DEM to study the wellbore instability of laminated and fissured rocks. Karatela et al. (2016) studied the effect of in situ stress ratio and discontinuity orientation on borehole stability in heavily fractured rocks using DEM. DEM seems fairly adapted to take into account the physical phenomena at the granular phase level (micro scale), and to analyze their impact on the mechanical behavior of the near-wellbore zone (macro scale). We propose to implement this approach using the code Particle Flow Code—2 Dimensions (PFC2D) (Itasca Consulting Group Inc. 2008a, b), and to question the role of thermal loadings in the wellbore. Chemical interaction of the drilling fluid may play a role in the thermal stimulation, for instance, through dissolution or precipitation of the minerals, triggered by temperature change. The quantification of these chemical effects in the specific context of IDDP-2 remains a scientific challenge. Thus, in the absence of available data, indirect chemical effects of thermal stimulation are not considered in this study.

It is worth mentioning that the thermal stimulation by injecting cold water may not necessarily have a long-term effect because of the thermal expansion and closure of fractures during production. Only the naturally propped fractures keep some permeability and hence improve productivity.

Contrary to common analytical approaches (see Appendix), the proposed numerical approach enables quantifying the depth and shapes of damages. The results will be compared with the logging observations (breakouts, induced fractures, petal fractures), trying to identify what the simulation captures successfully and what it does not. Note as a limit of the method that the logging is performed several days after the drilling; throughout this time lapse, the well has been exposed to more mechanical and thermal stresses than simulated in the numerical approach.
**Numerical approach**

PFC2D calculates the movement and interaction of stressed assemblies of rigid circular particles using the DEM. As a discrete element code, it allows finite displacements and rotations of discrete bodies (including complete detachment), and recognizes new contacts automatically as the calculation progresses. The setup is composed of distinct particles that displace independently of one another, and interact only at contacts or interfaces between them. The calculations performed in the DEM alternate between the application of Newton’s second law to the particles and a force–displacement law at the contacts, characterized by normal and tangential stiffnesses. Newton’s second law is used to determine the motion of each particle arising from the contact and body forces acting upon it, while the force–displacement law is used to update the contact forces arising from the relative motion at each contact (Itasca Consulting Group Inc. 2008a).

For a plutonic rock, we choose bonding behavior for contacts (also called “parallel bond”—PB), which allows to reproduce the behavior of cohesive materials (Potyondy and Cundall 2004; Itasca Consulting Group Inc. 2008b). A rupture criterion based on the beam theory is used for PB; when the bond stress exceeds its yielding strength (in tension or in shear), the bond breaks.

The thermal option of PFC2D allows simulation of transient heat conduction and storage in particles and development of thermally induced displacements and forces. Each particle can be seen as a heat reservoir. The temperature ($T_i, ^\circ C$), the specific heat coefficient ($C_v, J ~ kg^{-1} ~ ^\circ C^{-1}$) and the linear thermal expansion coefficient ($\alpha, ^\circ C^{-1}$) are initialized for each particle. The thermal power can be transmitted between two particles via a thermal pipe (contact between two particles). The parameters related to a thermal pipe are pipe length ($L_p, m$) and thermal resistance ($R_{th}, ^\circ C ~ W^{-1} ~ m^{-1}$). When particles ($i$ and $j$) at different temperatures ($T_i$ and $T_j$) are connected by a thermal pipe, a heat flux ($Q_p, W$) takes place in the thermal pipe (Itasca Consulting Group Inc. 2008b):

$$Q_p = \frac{T_i - T_j}{R_{th}L_p}.$$  \hspace{1cm} (1)

The temperature increment ($\Delta T, ^\circ C$) of the reservoir can be obtained by

$$\Delta T = \frac{Q_p}{mC_v} \Delta t_{th},$$  \hspace{1cm} (2)

where $m$ (kg) is the mass of the reservoir and $\Delta t_{th}$ (s) is the thermal time step. Note that by convention an increase of temperature is associated with a positive thermal power. Finally, the radius of the particle ($R, m$) is changed as a consequence. We compute the radius increment ($\Delta R, m$) through

$$\Delta R = \alpha R \Delta T.$$  \hspace{1cm} (3)

The integration of radii increment in the force–displacement law creates induced mechanical response of the system.
Numerical settings and scenarios

The calculation setup consists of a two-dimensional cross section perpendicular to the well. The numerical simulations focus on the deepest part of the well. As far as possible, the conditions observed at 4560 m MD of IDDP-2 are used in the numerical simulations. The wellbore section is assumed to be 21.6 cm (8.5 in.). The temperature of the rock is assumed to be 426 °C (corresponding to the fluid temperature measured at the end of drilling). For thermal stimulation, we assume a temperature of 30 °C for the injected fluid (corresponding to the targeted temperature of the cooling fluid). Please note that temperatures recorded during logging operations are above 70 °C, thus using 30 °C...
overestimates the cooling during drilling operations (but may be appropriate for the subsequent thermal stimulation). The direction of the wellbore dip direction is N220°E and the deviation from the vertical is approximated at 30°. The modeled 2D cross section is thus oriented N130°E–60°NE.

We focus our study on the behavior of the matrix of the fine-grained-textured rock. The well-detailed description of the dolerite (weekly report IDDP-2, 2016) cored at 4 km depth is used as a reference for the numerical rock model. Deeper coring shows that similar rocks exist in the deeper part of the wellbore.

The four scenarios proposed to scan the range of possible stress states are described in Table 1 for classical coordinate system defined by Andersonian faulting theory, and the corresponding stress state in the 2D cross section normal to the wellbore axis (Fig. 5). In all cases, we consider the vertical direction as the principal stress axis, and we estimate its magnitude at 134 MPa at 4560 m MD depth. The expected horizontal stress magnitudes are within the range of data extrapolated from Batir et al. (2012), i.e., between 60 and 180 MPa.

![Diagram showing temperature gradient in a rock for different heat transfer coefficients (h, from 20 W m⁻² K⁻¹ to 20,000 W m⁻² K⁻¹) inducing different heat flux, and evolution with the time.](image)
The impact of the thermal flux at the wellbore boundary and of the fluid pressure in the wellbore are evaluated through a parametric study. Investigated fluid pressures in the wellbore are from 34 MPa (measured pressure in the well) to 104 MPa. The heat flux is a linear function of the temperature differential between the rock and the fluid in the wellbore and of the heat transfer coefficient. This coefficient is a quantity that empirically translates the heat exchanges between the circulating fluid and the solid. For the sake of clarification, Fig. 6 illustrates the impact of the choice of heat transfer coefficients on temperature fields. With low values, the heat transfer is slower and the particles of the wellbore need more time to reach the target temperature (Fig. 6). The heat transfer coefficient depends notably on the fluid velocity in the wellbore and on the fluid properties. Due to insufficient data, we chose two extreme values for the heat transfer coefficient:

- a low value (1000 W m\(^{-2}\) K\(^{-1}\)) simulating a slow cooling of the rock mass on the boundary of the wellbore;
- a very high value (10,000 W m\(^{-2}\) K\(^{-1}\)) simulating an instantaneous cooling of the rock mass on the boundary of the wellbore.
Numerical rock setup

The elaboration of the numerical rock model setup is a preliminary essential task, often difficult due to insufficient data and thus high level of uncertainties. Before any numerical modeling, the real rock (here a dolerite) is conceptualized according to the role of each mineral phases in the behavior of the rock (more details in Peter-Borie et al. 2011, 2015). The dolerites are typical shallow intrusive bodies; they are micro-grained, composed entirely of 1–5-mm-wide crystallized minerals without glassy matter. Grains or crystals are interlocked as the growth of each crystal has stopped on other crystals (MacKenzie and Adams 1999). For the numerical dolerite model, each numerical particle represents a mineral grain or crystal (Fig. 7). Parallel bonds (PB) model the contacts between grains (Fig. 7). Note that in grained rock, failure can occur between the grains as well as inside a grain (following then the weakest paths like twins leading to cleavage plans—Kranz 1983). In the numerical rock model, failure can occur only between particles. To fit with the reality, mechanical properties of the PB are the mean properties of the surrounded particles, a failure between two particles can then be interpreted as an intergrain or intragrain failure.

Following the conceptualization step, the properties of the numerical particles and bond are assigned. In this regard, quantified data from studied or analogue rock are required. For the present application case, the coring of fine-grained dolerite retrieved at 4090.6 m depth (Zierenberg et al. 2017) provided detailed information on the rock composition (pyroxene 40%, plagioclase 55%, titanomagnetite 5%, grain size around 3 mm). The particles of the numerical dolerite model follow the same distribution. The heterogeneity of particles size is represented through the implementation of a particle-size distribution centered on 3 mm.

At the time of the study, macroscopic mechanical and thermal data were not available from the IDDP-2 cored samples. Thus, we chose a limited analogue rock with available macroscopic properties. Since petrographic characteristics affect mechanical properties, analogues are selected depending on the proximity in terms of rock petrographic characteristics as mineral composition and grain size. A North African gabbro, characterized by Keshavarz (2009), is retained as reference analogue. It contains almost 40% pyroxene and 60% plagioclase, with traces of other elements (among others magnetite). Laboratory tests performed on pressurized (stepwise up to 650 MPa) and heated (stepwise up to 600 °C) samples provide mechanical properties of the analogue rock covering

<table>
<thead>
<tr>
<th>Property</th>
<th>Plagioclase</th>
<th>Pyroxene</th>
<th>Olivine</th>
<th>Titanomagnetite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus (mean value, MPa)</td>
<td>84</td>
<td>162</td>
<td>178</td>
<td>230</td>
</tr>
<tr>
<td>Ratio normal stiffness/shear stiffness</td>
<td>2.5</td>
<td>2.2</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>30</td>
<td>75</td>
<td>27</td>
<td>45</td>
</tr>
<tr>
<td>Cohesion (MPa)</td>
<td>140</td>
<td>350</td>
<td>126</td>
<td>210</td>
</tr>
<tr>
<td>Thermal conductivity (W m⁻¹ K⁻¹)</td>
<td>1.98</td>
<td>4.52</td>
<td>4.48</td>
<td>2.10</td>
</tr>
<tr>
<td>Specific heat (kJ kg⁻¹ K⁻¹)</td>
<td>1112</td>
<td>800</td>
<td>800</td>
<td>910</td>
</tr>
<tr>
<td>Linear thermal expansion coefficient (K⁻¹)</td>
<td>6.81 x 10⁻⁶</td>
<td>1.00 x 10⁻⁵</td>
<td>3.85 x 10⁻⁶</td>
<td>3.40 x 10⁻⁵</td>
</tr>
</tbody>
</table>
As micro-gabbro/dolerite have very low porosity [below 0.5% in the analogue rock (Keshavarz 2009), matrix porosity between 3.6 and 0.1% (no microporosity included) for the cored dolerite (Claudia Kruber, Equinor internal report in progress)], we assume that the pores can be seen as singularities in the rock matrix. The numerical rock model does not integrate the rock porosity. Therefore, in our numerical approach, no poroelastic effects are considered. The heat transfer process is thus limited to conduction between grains.

The range of values of the mechanical, thermal and thermo-mechanical micro-properties (at the particle scale) has been first delimited according to a literature review on the properties of minerals (Simmons 1965; Carmichael 1989; Guéguen and Palciauskas 1992; Clauser and Huenges 1995). The properties must be physically consistent with the mineral phase characteristics and have to enable the reproduction of the macroscopic mechanical and thermo-mechanical behavior of the rock. The definitive calibration of the numerical particles and bonds particles is performed by fitting results of mechanical and thermal numerical tests (Uniaxial Compressive Strength—UCS, Ultimate Tensile

<table>
<thead>
<tr>
<th>Analogue</th>
<th>85–90</th>
<th>0.18</th>
<th>225</th>
<th>12</th>
<th>68</th>
<th>43</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical model</td>
<td>87</td>
<td>0.17</td>
<td>214</td>
<td>15</td>
<td>61</td>
<td>35</td>
</tr>
</tbody>
</table>

UCS: uniaxial compressive strength, UTS: ultimate tensile strength
Strength—UTS, Triaxial and Thermal conductivity tests) with the macroscopic properties of the analogue rock (see final values of micro-properties in Table 2, and resulted macro-properties computed from numerical tests in Table 3).

Near-wellbore setup
The calculation setup concerns a 2D plane perpendicular to the wellbore axis at 4560 m MD depth. The definition of the near-wellbore setup needs to take into account an adequate extended area around the wellbore—at least three times the diameter of the wellbore (here 21.6 cm–8.5 in.) to limit the impact of boundary conditions on the numerical results. A significant number of particles are needed to build up such a large setup while keeping the size distribution close to the mineral size level (here close to an average of 3 mm). To push away the boundary conditions, the DEM near-wellbore model is embedded within a continuum-mechanics-based frame describing the region far away from the wellbore (FLAC Itasca Consulting Group Inc. 2002). The PFC2D simulation setup size is 1.05 m × 1.05 m, integrating more than 141,500 particles, and is embedded within a 5.25-m × 5.25-m FLAC mesh (Fig. 8). The coupling method between the continuum model and the discontinuous model is realized by an edge-to-edge approach for which the relevant overlapped elements are, respectively, segments of mesh in FLAC and a series of particles in PFC2D (Xiao and Belytschko 2004). A detailed description of the near-wellbore setup and of the PFC2D/FLAC coupled calculations is available in Shiu et al. (2011).

Simulation stepwise
The numerical simulation is performed stepwise with the aim to reproduce, as far as possible, the state of the rock in the vicinity of the wellbore before the thermal stimulation. Randomization is used for the construction of the numerical model. The radius of each particle is randomly drawn following the normal distribution \( \mathcal{N}(1.37, 0.62) \) for pyroxene and plagioclase, and following \( \mathcal{N}(1.25, 0.5) \) for titanomagnetite (based on cores observations). A periodic sample duplication process is used to build the numerical model faster.
Once the numerical setup is constructed and confined under a small confining pressure (which is always less than its corresponding in situ stress), it is loaded with its in situ stress which is presented in Fig. 9, step 0. We use the full-strain method (Itasca Consulting Group Inc. 2008c) for which a displacement increment is applied to each particle. Cycles are performed between two increments of displacement to reach a new mechanical equilibrium. Note that no contact breakage is allowed during the stress installation cycling. Thus, a pure elastic deformation is performed in this step. This method is very efficient when a large number of particles are included in the numerical model.

After the initial stress field is established, the borehole drilling is simulated by removing the particles located on the wellbore surface (Fig. 9 step 1). To avoid a sudden increase of the unbalanced forces of particles placed on the surface of the wellbore, leading to numerical instabilities, a force-reduction procedure is used at this step to release progressively the unbalanced forces of particles situated along the wellbore surface (Shiu et al. 2011). Note that this step is a very rough and simplified approximation of the drilling impact on the formation stability. On the one hand, the impact of the drilling bit at the excavation step is not considered. On the other hand, the pressure considered in the wellbore is assumed zero, due to limitation in the calculation procedure, which can lead to damage overestimation as pressure actually exists in the well during real drilling at ECDs (equivalent circulation densities) even above the static fluid column.

During the fluid injection step of the calculation schedule, the wellbore is subjected to a hydraulic pressure and to a thermal loading. The fluid injection is assumed to act only on particles forming the wellbore surface. A specific procedure (Itasca Consulting Group Inc. 2008c; Shiu et al. 2011) is used to detect a set of closed linked particles (connected by parallel bonds) around the wellbore. These particles are recorded in a specific list and will be referred to as the wellbore list in the following description. To simplify the numerical modeling setup, and to limit the computational time, the hydraulic pressure and the thermal loading are applied in two steps. The hydraulic pressure is applied first (Fig. 9 step 2) and the thermal loading (Fig. 9 step 3) takes place later (assuming that no significant thermal propagation occurs before the hydraulic pressure is fully installed on the wellbore surface). The underlying assumption is that the characteristic time for pressure effects is far shorter than the characteristic time for thermal effects. The list of the wellbore particles is updated automatically when cracks appear between particles in the wellbore list. Hence, once the cracks start propagating from the wellbore, the injection pressure and the fluid temperature can penetrate into the crack as well.

**Results**

**Simulation of the drilling of the well**

Among the four simulated stress states (cases A, B, C, D, defined in “Numerical approach” section), the drilling of the wellbore is the most critical for case C characterized by the highest 2D deviatoric stress in the near-wellbore area. Numerous cracks are observed in the rock with greater density in areas closer to the wellbore (Fig. 10). At the wellbore boundary, the cracks are connected, forming a slight caving (up to a depth of 3 cm with radial extension up to 10 cm) breakout in the direction of the 2D minimum stress. For the second highest deviatoric stress (case A), the number
**Fig. 10** Results of simulations, after drilling, for the four stress states (see "Numerical approach" section for definition of cases A, B, C and D). Each red point corresponds to the apparition of a tensile crack, each blue point corresponds to the occurrence of a shearing crack. The total number of cracks is mentioned in each subplot. The field of view for each subplot is 1 m × 1 m.

**Table 4 Results of the analytical approach for breakouts**

<table>
<thead>
<tr>
<th>Name</th>
<th>Principal stress in the 2D plane perpendicular to the well</th>
<th>Breakout characteristics</th>
<th>$P_{\text{well}} = 0$ MPa</th>
<th>$P_{\text{well}} = 34$ MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_\theta$ (MPa)</td>
<td>$\sigma_r$ (MPa)</td>
<td>$r_{\theta, \sigma_\theta}$ (MPa)</td>
<td>$r_{\theta, \sigma_r}$ (MPa)</td>
</tr>
<tr>
<td>Case A</td>
<td>76</td>
<td>134</td>
<td>326</td>
<td>14.8</td>
</tr>
<tr>
<td>Case B</td>
<td>60</td>
<td>79</td>
<td>175</td>
<td>&lt; R</td>
</tr>
<tr>
<td>Case C</td>
<td>76</td>
<td>178</td>
<td>459</td>
<td>23.0</td>
</tr>
<tr>
<td>Case D</td>
<td>80</td>
<td>94</td>
<td>200</td>
<td>&lt; R</td>
</tr>
</tbody>
</table>

The computation of the borehole potential damage is linked to no to low wellbore fluid pressure ($P_{\text{well}}$). $\sigma_{\theta}$ is the circumferential stress at the wellbore boundary in the direction of the minimal 2D stress, $\sigma_r$, $r_{\theta, \sigma_\theta}$ is the distance from the wellbore center where the circumferential stress is equal to the UCS of the dolerite (214 MPa), in the direction of the minimal 2D stress, $R$ is the radius of the borehole. Principal stresses in the cross section perpendicular to the well are obtained by diagonalization of the stress state ($\sigma_\theta, \sigma_r, \tau_{\theta r}$) mentioned in Table 1 and are thus slightly different from horizontal principal stresses.
of cracks is four times less than for case C. It leads locally to a rock caving up to 1 cm. Other stress states (B and D) lead to a limited number of cracks.

These numerical results are compared with results obtained with the analytical Kirsch equations (see Appendix), presented in Table 4. The analytical solution predicts that breakout will occur for cases A and C for both zero fluid pressure and in case it is equal to 34 MPa.

There is good agreement between the analytical and numerical results. Most cracks in numerical results are in the area stress from analytical solution exceeds the rupture criterion. The ratios of cracks in this area compared to all cracks are, respectively, 88% and 89% for cases A and C for zero fluid pressure in the wellbore. Some differences between analytical and numerical results can nevertheless be noted (Fig. 11):

- In numerical simulation, cracks coalesce until creating a caved area; this area represents only a limited part of the area where the rupture criterion is exceeded in the analytical model.
- Cracks in the numerical model also occur outside of the area where the rupture criterion is exceeded according to the analytical solution.

Several possible explanations can be suggested to discuss these differences:

- As contact properties depend on the adjacent particle properties, the PB do not have all the same strength (the criterion of the analytical solution is the mean strength of the rock). Cracks may occur outside of the analytical breakout area when the strength of the PB is locally exceeded by the stress, even if it is lower than the criterion. Conversely, stronger bonds may resist in the numerical model, even if the analytical area predicts rupture.
Fig. 12 Confrontation of the numerical results and of the logging images. a Numerical results were transformed to logging-like images. The color intensity corresponds to the distance between the boundary of the wellbore and the center of the wellbore, after drilling, for case C, with zero fluid pressure in the wellbore. $\theta_n$ is the angle measured from the direction of maximum stress. b Electrical microimage extracted from the image presented in Fig. 2. The azimuthal origin for numerical results was adjusted manually for qualitative comparison ($\theta_l$ and $\theta_n$ scales have not the same origin).

Fig. 13 Fracture propagation depending on the hydraulic pressure in the wellbore for case C. a Evolution of the wellbore shape—tip of the induced fracture is represented by a dot for different levels of pressure in the wellbore; b plot of the number of cracks (in red) and of the maximum distance of the tip of the fracture from the wellbore (in blue) depending on pressure in the well.
Because of the heterogeneity of the properties of the particles and of the PB, stress local modification can occur. Thus, locally, a higher stress can lead to PB breaking, or a lower stress to PB integrity.

The caving in the breakout area will affect the stress further—this case cannot be taken into account in the analytical solution.

The qualitative analysis of the in situ logging images of the RN-15/IDDP-2 reveals numerous features that may be interpreted as breakout. The results of the numerical simulation of the effect of the drilling in the strike-slip regime (case C) could potentially fit these observations (Fig. 12). High resistivity on logging images (black color) might correspond to cavings filled with fluid, thus matching with increased well radius in numerical results. To go beyond, it would be interesting to have better knowledge of the stress state and to have quantitative estimation of breakout caving (with calipers), thus enabling the comparison of caving dimensions (depth and lateral extension).

**Effect of increased well pressure**

In this section, we discuss the mechanical impact of increased well pressure, without thermal loading effects, with tensile failure as expected result.
The numerical work focuses on case C (strike-slip regime). In the simulation, the pressure is applied by 1-MPa increment up to 90 MPa on the wellbore boundary. Figure 13 shows the result. The tensile fracture initiates for a well pressure close to 65 MPa, with 3 cm length into the rock matrix. Further stepwise increase of the pressure leads to progressive fracture depth. A pressure in the wellbore higher than 89 MPa is necessary for a wide propagation of the fracture.

For the sake of comparison, results obtained with the Kirsch equations (see Appendix) are presented in Table 5. The tensile failure appears for a pressure in the wellbore of 65 MPa, thus in good agreement with the numerical results. For the other stress states, a pressure in the well above 100 MPa is necessary to induce tensile failure.

In the RN-15/IDDP-2 wellbore, the pressure remained limited (below breakdown pressures computed in this section). Neither the analytical solution nor the numerical simulation results can explain the tensile fractures observed by the low well pressures. However, numerous features that may be interpreted as tensile fractures are observed in the image logs (see "Logging images" section and Fig. 2). Therefore, we study the effects due to the thermal cooling in the next section.

![Calculation results after 4 h of thermal loading for a heat transfer coefficient value of 1000 W m$^{-2}$ K$^{-1}$ (low thermal flux). The front color corresponds to the temperature (see legend). Each point corresponds to a crack (either tensile or shear crack). Grey uniform color corresponds to the area connected to the wellbore (penetration of hydraulic pressure and of thermal loading).](image-url)
Cooling effects on wellbore stability

The additional temperature term contributing to the hoop stresses in the analytical solution (Eq. 14 in Appendix) leads to tensile failure in all cases for a cooling larger than 190 °C (Fig. 14) without any need of fluid pressure in the well ($P_{\text{well}}=0$ MPa). In RN-15/IDDP-2 well, the host rock temperature is estimated to be between 426 and 549 °C (see "Geological knowledge" section), which means that any downhole drilling fluid temperature below 236 °C is likely to induce tensile fractures. This is in good agreement with the numerous tensile fractures observed on image logs (see "Logging images" section and Fig. 2).

Numerical simulations are proposed here for an in-depth view of the failure under thermal loading. Our motivation is twofold: first, the DEM approach allows to take into account thermal effects at the microscale (notably the differential expansion of the grains of the rock) and thus the approach is indeed more detailed for simulating the thermal

---

**Fig. 16** Influence of the heat transfer coefficient on the temperature field and on crack apparition (legend: colormap is the same as in Fig. 15), for a stress state corresponding to case C (defined in "Numerical approach" section), with no hydraulic loading. Results on left correspond to a low heat transfer coefficient ($1000 \text{ W m}^{-2} \text{ K}^{-1}$); Results on right correspond to a high heat transfer coefficient ($10,000 \text{ W m}^{-2} \text{ K}^{-1}$). On the top line, the comparison is made for the same duration of cool fluid injection (half-hour). On the bottom line, the comparison is made for a similar number of cracks (and different cooling durations).
effects. Second, the shape and size of damages can be retrieved and analyzed in comparison with observations. We investigate the impact of the thermal flux (through the heat transfer coefficient values) and of the pressure in the well. For the sake of comparison, and after a brief presentation of the stress state impact, a sensitivity analysis is presented.

**Thermo-mechanical tensile failures depending on the stress state**

Figure 15 shows the development of the cracks and of the induced fractures by the cracks’ coalescence for the different stress states, in the absence of hydraulic pressure in the wellbore. Tensile fractures developed in all the four cases, as predicted by the analytical results. However, depending on the stress state, the shape, the propagation direction and the intensity of the damage differ. With the largest 2D deviatoric stresses (cases A and C), the fracture propagates in the direction of the 2D maximum stress $\sigma_B^*$ (perpendicular to the direction of breakout caused by drilling, if any). In the most isotropic cases (cases B and D), fractures develop around the wellbore without preferential direction, following the path of least resistance defined by the local mineral distribution.

**Impact of the thermal flux at the wellbore boundary**

Figure 16 allows the comparison of the development of cracks in the rock depending on the thermal flux through extreme values of heat transfer coefficient for the stress state case C (strike-slip tectonic regime). With a low flux (low heat transfer coefficient value), the kinetics of the fracture development is drastically reduced. The second observation is less intuitive: besides kinetics, the cooling rate influences the shape of fractures. A fast cooling of the rock (high heat transfer coefficient, high thermal
gradient from the beginning of the cooling) creates several tortuous fractures, with dichotomy, while a slow cooling of the rock (low heat transfer coefficient value, progressive increase of the thermal gradient in the rock) allows the focusing of the crack within a single fracture. Moreover, it should be noticed that the coalescence of cracks observed in the case of high thermal flux can lead to separation of larger pieces of rock as shown in Fig. 17. This may be interpreted as caving on the wellbore images. In this case, cavings are not the result of overly low ECD but are due to the thermal loading. These temperature-induced cavings tend to be oriented in the maximum principal stress direction, contrary to breakouts caused by overly low ECD. The layout of crack development and coalescence in the case of fast cooling may provide explanations on some logging features: one can observe that the logging image is not symmetric but has a tendency to develop larger on one azimuth than the systematic one (note that the logging image is on a shallower depth than result of numerical modelling).

**Impact of the pressure in the wellbore**

The hydraulic pressure has a significant influence on the damage in the near-wellbore area as illustrated in Fig. 18. With high well pressure, towards the range of the least compressive hoop stress, the induced fractures localize towards a distinct plane with preferential orientation. For a pressure lower than the theoretical breakdown pressure in the wellbore (65 MPa, see "Impact of increased well pressure" section), the induced fracture is more restrained, split and discontinuous. Features observed on the logging images...
correspond rather to discontinuous fractures than to very localized fractures. Since pressure in the wellbore was limited, this lends credibility to the model.

**Discussion**

The presented study may shed light on the effects of the wellbore drilling and of the thermal stimulation in a deep and very hot fine-grained rock. Drilling and pressurization impacts on the wellbore stability have been studied first. The formation of breakouts and induced tensile fracture have been successfully described by the calculation results, even though we consider total deconfinement of the wellbore during drilling and no dynamic processes as tools impact in a first approach. Slight differences can be explained by the level of greater detail included in the numerical approach compared to the analytical solution: grain heterogeneity in the rock matrix, caving processes allowed and not pre-defined. From both analytical solution and numerical results, a fluid pressure no less than 65 MPa is needed for inducing tensile fracture without considering thermal effects. During the drilling phase and after, the pressure in the bottom of the well is under the breakdown pressure. However, numerous induced fractures have been observed in the logging images; a thermal component appears to be necessary to explain the observations.

In the RN-15/IDDP-2 well, there is a drastic difference in temperature between the fluid in the well and formation, probably higher than 150 °C during the drilling phase and even higher during the thermal stimulation (up to 400 °C). From both analytical and DEM calculations, which take into account thermo-mechanical loadings, this constant thermal stimulation induces tensile fracture. Note that considering the high temperature difference, fluid pressure in the well is not necessary for fracture inducing.

Complementary to the analytical solution, DEM allows a more detailed study of the thermo-mechanical processes: beyond the “macro” thermo-mechanical processes, the impact of the differential behavior of the minerals composing the rock can be considered thanks to a modeling at the grain scale. In addition, this approach allows notably the quantification of the damage around the wellbore, the visualization of the pathway of the induced fractures.

Beyond the above-presented results fitting with the observations, and as for any model, it is important to keep in mind the limitations when analyzing modeling results. Among the model limitations, we can quote the two dimensionality, the matrix considered as impermeable, and the impossibility to generate intragranular cracks.

Other limitations of simulations come from the complexity of the model and from the difficulty to have well-characterized parameters to feed into the model. The long computational time (on average 4–5 weeks to simulate a few hours of thermal loading) makes these limitations more pronounced since the number of possible investigations is limited. The variety of rock behavior under thermal loading, depending on the different studied parameters as the stress state, the thermal flux or the pressure in the wellbore, illustrates the necessity of data acquisition to reduce uncertainties. Indeed, the efficiency of the thermal stimulation as well as the stability of the borehole during the drilling evaluation need a sound knowledge of the in situ conditions (thermal and mechanical properties of the rock, direction and magnitude of stress state among others), and the control
of the thermal stimulation (depending notably on the flow rate, the temperature at surface, the pressure and the composition of the injected fluid). In addition to these influential uncertainties, the influence of the rock model should also be further investigated.

A second layer of uncertainties is introduced when comparing the modeling results with logging images, since these latter are also subject to uncertainties. Besides, note that the logging is performed more than 48 h after drilling while exposing the well to both thermocycling and pressure cycling; as a consequence, comparisons are mainly qualitative, but provide nonetheless a preliminary evaluation on the ability of the numerical approach to replicate successfully the observations.

Further investigations and numerical developments are needed to confirm the assumption and for a better understanding of the linked processes. Indeed, some limitations of the used version of the numerical code can lead to a misevaluation of the pathway and the propagation speed of the fractures: the energy of propagation of the fractures is not taken into account (Kanninen and Popelar 1985); the stability/instability of fracture growth in and out the zone of increased stress should be further investigated depending on the stimulation mechanism (either thermal or pressure effects). We have observed that the results are not accurately capturing the propagation of fractures into the far field once the close wellbore region is fractured when well pressures are larger than the minimum horizontal stress. The reason for that is found to be in the definition of the 2D plane strain cross section and the definition of the boundary conditions. The principal stress direction of the far field stresses is not aligned with the plane in which the 2D calculations are performed and also the axial stresses are not taken into the lower dimensional setup. For that reason, the system does not recognize that the out-of-plane, far-field stress is not a principal stress direction, but rather rotating with distance from the wellbore. This simplification overestimates the overall resistance against fracturing in the far field which in reality would be simply the minimum horizontal stress and rock resistance. Therefore, a fully 3D setup including all components of the stress tensor is proposed in future studies, which will shed light on stable vs unstable fracture growth beyond the close-wellbore region in the case of inclined wells exposed to temperature and pressure loading. This enhanced setup would then also enable a discussion of the paths of fractures propagating from the well into the far field eventually creating so-called “hackles.”

Further developments are also in progress for interpreting the induced fractures in terms of injectivity and later on also for studying productivity gains. The goal of such future simulations will be to enable the numerical reproduction of transient productivity loss as the previously created fracture closes due to thermal expansion of the matrix.

Conclusion

A DEM using micro–macro approach is proposed to simulate the thermo-mechanical processes in the surrounding of the wellbore of RN-15/IDDP-2. The results of this approach—chosen in consistence with the observations of the field—are compared with the classical analytical solutions and with the logging images. Considering the numerical limitations, modeling approximations and assumptions is necessary for a relevant interpretation of the results. The most impacting are the following:
• The long computational time resulting in limited number of possible investigations in the parametric study;
• The two dimensionality of the model leading to a poor capture of the propagation of fractures into the far field;

Some of these limitations can be improved in future works, in particular, by considering a 3D setup.

Nonetheless, numerical results are consistent with the results of the analytical solutions. According to the numerical results, as well as to the analytical solution, and fitting with the observations in RN-15/IDDP-2, breakouts result from the drilling process—arguing for a quite high local deviatoric stress—and tensile fractures appear because of the high thermal loading. Overpressure in the wellbore speeds up the process.

Moreover, the numerical simulation allows a deeper investigation into the effect of the drilling and into the thermal stimulation. In particular, the impact of the differential behavior of the minerals composing the rock can be considered thanks to a modeling at the grain scale. In addition, this approach notably allows the quantification of the damage around the wellbore and highlights the caved areas and the pathway of the induced fractures in the near field.

As emphasized, a fresh aspect of this study is the consideration of the thermal flux at the wellbore boundary. We have shown that a high thermal flux between the fluid in the wellbore and the rock leads to tortuous pathways for induced fractures; In this case, pieces of rock can be separated from the rock mass. This could be one explanation for the observed induced fractures and cavings in the logging images, oriented perpendicular to the direction of breakouts due to low ECD.

**Abbreviations**


**List of symbols**

- $\alpha_L$: linear thermal expansion coefficient (1 °C$^{-1}$);
- $\Delta P$: difference between the fluid pressure in the borehole and that in the formation ($P_{well} - P_p$) (MPa);
- $\Delta T$: thermal time step (s);
- $\Delta T$: temperature difference between the mud and the rock (°C);
- $\theta$: Azimuth measured from the direction of $\sigma_B^*$ (°);
- $\nu$: Poisson’s ratio;
- $\sigma_1$: major principal stress (MPa);
- $\sigma_2$: middle principal stress (MPa);
- $\sigma_3$: minor principal stress (MPa);
- $\sigma_{HF}$: major horizontal stress (MPa);
- $\sigma_{H}$: minor horizontal stress (MPa);
- $\sigma_v$: vertical stress (MPa);
- $\sigma_A^*$: 2D minimum principal stress component (MPa);
- $\sigma_B^*$: 2D maximum principal stress component (MPa);
- $\sigma_{dd}$: stress component parallel to the dip direction of the plan perpendicular to the well (MPa);
- $\sigma_{ss}$: stress component parallel to the strike direction of the plan perpendicular to the well (MPa);
- $\sigma_r$: radial stress around the borehole (MPa);
- $\sigma_\theta$: circumferential stress around the borehole (MPa);
- $\tau_{sd}$: tangential shear stress component in the plane...
perpendicular to the well (MPa); $\tau_{r\theta}$: tangential shear stress around the borehole (MPa); $C_v$: specific heat coefficient (J kg$^{-1}$ °C$^{-1}$); $E$: Young’s modulus (GPa); $L_p$: pipe length (m); $m$: mass of the heat reservoir (kg); $P_{frac}$: fracture pressure (MPa); $P_{well}$: well pressure (MPa); $P_p$: pore pressure of the formation (MPa); $Q_p$: power in the thermal pipe (W); $r$: distance from the center of the hole (m); $R$: radius of the borehole (m); $R_{th}$: thermal resistance (°C W$^{-1}$ m$^{-1}$); $T_i$: temperature of the numerical particle $i$ (°C); $T_j$: temperature of the numerical particle $j$ (°C).

### Authors’ contributions
BRGM’s authors performed modeling work and prepared the core of the manuscript. Equinor’s authors provided data from wellbore logging and enriched the discussion part. HsOrka provided data from RN-15/IDDP-2. All authors read and approved the final manuscript.

### Author details
1 BRGM, 3 av. C. Guillemin, BP36009, 45060 Orléans Cedex 2, France. 2 Equinor ASA, Research and Technology, Rotvoll, Norway. 3 HsOrka, Svartsengi, 240 Grindavík, Iceland.

### Acknowledgements
We would like to thank Kati Tänavsuu-Milkeviciene (Equinor) and Claudia Kruber (Equinor) who helped with the geology, mineralogy and porosity analyses; Théophile Guillon (BRGM) and Arnold Blaisonneau (BRGM) for fruitful discussion on modeling issues. The authors are grateful to the editor and to the two anonymous reviewers for their helpful comments and advice.

### Competing interests
The authors declare that they have no competing interests.

### Availability of data and materials
Not applicable (commercial code).

### Funding
This study was part of the DEEPEGS project, which received funding from the European Union HORIZON 2020 research and innovation program under Grant agreement no. 690771.

### Appendix: Simplified analytical approach for computation of stress development in the near-wellbore area
We propose to compute the analytical solution for the stress development in the near-wellbore area to evaluate the risk of breakout and breakdown. The proposed analytical solution is a simplified one: it requires the assumption of a wellbore parallel to principal stress that is not the case of the deep part IDDP-2 for the four stress states considered. For a cylindrical hole in a thick, homogeneous, isotropic, elastic plate subjected to effective minimum and maximum stresses (absolute values of minimum and maximum stresses are noted $\sigma_{A*}$ and $\sigma_{B*}$ hereafter), disregarding any thermal stresses, the following equations apply (Kirsch 1898 in Zoback et al. 1985):

\[
\sigma_r = \frac{1}{2} (\sigma_{A*} + \sigma_{B*}) \left( 1 - \frac{R^2}{r^2} \right) + \frac{1}{2} (\sigma_{A*} - \sigma_{B*}) \left( 1 - 4 \frac{R^2}{r^2} + 3 \frac{R^4}{r^4} \right) \cos 2\theta + \Delta P \frac{R^2}{r^2},
\]

\[
\sigma_\theta = \frac{1}{2} (\sigma_{A*} + \sigma_{B*}) \left( 1 + \frac{R^2}{r^2} \right) - \frac{1}{2} (\sigma_{A*} - \sigma_{B*}) \left( 1 + 3 \frac{R^4}{r^4} \right) \cos 2\theta - \Delta P \frac{R^2}{r^2},
\]

\[
\tau_{r\theta} = -\frac{1}{2} (\sigma_{A*} + \sigma_{B*}) \left( 1 + 2 \frac{R^2}{r^2} - 3 \frac{R^4}{r^4} \right) \sin 2\theta,
\]
where $\sigma_r$ is the radial stress, $\sigma_\theta$ is the circumferential stress, $\tau_{r\theta}$ is the tangential shear stress, $R$ is the radius of the hole, $r$ is the distance from the center of the hole, $\theta$ is the azimuth measured from the direction of $\sigma^*_B$, and $\Delta P$ is the difference between the fluid pressure in the borehole and the pore pressure (positive indicates overpressure in the borehole).

At the well boundary, when $r=R$, the set of equations becomes

\[
\sigma_r = \Delta P, \quad (7)
\]
\[
\sigma_\theta = \sigma^*_B + \sigma^*_A - 2(\sigma^*_B - \sigma^*_A) \cos 2\theta - \Delta P, \quad (8)
\]
\[
\tau_{r\theta} = 0. \quad (9)
\]

The most critical stresses at the well boundary, called hoop stresses, occur for $\sigma_\theta$ when $\theta = 0^\circ$ (minimal stress value, i.e., maximum tensile stress) and when $\theta = 90^\circ$ (maximal stress value, i.e., maximum compressional stress):

\[
\sigma_{0\theta} = 3\sigma^*_A - \sigma^*_B - \Delta P, \quad (10)
\]
\[
\sigma_{90\theta} = 3\sigma^*_B - \sigma^*_A - \Delta P. \quad (11)
\]

According to the analytical model, and for a Mohr–Coulomb strength criterion, damages occur if $\sigma_{0\theta}$ reaches the UTS or if $\sigma_{90\theta}$ exceeds the UCS. In the first case, drilling-induced tensile fractures develop in the direction of the maximum stress; the fluid pressure in the well has reached the so-called breakdown pressure. On the contrary, for $\theta=90^\circ$, damages appear in the form of breakout in the direction of the minimum stress; high pressure acts as a stabilizer.

Thermal effects can be integrated into the analytical model, by adding the thermal stress coefficient in the equations (Stephens and Voight 1982): $\alpha_L E \Delta T / (1 - \nu)$, where $\alpha_L$ is the linear coefficient of thermal expansion, $E$ the Young’s modulus, $\Delta T$ the temperature difference between the fluid in the wellbore and the rock ($\Delta T$ is negative for cooling), and $\nu$ the Poisson’s ratio. The equations for $\sigma_\theta$ at the well boundary become

\[
\sigma_{0\theta} = 3\sigma^*_A - \sigma^*_B - \Delta P + \frac{a \alpha L E \Delta T}{(1 - \nu)}, \quad (12)
\]
\[
\sigma_{90\theta} = 3\sigma^*_B - \sigma^*_A - \Delta P + \frac{a \alpha L E \Delta T}{(1 - \nu)}. \quad (13)
\]

From these equations, it can be seen that the thermal effects favor the occurrence of induced fractures when cooling the wellbore ($\sigma_{0\theta}$ decreases since $\Delta T$ is negative for cooling, thus the failure may occur sooner). In the present case, in the absence of pore pressure, $\Delta P = P_{out}$ and thus the fracture pressure $P_{frac}$ considering the thermal effect is

\[
P_{frac} = 3\sigma^*_A - \sigma^*_B + \text{UTS} + \frac{a \alpha L E \Delta T}{(1 - \nu)}. \quad (14)
\]
References


Itasca Consulting Group Inc. PFC2D—Particle flow code in 2 dimensions, Version 4.0, MN. ICG. Minneapolis; 2008b.


Kereyraze M. Contribution à l'étude expérimentale de l'endommagement mécanique et thermique de roches cristallines. Thèse de doctorat en Terre solide, sous la direction de Frédéric Pellet et de Benoît Loert, à l'Université Joseph Fourier (Grenoble), 2009.


Pálissonn G. Crustal structure of Iceland from explosion seismology. Science Institute, University of Iceland, Reykjavik; 1978.


Temperature log simulations in high-enthalpy boreholes

Jia Wang*, Fabian Nitschke, Maziar Gholami Korzani and Thomas Kohl

Abstract

Temperature logs have important applications in the geothermal industry such as the estimation of the static formation temperature (SFT) and the characterization of fluid loss from a borehole. However, the temperature distribution of the wellbore relies on various factors such as wellbore flow conditions, fluid losses, well layout, heat transfer mechanics within the fluid as well as between the wellbore and the surrounding rock formation, etc. In this context, the numerical approach presented in this paper is applied to investigate the influencing parameters/uncertainties in the interpretation of borehole logging data. To this end, synthetic temperature logs representing different well operation conditions were numerically generated using our newly developed wellbore simulator. Our models account for several complex operation scenarios resulting from the requirements of high-enthalpy wells where different flow conditions, such as mud injection with- and without fluid loss and shut-in, occur in the drill string and the annulus. The simulation results reveal that free convective heat transfer plays an important role in the earlier evolution of the shut-in-time temperature; high accuracy SFT estimation is only possible when long-term shut-in measurements are used. Two other simulation scenarios for a well under injection conditions show that applying simple temperature correction methods on the non-shut-in temperature data could lead to large errors for SFT estimation even at very low injection flow rates. Furthermore, the magnitude of the temperature gradient increase depends on the flow rate, the percentage of fluid loss and the lateral heat transfer between the fluid and the rock formation. As indicated by this study, under low fluid losses (< 30%) or relatively higher flow rates (> 20 L/s), the impact of flow rate and the lateral heat transfer on the temperature gradient increase can be ignored. These results provide insights on the key factors influencing the well temperature distribution, which are important for the choice of the drilling data to estimate SFT and the design of the inverse modeling scheme in future studies to determine an accurate SFT profile for the high-enthalpy geothermal environment.

Keywords: Temperature logs, Static formation temperature, Wellbore simulation, High-temperature well, Horner-plot method, Heat transfer, Fluid loss
Introduction

Geothermal explorations depend strongly on reservoir conditions which are evaluated by increasingly sophisticated reservoir simulators (Cacace et al. 2010; O’Sullivan and O’Sullivan 2016; Konrad et al. 2019). Also, data acquisition, mostly of seismic data, has reached a high degree of complexity. This is, however, contrasted by little effort in the evaluation of logging data, especially of temperature logs. Usually, the primary objectives of running a temperature survey in a well are to obtain valuable information on geothermal reservoirs such as the static formation temperatures (SFT) and the location of fluid loss zones. This requires temperature logs measured at different stages (mud circulation and shut-in) during the evolution of the temperature in the borehole fluid-formation system as well as different interpretation techniques of these temperature logs (Witterholt and Tixier 1972).

The SFT is usually inferred from the measurement of bottom-hole temperature (BHT) when the drilling circulation has stopped and the borehole fluid temperature gradually develops towards the initial or unperturbed formation temperature. Due to the thermal disturbances caused by the drilling mud, the measured BHT is usually lower than the true SFT and needs to be corrected to obtain a reliable estimate (Deming 1989; Gou-torbe et al. 2007). Various temperature correction methods based on different simplified physical models have been developed, e.g., the Horner-plot method [or constant line source method (Bullard 1947; Dowdle and Cobb 1975)]; the spherical and radial heat flow method (Ascencio et al. 1994, 2006); the Hasan-Kabir method (or conductive-convec-tive cylindrical heat source model (Hasan and Kabir 1994) and the Kutasov–Eppel-baum method [or generalized Horner method (Kutasov and Eppelbaum 2005)]. These methods are based on linear or non-linear regression models that describe the relationship between measured BHT and time functions (Verma et al. 2006a, Verma et al. 2006b; Wong-Loya et al. 2012) accounting for the transient effects of thermal recovery during the shut-in phase of the borehole. The simplicities in these methods make them very prevalent engineering tools for estimating SFT.

Another important application of temperature logs is the identification of fluid loss or feed zones from temperature data obtained under hydraulic testing conditions (Okandan 2012; Steinigrmsson 2013). Examples of using temperature measurements in boreholes are multifold. Pehme et al. (2010) identified hydraulically active fractures in dolomite and sandstone aquifers; Klepikova et al. (2011) estimated local transmissivities and hydraulic head differences; Nian et al. (2015) predicted flow rates in oil and gas production wells. These authors stressed the satisfactory accuracy of temperature-derived flow velocities compared to direct flow measurement. In recent years, fiber-optic distributed temperate sensing (DTS), which is a robust means of acquiring continuous temperature profiles instantaneously along the length of the cable (Großwig et al. 1996), has also been extensively used to improve the accuracy of flow rate profiling and the detection of fracture zones (Read et al. 2013; Coleman et al. 2015; Read et al. 2015; Bense et al. 2016).

In a high-temperature environment, the acquisition of logging data from exploration and drilling projects in geothermal fields is more challenging compared to its petroleum counterparts. In recent years, high-temperature geothermal systems have gained attention due to their large potential for energy extraction. In fact, a number of wells drilled in geothermal fields such as The Geysers (USA), Los Humeros (Mexico), Kakkonda (Japan), Larderello
(Italy), and Reykjanes (Iceland) have been reported (Reinsch et al. 2017; Kruszewski and Wittig 2018) to even reach supercritical conditions for water ($T > 374$ °C, $P > 221$ bar). Reliable logging in such extreme well conditions is currently very challenging using conventional tools, which are normally rated up to 175 °C bottom-hole temperature (Baird et al. 1993). Although high temperature and pressure logging tools are available (Ikeuchi et al. 1998; Sekine et al. 2004; Reinsch et al. 2013), these tools are generally all restricted to specific operating conditions in harsh environments. For example, the electronic Kuster K10, a commonly used commercial tool in the industry, can operate at a maximum of 350 °C only up to 4 h (Danielsen 2008). This short period may be sufficient for the tripping of the logging tools but not for collecting data to resolve the transient thermal response under shut-in condition. DTS, which is considered better suited for use at elevated temperatures, gives erroneous temperature readings under high temperatures (> 300 °C) due to the chemical and thermal degradation of the optical fiber (Reinsch et al. 2013; Laarossi et al. 2019). To keep the temperature of the measuring device below its maximum tolerance, cooling through continuous injection during logging is necessary for extreme high-temperature boreholes (Friðleifsson et al. 2018).

The present study focuses on the analysis of temperature logging data from high-temperature geothermal wells. It particularly addresses the specific conditions (e.g., drill pipe-and-annulus geometry and continuous injection) which result from the requirements of such an environment. Two sets of simulation examples are analyzed to reflect possible logging conditions in a high-enthalpy well. In the first example, fluid injection followed by shut-in is simulated. This example is used to examine the validity of applying simple BHT correction methods on the shut-in temperature data to estimate SFT, as well as to evaluate the impact of the free convection heat transfer in the build-up of borehole fluid temperature and the SFT estimation results. To the authors’ knowledge, the latter was hardly discussed in former wellbore simulation studies (Espinosa-Paredes et al. 2009; Yang et al. 2015). The second example investigates two new topics for high-temperature geothermal wells under-injection. One scope of the investigation is whether simple BHT type correction methods are still applicable to logging data from boreholes which are under continuous cooling due to the restriction of the logging tool. Furthermore, a new method is discussed to quantify the fluid loss percentage from temperature logs by computing the ratio of temperature gradient below and above the fluid loss point.

**Methods**

**Analytical approach to estimate SFT-Horner-plot method**

Herein, the Horner-plot method (HM) for SFT estimation using shut-in temperature logs is analyzed. This method was selected due to its wide application in the geothermal industry (Andaverde et al. 2005; Kutasov and Eppelbaum 2018). The evaluations of other SFT estimation methods fall outside the scope of this paper but can be achieved similarly. The HM approximates the thermal effect of the drilling as an infinitely thin and long axial heat source extracting heat at a constant rate and, therefore, perfect conducting conditions in the well are assumed. The mathematical form of the HM is simplified as follows:

$$T_s = T_i + \frac{q}{4\pi i_s} \ln \frac{t_s + t_i}{t_i}.$$  (1)
where $T_s$ is the borehole shut-in temperature, $T_i$ is the SFT, $t_i$ is the shut-in time, $t_c$ is the circulation time, $q$ is the heat extraction rate. According to Eq. 1, a semi-logarithmic plot of $T_s$ against the Horner dimensionless time $(t_c + t_i)/t_i$ should be a straight line intercepting with the vertical axis at $T_i$. The standard procedure of applying the Horner-plot method has been to extrapolate this line until $t_i \to \infty$ (Horner dimensionless time = 1) with the intercept yielding the SFT value.

**Numerical approach**

An in-house numerical simulation tool is used to model the thermal behavior of the wellbore and its surrounding formation. The simulator is an application developed based on the MOOSE framework which provides a multiphysics object-oriented simulation environment (Gaston et al. 2009). MOOSE allows for efficient utilization of a wide range of computational hardware using both shared-memory and distributed-memory parallelism (Permann et al. 2013). The MOOSE-based application consists of different physics modules which can be easily added, removed and coupled for solving variables in an implicit and fully coupled manner.

Figure 1 shows the schematic of typical wellbore flow and heat transfer scenarios. The cold drill fluid is considered to be either injected both in through the drill pipe and the annulus (coflow); or injected in the drill pipe and circulated back to the surface (counterflow). The simulator assumes the wellbore to be treated either as a one-dimensional or a two-dimensional structure depending on the problem being studied. When a two-dimensional wellbore structure is considered, the wellbore components, such as the fluid inside the drill pipe, the drill pipe wall, the annulus, and the casings,
are treated as different regions (region 1, 2, 3, 4, respectively) in which the temperatures \((T_1, T_2, T_3, T_4)\) need to be solved as individual variables (Fig. 1). These variables are linked through the interfacial heat transfer relationships between the fluid and the solid. The injection fluid was assumed to be pure liquid water. Fluid properties such as density, viscosity, and heat capacity were calculated according to the IAPWS-IF97 formulation (Cooper and Dooley 2007). The fundamental assumptions of the models considered in this work are: the geometries of the wellbore and formation are cylindrical, the fluid is incompressible, fluid flow is in the axial direction only, the rock formation is impermeable, there is no radial temperature gradient within the fluid when the wellbore is considered to be a two-dimensional structure, thermal dissipation and expansion effects are negligible.

Making these assumptions, the energy conservation equation for the fluid inside the drill pipe and annulus is written in the following form:

\[
\rho_f C_{pf} \left( \frac{\partial T_f}{\partial t} + v_r f \frac{\partial T_f}{\partial r} + v_z f \frac{\partial T_f}{\partial z} \right) - \frac{j_f}{r} \frac{\partial T_f}{\partial r} - \lambda_f \frac{\partial^2 T_f}{\partial r^2} - \lambda_f \frac{\partial^2 T_f}{\partial z^2} = 0
\]  

(2)

The continuity equation for incompressible flow is given by:

\[
\frac{1}{r} \frac{\partial (rv_f)}{\partial r} + \frac{\partial v_z f}{\partial z} = 0,
\]  

(3)

where \(\rho_f\) is the fluid density, \(C_{pf}\) is the fluid specific heat capacity, \(v_r\) and \(v_z\) are the axial and radial flow velocities, respectively, \(\lambda_f\) is the thermal conductivity.

The energy conservation equation for the pipe wall, casing and formation can be expressed as:

\[
\rho_s C_{ps} \frac{\partial T_s}{\partial t} - \frac{\lambda_s}{r} \frac{\partial T_s}{\partial r} - \lambda_s \frac{\partial^2 T_s}{\partial r^2} - \lambda_s \frac{\partial^2 T_s}{\partial z^2} = 0,
\]  

(4)

where \(\rho_s\), \(C_{ps}\), \(\lambda_s\) is the density, heat capacity and thermal conductivity of the pipe wall, casing and formation, respectively.

The final forms of the above governing equations for regions 1, 2, 3, 4 (Fig. 1) are simplified into:

\[
\frac{\partial v_z f}{\partial z} = 0, \quad i = 1, 3
\]  

(5)

\[
\rho C_p \frac{\partial T_i}{\partial t} + \frac{j_i}{r} \frac{\partial T_i}{\partial r} - \lambda \frac{\partial^2 T_i}{\partial r^2} - \lambda \frac{\partial^2 T_i}{\partial z^2} = 0, \quad i = 1, 3
\]  

(6)

\[
\rho C_p \frac{\partial T_i}{\partial t} - \lambda \frac{\partial T_i}{\partial r} - \lambda \frac{\partial^2 T_i}{\partial r^2} - \lambda \frac{\partial^2 T_i}{\partial z^2} = 0, \quad i = 2, 4
\]  

(7)

where \(i\) refers to the region number.

The initial and boundary conditions of the thermal–hydraulic models considered in this work are given in Table 1. The validation of the numerical tool is done by comparing the numerical simulation results and analytical solutions of Ramey’s wellbore
Heat transfer coefficients

As mentioned above, the thermal exchange between different wellbore regions is modeled via thermal transfer relations at their interfaces (Table 1, BC2). The heat transfer coefficient, $h$, is the proportionality constant between the heat flux and the thermodynamic driving force for the heat flow (i.e., the temperature difference between adjacent wellbore components, $\Delta T$). In this work, the heat transfer coefficients under forced convection and shut-in condition are correlated and calculated using different approaches.

**Forced convection**

Under forced convection, the heat transfer coefficient is defined as (Yang et al. 2015):

$$ h = \frac{\text{Nu} \cdot \dot{m}}{d} $$

where Nu is the Nusselt number, $d$ is the hydraulic diameter of the drill pipe and annulus.

For laminar flow inside the annulus, Nu is calculated using the Sieder–Tate correlation (Kohl et al. 2002):

$$ \text{Nu} = 1.86(\text{Re Pr})^{1/3} \left( \frac{d}{L} \right)^{1/3} \left( \frac{\mu}{\mu_w} \right)^{0.14}, \quad \text{Re} \leq 2300, $$

where $L$ is the length of the tube, Pr is the Prandtl number, $\mu$ is the dynamic viscosity of the bulk fluid, $\mu_w$ is the fluid viscosity at the temperature of the tube wall.
In the laminar regime inside the drill string

\[ \text{Nu} = 4.364, \quad \text{for} \quad \text{Re} \leq 2300 \]  
\[ \text{Nu} = 0.023 \cdot \text{Re}^{0.8} \cdot \text{Pr}^{0.3}, \quad \text{for} \quad \text{Re} \geq 1e4. \]  

For highly turbulent flow, the Dittus–Boelter equation (Dittus and Boelter 1985) is applied:

\[ \text{Nu} = (1 - \gamma) \cdot 4.364 + \gamma \cdot 0.023 \cdot \text{Re}^{0.8} \cdot \text{Pr}^{0.3}, \quad \text{for} \quad 2300 < \text{Re} < 1e4 \]

with

\[ \gamma = \frac{\text{Re} - 2300}{10^4 - 2300} \]

**Shut-in condition**

So far in most theoretical and simulation studies, pure conductive heat flow in a static water column is assumed when estimating temperature recovery during borehole shut-in (Shen and Beck 1986; García et al. 1998; Espinosa-Paredes et al. 2001; Yang et al. 2015). The heat transfer coefficient in the borehole fluid is then approximated by:

\[ h_c = \frac{h_f}{r_{wb}}, \]

where \( r_{wb} \) is the borehole radius.

However, several studies have reported the existence of another key factor in the heat transfer which is free convection caused by density differences arising from vertical temperature gradients (Diment 1967; Gretener 1967; Pfister and Rybach 1995; Berthold and Börner 2008; Eppelbaum and Kutasov 2011; Klepikova et al. 2018). The critical parameters for the free convection process can be indicated by the following equation (Diment and Urban 1983):

\[ \nabla T_{cr} = \frac{g \cdot \alpha \cdot T_{abs}}{C_p} + \frac{C \cdot \nu \cdot D_T}{g \cdot \alpha \cdot r_{wb}^4}, \]

where \( \nabla T_{cr} \) is the critical thermal gradient to initiate free convection, \( g \) is the acceleration due to gravity, \( \alpha \) is the thermal expansion coefficient, \( T_{abs} \) is the absolute temperature (K), \( C_p \) is the specific heat capacity, \( C \) is a constant with a value of 216 for tubes, \( \nu \) is the fluid kinematic viscosity, \( D_T \) is the fluid thermal diffusivity. Taking the following values as typical for the borehole fluid: \( \nu = 1e-6 \, \text{m}^2/\text{s}, \, \alpha = 2e-4 \, \text{K}^{-1}, \, D_T = 1.4306e-7 \, \text{m}^2/\text{s}, \, C_p = 4149 \, \text{J/(kg K)}, \) absolute temperature range of 273.15–573.15 K. This equation reveals that for a borehole with a radius of 35–150 mm, the average critical thermal gradient needed to initiate free convection is \( 2.36e-4 \) to \( 1e-2 \, \text{K/m} \).

Unlike forced convection, which normally acts only in the axial direction, free convection enhances the heat transfer in all directions through fluid circulation and mixing. However, a well-established quantitative description of the thermal effect of free
convection in boreholes is still missing, and a general modeling approach is not available. Luheshi (1983) showed that free convection does not significantly enhance vertical heat transfer. Since the radial temperature gradient is typically much larger, the contribution to heat flux in the vertical direction by free convection is considered negligible. However, he mentioned it might be necessary to account for the enhancement in radial heat flux due to the mixing effect of fluid motion induced by buoyancy forces. In our work, we have assumed the increase of the heat transfer rate due to free convection only acts in the radial direction. The overall heat transfer coefficient can be written as:

\[ h = h_c + h_{\text{free}}, \]  

which means that the heat transfer for the shut-in condition results from conduction and free convection.

In our models, the heat transfer coefficient for forced convection was calculated explicitly according to Eqs. (8)–(13). While for the shut-in condition, the heat transfer due to free convection was either neglected \((h_{\text{free}} = 0)\) or was implicitly evaluated (e.g. \(h_{\text{free}} \) is a factor or fraction of \(h_c\)).

**Simulation scenarios**

In the simulation studies, we began with the application of HM to the simulated shut-in temperature logs. Then we simulated two logging scenarios in a high-temperature environment. In one scenario, temperature logs obtained under continuous borehole cooling were used to estimate SFT and the sensitivity of the estimation error to different flow rates was investigated. In another scenario, temperature logs were used to quantify the fluid loss in the well.

**Shut-in temperature logs simulation**

The evaluation of the HM was conducted by numerical simulation of both the circulation and shut-in stage of well operation. In this model, fluid flow in a straight, non-cased two-dimensional well embedded in the two-dimensional formation was considered. The modeling parameters can be found in Table 2. The model domain size of 2500 m in the axial direction and 50 m in the radial direction was chosen to reflect the reservoir depth and to ensure that the lateral outer boundary represents far-field conditions which were not affected by thermal perturbations from well operations. The FE mesh was discretized with 150 layers in the axial direction \((\Delta z = 16.7 \text{ m})\). In the radial direction, the mesh was refined near the well \((\Delta r_{\text{min}} = 10^{-3} \text{ m})\) and coarsened at a larger lateral distance \((\Delta r_{\text{max}} = 4 \text{ m})\). The final mesh size was determined by performing a sensitivity analysis yielding asymptotic smaller variations for the calculated temperatures (maximum temperature variations of less than \(10^{-2} \text{ °C})\). The procedure mentioned above for determining the model domain, mesh sizes, etc., has been applied analogously to each of the models in this work.

The total simulation time was 150 days with 10 days being the cooling (injection) period followed by the shut-in period. The numerically predicted temperatures of borehole fluid during shut-in were used to estimate the SFT according to Eq. 1. The rate of heat transfer during the shut-in period was controlled by the magnitude of the heat transfer coefficient in the model. To investigate the impact of free convection on the
temperature recovery during shut-in, we considered different values of \( h_{\text{free}} \): 0, \( h_c \), \( 9h_c \), \( \infty \). According to Eq. (16), the heat transfer coefficients then became: (1) \( h = h_c \); (2) \( h = 2h_c \); (3) \( h = 10h_c \); (4) \( h = \infty \). Case (4) corresponds to the condition where the fluid acts as a perfect conductor and thermal resistance in the well does not exist.

### High-temperature environment simulation

In this section, we focus on the simulation of temperature logs in a high-temperature environment. For this purpose, we have assumed the SFT to be in a temperature range from 5 °C (surface) to 500 °C (bottom-hole). Two different SFT profiles were analyzed. The profile was either linear-shaped which could be linked to a geothermal system controlled by pure heat conduction, or S-shaped representing commonly observed heat convection zones (Fig. 2). The wellbore layout included the drill pipe, annulus and several casings (Table 3). The above-described SFT profiles and wellbore layout were used in each of the following simulation cases.

#### Continuous borehole cooling

The simulations assumed that cold water (7 °C) was injected for 10 days both into the drill pipe and into the annulus at a flow rate of 15 L/s and 45 L/s, respectively (first period). In the second period (thermal recovery), injection into the drill pipe stopped while annulus injection continued but the flow rate was reduced to \( Q \) (\( Q \) ranged between 0 and 5 L/s). The borehole was under the full shut-in condition when \( Q = 0 \) L/s; otherwise, it was under partial shut-in condition. Temperatures of the fluid inside the drill pipe at different warm-up times were measured and then used to estimate SFT by applying the HM.

#### Fluid loss

The impact of fluid loss on the temperature response in a borehole is analyzed by generating a series of dynamic temperature logs based on forward simulations where different fluid loss amounts under different flow rates in the borehole were assumed.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation temperature at the surface</td>
<td>°C</td>
<td>20</td>
</tr>
<tr>
<td>Bottom-hole temperature</td>
<td>°C</td>
<td>245</td>
</tr>
<tr>
<td>Formation rock density</td>
<td>kg/m³</td>
<td>2650</td>
</tr>
<tr>
<td>Formation thermal conductivity</td>
<td>W/(m °C)</td>
<td>2.92</td>
</tr>
<tr>
<td>Formation specific heat capacity</td>
<td>J/(kg °C)</td>
<td>1000</td>
</tr>
<tr>
<td>Well depth</td>
<td>m</td>
<td>2500</td>
</tr>
<tr>
<td>Well radius</td>
<td>m</td>
<td>0.15</td>
</tr>
<tr>
<td>Water injection rate ( (Q_{inj}) )</td>
<td>kg/s</td>
<td>20 (first 10 days); 0 (after 10 days)</td>
</tr>
<tr>
<td>Water injection temperature ( (T_{inj}) )</td>
<td>°C</td>
<td>20</td>
</tr>
<tr>
<td>The geothermal gradient</td>
<td>°C/m</td>
<td>0.09</td>
</tr>
<tr>
<td>Water specific heat capacity</td>
<td>J/(kg °C)</td>
<td>3160</td>
</tr>
<tr>
<td>Water thermal conductivity</td>
<td>W/(m °C)</td>
<td>0.6</td>
</tr>
</tbody>
</table>
temperature logs were used as samples for the analysis of the temperature response to the fluid loss in the borehole. Again cold water (7 °C) was injected through the drill pipe and the annulus separately, and the temperature logs were only ‘recorded’ in the drill pipe. For simplicity, the total amount of fluid being injected was distributed such that the flow velocities in the string and the annulus were equal. The fluid loss occurred at 3.35 km depth from the annulus through a hydraulic connection to the formation. The total amount of injected fluid was varied from 5 to 50 L/s. The percentage of fluid loss from the annulus was varied between 0 and 100%.

**Results and discussion**

**Estimating SFT using shut-in temperature logs**

The evolutions of BHT with respect to time considering four different heat transfer rates are given in Fig. 3a. It is shown that the recovery of BHT is influenced by
the heat transfer rate in the borehole during the early stage of shut-in. The higher
the heat transfer rate is, the faster the temperature builds up. A maximum differ-
ence of 30 °C between the predicted BHTs is found. However, the four temperature
curves have approximately the same build-up rate after 20 days. Furthermore, the
sensitivity of temperature build-up on the heat transfer rate decreases when the heat
transfer rate reaches 10h_c. Figure 3b shows the plots of the BHT against the Horner
dimensionless time. For each curve, two different BHT data sets are used to estimate
the SFT. One contains the early shut-in-time temperature data measured within
1 day (t_s = 12, 18, 24 h); another one contains long-term shut-in measurements
of several days (t_s = 2, 3, 4 days). The regression lines for the early and the long-term
shut-in BHT measurements are plotted in Fig. 4a, b, respectively. Figure 4c displays
the comparison between the intercepts of these regression lines (SFT estimates) and
the true SFT value. In all cases, the SFT is underestimated with a large error when
early shut-in-time temperature data are used. The underestimation errors range
from −61.9 to −31.3 °C depending on the rate of heat transfer rate assumed in the
model. On the other hand, the accuracy for SFT estimation is improved when using
long-term shut-in temperature data, and again, the influence of the heat transfer
rate on SFT estimation is observed. The SFT tends to be overestimated under low
heat transfer rates (h = h_c, 2h_c) and underestimated under higher heat transfer rates
(h = 10h_c, ∞).
Estimating SFT using temperature logs obtained under borehole cooling

As shown earlier, both the heat transfer rate in the borehole and the measurement time have an impact on the final result of the estimated SFT. In the following SFT calculations, long-term shut-in temperature data measured after 1 day, 2 days and 3 days since the start of the second period were used. The heat transfer coefficient $h$ for the full shut-in conditions was then calibrated by trial and error until an accurate SFT estimation was achieved (see Fig. 5, shut-in case). The calibrated $h$ was examined to be $1.4 h_b$, ($h_b$ being the SFT estimation error at the bottom-hole was 0.15 °C for the linear SFT profile scenario, and 0.24 °C for the S-shaped SFT profile scenario) and it was used to account for the heat transfer rate within the drill pipe in the second period. In the annulus, forced convection heat transfer dominates the heat transfer process. The SFT was estimated assuming different annulus flow rates and the estimation error at bottom-hole was calculated (Fig. 5).

As expected, the SFT was underestimated when temperature measurements under cooling conditions were used in all cases. This is because with continuous cold injection in the annulus during the second period, the temperature was only partially recovered in the borehole compared to the shut-in condition. The higher the flow rate in the annulus was, the less the heat would recover and the larger the resulting underestimation error.
in the SFT (Fig. 5c, d). For small values of flow rate in the annulus up to 0.7 L/s (corresponding fluid velocity of 0.05 m/s at the bottom-hole), the maximum estimation error at the bottom-hole was around 74 °C (percentage error 14.8%) when the linear SFT profile was assumed and 24 °C (percentage error 4.8%) for the S-shaped SFT profile. The reason for the smaller estimation error for the S-shaped profile is the higher SFT value along most parts of the well. Therefore, the fluid is less cooled, resulting in earlier thermal recovery. However, it is noticed that the maximum SFT estimation error along the well depth could be in some cases much greater than the error at the borehole bottom (Fig. 5b, maximum underestimation error of 143 °C was found at 1800 m depth for the flow rate of 0.5 L/s in the annulus).

Characterization of the fluid loss in the well
Herein, we present exemplary simulated temperature logs under flow rates of 5 L/s and 50 L/s for an S-shaped SFT profile (Fig. 6). The results for the linear SFT profile were omitted since it was observed that the shape of the SFT profile had a negligible influence on the temperature response to fluid loss. An abrupt increase in the vertical temperature gradient below the loss zone at 3.35 km depth is detected in each temperature log. It is also noticed that the relationship between the increase of the temperature gradient and the percentage of fluid loss is not monotonic. On the one hand, when the percentage of fluid loss is below 95%, a steeper temperature
a higher amount of fluid loss in the borehole. Such behavior can be explained by the fact that with more fluid being lost from the annulus, the fluid remaining in the borehole has more residence time to gain heat from the hotter surroundings and thereby the fluid temperature tends to increase. On the other hand, the increase in the temperature gradient drops when the fluid is almost completely lost. This is due to the fact that very high fluid losses cause very low remaining flow rates. As a result, the heat transfer rate from the formation to the annulus fluid is also strongly impaired. The reduced heat flux results in lower fluid temperatures both in the annulus and drill pipe.

We performed further analyses by calculating the increase of the vertical temperature gradient due to the presence of fluid loss for each of the generated temperature logs. This increase was quantified by computing the ratio of the slope of the temperature profile above the loss zone to the slope below the loss zone. Since the borehole temperature was considered to approach steady-state after 10 days, the temperature slope could be approximated using a linear gradient. The relationship between the gradient ratio and the percentage of fluid loss under different flow rates is illustrated in Fig. 7. The non-monotonic relationship between the gradient ratio and the fluid loss (with maximum temperature gradient ratios occurring when the fluid loss exceeds 95%), which has already been discussed earlier, is observed for each flow rate under consideration. Moreover, the dependence of the gradient ratio on the flow rate seems to be more complex. The gradient ratio tends to be independent of the flow rate if the percentage of fluid loss is low, e.g., < 30%. For fluid losses > 30%, smaller temperature gradient ratios are observed for lower flow rates. However, for flow rates greater than 20 L/s (flow velocity > 0.5 m/s),
the gradient ratio is almost independent to the flow rate except when the fluid loss is greater than 90%.

**Conclusion**

The assessment of geothermal reservoirs relies on the information supplied by logging tools, with temperature logs among the most important ones. The in-house numerical tool developed to simulate the thermal response of the wellbore and the formation during fluid circulation and shut-in conditions is intended to fill the absence of a quantitative interpretation of temperature logs and the associated uncertainties. It accounts especially for the heat transfer process from the formation towards the specific location of the measurement tools including the drill pipe, annulus or open borehole. Particular care is given to the correct treatment of the transient heat transfer through the multiple interfaces (casing–annulus–drill pipe–drill fluid) in such a complex thermal system. The quality of the simulation tool was demonstrated by comparison with borehole temperatures from analytical solutions. In this study, the simulator was applied to generate synthetic shut-in and dynamic temperature logs.

The temperature logs were interpreted for two purposes: SFT estimation and characterization of loss zones. The major findings and the underlying messages conveyed in this study are as follows:

1. The shut-in temperature depends significantly on the magnitude of free convection, which enhances the heat transfer rate. In this study, a maximum difference of 30 °C in BHT predictions between the two extrema scenarios of free convection is found. In this regard, a careful parameterization of the heat transfer rate is especially important in the early transient stage of shut-in heat recovery.
2. The Horner-plot method may strongly underestimate the SFT if early shut-in (within 24 h) temperature measurement data are used. However, it provides high accuracy
SFT estimates (percentage error < 3%) when using long-term shut-in (2 days up to 4 days) temperature measurement data.

3. Using temperature logs obtained under borehole cooling conditions can become inauspicious for the Horner-plot interpretation method even at small cooling flow rates. This can yield significant errors (24 °C and 74 °C at a flow rate of 0.7 L/s for a linear- and S-shaped SFT, respectively) in the bottom-hole SFT estimation.

4. In the presence of fluid loss, the local temperature gradient change is affected by the flow rate, the percentage of fluid loss as well as the overall rate of the lateral heat transfer from the formation to the borehole fluid. It was found that for fluid losses less than 30%, or under relatively high flow rates (> 20 L/s), the gradient change can be independent on the flow rates.

Under the specific conditions of high-temperature boreholes the temperature logging data represent a complex response to the wellbore layout, the flow conditions, the heat transfer mechanism, etc. Under these constraints, a simple interpretation of temperature logs can be strongly misleading and more sophisticated techniques accounting for key factors by numerical simulation are required. Herein, the impacts of these factors were investigated by individual sensitivity analysis. However, in real geothermal applications, these impacts may overlap. Therefore, simulations in this context need to be joined by inverse procedures. In this way, the present contribution represents an important step towards a more sophisticated interpretation of real project data. It requires accounting, in a detailed manner, for the geometrical setting, on the history of injection, drilling, logging (even the time lapse of logging start to logging end) and on the appraisal of measurement errors. Work is now underway to interpret dynamic temperature logs using inverse modeling techniques.

List of symbols

Roman letters

- \( T \): temperature (\( \Theta \)); \( c_p \): specific heat capacity (\( \Theta \) L\(^2\) T\(^{-2}\)); \( t \): time (\( T \)); \( r \): radius (\( L \)); \( v \): velocity (\( L T^{-1} \)); \( z \): axial coordinate (\( L \)); \( i,j \): simulation region number; \( n \): depth (\( L \)); \( m \): mass flow rate (\( M T^{-1} \)); \( A \): cross-section area (\( L^2 \)); \( q \): heat flux (\( M T^{-3} \)); \( T_s \): shut-in temperature (\( \Theta \)); \( Ti \): static formation temperature (\( \Theta \)); \( t_s \): shut-in time (\( T \)); \( t_c \): circulation time (\( T \)); \( h \): heat transfer coefficient (\( M T^{-3} \Theta^{-1} \)); \( Nu \): Nusselt number (1); \( Pr \): Prandtl number (1); \( d \): diameter (\( L \)); \( L \): length (\( L \)); \( \Delta T \): temperature difference (\( \Theta \)); \( \gamma \): weighting coefficient for linear interpolation; \( g \): the acceleration of gravity (\( L T^{-2} \)); \( \alpha \): thermal expansion coefficient (\( \Theta^{-1} \)); \( \nu \): kinematic viscosity (\( L^2 T^{-1} \)).

Greek letters

- \( \rho \): density (\( M L^{-3} \)); \( \lambda \): thermal conductivity (\( M L T^{-3} \Theta^{-1} \)); \( \Gamma \): interfacial region; \( \mu \): dynamic viscosity (\( M L^{-1} T^{-1} \)); \( \gamma \): weighting coefficient for linear interpolation; \( g \): the acceleration of gravity (\( L T^{-2} \)); \( \alpha \): thermal expansion coefficient (\( \Theta^{-1} \)); \( \nu \): kinematic viscosity (\( L^2 T^{-1} \)).

Subscripts

- \( f \): fluid; \( inj \): injection; \( r \): radial direction; \( z \): axial direction; \( wb \): wellbore; \( c \): conduction; \( free \): free convection; \( cr \): critical; \( abs \): absolute.

Acknowledgements

The study is part of the DEEPEGS "Deployment of Deep Enhanced Geothermal Systems for Sustainable Energy Business" Project within European Union’s Horizon 2020 research and innovation program. The support from both the Helmholtz portfolio project “GeoEnergy” and the program “Renewable Energies” under the topic “Geothermal Energy Systems”, is also gratefully acknowledged. We also thank the EnBW Energie Baden-Württemberg AG for supporting geothermal research at KIT. Special thanks to Dr. Emmanuel Gaucher (KIT) for the support on the DEEPEGS project and to Dr. Steinthor Nielsson (ISOR), a partner in the DEEPEGS project. The authors would also like to thank Dr. Thorsten Agemar (Leibniz Institute for Applied Geophysics, Hannover, Germany) for fruitful discussions during the preparation of this paper. We also thank two anonymous reviewers who helped to improve the quality of this manuscript.
Authors’ contributions
JW performed the numerical modeling, analysis of the results and wrote the manuscript. FN supervised and provided support in the design of the study. MG provided the numerical simulation tool applied in this study. TK supervised the research and finalization of the manuscript. All authors read and approved the final manuscript.

Funding
The research was funded by the European Union’s HORIZON 2020 research and innovation program under Grant Agreement No. 690771.

Availability of data and materials
Data on which conclusions of the manuscript are based on are presented in the text, otherwise, they are adequately cited.

Competing interests
The authors declare that they have no competing interests.

Appendix
Appendix A. Validation of the Ramey’s heat transmission model
Most of the literature on wellbore heat transmission is based on the classical work of Ramey (Ramey 1962, 1964). A simple physical model that describes the wellbore heat transmission consists of fluid flow in a straight, non-cased, one-dimensional well which is embedded in the two-dimensional formation. Ramey derived an analytical solution for the transient temperature distribution in injection and production wells based on simplified heat balances. However, it was found that Ramey’s solution is normally valid for long times but is significantly inaccurate for early-stage transient periods. A number of studies have attempted to adjust Ramey’s solution and derive more efficient and stable approximations to small, medium, and large-time solutions by giving specific expressions in terms of the so-called dimensionless time function which represents the transient heat transfer from wellbore to the formation (Kutasov 1987, 2003; Wu and Pruess 1988; Hagoort 2004; Kutun et al. 2014, 2015). In this work, we adopted the simplified expression for dimensionless time function given by Kutun et al. (2015), which is based on the best curve fit of Ramey’s dimensionless time function data.

The injection and production cases were modeled by considering three different scenarios: (i) water being injected at the same temperature as the surface temperature; (ii) water being injected at a higher temperature than the surface temperature; (iii) water being extracted from the reservoir. The model set up and geometry and thermal properties data used in the simulations were the same as defined in “Shut-in temperature logs simulation”, except that the well with 0.15 m radius is simplified as a one-dimensional structure.

Figure 8 presents a comparison of temperatures obtained from analytical solutions given by Ramey (Ramey 1962) and our numerical models. Maximum temperature differences (errors) for the three different simulations on day 1, day 5 and day 10, respectively. Case (i): |ΔT|_{max} ≤ 1.9 °C, case (ii): |ΔT|_{max} ≤ 0.21 °C, and case (iii): |ΔT|_{max} ≤ 1.9 °C.
Appendix B. Validation of the counterflow heat exchange model

The counterflow heat exchange model is essentially the physical model for mud circulation under the drilling process in a wellbore. During circulation, the drilling mud flows downwards (axial direction) in the drill pipe. The heat exchange process of the system involves two mechanisms: convective heat transport and heat transfer of the drilling mud with the pipe wall (forced convection heat transfer). At the bottom, fluid exited through the drill bit into the annulus. The temperatures at the outlet of the drill pipe and the inlet of the annulus are considered to be the same. The fluid in the annulus moves upwards to the surface. The annulus fluid temperature is controlled by the rate of convective heat transport and forced convection heat transfer at two fluid–solid interfaces: annulus fluid/outer drill pipe wall, annulus fluid/wellbore wall.

The model size was 4600 m in the axial direction and 50 m in the radial direction. The mesh was discretized in 15 m steps in the axial direction, mesh sizes in the radial direction ranged between $10^{-3}$ and 6.5 m. The geometric parameters of the wellbore and thermal properties data used in the modeling are given in Table 4. The analytical solution for the fluid temperature distribution inside the drill pipe and the annulus given by Bobok and Szarka (2012) was used for the numerical validation of the mud circulation model. The comparison of the analytical solution and the simulated solution of the drill pipe fluid and annulus temperature is shown in Fig. 9. Maximum estimation differences for the temperature of drill pipe fluid and annulus fluid were calculated, respectively: 0.72 °C, 1.06 °C after 4 days’ circulation; 0.32 °C, 0.51 °C after 10 days’ circulation; 0.08 °C, 0.17 °C after 20 days’ circulation (Table 4).
Table 4: Geometric parameters and material properties used in the simulation of the counterflow heat exchange model

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation temperature at the surface</td>
<td>°C</td>
<td>7</td>
</tr>
<tr>
<td>The geothermal gradient</td>
<td>°C/m</td>
<td>0.1</td>
</tr>
<tr>
<td>Casing thermal conductivity</td>
<td>W/(m °C)</td>
<td>50</td>
</tr>
<tr>
<td>Cement thermal conductivity</td>
<td>W/(m °C)</td>
<td>1.2</td>
</tr>
<tr>
<td>Formation rock density</td>
<td>kg/m³</td>
<td>3000</td>
</tr>
<tr>
<td>Formation thermal conductivity</td>
<td>W/(m °C)</td>
<td>1.5</td>
</tr>
<tr>
<td>Formation specific heat capacity</td>
<td>J/(kg °C)</td>
<td>840</td>
</tr>
<tr>
<td>Well depth</td>
<td>m</td>
<td>4600</td>
</tr>
<tr>
<td>Inside radius of the drill pipe</td>
<td>m</td>
<td>0.0352</td>
</tr>
<tr>
<td>The outside radius of the drill pipe</td>
<td>m</td>
<td>0.0445</td>
</tr>
<tr>
<td>Inside radius of the casing</td>
<td>m</td>
<td>0.0797</td>
</tr>
<tr>
<td>The outside radius of the casing</td>
<td>m</td>
<td>0.089</td>
</tr>
<tr>
<td>The radius of the wellbore/formation interface</td>
<td>m</td>
<td>0.1</td>
</tr>
<tr>
<td>Water production rate</td>
<td>kg/s</td>
<td>15</td>
</tr>
<tr>
<td>Water specific heat capacity</td>
<td>J/(kg °C)</td>
<td>4194</td>
</tr>
<tr>
<td>Water density</td>
<td>kg/m³</td>
<td>1000</td>
</tr>
<tr>
<td>Water viscosity</td>
<td>Pa∙s</td>
<td>1e-3</td>
</tr>
<tr>
<td>Water thermal conductivity</td>
<td>W/(m °C)</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Fig. 9: Comparison of analytical solution and simulated solution for the counterflow heat exchange model. Black color represents the temperature of the fluid inside the drill pipe, red color represents the temperature of annulus fluid. Solutions were calculated and compared at three different circulation time: 5 days, 10 days, 20 days. The analytical solution was plotted in lines: solid lines (5 days), dash-dot lines (10 days), dot lines (20 days). The simulated solution was marked in symbols: circles (5 days), squares (10 days), crosses (20 days).

References
Goss 

Received: 23 May 2019 Accepted: 24 October 2019

Published online: 07 November 2019


Page 20 of 21

129

BOOK OF PUBLICATIONS | PART 1

DEEPEGS

129


Publisher’s Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
The need for integrated valuation tools to support decision-making – The case of cultural ecosystem services sourced from geothermal areas

David Cooka,⁎, Reza Fazelib, Brynhildur Davíðsdóttirc

⁎Faculty of Economics and Faculty of Environment and Life Sciences, University of Iceland, Garðar, Sæmandargötu 2, 101 Reykjavík, Iceland
bSchool of Engineering and Natural Sciences, University of Iceland, Garðar, Sæmandargötu 2, 101 Reykjavík, Iceland
cEnvironment and Natural Resources, School of Engineering and Natural Sciences, University of Iceland, Oddi, Sæmandargötu 2, 101 Reykjavík, Iceland

ARTICLE INFO

Keywords:
Decision-making
Valuation
Geothermal energy
Environmental impacts
Ecosystem services

ABSTRACT

Developing geothermal power projects may lead to trade-offs, whereby the economic and social benefits of the venture are difficult to compare with its cultural consequences, which include impacts to ES such as aesthetics, spiritual enrichment and inspiration. The socio-cultural rather than monetary character of such impacts reinforces the importance of a pluralist approach to valuation, in order to ensure that all human well-being impacts linked to the development of geothermal power projects are accounted for in appropriate decision-support tools, which can successfully integrate diverse values concerning the environment. In this short communication, this paper considers the various impacts to cultural ecosystem services that are associated with the development of geothermal power projects, and a literature review is conducted concerning the extent to which cultural impacts have been included within Multi-Criteria Decision Analysis (MCDA). Using the Search, Appraisal, Synthesis and Analysis, and snowballing methods, eight studies are identified. This review finds, with one exception, a lack of focus on cultural impacts and limited stakeholder consultation. This issue could potentially be of particular concern in relation to geothermal power projects impacting indigenous communities, whereby decision-making is frequently conducted according to the notion of the national good, with local interests relegated in importance.

1. Introduction

Environmental conflicts often originate from a failure to reconcile trade-offs between values (Bark et al., 2016; Jacobs et al., 2016; Mueller et al., 2016; Egh et al., 2017; Jacobs et al., 2018), and this is especially important in relation to the energy sector (Phelan and Jacobs, 2016). It is widely acknowledged in the ecosystem services (ES) literature that one of the major ongoing research lines is to develop methodologies which successfully integrate multiple and often conflicting values about the environment, including from the ecological, socio-cultural and monetary domains (Liu et al., 2010; Escobedo et al., 2011; Martín-López et al., 2014; Jacobs et al., 2016; Saarikoski et al., 2016b; Wam et al., 2016; Costanza et al., 2017). In recent years, a body of academic research has emerged endorsing the value pluralism perspective, arguing for its adoption as a fundamental principle in all ecosystem services assessments (Pascual et al., 2010; Chan et al., 2012; Jax et al., 2013; Martín-López et al., 2014; Baral et al., 2016; Saarikoski et al., 2016a,b). It necessitates a transdisciplinary approach, as well as the adoption of decision-support tools such as Multi-Criteria Decision Analysis (MCDA) that can satisfactorily combine quantitative and qualitative information (Saarikoski et al., 2016b).

Recently, the work of Hastik et al. (2015) on the ES impacts of renewable energy technologies was further advanced through Cook et al.’s thematic assessment of the effects of developing geothermal power plants (Cook et al., 2017). This study determined that the majority of the ES impacts linked to the development of high-temperature geothermal areas belonged to the cultural typology (Cook et al., 2017). Cook et al. (2017) also highlighted several examples whereby individuals could hold different types of values concerning a geothermal area, leading to trade-offs with the economic and social objectives of such projects. One person may wish to enjoy recreational experiences, business leaders may be motivated via profit-making opportunities involving electricity generation, while indigenous peoples may have no economic motive, instead viewing geothermal phenomena as fundamental to their way of life. Although acknowledging the importance of value pluralism in the process of valuing the cultural ES of geothermal areas, the paper by Cook et al. (2017) did not consider the ensuing decision-making complexities involved in evaluating simultaneous...
impacts with non-material consequences for human well-being.

The aims of this short communication are: (a) to summarise the impacts to cultural ES occurring due to the pursuit of geothermal power projects, and provide specific examples of socio-cultural impacts, and (b) conduct a literature review of the extent to which MCDA studies focused on geothermal power projects have evaluated cultural impacts. Section 2 summarises the main cultural ES impacts linked to the development of geothermal power projects. Cases of socio-cultural impacts are outlined and a brief summary detailed of the merits of MCDA as a decision-support tool in an energy and ecosystem services assessment context. Section 3 details the paper’s methodology with regards to the selection of MCDA literature. Section 4 summarises the results from the review of MCDA studies and discusses the main decision-making implications. Section 5 provides a conclusion.

2. Cultural ES of geothermal areas, MCDA and integrated valuation

2.1. Value domains and the cultural ES of geothermal areas

Human beings can hold multiple values concerning the environment, including ecological, economic, social, cultural, spiritual, symbolic, therapeutic, insurance and place values (Chan et al., 2012; Martín-López et al., 2014). Although their boundaries are invariably blurred and overlapping, these have been further categorised as monetary, socio-cultural and ecological value-domains (Castro et al., 2014; Martín-López et al., 2014).

Based on the list of cultural ES typical1 of geothermal areas identified in Cook et al. (2017), several can derive from the socio-cultural domain, including spiritual enrichment, aesthetics, inspiration, heritage, non-use value and recreation. With the exception perhaps of recreation, such values are poorly captured using monetary metrics, payment vehicles and non-market valuation techniques.

2.2. Cultural ES pertaining to the socio-cultural value domain and the impacts of geothermal power projects

Preferences for cultural ES, such as spiritual enrichment, are often formed collectively based on Traditional Knowledge (Martín-López et al., 2014), involve interactions with formal and informal governance institutions (CAFF, 2015), and occur through direct relationships with an environment rather than instrumental or intrinsic associations. In these cases, which are often common in indigenous communities where notions of the sacredness of land are important, willingness to pay for a particular service is likely to be zero, yet these individuals will still hold a value in socio-cultural terms (Cooper, 2009; Zeppelin, 2009; Martín-López et al., 2014). Potential impacts to the cultural ES of spiritual enrichment in a geothermal context highlight the decision-making challenges when resource situations involve multiple stakeholders and diverse values about the environment. In cases such as these, a choice-informing judgement about the effects of different development scenarios cannot be formed through a monetary value alone (Altmann et al., 2014; Ishizaka and Nemery, 2013; Raymond et al., 2014).

American Indian land currently comprises approximately 5% of US land, yet holds an estimated 10% of its energy resources (Farhar and Dunlevy, 2003). Nothing illustrates the character of value incommensurability more than a comparison between the economic benefits of developing geothermal resources on Native American land in States such as Arizona and Nevada, some of which would likely accrue to the indigenous population, and deep, resonant socio-cultural traditions. These tribes define themselves and honour spiritual values with respect to their land, which many traditional elders believe they hold sovereignty over and must ensure remains undisturbed as a form of ancestral right (Farhar, 2012; Lund, 2006). Furthermore, decision-making within Native American peoples, such as the Hopi Tribe, is a private and collective process, which can take a long time to resolve due to the presence of two types of leadership – the traditional and tribal councils – and frequent changes to leadership personnel.

Similar conflicts and trade-offs have emerged in recent years in New Zealand connected to potential geothermal developments on Maori land (Hiluva et al., 2010). These have been resolved, at least in part, through the Maori’s receipt of dividends and revenue from power plants on sacrificed indigenous lands, a process facilitated through recognition in New Zealand law that the Maori owned the resources mined from their land (Mvwanza, 2018). This legal entitlement has not applied in the case of Olkaria, Kenya, where sub-surface geothermal resources are owned by the state rather than the Maasai tribes who use their surface manifestations for cooking, heating and traditional rituals. Conflicts emerged linked to the relocation of more than 100 Maasai families by Kenya Electricity Generating Company (KenGen), the state-run geothermal operator. A report by the World Bank found adverse impacts on those affected, partly due to the limited suitability of the new land for traditional spiritual practices compared to Olkaria (World Bank, 2015). More recently, a revenue-sharing bill has been tabled in the Kenyan Parliament to try and ensure adequate economic compensation for indigenous communities. This would ensure that 2.5% of KenGen’s revenue from Olkaria plants would be directed to a special fund. Of this, 75% would return to national government, with 20% and 5% directed to local governments and affected communities respectively (Mvwanza, 2018).

With regards to aesthetics, inspiration and heritage, these three ES are considered as a bundle together due to their role as intermediate services contributing to recreation in geothermal areas (Dowling, 2013; Borović and Marković, 2015; Liu and Chen, 2015), as well as non-use value (Cook et al., 2018). Peaceful surroundings and the presence of multi-coloured and geo-diverse environments in geothermal areas generate rare aesthetics. As well as forming a motivation for undertaking recreational activities (e.g. hiking and bathing), geothermal environments can often be inspiring for artists due to their diversity and uniqueness (Gray, 2012). Due to their age, aesthetic diversity and rarity, geothermal areas can also constitute feelings of nostalgia, tradition and history. For sites such as the geysers in Yellowstone National Park, heritage can be considered to be an intermediate benefit contributing to demand for recreation in the form of tourism activities. In addition, although geothermal areas are generally sparsely populated, they can sometimes include valued archaeological remains (Borović and Marković, 2015). Cook et al. (2017) discuss how noise emissions and visual blight caused during the construction, operation and decommissioning phases of geothermal power plants can contribute to negative impacts to the aesthetics of surrounding landscapes, which may lead to trade-offs in terms of the quality of the recreational experience. These were the findings of a cultural impact study by Edelson and Kleese (1995) investigating native Hawaiian opposition to geothermal power projects.

2.3. MCDA and integrated valuation of ES

A decision-making apparatus that has gained some traction in recent years is MCDA, an overarching term and framework describing approaches which attempt to account for multiple criteria and stakeholder objectives in decision-making. MCDA methods enable information to be integrated from non-market valuation studies (monetary value domain)
and the outcomes from deliberative research (socio-cultural value domain) (Chan et al., 2012). Given these advantages, MCDA has become increasingly popular in energy project planning, as its processes and outputs can assist decision-makers in identifying applicable objectives and trade-off criteria linked to affected stakeholders, and making appropriate decisions as per determined priorities (Kumar et al., 2017).

3. Methodology

A literature review was conducted on the application of MCDA for geothermal power projects. The Search, Appraisal, Synthesis and Analysis (SALSA) framework was applied (Cromin et al., 2008; Grant and Booth, 2009) (see Fig. 1), which applies an organised and replicable approach to find, select, and analyse published academic research (Tranfield et al., 2003; Jones, 2004). The SALSA framework was first applied in health sciences but its simplicity and rational order of stages means that it has increasingly been applied in ES research (Mastrangelo et al., 2015; Yang et al., 2018; Malinauskaite et al., 2019). In addition, in line with the approach of Malinauskaite et al. (2019), as there were only a small number of identified relevant scientific articles, it was decided to also apply the ‘snowballing’ technique (Greenhalgh and Peacock, 2005; Creswell, 2007; Malinauskaite et al., 2019) between the Appraisal and Synthesis stages to expand the list of relevant publications.

The main stages of the method were as follows:

1) Step 1: Search
- Search for terms ‘Geothermal’, ‘Multi-criteria Decision Analysis’ and ‘ecosystem services’ in Science Direct, Scopus, Web of Science and Google Scholar databases; use of additional search terms added to narrow down the search.

2) Step 2: Appraisal
- Read abstracts to determine suitability of publications for the review according to two criteria: use of ES concept, consideration of multiple criteria.
- Selected publications read in full.

3) Additional Step 3: Snowballing Technique
- Apply snowballing technique to identify more relevant articles.

4) Step 4: Synthesis
- Review the main aims and objectives of the publications, classifying these according to topic and scope.

5) Step 5: Analysis
- Analyse literature based on (a) evaluative scope, and (b) levels and type of stakeholder participation
- Focus of (a) was particularly on whether cultural impacts were included

The literature search was done in July 2018, to select studies published in any year that contained the following terms in the title, abstract or keywords (“Multi-criteria” OR “Multicriteria”) AND “ecosystem services”*, AND Geothermal. All of the results from Scopus (n = 73), Web of Science (n = 11), Science Direct (n = 14) and Google Scholar (n = 42), were reviewed, while additional search words (“power plant” and “decision making”) were used to remove a total of 77 articles that were deemed not relevant for this literature review, leaving six articles. Then, ‘Snowballing technique’ was applied, resulting in an additional two publications. In total, eight publications were then analysed.

4. Results and discussion

Table 1 provides a summary of the existing MCDA studies for geothermal energy projects, including details of the authors and year of publication, study location, scale, levels of stakeholder participation, and scope of evaluative criteria. Stakeholder analysis is essential in order to ensure that an ecosystem services perspective has the potential to become embedded into decision-making processes. Of equal importance is the use of a wide range of criteria in evaluation processes, otherwise different values and perspectives will be omitted from the MCDA tool.

4.1. Main review outcomes

Three main features emerge from the results of the literature review: (1) a tendency for current work to be derived from limited or undefined levels of public participation; (2) a predominant focus on economic and technical efficiency objectives and omission of cultural impacts; and (3) a tendency for studies not to be used in decision-making protocols. With regards to the second observation, this is likely a direct consequence of the first. None of the eight studies reviewed in this paper were specific in valuing impacts to cultural ES, although Rammaáætlun (2011) did so without directly referring to the concept. Economic, energy efficiency and design optimisation objectives were the most common evaluative criteria, with much more limited focus on the environmental and social acceptability of proposals, and, in four of the eight papers, limited (undefined in two cases) or zero levels of stakeholder participation. The studies by De Jesus (1997) and Borsani et al. (2014) were more extensive in terms of their objectives, encompassing social and environmental criteria, but they were still demonstrative of either zero stakeholder consultation or a lack of transparency concerning the degree to which they integrated insights from stakeholder consultation, which entails the risk that the full links between the impacts of developing geothermal power and human well-being are poorly understood.

With the exception of Rammaáætlun (2011) and as far as we are aware, all of the studies in Table 1 represent purely academic analyses, which were not used in practice by decision-makers. Rammaáætlun (2011) has been enshrined in Icelandic law since 2013, as a means of determining the strategic suitability of Iceland’s potential energy projects, including geothermal and hydro power sites. An overarching Steering Committee was responsible for co-ordinating four separate working groups to assess the many impacts of geothermal power projects. The first evaluated environmental impacts and cultural heritage (Thorhallsdóttir, 2007; Kristjánsson et al., 2015; Cook et al., 2016). The expert working group focused on environmental impacts and cultural heritage applied a three step procedure to the evaluation of cultural impacts from potential geothermal and hydro power developments, as follows: (1) assessment of the site values; (2) assessment of developmental impacts; and (3) ranking of projects from worst to best. Values for sites were assessed in expert panel workshops using numeric scales ranging from 1-10 in relation to the severity of their impacts in relation to, the following attributes: richness and diversity; rarity; size;
<table>
<thead>
<tr>
<th>Publication</th>
<th>Study location</th>
<th>Scale</th>
<th>Stakeholder participation</th>
<th>Scope of evaluative criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>De Jesus (1997)</td>
<td>Mount Apo Project (Philippines)</td>
<td>Environmental soundness and social acceptability</td>
<td>Government leaders, and institutional leaders from the religious, academic, and other concerned NGO sectors.</td>
<td></td>
</tr>
<tr>
<td>Goumas et al. (1999)</td>
<td>Nea Kessani, Northern Greece</td>
<td>Local</td>
<td>Environmental soundness and social acceptability</td>
<td>Energy use; return on investment; new jobs</td>
</tr>
<tr>
<td>Goumas and Lygerou (2000)</td>
<td>Nea Kessani, Northern Greece</td>
<td>Local</td>
<td>Environmental soundness and social acceptability</td>
<td>Net present value of the investment; new jobs; energy consumed; risk index.</td>
</tr>
<tr>
<td>Haralambopoulos and Polatidis (2003)</td>
<td>The island of Chios, Greece</td>
<td>Region</td>
<td>Environmental soundness and social acceptability</td>
<td>Conventional energy saved; return of investment; number of jobs created; environmental pressure index and entrepreneurial risk of investment</td>
</tr>
<tr>
<td>Rammaáætlun (2010)</td>
<td>Iceland</td>
<td>National</td>
<td>Environmental soundness and social acceptability</td>
<td>Various workshops involving a wide range of stakeholders from regional and economic consequences; energy capacity and project costs</td>
</tr>
<tr>
<td>Borzoni et al. (2014)</td>
<td>Tuscany, Italy</td>
<td>Regional</td>
<td>Environmental soundness and social acceptability</td>
<td>Electricity production; profitability; municipality revenues; direct heat uses; avoided GHG emissions; H2S emissions; Hg emissions; NH3 emissions; Annual energy saved; return on the investment; new jobs; environment; risk of suicide.</td>
</tr>
<tr>
<td>Polatidis et al. (2015)</td>
<td>The island of Chios, Greece</td>
<td>Broad but based on secondary data (focused on investors and local stakeholders, including the mayor, members of municipal councils, NGOs, local development companies and regional authorities, but taken from an earlier study 11 years previously)</td>
<td>Environmental soundness and social acceptability</td>
<td>Energy efficiency; energy efficiency; energy efficiency; exergy efficiency; net power output; production cost; and total cost rate.</td>
</tr>
<tr>
<td>Sabalan, Iran</td>
<td>Local</td>
<td>Environmental soundness and social acceptability</td>
<td>Energy efficiency; exergy efficiency; net power output; production cost; and total cost rate.</td>
<td></td>
</tr>
</tbody>
</table>

4.2. Barriers, challenges and future uses of MCDA in a geothermal context

The general omission of cultural impacts from the MCDA studies could have been for many reasons, including a thematic or discipline-specific focus of the paper, limited public participation in terms of shaping study design, or alternatively it could have been because of the challenges inherent in conducting integrated valuation – these necessitate the use of multiple valuation techniques, both monetary and non-monetary, and the investment of considerable time and resources on the part of researchers (Martinez-Alier and Muradian, 2015; Jacobs et al., 2016; Pandeya et al., 2016; Villegas-Palacio et al., 2016; Jacobs et al., 2018). In practice, decision-making in a geothermal context needs to be undertaken through careful evaluation of the main value dimensions existing in a system, but must not overburden planning resources and processes, which are often very limited in developing countries where a significant proportion of untapped resources are located (Szabó et al., 2013).

Challenges also remain concerning the conflicting nature of the different value dimensions. MCDA approaches maintain the need for stakeholders to consider trade-offs linked to policy alternatives – where these relate to certain cultural ES of geothermal areas, such as spiritual enrichment, there may still be issues of categorical non-commensurability that cannot be satisfactorily resolved (Saarikoski et al., 2016a,b). In order to facilitate integrated valuation, it is essential that stakeholder consultation is embedded at the earliest stage, enabling a very broad array of policy alternatives to be considered, objectives to be determined, and weightings to be evaluated. This was the case in Rammaáætlun (2011), which was forged and ultimately enshrined in Icelandic law.

4.3. Decision-making implications of results

This study has reinforced the importance of considering different value dimensions concerning the trade-offs of developing geothermal power projects. Moreover, this paper’s results concerning existing MCDA studies communicate the need for more effective stakeholder engagement relating to planning and decision-making, and the need for academic analyses to be far broader in scope in order to facilitate relevant information provision to decision-makers. This is all the more important considering the indigenous and often marginalised character of affected communities, such as the Kenyan Maasai in Olkarrie. This example typifies the afflictions that can occur when international and domestic legal frameworks are insufficient, leading to multiple cultural impacts with considerable associated implications in terms of human rights, gender equality and identity impacts (Koonsaha, 2017). Effective stakeholder consultation can only be facilitated through the provision of sufficient financing to support and develop community capacity in relation to entrepreneurial projects seeking to harness geothermal...
resources. Through financing of stakeholder consultation and deliberation on objectives, MCA approaches can be helpful in terms of refining and embedding community needs into the goals of the projects. In so doing, MCA studies are broadened in scope because - focus on technical feasibility and contribution to the national economic good, encompassing cultural ES impacts and an array of socio-economic evaluative criteria. In particular, MCA approaches that place an objective the extent to which geothermal power projects deliver benefit-sharing, regarding indigenous communities as co-owners, are likely to be more inclusive and equitable than those seeking to provide economic compensation for land losses.

5. Conclusion

Although the current pool of studies is limited, it is evident that MCA approaches have potential as an integrative decision-support device in the context of geothermal resources. However, only one study embedded cultural impacts into its evaluative criteria and current studies have demonstrated limited stakeholder engagement, with objectives focused mainly on economic and technical criteria. A broadening of scope and standardisation of approaches to encompass the full array of cultural ES impacts is necessary, but does remain challenging in practice because of budgetary constraints and various economic agendas within research-design and decision-making protocols. The example of Rannís provided an example of an applied MCA work, which came to fruition after more than ten years of stakeholder engagement and analysis.

The next stages in this research project will focus on the non-monetary evaluation methods suitable for elicitation of public preferences relating to cultural impacts in a geoethical context. The outcomes from such evaluations will then be used to develop an illustrative MCDA case study, highlighting best practice procedures, participation and the formation of informed project objectives, with impacts to cultural ES fully embedded into the platform. Future research also needs to focus more intensely on how to ensure that MCA studies in a geoethical context are not merely academic exercises, but can support decision-making in practice.

Acknowledgements

This paper has been subject to funding from the European Union’s Horizon 2020 programme in relation to the DEEPGRS project (grant no. 690771), RANNÍS (The Icelandic Centre for Research) (grant no. 163464053), the Landvíkjun Energy Research Fund, and Vegagerðin (The Icelandic Road and Coastal Administration).

References

Reykjanes, Iceland: Structure and dynamics of mid-oceanic ridge geo/hydrothermal systems

1. Introduction

Our understanding of volcanic processes is hampered by our limited knowledge of source processes generating signals observed at the surface. Much has been learned about subsurface structures of volcanoes from disciplines such as volcanology, geology, petrology, geophysics, and studies of ore deposits in the mining sector. Moreover, fluid extraction and injection in exploited geothermal areas are analysed and measured, providing good proxies for the estimate of parameter ranges (density, seismic velocities, rock permeability, fluid composition, etc.) applicable to undrilled volcanoes.

However, detailed information on structures at depth beneath active volcanoes is usually poor (only a few volcanoes have been drilled) and not sufficient for a clear understanding of magmatic processes leading to eruption, hampering acute hazard assessment. The temporal evolution in terms of magma accumulation, storage or solidification at depth is mostly unknown. As a result, studies in areas where parameters defining those processes are better known due to in-situ observations brought by drilling and exploitation are of considerable importance. In volcanic exploited geothermal systems, many wells provide detailed structural control.

Iceland is the ideal place for this type of research. Iceland has for a long time been a natural laboratory for the study of geological processes associated with rifting and hot spots. Volcanic eruptions are frequent; volcanic activity mainly occurs within volcanic systems comprising a central volcano and an associated fissure swarm. Reykjanes is somewhat of an anomaly, as the volcanic systems have only fissure swarms but no central volcanoes. A by-product of the intense volcanic activity is major geothermal activity. There is intensive use of geothermal energy for heating and electricity production. Active search for energy resources beyond conventional volcanic geothermal systems also occurs. Specifically, conditions where super-critical fluids are anticipated to occur at several locations in Iceland. Harnessing such reservoirs are estimated to produce fluids with about 10 times more energy than found in conventional systems. Their use is considered to provide an important future energy resource, e.g. for large industries. The IDDP-1 drilling in Krafla was designed to find such conditions at depth, but the drill entered magma at an unexpectedly shallow depth and the geothermal objective could not be reached. The IDDP-1 work is noteworthy for the fact that there was no geophysical indication of such a magma pocket at shallow depth; the geophysical methods used were basically “blind” to relatively small bodies of magma.

The development of new technologies and approaches for imaging magma and supercritical conditions are therefore required. The integration of several methods is also a key to understand better both structures and mechanisms in geothermal systems (e.g., Jousset et al., 2011).

This special issue of JVGR has been dedicated to provide a case study for such a complementary, integrated approach. It is mainly based of the results of IMAGE (Integrated Methods for Advanced Geothermal Exploration), a FP7 EU funded project, but also includes results and data obtained after the completion of the project. The idea was to gather in one volume several publications on studies from one of the best places in the world to perform this kind of approach, the Reykjanes thermal area on the southwestern margin of the Reykjanes Peninsula, Iceland. Conventional exploration approaches were applied, and complemented by cutting edge methods used for imaging at depth, prior to drilling the deepest well found in volcanic and geothermal environment in Iceland, the IDDP-2 (Friðleifsson et al., 2019).

The IMAGE FP7 EU project focused on improving and integrating existing exploration methods, and implementing new ones such as ambient noise tomography or Fibre optic Distributed Acoustic Sensing (Jousset et al., 2018). The final achievements of the IMAGE project are illustrated by many contributions in this special issue. The main results exposed here lead to more robust predictive models of the critical exploration parameters on local scales. They comprise:

1) The identification of the key situations where favourable reservoir parameters (temperature, permeability, resource extent) can be expected, which includes the relationships between geological structures and geothermal resources, defining the exploration methods to be applied.

2) A better understanding of the processes that control permeability.

3) The determination of the fundamental properties of supercritical geothermal reservoirs and the respective technologies to measure and define them, a major step forward in making this so far untapped resource available.

Advanced exploration techniques developed and tested in IMAGE present a significant step forward towards the goal of imaging geothermal systems with a higher degree of accuracy and resolution, thus making geothermal targets for industrial exploitation more accessible. Those results lead to new ways for studying active volcanoes where supercritical conditions occur.

https://doi.org/10.1016/j.jvolgeores.2019.106692
2. Structure of the special issue

The special issue has 27 original papers, mostly about the topics and results from IMAGE, but it also includes papers on related subjects. We ordered and group them by geographic location, starting on the Reykjanes Peninsula and ending in the North of Iceland in Krafla.

An initial paper by Voight et al. (2019) is a tribute to Kristjan Saemundsson who has made major contributions to unravelling the nature and workings of geothermal activity, as well as the volcanic and regional geology of Iceland, through his almost six decades of work on geology and tectonics of Iceland. A review paper (Sigmundsson et al., 2020) explores the link between the geodynamics of Iceland, the volcanic and tectonic activity and the geothermal exploitation.

2.1. Reykjanes Peninsula

Reykjanes Peninsula extends from south-west Iceland up to the triple junction expressed in Hengill. A review of the geology of Reykjanes is given by Saemundsson et al. (2019). Reykjanes has been seismically very active Bjornson et al. (2019). An important paper addresses the underestimated seismic hazard in Reykjanes (Einasson et al., 2019).

2.1.1. Reykjanes geothermal reservoir

Reykjanes as such is defined as being the geothermal reservoir at the tip of the Peninsula.

Imaging of Reykjanes has been performed by many geophysical techniques, including conventional and recent ones. Blank et al. (2019) analyse the seismicity during the deployment of a dense seismic network. Martins et al. (2019) perform 3D imaging of the Reykjanes peninsula high-enthalpy geothermal field with ambient-noise tomography. Toledo et al. (2019) developed an optimization technique and applied it at the Reykjanes network, demonstrating that the network was adequate for imaging properly the Reykjanes reservoir. The resistivity structure is presented by Karlsdottir et al. (2019).

The results obtained are validated by the drilling results of IDDP-2 (Fridleifson et al., 2019), and were actually used to guide the latest steps of the IDDP-2 drilling (Jousset et al., 2016). Nono et al. (2019) analysed samples of the IDDP-2 measuring in the laboratory the electrical conductivity of samples from the deep supercritical geothermal reservoirs. Kummerow et al. (2019) conducted non-reactive and reactive experiments to determine the electrical conductivities of aqueous geothermal solutions up to supercritical conditions.

Exploitation generates mass and energy transfer and produces deformation. Parks et al. (2019) found the source of the exploitation-induced deformation at Reykjanes, while Darnet et al. (2019), focussed on monitoring the geothermal reservoir using the Controlled-Source Electro-Magnetic method.

2.1.2. Krýsuvík geothermal area

The geothermal site Krýsuvik is also a potential target for exploitation. Horsir et al. (2019) discussed the structure of the geothermal reservoir using results from inversion of magnetotelluric (MT) resistivity data. Guðjonsdottir et al. (2019), explores the link between deformation and gas emissions.

2.1.3. Hengill geothermal reservoir

At the eastern termination of the Reykjanes Peninsula lies the complex triple junction volcano, Hengill. It has been a site of geothermal exploitation for decades. The special issue has two papers on Hengill: Steingerwald et al. (2019) analyse the fracture patterns at the surface, while Juncu et al. (2019) interpret induced seismicity and deformation associated to geothermal exploitation.

2.2. Krafla

In the North of Iceland, another transform fault system is present and is introduced by Young et al. (2019). At Krafla, the structural knowledge of one of the most productive geothermal area in Iceland is improved with the results presented in three papers using conventional VSP techniques (Kästner et al., 2019; Millett et al., 2019; Reiser et al., 2019).

The exploitation of a geothermal reservoir sometimes requires stimulation to prompt efficient extraction of fluids, as illustrated in Krafla by Eggertsson et al. (2019). The exploitation of geothermal systems produces induced seismicity (due to the stimulation) and this induced and natural seismic activity can be used to image structures at depth, as is done by Kim et al. (2019).

2.3. Iceland past and present volcanic and geyser activity

As for completeness of the processes with time associated to geothermal activity in Iceland, two papers address seismic activity at active volcanoes (Greenfield et al., 2019) and at natural unexploited hydrothermal systems, Geysir (Walter et al., 2019).

Finally, in order to understand the structure of present geothermal systems and possibly the reservoirs associated with active volcanoes, it is also useful to study old inactive systems that allows discovery of features inaccessible in active reservoirs (Liotta et al., 2019).

3. Concluding remarks

This special issue does not solve all questions regarding the Reykjanes geothermal system or other related sites. Many more studies involving the integration of different methods at several different sites are required to address those issues more fully.

However, it provides an interesting update on the state of the art in the research on the interaction between volcanoes, hydrothermal systems and earthquakes at different spatial and temporal time scales, with a focus on Iceland and Reykjanes. It demonstrates that the combination of knowledge from volcanoes and exploited geothermal systems is beneficial for a better understanding for both volcanic hazard and exploited geothermal reservoirs. This applies in particular to the case where super-critical fluids are encountered. Those places at depth are close to magma chambers in the crust: this region may hold great potential for harnessing of thermal energy from the Earth’s crust. Specifically, an approach combining conventional and new methods surface geological, structural, geochemical and geophysical monitoring and deep drilling in those regions where supercritical fluids are sought (for both harnessing more geothermal energy and searching for volcanic hazard mechanisms) is certainly of great benefit for ensuring sustainable energy and resilient future for human societies.

Additional note

At the time of the printing of the Special Issue (02.2020), unrest involving uplift and elevated seismicity has been ongoing for some weeks. As a result, the Icelandic Civil Protection Department of the National Commissioner of the Icelandic Police declared a state of uncertainty on January 26. The areas involved in the unrest include the geothermal systems of Svartsengi and Reykjanes. This special issue contains several papers that should serve as a useful reference for understanding the underlying processes.
Declaration of competing interest

We have no conflict of interest.

Acknowledgements

We would like to thank all the authors for their contribution to the special issue and patience in the review process. This work was supported by the 7th Framework Programm of the European Union under the grant agreement No. 608553 (Integrated Method for Advanced Geothermal Exploration, IMAGE project). Part of the work was also supported by the H2020 programme of the European Union under the grant agreement No. 690771 to DEEPEGS (Deployment of Deep Enhanced Geothermal Systems for Sustainable Energy Business).

References

Blanck, et al., 2019. Analysis of Seismological Data on Reykjanes Peninsula. Analyse the seismicity during the deployment of a dense seismic network, SW-Iceland.

Philippe Jousset*
GFZ, German Research Center for Geosciences, Potsdam, Germany
Anette K. Mortensen
Landsvirkjun, National Power Company of Iceland, Reykjavik, Iceland
Gudmundur Ómar Fridleifsson
HS Orka hf, Svartsengi, Grindavik, Iceland
Kristjan Agústsson
Island GeoSurvey, Reykjavik, Iceland
Magnús T. Gudmundsson
Nordvulk, Institute of Earth Sciences, University of Iceland, Reykjavik, Iceland

* Corresponding author.
E-mail address: philippe.jousset@gfz-potsdam.de
(P. Jousset)

Available online 7 November 2019
Materials investigation of the high temperature IDDP-1 wellhead

I.O. Thorbjornsson a,*, G.S. Kaldal a, B.C. Krogh b, B. Palsson c, S.H. Markusson c, P. Sigurdsson d, A. Einarsson e, B.S. Gunnarsson a, S.S. Jonsson a

a ÍSOR - Iceland GeoSurvey, Grensasvegur 9, 108 Reykjavik, Iceland
b Equinor ASA, Arkitekt Ebbels veg 10, 7005 Trondheim, Norway
c Landsvirkjun, Hlandisinsmat 68, 103 Reykjavik, Iceland
d Orkuveita Reykjavikur, Bæjarhalsi 1, 110 Reykjavik, Iceland
e Consultant, Hordukor 1, 203 Kopavogi, Iceland

ARTICLE INFO
Keywords: Geothermal energy Medium carbon steel HTHA-high temperature hydrogen attack Methane cracking SCC cracking Geothermal superheated steam Hydrogen sulfide Hydrogen embrittlement Well IDDP-1 Krafla Iceland

ABSTRACT
The Iceland Deep Drilling Project (IDDP) well IDDP-1 in the Krafla geothermal field in Iceland is the most powerful geothermal well on record, with a maximum wellhead temperature of 452 °C and 140 bar pressures. In the end, the well had to be abandoned and closed permanently due to several casing failures, including a number of collapses and tensile coupling failures of the innermost casing – the production casing. The history of this first IDDP well is discussed in this paper, revealing the conditions the carbon steel was exposed to. The metal samples degrading mechanism was investigated by mechanical testing and microstructure analysis. For the first time, material used in geothermal steam in situ above 400 °C for a long period was investigated and a new alarming cracking mechanism detected. This cracking mechanism due to formation of methane inside the carbon steel structure results in severe cracks and as a result the steel loses its strength and ductility. This study reveals the need for review of material selection for high-temperature geothermal wells.

1. Introduction

Well IDDP-1 was constructed for exploration of superhot/supercritical geothermal utilisation and after drilling and completion it was flow tested periodically from March 2010 until July 2012. Several studies were conducted to test materials for the conditions found at the wellhead (Karlsdóttir et al., 2015; Thorbjörnsson and Karlsdóttir, 2015). In the end, the well had to be closed permanently due to several casing failures, including multiple collapses and tensile coupling failures. After the well was permanently plugged, the National Power Company (Landsvirkjun) retrieved the top 8 m of the multi-layered well. Samples from the metallic casings were subjected to research within the EU funded projects DEEPEGS (www.deepegs.eu) and GeoWell (www.geoowell-h2020.eu) and were analysed at ÍSOR - Iceland GeoSurvey and by Equinor (formerly known as Statoil). The well was constructed with carbon steels according to API grade K55 and T95 traditionally used for the geothermal wells. The history of this first IDDP well is discussed, revealing the conditions the material was exposed to, and the degrading mechanism analysed and discussed. A new alarming cracking mechanism, High Temperature Hydrogen Attack (HTHA), was detected at these high-temperature geothermal conditions. The formation of methane inside the carbon steel structure results in severe cracks and as a result the steel loses its strength and ductility. This study reveals the need for a review of material selection for high-temperature geothermal wells.

2. IDDP-1

2.1. Drilling and flow testing

The drilling of the well began in June 2008 with Iceland Drilling Ltd. drill rig Saga (A Drillmec G55 truck mounted rig). The drilling continued for two intermediate casings in November 2008 with the drill rig Jötunn (Gardner Denver 700 E). Týr (Drillmec HH-300) continued drilling for the two last casings and the production section in March 2009 and finished late July the same year. The last drilling phase was delayed due to unexpected difficulties. Instead of reaching 4000–5000 m depth as planned, the drilling came to an end at 2096 m depth, after three side-tracking attempts and the discovery of fresh glass in drill cuttings suggesting drilling into magma (Thórhallsson et al., 2010) (Pálsson et al., 2014). The well was completed by inserting a perforated liner. Table 1 lists the casing programme of the well.
(Fig. 3). The casing section retrieved was shipped to a machine shop consisted of all retrieved in early 2016 along with some parts of the wellhead. The 8 m cement plug.

2.2. Wellhead retrieval and sampling

Three tensile ruptures were found where threads had been shaved off the casing in couplings at depths of 300 m, 356 m and 505 m (Kaldal et al., 2016). The collapsed casing was later milled out in an attempt to enable further inspection of the well. It became clear that the production casing was severely damaged in multiple places and at the uppermost collapse severe erosion damage cases were observed. A decision was made to abandon the well by blocking it with gravel and a cement plug.

2.2. Wellhead retrieval and sampling

Approximately 8 m of the uppermost part of IDDP-1 well were retrieved in early 2016 along with some parts of the wellhead. The 8 m consisted of all five casings and cement layers in between the casings (Fig. 3). The casing section retrieved was shipped to a machine shop where the outer casings where cut off. In total eight samples were analysed, each marked with a letter and a number according to the location. Five out of eight locations were selected for further investigation (Fig. 2). The samples were as follows:

- 5T and 5A from the production casing close to where the wellhead was cut off at the top.
- 4A from the anchor casing close to the cut.
- C1 from one of the sealing rings just above the cut.
- SB from the production casing approximately 6 m below the cut.

2.2. Wellhead retrieval and sampling

An overview of phases (I–V) for Well IDDP-1 is shown in Table 2 and Fig. 1. The well was allowed to warm-up and was flow tested in March 2010, half a year after drilling was completed (Ingason et al., 2014), as documented in Table 2. At the end of phase V neither of the two master valves could be operated and were stuck in open positions. The situation was critical leaving no other option than to kill the well by pumping water into it (Ingason et al., 2014).

From the initial flow test, it was known that a collapse in the production casing partly blocked the well at about 620 m depth near a suspected intersection between two cementing operations (Pálsson et al., 2014). After the well had been killed and shut-in, the casing was logged with a video camera to inspect potential casing damage cases. A decision was made to abandon the well by blocking it with gravel and a cement plug.

2.2. Wellhead retrieval and sampling

Approximately 8 m of the uppermost part of IDDP-1 well were retrieved in early 2016 along with some parts of the wellhead. The 8 m consisted of all five casings and cement layers in between the casings (Fig. 3). The casing section retrieved was shipped to a machine shop where the outer casings where cut off. In total eight samples were analysed, each marked with a letter and a number according to the location. Five out of eight locations were selected for further investigation (Fig. 2). The samples were as follows:

- 5T and 5A from the production casing close to where the wellhead was cut off at the top.
- 4A from the anchor casing close to the cut.
- C1 from one of the sealing rings just above the cut.
- SB from the production casing approximately 6 m below the cut.

2.2. Wellhead retrieval and sampling

Approximately 8 m of the uppermost part of IDDP-1 well were retrieved in early 2016 along with some parts of the wellhead. The 8 m consisted of all five casings and cement layers in between the casings (Fig. 3). The casing section retrieved was shipped to a machine shop where the outer casings where cut off. In total eight samples were analysed, each marked with a letter and a number according to the location. Five out of eight locations were selected for further investigation (Fig. 2). The samples were as follows:

- 5T and 5A from the production casing close to where the wellhead was cut off at the top.
- 4A from the anchor casing close to the cut.
- C1 from one of the sealing rings just above the cut.
- SB from the production casing approximately 6 m below the cut.

Table 1

<table>
<thead>
<tr>
<th>Name</th>
<th>Steel Grade</th>
<th>Weight (lb/ft)</th>
<th>Outer Diameter (m)</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Casing</td>
<td>K55, Welded</td>
<td>32 3/8</td>
<td>57</td>
<td>97</td>
</tr>
<tr>
<td>Intermediate 1</td>
<td>K55, Welded</td>
<td>162 1/2</td>
<td>254</td>
<td></td>
</tr>
<tr>
<td>Intermediate 2</td>
<td>K55, BTC</td>
<td>114 3/4</td>
<td>785</td>
<td></td>
</tr>
<tr>
<td>Anchor Casing</td>
<td>T95, Hydill</td>
<td>88.2</td>
<td>13 3/4</td>
<td>290</td>
</tr>
<tr>
<td></td>
<td>S63</td>
<td>72</td>
<td>13 3/4</td>
<td>1949</td>
</tr>
<tr>
<td></td>
<td>S63</td>
<td>53.5</td>
<td>9 5/8</td>
<td>1935</td>
</tr>
<tr>
<td></td>
<td>S63</td>
<td>47</td>
<td>9 5/8</td>
<td>2072</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Phase</th>
<th>Date</th>
<th>T</th>
<th>P</th>
<th>h</th>
<th>Remarks</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>May 11 – August 24, 2010</td>
<td>230–380</td>
<td>20–60</td>
<td>2700–3200</td>
<td>25–45</td>
<td>SUPERHEATED FROM MAY 18, DEBRIS FROM DOWNHOLE</td>
</tr>
<tr>
<td>IV</td>
<td>August 9 – 11, 2011</td>
<td>320–410</td>
<td>40–100</td>
<td>3000–3160</td>
<td>30–48</td>
<td>DEBRIS BLOCKS SOURCE</td>
</tr>
</tbody>
</table>

Table 3 lists the standardised chemical composition of the casing grades and from the material of the sealing rings. Table 4 shows the chemical analysis of the superheated steam from IDDP-1 (Ármannsson et al., 2014). The low pH of the condensate can be attributed to the presence of hydrogen chloride (HCl) and hydrogen fluoride (HF) causing severe corrosion of many metals if condensation occurs. Later tests on steam also showed high amounts of gaseous silica and sulphur dissolved in the superheated steam. The exact amount of silica was difficult to determine due to rapid scaling in surface equipment, but the sulphur was estimated as 80–100 mg/kg. Analysis of dry steam from two earlier wells at Krafla are also shown for comparison. In both these wells, acid condensate caused severe corrosion of carbon steel.

3. Results

3.1. XRD diffractometer analysis of corrosion scaling

A sample of corrosion scale was removed from the surface of sample 5A. The sample was a notably corroded piece of the 9½” production casing (Fig. 3). The cut section of the sample reveals in places a significant layer (3-4 mm) of nearly black material with veining of light-brown to reddish matter. The sample was examined in a binocular microscope prior to a sampling of the deposited crust.

A small chip from the rust-layer was crushed, ground in a mortar, and transferred to a zero background (quartz) sample-holder. The sample was analysed using a Bruker AXS D8 Focus XRD diffractometer, set at 40 kV and 40 mA, with 1° slits before and after sample in the optic path and 0.2 mm detector slit. A Ni-filter was placed in the optic path in front of a NaI scintillation counter. Cu kα radiation at 1.54 Å was utilized. In Fig. 6 the diffraction pattern is shown, both raw (green) and with background subtraction (lower pattern, light-blue).

The sample comprises a notably crystalline material with very high iron concentration. Comparison of the pattern obtained with ICDD PDF-2 database reveals that the phase corresponds well to that of (071–6336) magnetite ($Fe_3O_4$). Amorphous or poorly crystalline iron hydroxides are not specifically noted, and neither are silicates nor other crystalline phases, except magnetite.

3.2. Tensile testing

For tensile testing, a 100 kN MTS tensile testing machine with an Interlaken extensometer at the Innovation Center Iceland was used. Tensile specimens were machined from samples collected from the same locations as the samples for microstructural analysis, see Figs. 2 and 4. All tensile specimens were taken in longitudinal direction from the centre of the steel samples. In total three tensile specimens were machined according to ISO/DIS 11960 and EN 10002 part 1 for each location. Two tensile specimens from each location were tested and one was kept as a reserve (Fig. 7).

Standard values for mechanical properties for the material tested are given with reference to standard API 5CT /ISO 11960. Material grades are shown in Table 3.

In Table 5 no values are given for the C1 material. Tensile test curves shown in Fig. 12 reveal brittle material with limited confidence
in measured values as the material was severely affected by the geothermal environment. Stress-Strain curves for the material tested are shown in Fig. 8–12. Note that scales on diagrams are not the same for the materials.

Tensile testing revealed that the yield strength of both production and anchor casing was lower than the minimum requirement according to the values given in the material standard (Table 5). For the production casing, samples from the upper part (5 T and 5A) showed a lower strength than the samples from 6 m depth where the yield strength for one of two specimens was below the minimum value according to the standard. Results for the anchor casing show a slightly lower value than required by the standard for one specimen but over the limit for the other, see Fig. 13.

Tensile ultimate strength values revealed the same pattern as for the yield stress. Values for all specimens from the upper section of the production casing (5 T and 5A) failed to meet the minimum values set by the standard, see Fig. 14, but both values for the lower part (5B) showed tensile strength above the required minimum values. Both specimens for the anchor casing (4A) had a tensile strength above the required minimum values (Table 5). For the anchor casing 4A, both samples revealed ductile fractures with a measured elongation above the minimum requirements.

3.3. Microstructural analysis

Samples were fitted for investigation in Light Optical Microscopy (LOM) and Scanning Electron Microscopy (SEM) equipped with an X-ray energy dispersive spectroscope (XEDS) for chemical analysis.

3.3.1. Sample from the anchor casing – 4A

Specimen 4A was removed from the anchor casing just below the cut at the top (Fig. 4). The grade used for the anchor casing was T95, a Cr-Mo low-alloyed steel with a relatively low carbon content, whereas the K55 used for the production casing contains no Cr or Mo but has higher carbon content (Table 3). Before the microscopy examination, the specimens were visually inspected. On both sides, inner and outer, there are visible marks of corrosion (Fig. 15). On the inner side, there are white/grey scales of cement. The thickness of the specimen was approximately the same as the original thickness of 16 mm.

After grinding and polishing, the specimen was examined in a LOM. Both the inner and outer surfaces were examined. On both surfaces there were some signs of corrosion, both uniform and slightly pitting corrosion. The corrosion is most likely due to conditions after retrieval from the wellhead (Figs. 16–18).

The microstructure of 4A did not show any cracks. A corrosion iron oxide film was examined on both sides in a SEM, as well as some minor corrosion pits.

Fig. 1. Operation history, maximum temperature and pressure of each discharge phase of IDDP-1.
Table 3
Chemical composition of casing grades K55 and T95 and material AISI 4130 acc. to standards API 5CT / ISO 11,960 and AISI 4130 / ASTM A29. Iron (Fe) is the balancing element. Measured values by Optical Emission Spectroscopy shown for comparison with exception of C1.

<table>
<thead>
<tr>
<th>IDDP-1 Well head</th>
<th>API 5CT and ASTM A29 Grade</th>
<th>C [%w]</th>
<th>Mn [%w]</th>
<th>Si [%w]</th>
<th>Cr [%w]</th>
<th>Ni [%w]</th>
<th>Cu [%w]</th>
<th>P [%w]</th>
<th>S [%w]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 T, SA &amp; SB</td>
<td>K 55</td>
<td>Spec.</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&lt; 0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OES</td>
<td>0.35</td>
<td>1.37</td>
<td>0.06</td>
<td>0.01</td>
<td>0</td>
<td>0.12</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.04</td>
<td>0.4</td>
<td>0.25−0.85</td>
<td>0.4−1.5</td>
<td>&lt; 0.99</td>
<td>&lt; 0.62</td>
<td>0.003</td>
</tr>
<tr>
<td>4A</td>
<td>T 95</td>
<td>Spec.</td>
<td>&lt; 0.35</td>
<td>&lt; 1.2</td>
<td>0.25</td>
<td>0.8</td>
<td>0.01</td>
<td>0.09</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OES</td>
<td>0.35</td>
<td>1.37</td>
<td>0.06</td>
<td>0.01</td>
<td>0</td>
<td>0.12</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.04</td>
<td>0.4</td>
<td>0.25−0.85</td>
<td>0.4−1.5</td>
<td>&lt; 0.99</td>
<td>&lt; 0.62</td>
<td>0.003</td>
</tr>
<tr>
<td>C1</td>
<td>AISI 4130</td>
<td>Spec.</td>
<td>0.28−0.33</td>
<td>0.40−0.60</td>
<td>0.15−0.25</td>
<td>0.8−1.10</td>
<td>-</td>
<td>&lt; 0.035</td>
<td>&lt; 0.040</td>
</tr>
</tbody>
</table>

Table 4
Results of analysis of a superheated steam sample from well IDDP-1 with selected data from wells K-12 and K-36 (Ármannsson et al., 2014).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IDDP-1</th>
<th>KG-12 1979</th>
<th>KJ-36 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>T [°C]</td>
<td>440</td>
<td>176.5</td>
<td>175</td>
</tr>
<tr>
<td>P [bars]</td>
<td>158</td>
<td>7.9</td>
<td>9.0</td>
</tr>
<tr>
<td>Conductivity [μS/cm°C]</td>
<td>977/25</td>
<td>290/25</td>
<td>–</td>
</tr>
<tr>
<td>B [mg/kg]</td>
<td>2.2</td>
<td>0.46</td>
<td>–</td>
</tr>
<tr>
<td>SiO₂ [mg/kg]</td>
<td>6.2</td>
<td>28</td>
<td>–</td>
</tr>
<tr>
<td>TiO₂ [mg/kg]</td>
<td>70</td>
<td>81.2</td>
<td>–</td>
</tr>
<tr>
<td>Fe₂O₅ [wt%SMOW]</td>
<td>–5.1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>δI₀ [wt%SMOW]</td>
<td>–9.77</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Na [mg/kg]</td>
<td>0.08</td>
<td>0.17</td>
<td>–</td>
</tr>
<tr>
<td>Mg [mg/kg]</td>
<td>0.004</td>
<td>0.04</td>
<td>–</td>
</tr>
<tr>
<td>Ca [mg/kg]</td>
<td>&lt; 0.1</td>
<td>0.43</td>
<td>–</td>
</tr>
<tr>
<td>F [mg/kg]</td>
<td>8.45</td>
<td>0.24</td>
<td>8</td>
</tr>
<tr>
<td>Cl [mg/kg]</td>
<td>89.6</td>
<td>112</td>
<td>400</td>
</tr>
<tr>
<td>SO₄ [mg/kg]</td>
<td>5.78</td>
<td>–</td>
<td>6.5</td>
</tr>
<tr>
<td>Cr [mg/kg]</td>
<td>4.9</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Fe [mg/kg]</td>
<td>21.5</td>
<td>26</td>
<td>–</td>
</tr>
<tr>
<td>Li [mg/kg]</td>
<td>0.612</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mn [mg/kg]</td>
<td>0.531</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Ni [mg/kg]</td>
<td>3.18</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ [mg/kg]</td>
<td>560</td>
<td>17.08</td>
<td>6463</td>
</tr>
<tr>
<td>H₂O [mg/kg]</td>
<td>250</td>
<td>11.27</td>
<td>3120</td>
</tr>
<tr>
<td>H₂ [mg/kg]</td>
<td>8.77</td>
<td>44.4</td>
<td>32.8</td>
</tr>
<tr>
<td>N₂ [mg/kg]</td>
<td>16.3</td>
<td>0</td>
<td>175</td>
</tr>
<tr>
<td>CH₄ [mg/kg]</td>
<td>0.27</td>
<td>6.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Ar [mg/kg]</td>
<td>0.53</td>
<td>–</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Fig. 3. Photographs of casings and cement layers in between. Left: Cross-section five casings with cement in between. Right: The top 6 m of IDDP-1.

3.3.3. Production casing – sample 5 t
Sample 5 t, shown in Fig. 19, was collected from the production casing just above the cut at the top, see Fig. 4. Before microscopy examination, the specimen was visually inspected. On both sides there were visible marks of severe corrosion and thinning in some areas. Flaws in the microstructure were seen with the naked eye. According to the supplier (Tenaris), the wall thickness was 14 mm after production, but it proved as thin as 6 mm at location 5 T. A large crack was visible on the thinnest part of the specimen, seen between white lines in Fig. 19.

3.3.3.1. 5T – Inner side. The inner side of 5 T showed a corrosion scale with large corrosion pits, reaching a thickness of 0.5 mm. Corrosion pits were also visible on the inner surface. The inner surface was severely damaged with cracks. The cracking is categorized as hydrogen stress cracking (HSC) due to the abundance of hydrogen and severe corrosion during the discharge phases of IDDP-1. The HSCs were observed dense and both in longitudinal and transverse directions see Figs. 20 and 21.

3.3.3.2. Samples from the Production Casing – 5 T, SA and SB
The grade of the production casing was K55, a low carbon steel. According to API 5CT/ISO 11960 standard, K55 is specified with only two elements having maximum values; 0.03 %wt, phosphorus and 0.03%wt sulphur. The composition of the production casing samples was determined as: 0.35%wt carbon, 1.37%wt manganese, 0.3%wt silicon and smaller concentrations of copper, molybdenum and chromium (Table 3).
well operation is more difficult to explain. Wetting of the surface seems unlikely at this temperature. The process is therefore most likely some form of adsorption of water and/or hydrogen sulphide molecules on the steel surface with subsequent splitting of either or both resulting in hydrogen atom formation. Possibly the sulphur, which comes out with the steam, as a gas is a part of this process. The hydrogen diffusion into the steel then assists the already formed HSC cracks near the surface but further inside the metal pure methane cracking sets in. If this is the case, the methane cracking process could be present downhole to some extent. Fig. 21 and Fig. 22 show micrographs of revealing cracks and corrosion close to surface of sample 5 T. Table 6 show the chemical
Table 5
Mechanical properties of casing material with comparison to standard values acc. to API 5CT/ISO 11960. Samples 5 T, 5A and 5B were taken from the production casing (grade K55), while sample 4A is from the anchor casing (grade T95). – indicates no measurements.

<table>
<thead>
<tr>
<th></th>
<th>5T</th>
<th>5A</th>
<th>5B</th>
<th>K55</th>
<th>4A</th>
<th>T95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>309</td>
<td>303</td>
<td>358</td>
<td>333</td>
<td>372</td>
<td>424</td>
</tr>
<tr>
<td>Min</td>
<td>379</td>
<td>424</td>
<td>457</td>
<td>457</td>
<td>674</td>
<td>675</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>115</td>
<td>266</td>
<td>255</td>
<td>239</td>
</tr>
</tbody>
</table>

Yield strength [MPa] 309 303 358 333 372 424 379 662 649 655
Tensile strength [MPa] 422 409 550 457 674 675 552 794 781 758
Elongation A5 [%] 195 153 – 115 246 298 19 255 239 18

Fig. 8. Stress-Strain diagram for material and samples after testing from anchor casing – 4A. Ductile fracture for both specimens.

Fig. 9. Stress-Strain diagram for material and samples after testing from production casing – 5 T. Brittle fracture for both samples with lower ductility in sample 5 T-2.

Fig. 10. Stress-Strain diagram for material and samples after testing from production casing – 5 A. Note the brittle fracture at 5-A2 but some ductility in 5-A-1.
3.3.3.2. 5T – Outer side. The outer side of 5T had a thinner corrosion scale than the inner side but showed similar signs of corrosion, e.g. pitting corrosion (Fig. 23). In both SEM and LOM analysis, effects of hydrogen attacks were examined. Less hydrogen embrittlement was visible on the outer surface than the inner one. A similar extent of methane cracking or HTHA was found as on the inner side. The larger cracks were visible throughout the specimen, only being absent the first 3 mm from the inner surface.

3.3.4. Production casing – sample 5A

Specimen 5A, shown in Fig. 24, is from the production casing just below the cut at the top (Fig. 4). Before microscopy examination, the specimen was visually inspected. On both sides there were visible marks of severe corrosion and thinning in some areas. Flaws in the microstructure could be seen with the naked eye. According to the supplier Tenaris, the wall thickness was 14 mm after production, but it was found to be as thin as 5 mm at location 5A.

3.3.4.1. 5A – Inner side. Both the inner and outer sides of 5A were inspected. The inner side of 5A showed a corrosion scale with a variable thickness, reaching a measured thickness of 4.5 mm. Corrosion pits where also visible on the inner surface. Close to the inner surface, there was an abundance of cracks due to hydrogen embrittlement see Figs. 25, 26 and 27. The cracking can be categorized as SSC most probably forming during cooling of the well. The SSC-cracks were observed as dense and both in longitudinal and transverse directions, same as for 5T.

The crack pattern changed approximately 1.5 mm from the inner
There the cracks became less dense, larger and in a transverse direction. These larger cracks are caused by degradation due to HTHA and could be seen throughout most of the whole specimen thickness.

3.3.4.2. 5A – Outer side. The outer side had a thinner corrosion scale than the inner side but showed similar signs of corrosion and cracking (Fig. 28). The large cracks due to HTHA were prevalent throughout the thickness of 5A, some of them within 1 mm from the outer surface. As

---

**Fig. 15.** Specimens from location 4A, anchor casing just below the cut at the top. Left: Inner side, visible corrosion and remains of cement (white/grey). Right: Outer side, visible uniform corrosion.

**Fig. 16.** Inner surface of 4A examined in a LOM. Left: Visible small corrosion pits on surface. Right: Enlarged view of a small corrosion pit in polarized light.

**Fig. 17.** Inner surface of 4A examined in a SEM. Left: Corrosion pits at surface. Right: Enlarged view.

**Fig. 18.** Inner surface of 4A examined in a SEM. Left: Corrosion pits at the surface. Right: Enlarged view.
with 5 T, it can be assumed that the material from location 5A had lost most or all structural properties.

3.3.5. Production casing – sample 5B

Specimen 5B is from the production casing approximately 6 m below the cut at the top. The specimen was visually inspected before a microscopy examination. On the inner side, visible marks of minor corrosion are seen, and on the outer side, there were remains of the cement (Fig. 29). The thickness of the specimen was approximately 14 mm, the same as the original thickness.

3.3.5.1. 5B – Inner side. The inner side of 5B showed a thin corrosion scale with a few corrosion pits. Cracks most likely from SSC were visible within 4 mm from the inner side. Some larger cracks were seen but fewer than in the two other specimens from the production casing, 5 T and 5A. The larger cracks, created most likely by the formation of methane, were not prevalent throughout the specimen (Fig. 30). Some larger cracks were observed approximately 4 mm from the inner side but none further than that.

3.3.5.2. 5B – Outer side. The outer side of 5B showed some signs of general corrosion (Fig. 31) most likely coming from outside water either excess water from cementing or leak from the top. The thickness of the scale varied from 0.1 to 0.3 mm. The microstructure of 5B had few cracks or other signs of HE.

3.4. Sealing ring – C1

Specimen C1 is from the lowest sealing ring around the expansion spool above the cut, see Fig. 4. Before a microscopy examination, the specimen was visually inspected. There were visible marks of corrosion and a corrosion layer on both inner and outer sides. The black corrosion layer on the inner side was evenly distributed and of a uniform thickness but the layer on the outer side was discontinuous, uneven, of

---

**Table 6**

Chemical analyses by XEDS, locations, see Fig. 22. Values for Carbon and Oxygen are only shown as indicative values with higher uncertainty due to the EDS method.

<table>
<thead>
<tr>
<th>Location</th>
<th>O %wh</th>
<th>Si %wh</th>
<th>C %wh</th>
<th>S %wh</th>
<th>Mn %wh</th>
<th>Cr %wh</th>
<th>Fe %wh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26.30</td>
<td>0.45</td>
<td></td>
<td>73.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>33.19</td>
<td>1.18</td>
<td>6.98</td>
<td>0.57</td>
<td>0.55</td>
<td>0.50</td>
<td>57.02</td>
</tr>
<tr>
<td>3</td>
<td>28.31</td>
<td>7.35</td>
<td></td>
<td>5.54</td>
<td></td>
<td></td>
<td>58.79</td>
</tr>
<tr>
<td>4</td>
<td>26.85</td>
<td>0.60</td>
<td>2.76</td>
<td></td>
<td></td>
<td></td>
<td>69.79</td>
</tr>
<tr>
<td>5</td>
<td>27.98</td>
<td>4.91</td>
<td>3.15</td>
<td>0.77</td>
<td></td>
<td></td>
<td>63.19</td>
</tr>
<tr>
<td>6</td>
<td>26.75</td>
<td>1.88</td>
<td>1.21</td>
<td></td>
<td></td>
<td></td>
<td>70.17</td>
</tr>
<tr>
<td>7</td>
<td>0.44</td>
<td>1.44</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>98.10</td>
</tr>
</tbody>
</table>
variable colours and some of it had clearly broken off (Fig. 32). The sealing rings which were used in IDDP-1, did not work as intended and this particular area possibly leaked as a result of multiple discharge phases.

3.4.1. Inner side
The inner side of C1 has a corrosion scale with a few corrosion pits. A rather uniform corrosion scale was seen on the inner side, the thickness of it ranging from 0.5 to 1 mm (Fig. 33). Minor corrosion pits were found in the bulk material, under the iron oxide corrosion scale. In both LOM and SEM inspections, minor or no marks of degradation due to cracking were found.

3.4.2. Outer side
A corrosion scale is observed on the outer surface. The colour of it was mostly black with some rusty red and grey. After LOM and SEM
Fig. 26. Inner surface of 5A examined in SEM. Top left: Figure showing the corrosion scale, pitting corrosion, SSC and HTHA. Top right: Enlarged view revealing Hydrogen Embrittlement. Bottom left: Corrosion film and pitting corrosion. Bottom right: Cracks due to the formation of methane.

Fig. 27. Inner surface of 5A examined in SEM. Left: Assembled figure of the inner side showing the corrosion scale with a thickness of approximately 4 mm. Top right: Corrosion pit examined on the inner surface. Bottom right: Large cracks due to the formation of methane.
inspections, it was obvious that the scale had been broken in some areas
and was not as uniform as on the inner side. In the bulk material, there
is a discontinuous corrosion layer, where large corrosion pits with
creacks progress in both longitudinal and transverse directions are pre-
sent. The degradation observed in both Figs. 34 and 35 is due to pitting
corrosion but also cracking from hydrogen effects. These cracks were
observed as far as 1 mm from the outer surface.

4. Summary and conclusions

Material from the wellhead retrieved from IDDP-1 that has been
exposed to geothermal steam at temperatures as high as 452 °C and 144
bar pressure has been investigated by mechanical testing and micro-
structural analyses. This unique opportunity to look at the damaging
effect of the chemical composition of the steam and cyclic temperature
changes for shorter and longer periods, has revealed severe problems in
using conventional carbon steel as casing material in such conditions.
Fig. 31. Outer surface of 5B examined by SEM. Left: Bulk material with minor degradation. Right: No visible signs of cracking. A scale at the outer surface, mixture of Portland cement and a corrosion scale.

Fig. 32. A specimen from location C1, sealing ring around expansion spool above the cut at the top. Both the inner and outer side have a black corrosion layer. Left: Inner side on top. Right: Outer side on top.

Fig. 33. Inner surface of C1 analysed by SEM. Left: An almost uniform iron oxide corrosion layer. Right: Corrosion layer, small corrosion pits and minor degradation in bulk material.

Fig. 34. Outer surface of C1 analysed by SEM. Left: A broken corrosion layer on top with large corrosion pits in the bulk material. Right: Enlarged view of the pitting corrosion. Cracks progressing both in longitudinal and transverse directions.
For the low alloyed steel (T95) used for the anchor casing a much lower degradation could be found compared to the other grades used. The corrosion observed on the surface could be regarded as minor and no sign of cracking due to hydrogen could be found. Small corrosion pits were detected on the inner surface. Mechanical properties were slightly below minimum values for yield stress but both tensile stress and ductility were higher than the minimum values of the standard.

The top section of the production casing has suffered from severe corrosion with the expected drop in pH when the fluid condensed on the material. Severe deep and pitting corrosion is found on both the inner and outer surfaces. Due to the extremely low pH of the condensate which accelerate the corrosion rate on the surface of the carbon steel, SSC is widespread. Close to the surface SSC is visible but deeper inside the material severe cracking in the longitudinal direction is found. This cracking mechanism, found for the first time in Icelandic geothermal material, is assumed to be produced by a high temperature hydrogen attack (HTHA) where methane CH₄ is formed. Hydrogen from the corrosion process diffuses as atomic hydrogen into the steel and at boundaries between pearlite and ferrite phases in the metal, the hydrogen binds to carbon from cementite Fe₃C and forms methane gas. This results in a high pressure in the grain boundaries resulting in severe intergranular cracking.

The material in the sealing ring is in such a condition that it cannot be a choice for conditions such as those found in IDDP-1.

Investigation of material from the IDDP-1 production and anchor casing reveal severe damage cases due to the conditions found in the well during the flow testing. The results indicate strongly that the carbon steel as casing material is not suitable for such conditions.

Author statement
I.O. Thorbjörnsson: Principal Investigator – Writing – Original draft preparation.
G.S.Kaldal and B.C.Krogh: Analyses, testing and data interpretation.
P.Palsson, S.H.Markusson: Material providers.
P.Sigurdsson, A.Einarsson, B.S.Gunnarsson and S.S.Jonsson: Participation in testing and analysing data.

Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement
The authors want to acknowledge the funding of H2020 programme by the European Commission under the project DEEPEGs with grant agreement No 690771.

Appendix A. Supplementary data
Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.geothermics.2020.101866.

References


Conference proceedings
Successful Drilling for Supercritical Geothermal Resources at Reykjanes in SW Iceland

Guðmundur Ó. Friðleifsson¹, and Wilfred A. Elders²

¹HS Orka, Orkubraut 3, Svartsengi, 240 Grindavík, Iceland and
²Dept. of Earth Sciences, University of California, Riverside, CA 92521, USA

Keywords
Iceland Deep Drilling Project, RN-15/IDDP-2, supercritical, DEEPEGS, Reykjanes

ABSTRACT
The Iceland Deep Drilling Project (IDDP) passed a significant milestone in January 2017 when its IDDP-2 well penetrated a supercritical reservoir at a depth of 4.5 km. After only 6 days of heating, the temperature measured at the bottom of the well was ~426°C, with fluid pressure of 340 bars, with indications of permeability at depth. The IDDP is a project of a consortium of Icelandic energy companies, National Energy Authority of Iceland and Statoil, aimed at greatly increasing the production of usable geothermal energy by drilling deep enough to reach the supercritical zone beneath high-temperature geothermal fields. Modeling indicates that, because of the higher enthalpy of supercritical fluid, and more favorable flow properties, a well producing supercritical water could produce an order of magnitude more usable energy than that produced from conventional high-temperature geothermal wells.

The IDDP-2 well is located in the Reykjanes geothermal field which lies near the southern tip of the Reykjanes Peninsula, the landward extension of the Mid-Atlantic Ridge. At Reykjanes, some 34 production and injection wells supply a 100 MWe power plant, producing from a < 300°C reservoir at 1 to 2.5 km depth. It is unique among Icelandic geothermal systems because its reservoir is recharged by seawater, which has a critical point of the 406°C at 298 bars.

Drilling the IDDP-2 began by using an existing 2.5 km deep production well, RN-15, that was deepened and cased to 3,000 m depth and then angled towards the main upflow zone of the system for a total slant depth of 4,659 m (~4.5 km vertical depth). Total circulation losses were encountered below 3 km depth which could not be cured by lost circulation materials or by multiple cement jobs. Accordingly, drilling continued "blind" to total depth, without return of drill cuttings. We attempted 13 core runs below 3 km depth, only 9 of which recovered some
core. The cores are basalts and dolerites in a sheeted dike swarm with alteration ranging from lower greenschist facies to lower amphibolite facies, suggesting formation temperatures >450°C, but with low water/rock ratios.

A perforated liner was inserted to 4,620 m and the well subsequently logged for temperature, pressure and injectivity. The T-log showed the main permeable zones to be at above 3380 m, with smaller feed zones at 3,820 m, 3,990 m, 4,100, 4,200 m, 4,375 m, and 4,550 m depths. The deeper feed zones accepted ~5% of the injected water. This year we will attempt to enhance the deeper permeability by massive soft stimulation, and then carry out flow tests to determine the thermodynamic and chemical properties of the fluid produced.

1. Introduction

The RN-15/IDDP-2, a 4.5 km deep exploratory/research well, has been successfully drilled in the Reykjanes geothermal field, in SW Iceland, operated by HS Orka. From a scientific perspective, this location is of great interest because the Reykjanes Peninsula is the landward extension of the Mid-Atlantic Ridge. Furthermore, the geothermal reservoir fluid in the Reykjanes system is modified seawater. It is therefore possible at Reykjanes to test a subaerial analogue of a mid-ocean ridge “black smoker”.

HS Orka was motivated to undertake this challenging drilling operation primarily to search for supercritical geothermal resources but also to address several basic questions important for the future development of the geothermal resource (Friðleifsson et al., 2014b). These include: 1) locating the base of the productive reservoir, 2) testing if use of deeper heat sources is practical, 3) studying if injecting fluid beneath the current production zone would increase productivity, and 4) determining what is the ultimate heat source of this saline, ocean floor related, hydrothermal system.

2. The Iceland Deep Drilling Project (IDDP)

The IDDP is a long-term project aimed at greatly increasing the production of usable geothermal energy by drilling deep enough to reach the supercritical conditions believed to exist beneath active high-temperature geothermal fields in Iceland (www.iddp.is, Friðleifsson and Elders, 2005; Friðleifsson, Elders, and Albertsson, 2014a). When the IDDP consortium was formed in year 2000, three geothermal fields in Iceland were chosen as suitable to search for supercritical resources, Krafla in the north-east of Iceland, and Hellisheidi and Reykjanes in the south-west (Figure 1). The first attempt to drill into a super critical reservoir was made in 2009 in the Krafla caldera, but the IDDP-1 well did not reach supercritical fluid pressures because drilling had to be suspended at a too shallow depth (Elders, et al., 2009). This was because 900°C rhyolite magma flowed into the well at only 2,100 m depth. However, the IDDP-1 was completed with a liner set above the rhyolite intrusion. When the well was tested, it produced superheated steam at 452°C at a flow rate and pressure sufficient to generate about 35 MWe. After two years of flow testing, unfortunately repair of the surface installations was necessary, and the well had to be quenched due to failure of the master valves. This caused collapse of the well casing and abandonment of
the well. While the success of drilling IDDP-2 at Reykjanes is this subject of this paper, IDDP-3 is scheduled to be drilled at Hellisheidi within few years, possibly as early as in 2020?

Figure 1. Geologic map of Iceland showing the three geothermal fields selected by the IDDP as suitable to explore for supercritical geothermal fields

3. Supercritical Geothermal Resources

The main motivation of the IDDP is to investigate the power potential and economics of the temperature-pressure regime of supercritical fluids. The critical point for pure water occurs at 374°C and 22.1 MPa, but is higher for solutions containing dissolved salts (Figure 2). For example, the critical point for seawater is at 406°C and 29.8 MPa (Bischoff and Rosenbauer, 1988).

An aqueous hydrothermal fluid at supercritical conditions with a temperature of 400°C and a pressure of 25 MPa has more than five times the power-producing potential of liquid water at temperature of 225°C (Tester (ed), 2006, p.24). Not only do such fluids have higher enthalpy than conventional geothermal reservoir fluids, but they also exhibit extremely high rates of mass transport due to the greatly enhanced ratios of buoyancy forces to viscous forces in the
supercritical state (Dunn and Hardee, 1981; Fournier, 1999; Fournier, 2007; Hashida et al., 2001; Yano and Ishido, 1998).

Figure 2. The boiling point curve and critical point curves for water. The critical point for pure water is indicated by the open circle at 374°C and 22.1 MPa. As shown by the relevant critical point curves for H$_2$O-NaCl and H$_2$O-CO$_2$, dissolved salt increases the temperature and pressure of the critical point whereas dissolved gas reduces the temperature and elevates the pressure of the critical point (Hashida et al., 2001).

Among the potential advantages of the approach of accessing hotter and deeper geothermal resources are: (1) Improvement in the ratio of drilling costs to power output per well. Although deeper wells would be more expensive, this would be offset by high enough outputs per well. (2) Improvement in the power output of existing geothermal fields without increasing their environmental footprints. (3) Improvement in the lifetime of existing geothermal fields by increasing the size of the producible resource by extending it downwards. (4) Accessing a deeper, hotter, environment for injection. (5) Improvement in the economics of geothermal power production. As mentioned above, higher-enthalpy aqueous working fluids in a turbine have a higher heat-to-power efficiency and therefore should potentially yield more favorable economics. Higher temperatures of the working fluid result in higher exergy (i.e., availability of maximum electrical power production potential for a given flow rate). This is the main incentive to develop supercritical geothermal reservoirs. For example, a modeling study by IDDP indicated that, whereas the available power production from typical geothermal wells in Iceland is about 5 MWe, for the same flow rate, a supercritical well could potentially produce about 50 MWe (Friðleifsson, ed.), 2003).
Recent numerical simulations of magma-heated, saline, hydrothermal systems indicate that the first-order control on the dynamics and efficiency of heat and mass transfer is phase separation near the intrusion. Above deep intrusions emplaced at >4 km depth, where fluid pressure is >30 MPa, phase separation occurs by condensation of hypersaline brine from a saline intermediate-density fluid. The fraction of brine remains small, and advective, thus vapor-dominated mass and heat fluxes are therefore maximized for exploitation of supercritical geothermal resources (Scott, Driesner and Weis, 2017). Thus the saline Reykjanes system is an attractive target to test exploitation of supercritical geothermal resources.

4. The Reykjanes Geothermal Field

Figure 3 shows a copy of a geological map of the very tip of the Reykjanes peninsula. Inserted is the location of the wellhead and track (red) of RN-15/IDDP-2, and locations and tracks (black) of production and injection wells (map from ISOR based on Sæmundsson et al., 2016). Most of the wells are within the center of the geothermal field, towards which the RN-15/IDDP-2 well was directed.
The peninsula is just about 4 km across from NW-SE, and mostly covered by Holocene lava flows which are shown in different shades of violet. Most of them were erupted from several kilometers long volcanic fissures, parallel to the NE-SW rift zone (see Figure 1). The youngest of these, light colored lava on the left side in figure 3, is of historic age from 13th century. Along the center of the peninsula, shown in shade of brown, are two SW-NE elongated hyaloclastite ridges of late Pleistocene age. The center of the Reykjanes geothermal field is located at the southwest end of the younger hyaloclastite ridge. RN-15/IDDP-2 was drilled parallel to this ridge on the west side, as shown by the red line on the map in Figure 3.

A simplified cross section is shown schematically in Figure 4, where the main lithological character of the submarine volcanic sequence at Reykjanes, down to a depth of 2-2.5 km is reasonably well known from 34 drill holes. Shallow marine volcanic sequence characterizes the upper part, below the cap of Holocene lavas, whereas deeper water pillow basalts characterize the lower part. Intrusive dike intensity increases downwards into a sheeted dyke complex. While the spreading rate at the Reykjanes is about 1.8 cm/yr, the sinking rate is about 0.6 cm/yr (Fridleifsson and Richter, 2010; Vadon and Sigmundsson, 1997), as estimated from shell remnants in an IDDP drill core from ~2500 m depth in well RN-17B at Reykjanes. Volcanic underplating by dike injections and occasional volcanic eruptions, which occur at roughly at 1000 year intervals, constitute the heat source for the geothermal system at Reykjanes.

Figure 4. A simplified section across the Reykjanes peninsula, perpendicular to the rift zone. The relative location of the IDDP-2 well is indicated. The basic lithology down to ~2.5 km is known from 34 exploration and production wells. The 300°C isotherm shown is based on temperature logs, whereas the deeper isotherms are extrapolated. From seismic studies the brittle/ductile boundary (between 600-700°C for basaltic rocks) is expected at about 6 km depth.
As most the drill holes at Reykjanes are shallower than about 2.5 km, the drilling of IDDP-2 towards 4-5 km depth was anticipated to add considerable information about the deeper zones of the Reykjanes geothermal system. However, as discussed below, almost total loss of circulation fluid from below 3 km depth in the RN-15/IDDP-2 well interfered with this expectation. Fortunately, IDDP had funds for obtaining drill cores from the ICDP (International Continental Drilling Program) for the IDDP science program which supported the model of an ophiolitic sheeted dike system.

5. The well RN15/IDDP-2

A site was selected for the IDDP-2 located on the north side of the Reykjanes drill field (Figure 3) making use of an existing production well RN-15 as a “well of opportunity”. In 2004 RN-15 was drilled vertically to a depth of 2,500 m with a production casing down to 794 m, and was barefoot below (Jónsson et al. 2010). The well is now identified as RN-15/IDDP-2. After taking the well out of production, it was cooled down slowly, deepened with 12 ¼” bit to 3,000 m, and a new production casing was cemented in place. Drilling then continued with 8 ½” rotary bits towards a target depth of 5 km. We planned to attempt to take 8 ½” spot cores for about 10% of the rock depth to be drilled.

The IDDP passed a significant milestone in geothermal research when the well reached a slant depth of 4,659 meters on the 25th of January 2017, after 168 days of drilling. The IDDP-2 achieved its initial targets, (a) to drill deep enough to reach supercritical conditions (4 to 5 km), (b) to measure the fluid temperature and pressure, (c) to search for permeability, and (d) to recover drill cores. The deepest geothermal wells existing at Reykjanes were about 2.5-3 km deep, thus the IDDP-2 has the deepest casing and is the deepest well so far drilled in Iceland. The IDDP-2 was drilled vertically down to 2,750 meters and below that drilled directionally to the southwest to intersect the main upflow zone of the Reykjanes system. The bottom of the well has a vertical depth of about 4,500 meters, and is situated 738 meters southwest of the wellhead. After only 6 days of heating, the temperature measured at the bottom of the well was ~426°C, with fluid pressure of 34 MPa, and good indications of permeability at depth (Figure 5).

When the PT log shown in Figure 5 was measured the fluids in the well were a mixture of injected water and formation fluids. Although we do not yet know the salinity of this mixture, it is hard to argue that it was not at supercritical conditions during that logging operation. It is clear therefore that condition of fluid at the bottom of the well is supercritical, so that the main objectives of the drilling phase of the project had been achieved.

6. Drilling the well

More information in the drilling of this well is presented in an accompanying paper submitted to be presented at this meeting (Stefansson et al., 2017). Drilling in formation below 3,000 m in the production part of the well began 17th September on 38th workday, and was concluded 26th of January 2017 on the 168th workday at 4,659 m. Various challenges arose as the drilling progressed; there were weather delays, problems with hole stability that required frequent
Fridleifsson and Elders

reaming, and the drilling assembly becoming stuck several times. These instances were successfully solved as they happened.

However, the major unsolved problem was a near complete loss of circulation just below the 9 5/8” production casing shoe, that could not be cured with lost circulation materials, or by 12 successive attempts to seal the loss zone with cement. As cementing was not successful, drilling had to continue without any return of drill cuttings to the surface from deeper than 3,200 m. Above that depth drill cutting could intermittently be sampled between 3,000-3,200 m depth (Weisenberger et al., 2017). Consequently, the drill cores were the only deep rock samples recovered from this important hole.

Figure 5. Temperature and pressure log to 4,560 m depth in IDDP-2 after only 6 days of heating. As can be seen from the temperature profile, because of cold water injection, the well is far from thermal equilibrium. When thermal recovery is complete, it is likely that temperatures will exceed the estimated 426°C measured at the bottom of the hole. The PT logging was done with a K-10 logging tool, which was calibrated to only 380°C. (Source ISOR logging group).
At first, we had considerable difficulties recovering drill cores and overall only a total of 27.3 meters of core was retrieved in 13 attempts, or about 63 % recovery of the cored intervals (Table 2). We were using an IDDP designed 8 ½" coring tool (Skinner et al. 2010), which had yielded good core recoveries in RN-17B, an inclined 8 ½" hole from 2,800 m depth, and also from 3 successive core runs in well RN-30 at Reykjanes from similar depth, while below a 9 5/8" liner.

Table 2 gives an overview on the core recovery in 10 core runs with the IDDP 8 ½" coring tool and 3 successive core runs with 6" Baker Hughes tool at the bottom of IDDP-2, beneath the 7" liner. Prior to coring with the 6" tools, an 8 m deep 6" pilot hole had been drilled with tri-cone bit from 4,626-4,634 m, to clean out the bottom fill after casing and to condition the well.

Table 1. Overview of the 13 core runs attempted in well RN-15/IDDP-2 at Reykjanes.

<table>
<thead>
<tr>
<th>Core run</th>
<th>Start</th>
<th>Coring interval</th>
<th>Cored length [m]</th>
<th>Drilling time [h]</th>
<th>ROP [m/h]</th>
<th>Core recovered [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.9.2016</td>
<td>3068,7-3074,1</td>
<td>5,4</td>
<td>7,12</td>
<td>0,8</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>4.10.2016</td>
<td>3177,6-3179,0</td>
<td>1,4</td>
<td>2</td>
<td>0,7</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>30.10.2016</td>
<td>3648,0-3648,9</td>
<td>0,9</td>
<td>5</td>
<td>0,2</td>
<td>0,52</td>
</tr>
<tr>
<td>4</td>
<td>2.11.2016</td>
<td>3648,9-3650,7</td>
<td>1,8</td>
<td>10,25</td>
<td>0,2</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>11.11.2016</td>
<td>3865,5-3869,8</td>
<td>4,3</td>
<td>8,5</td>
<td>0,6</td>
<td>3,85</td>
</tr>
<tr>
<td>6</td>
<td>12.11.2016</td>
<td>3869,8-3870,2</td>
<td>0,4</td>
<td>2,5</td>
<td>0,2</td>
<td>0,15</td>
</tr>
<tr>
<td>7</td>
<td>22.11.2016</td>
<td>4089,5-4090,6</td>
<td>1,1</td>
<td>2,25</td>
<td>0,5</td>
<td>0,13</td>
</tr>
<tr>
<td>8</td>
<td>28.11.2016</td>
<td>4254,6-4255,3</td>
<td>0,7</td>
<td>0,5</td>
<td>0,1</td>
<td>0,28</td>
</tr>
<tr>
<td>9</td>
<td>6.12.2016</td>
<td>4308,7-4309,9</td>
<td>1,2</td>
<td>3</td>
<td>0,4</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>7.12.2016</td>
<td>4309,9-4311,2</td>
<td>1,3</td>
<td>8,25</td>
<td>0,2</td>
<td>0,22</td>
</tr>
<tr>
<td>11</td>
<td>16.1.2017</td>
<td>4634,2-4642,8</td>
<td>8,6</td>
<td>1,25</td>
<td>0,6</td>
<td>7,58</td>
</tr>
<tr>
<td>12</td>
<td>17.1.2017</td>
<td>4642,8-4652,0</td>
<td>9,2</td>
<td>1</td>
<td>9,2</td>
<td>9</td>
</tr>
<tr>
<td>13</td>
<td>19.1.2017</td>
<td>4652,0-4659,0</td>
<td>7</td>
<td>0,75</td>
<td>9,3</td>
<td>5,58</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>43,3</td>
<td></td>
<td></td>
<td>27,31</td>
</tr>
</tbody>
</table>

The cores recovered were valuable as they indicate that the IDDP-2 drilled through a basaltic sheeted dike complex that shows progressive metamorphism from greenschist facies to lower amphibolite facies, consistent with hydrothermal alteration at temperatures up to 450-500°C. A detailed description of the petrology of these cores is presented in an accompanying paper submitted for presentation at this meeting (Zierenberg et.al., 2017). The deepest core, returned from the bottom of the well is reasonably fresh dolerite, with minor intrusions of felsite. Although the bimodal igneous association of basalt and felsite is observed in other geothermal systems in Iceland, this is the first time it has been observed at Reykjanes.
Fridleifsson and Elders

The main indications of hydrothermal alteration in this rock are quartz + biotite + magnetite mineralization on some open space fracture surfaces. A red hematic stain on open space fracture surfaces and on the core surface in some cases, provides a clear evidence that superheated and/or supercritical fluid (depending on fluid pressure) was in the open fractures and pores in the rock formation that was cored. Cooling and mixing of this fluid with the cold drilling water resulted in oxidation of the primary fluid, resulting in hematite staining on open fractures and in places on the outside of the core itself. Oozing of pore fluid post drilling further caused a yellowish precipitate of Fe-K chloride (Zirerenberg et al., 2017).

After that pressure-temperature log run on 3 January 2017, a 7” perforated hanging liner was inserted to the bottom. Subsequently a 7” sacrificial casing was lowered from surface down to 1,300 m, and cemented up to the surface. Casing shoes were then drilled out and the well deepened by 6” bits, ending with 3 successive coring runs to the 4,659 m final depth. After the deepest coring run, a 3 ½” drill string was lowered to the bottom of the hole. The aim is to enhance the permeability deep in the hole by pumping in cold water for several months through the 3 ½” drill string. There are already some positive indications of enhancement of injectivity. Tests made after the last coring runs showed that cold water injection increased the injectivity index from 1.7 (l/s)/bar to 3.1 (l/s)/bar. We expect that continued deep stimulation with cold water is likely to further improve the fracture permeability at depth.

After the stimulation efforts, a surface test bed, with two parallel flow lines, will be constructed for long term flow testing 2018. Only after these fluid handling and flow tests are concluded can we determine the nature of the formation fluids, their enthalpy and flow characteristics, and hence estimate their engineering and economic potential. The total loss of circulation below 3 km depth was unexpected, but the existence of large permeability, a kilometer deeper than the current production zones at Reykjanes, may have implications for the future development of the geothermal resource that are independent of supercritical production. An interesting prediction of temperatures at target depth is presented in Hokstad and Tänavsuu-Milkeviciene, (2017).

7. Significance of the IDDP-2

Iceland is fortunate in having several likely sites for the development of supercritical geothermal resources. Planning for drilling the IDDP-3 well at Hellisheidi is already underway, and, subject to the availability of funding, drilling could begin in 2020. However supercritical conditions are not restricted to Iceland, but should occur deep in any young volcanic-hosted geothermal system. Deep wells drilled in geothermal fields such as Kakkonda in Japan, Larderello in Italy, Los Humeros in Mexico, and The Geysers and Salton Sea in USA, have encountered temperatures above 374°C. Development of supercritical geothermal resources could be possible there and in many other volcanic areas worldwide (Dobson et al., 2017).

More information on the IDDP can be found at www.iddp.is and at www.deepegs.eu.
Fridleifsson and Elders

Acknowledgements

The IDDP-2 was funded by HS Orka, Landsvirkjun, Orkuveita Reykjavíkur, and the National Energy Authority in Iceland, together with Statoil, the Norwegian oil and gas company. The IDDP has also received funding from the EU H2020 (DEEPEGS, grant no. 690771), and science funding from ICDP and NSF. In 2005, funding for IDDP to obtain spot cores at Reykjanes and elsewhere was provided by ICDP and the US NSF (grant no. 05076725), all greatly appreciated. Successful coring attempts exist from wells RN-17B, RN-19, RN-30, and now from RN-15/IDDP-2. The drilling contractor was the Iceland Drilling Company (IDC). We thank the IDC drilling team and managers, and our drilling engineers and managing team, for conducting the entire drilling operation so well, and deciding on where and when it was safe to attempt coring and logging. Similarly we acknowledge our numerous colleagues from ISOR, and numerous members of our IDDP science team, domstic and international, for collaboration and fruitful discussions throughout the years on this challenging IDDP/DEEPEGS project.

References


Friðleifsson and Elders


Fridleifsson and Elders

The Drilling of RN-15/IDDP-2 Research Well at Reykjanes in SW Iceland

Ari Stefánsson, Pór Gíslason, Ómar Sigurðsson, Guðmundur Ó. Friðleifsson
HS Orka, Orkubraut 3, Svartsengi, 240 Grindavík, Iceland

Keywords
IDDP-2, Reykjanes, Iceland, drilling and coring, DEEPEGS

ABSTRACT

In January 2017 after 168 days of drilling, the target was reached for the deepest high-temperature geothermal well in Iceland, IDDP-2. The length of the well is 4,650 m and true vertical depth about 4.5 km. Drilling began by deepening an existing 2.5 km, RN-15 to 3 km, and case it with 9 7/8” – 9 5/8” casing and cementing to surface. To reach the main up-flow zone of the Reykjanes system it was necessary to build from 2,750 m with an azimuth of 210°deg. Below 3 km depth total loss of circulation was experienced to the end of drilling. A 7” perforated liner was run into hole and then a 7” production (sacrificial) casing to 1,300 m and cemented to surface. This was followed by running in with 6” rotary assembly to drill out casing shoes for the sacrificial casing and the liner. Eight meter of 6” pilot hole was then drilled before pulling out for 3 successive 6” coring runs to final depth. The well was left with 3 ½” drill pipe to 4,590 m for long term stimulation and tracer injection.

1. Introduction

The Iceland Deep Drilling Project (IDDP) is a Research and Development project initiated by an Icelandic energy consortium since 2000 (www.iddp.is). It’s main goal is to find and investigate the economics of deep, high-enthalpy geothermal resources at supercritical conditions. The first formal well, IDDP-1, was drilled in Krafla, NE Iceland, in 2009. That well was drilled into magma at 2.104 m depth resulting in termination of the deep drilling itself, but valuable pilot study followed on production from the contact aureole of the magma (Pálsson et al., 2014, Hauksson et al., 2014, and other papers in Geothermics, Special Issue on IDDP, V 49, 2014). Lesson learned and experience from the IDDP-1 well was used in designing the second well, IDDP-2, to be drilled at Reykjanes in 2016 (Ingason et al. 2015). Originally the plan was to drill a new well, but later the drilling plan for IDDP-2 was modified to deepen an existing production well RN-15 at the north side of the Reykjanes geothermal field. Well RN-15 had been drilled vertically in 2004 to 2,507 m depth, with production casing set to 794 m and open hole below that. The final preparation for the drilling of IDDP-2 began early December 2015 and drilling then began in August 2016. In December 2015, the plans for the IDDP-2 had been accepted as a part of the European Union Horizon 2020 program DEEPEGS (Deployment of Deep Enhanced Geothermal Systems for Sustainable Energy Business, www.deepegs.eu), and an agreement had
been reached a month earlier with Statoil, to participate in the IDDP consortium to 2020. The main aim of the IDDP project is to drill a 4-5 km deep drill hole to reach 400-600°C hot supercritical hydrous fluid (Friðleifsson and Elders, 2017). The main purpose is to find out if it is economically feasible to extract energy and chemicals out of such a system.

The preparation for the RN-15/IDDP-2 drilling started at full force in December 2015 by ordering the wellhead valves, casings, casing accessories and other drilling materials. Negotiations with Iceland Drilling as the drilling contractor began January 2016, and a day rate contract was signed shortly later. The drill rig Þór (Thor) 350Hp Bentec rig was to be used for the drilling of the well. Drilling of a shallow water well was also made to ensure sufficient water for the main drilling operation. The well RN-15 was disconnected from the piping to the power plant in June 2016 and the drill pad subsequently prepared to accommodate the large rig, which was mobilized late July 2016 and ready to spud 11\textsuperscript{th} of August 2016. Figure 1 shows the drill rig on site.

2. Well RN-15 and modification to adopt IDDP-2

Well RN-15 was completed as a vertical well in March 2004 to 2,507 m depth. The production casing 13 3/8” was set to 794 m (from ground level) and the well was left as open hole, not supported by a liner. Circulation losses had been relatively small during drilling, until at 2,395 m when a total loss of circulation fluid was observed for a while. At well completion the injectivity index was estimated \(~3.5\) (kg/s)/bar or just below the reference limit of 4 (kg/s)/bar for a production wells at Reykjanes. Consequently the well was stimulated by heating and cooling cycles which improved the injectivity slightly or up to 4.5 (kg/s)/bar. The well was connected to the power plant in 2006. Its output capacity was always considered moderate to low compared to
Stefánsson et al.

the better producers, and before it was closed for deepening it produced around 2-3 MWe (Friðleifsson and Sigurðsson, 2016).

Figure 2. RN-15/IDDP-2 as built diagram. Information on the location of thermocouples from Petrospec, and depth intervals of coring attempts are also shown in the diagram, and discussed in text below.
Stefánsson et al.

An early IDDP-2 well design had been made by Mannvit consulting engineers and introduced at the WGC-2015 (Ingason et al., 2015). Once it was clear that HS Orka was to provide the production well RN-15 for deepening as IDDP-2, an immediate modification on the well design was needed. Shown in Table 1 are the essential design details for each drilling phase, and a design diagram showing the well as built is shown in Figure 2.

Table 1 Drilling, casing and cementing program

<table>
<thead>
<tr>
<th></th>
<th>Conductor</th>
<th>* (Phase 0) Surface Casing</th>
<th>* (Phase 1) Intermediate Casing I</th>
<th>* (Phase 2) Intermediate Casing II</th>
<th>(Phase 3) Anchor Casing</th>
<th>(Phase 4) Production Casing</th>
<th>(Phase 5) Perforated Liner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well dia (inch)</td>
<td>Dug</td>
<td>26”</td>
<td>21”</td>
<td>17 ½”</td>
<td>12 ½”</td>
<td>8 ½”</td>
<td>8 1/2”</td>
</tr>
<tr>
<td>Well depth (MD in meters)</td>
<td>~ 7</td>
<td>87</td>
<td>293</td>
<td>798</td>
<td>~3000</td>
<td>~5000</td>
<td>~5000</td>
</tr>
<tr>
<td>Well depth (TVD in meters)</td>
<td>~ 7</td>
<td>87</td>
<td>293</td>
<td>798</td>
<td>3000</td>
<td>~5000</td>
<td>~5000</td>
</tr>
<tr>
<td>Casing specs</td>
<td>28”</td>
<td>22 1/2”</td>
<td>18 5/8”</td>
<td>13 3/8”</td>
<td>9 7/8” &amp; 9 5/8”</td>
<td>7”</td>
<td>7”</td>
</tr>
<tr>
<td>Weight</td>
<td>117lb/ft</td>
<td>96.5lb/ft</td>
<td>68lb/ft</td>
<td>42.8-47 lb/ft</td>
<td>24 lb/ft</td>
<td>26 lb/ft</td>
<td>26 lb/ft</td>
</tr>
<tr>
<td>Grade</td>
<td>API-LP</td>
<td>X-52</td>
<td>K-55</td>
<td>K-55</td>
<td>T95-L80</td>
<td>TN 80HS</td>
<td>L80</td>
</tr>
<tr>
<td>Threads</td>
<td>Welded</td>
<td>Welded</td>
<td>Welded</td>
<td>BTC</td>
<td>GeoConn</td>
<td>TSH</td>
<td>BTC</td>
</tr>
<tr>
<td>No. of joints</td>
<td>~1</td>
<td>~8</td>
<td>~25</td>
<td>~69</td>
<td>~260</td>
<td>~110</td>
<td>~175</td>
</tr>
<tr>
<td>Cementing method</td>
<td>Cemented by Civil Contractor</td>
<td>Cementing Head</td>
<td>Stab in</td>
<td>Stab in</td>
<td>Reverse</td>
<td>Cementing Head, packer and port</td>
<td></td>
</tr>
<tr>
<td>Drilling fluid</td>
<td>N/A (Dug)</td>
<td>Air and foam</td>
<td>Water based Bentonite</td>
<td>Water based Bentonite</td>
<td>Water with high visc. sweeps</td>
<td>Water with high visc. sweeps</td>
<td>Water with high visc. sweeps</td>
</tr>
<tr>
<td>Max. predicted temp</td>
<td>NA</td>
<td>100°C</td>
<td>150°C</td>
<td>260°C</td>
<td>~300°C</td>
<td>&gt;400°C</td>
<td>&gt;400°C</td>
</tr>
</tbody>
</table>

3. Drilling plan

The plan was to deepen well RN-15 which should be identified onwards as RN-15/IDDP-2, in order to keep the original data base ID number. After slowly cooling the well down, the first drilling operation was to deepen it from 2,500 m depth, with 12 ½” rotary assembly, to about 3,000 m. An anchor casing (9 7/8” and 9 5/8”) should follow and be cemented to surface. Thermocouple cables, from surface to about 2,700 m, a strain gauge (0–26 m) and a fiber optic cable (0–900 m) were to be strapped to the outside of the anchor casing string. An inclination to about 20° max, was to be built up for southwestward drilling (210°) from a KOP at 2,750 m depth. 20° inclination should be reached at about 3,100 m depth (MD). From 3,100 m Azimuth and Inclination should be kept (Hold drilling). The plan was to have the MWD tool in the drill string during the Hold section until its temperature limit was approached. The plan was then to drill to target depth of 4,500 m to 5,000 m with a conventional hold assembly, preferably including high temperature downhole motor. During the drilling from ~ 3,100 m depth to the bottom, around 15-20 spot cores were planned to be drilled at regular intervals. A 7” perforated
liner was then planned to be set from 2,970 m to TD. Thereafter 7” production casing (sacrificial casing) to be RIH from top to about 1,300 m depth, and cemented in. The drilling operation was to be completed by RIH with 3 ½” drill string which should be left at bottom for post drilling soft hydraulic stimulation. Estimated overall timing for the drilling operation was 151 days. The drilling schedule was based on normal drilling operations, excluding rig mobilization and rig demobilization. Unexpected maintenance stops of the rig and other non-productive time where not included in the drilling schedule.

4. Drilling of the RN-15/IDDP-2

After rig up and BOP’s installation the rig was ready to spud August 11th 2016. At beginning of entry a casing bulge was discovered at 140 m, followed by RIH with camera for inspection (Figure 3). It was necessary to RIH with 12 ¼” milling bit and mill out the bulge between 141 m to 158 m, followed by a run to the casing shoe to ensure there were no further obstructions in the casing. This was followed by a wiper trip with a new BHA to 2,500 m.

Known loss zones were between 1,400 m to 2,400 m depth in the production section, and a total loss of circulation was experienced from the beginning of the deepening operation. This was expected and thus the 12 ¼” section was planned to be drilled blind, without any mitigation treatment, or at least until the cleaning of the drill cuttings would involve too severe problems to call for mitigation. At KOP we drilled into opening at around 2,750 m which had to be cemented to solve cleaning problem. Cement was drilled out between 2,753-2,776 m and the well cleaned and drilled to 3,000 m. Wiper trip followed and then POOH to run in the 9 7/8” – 9 5/8” casing string. Cables with 8 thermocouples from Petrospec, were attached to the outside of the casing string as it was run into the hole. The thermocouples were rated to tolerate up to 600°C. They were expected to enable continuous measure of temperatures at 341 m, 641 m, 941 m, 1,541 m, 1,841 m, 2,141 m, 2,341 m and 2,641 m depths (listed in Figure 2). The thermocouple at 2,141 m was damaged during the insert of the casing and due to that, in order to try to prevent damage of other cables along the casing, we stopped running in the casing at 2,941 m. In addition, a pressure/temperature sensor was installed at 1,241 m depth, and a fiber optic cable for temperature, and seismic logging was installed by GFZ Potsdam, to 841 m depth. Data from the thermocouples were used to evaluate the progress of the cementing operation.

To cement the 2,941 m long casing string a reverse cementing method was used. The cement was pumped through two kill-line inlets with the pumping rate 1.5 m³/min and slowed down after 80m³, first to 0.5 m³/min and then to 0.25 m³/min. Two pumping unit where used and a premixed slurry of 40m³. Total amount of cement slurry was ~150m³. The cementing was completed September 6th, followed by two separate cement bond logs which indicated that a proper cementing job had been achieved, in this longest production casing ever in an Icelandic high-temperature field.

September 8th the casing was cut. BOP’s nipple down and the previous casing flange cut off and a 10” ANSI 2500 flange mounted on the 9 7/8” casing. After BOP’s nipple up, followed by a pressure test, the 8 ½” rotary assembly was made up and run in hole. The drill bit hit cement at 2,787 m, followed by cleaning out of a 30 m thick bottom fill to 3,000 m. After cleaning the well the string was pulled out of hole and followed by run in hole with a cement string for cementing big loss below the casing shoe to 3,000 m. A run in hole with 8 ½” motor and MWD followed to

Stefánsson et al.
drill out cement. Hit the cement at 2,927 m or about 40 m above the casing shoe, at 3,003 m the losses began again and total loss experienced at 3,060 m.

Making up a coring string and run in hole for the first core run followed. Once retrieved the core barrel was in worn condition without core in the barrel. A steel thermistor holder for T-logging during coring, was missing so a cement job and side tracking had to follow. Again, losses began soon after we began drilling and total loss at 3,117 m. POOH for cementing the loss zone followed, and this was repeated 12 times or until depth of 3,185 m, after a month’s work in trying to cementing off the loss zone, including 2 failed coring attempts and weather delays. At that time it became clear that the well would not be drilled unless we accepted total loss of circulation from then on to target depth. As we expected cleaning problem at any time we decided to drill slower than preplanned. We had a few stuck pipe situations along the drilling progress, and noticed they occurred right after a polymer pill went through the bit. Then we decided to bleed polymer and Guar gum while drilling (25 l polymer + 25 kg Guar gum)/hour to help cleaning the well. That seemed to improve the situation compared to insert polymer pills at every single. Fortunately, we drilled into an open fracture zone near to 3,350 m that also helped with the cleaning process, and cooling of the well while drilling. The ROP was kept below 5 m/h below 3,500 m to prevent stuck pipe and cleaning problems. We did get several more openings or feed points deeper down, mostly detected by down hole T-log near the end of drilling.

At the beginning, we had difficulties in recovering drill cores and overall only a total of 27.3 meters of core was retrieved in 13 attempts, or about 63 % recovery of the cored intervals. We attempted 10 core runs with an IDDP 8 ½” coring tool, and 3 successive core runs with 6” Baker Hughes tool at the bottom of IDDP-2, beneath the 7” liner. Prior to coring with the 6” tools, an 8 m deep 6” pilot hole was drilled with a tri-cone bit from 4,626-4,634 m, to clean out a bottom fill after casing and to condition the well. Closer description of the coring and its implication for the
lithology and hydrothermal alteration is discussed elsewhere (Friðleifsson and Elders, 2017, Fowler and Zierenberg, 2017), while we list the core runs giving some core recovery in Figure 2 above.

Finally, in Figure 4 a comparison is shown between the drilling progress and the scheduled estimate. By looking at the figure we can see when loss zone problems start, right below 3,000 m resulting in one month’s gap between scheduled and actual progress while we tried to cure the loss zone for better hole cleaning. The coring attempts are only 13 not 18 as planned and that is due to drilling problems and that we had coring problems and poor core recoveries. The planned depth in the figure was 5,000 m but we had to stop earlier as explained below, where the drill pipe came out of hole after stuck pipe for 3 days, seriously damaged as can be seen in Figure 5 below.

Figure 4. Planned drilling and progress of drilling
5. Logging while drilling

During the planning stage of deepening well RN-15 it was anticipated that losses would be small below 3,000 m depth. Known temperature at 2,500 m depth in the well was 285°C and the formation temperature was expected to increase with depth and likely approach the boiling point temperature (BPC) for seawater which would make the extrapolated temperature over 410°C at 5,000 m depth. Thus it was expected that the well would warm-up rather quickly below 3,000 m so use of regular wireline logging tools would not be feasible. For obtaining logs from the deeper part of the well a search for LWT and LWD tools was conducted. However, as loss zones were encountered below 3,000 m during the deepening an attempt was made to obtain logs with the conventional logging tools available at ISOR in Iceland, rated for temperatures up to about 150°C.

A regular logging suit was measured in the well before cementing the production casing. The wireline suit consisted of normal resistivity, neutron and natural gamma to 2,775 m, and XY-caliper to 2,870 m. The tools stopped at sills or washouts in the well and would not go deeper. Also an acoustic televiewer imaging was obtained for selected intervals between 860-2,305 m. When the well was 3,648 m deep an attempt was made to log the well again with the available wireline tools. Normal resistivity, neutron and natural gamma, and sonic log was obtained from casing depth to 3,440 m. Televiewer log was attempted but had poor quality due to bad centralization. As earlier the tools stopped at some sills or washouts in the well that limited the depth coverage of the logs.

At end of drilling when the depth was 4,626 m a special logging run with LWD tools from Weatherford was carried out. Such tools had not been used earlier in Iceland. The logging suit consisted of natural gamma, temperature, pressure (HEL/BAP), and multi frequency resistivity (MFR) from casing to 4,615 m. Micro-resistivity imaging (SMI) to 4,490 m (good quality) and acoustic velocity (SST) to 3,045 m. The acoustic tool and the imaging tool were damaged possibly due to relatively stiff logging string and high rotation hence the logs below the indicated depths are not reliable. With the circulation, the temperature on the tools could be kept below 65°C during the log-run though the tools were logging where the formation temperature was well over 400°C.

Additionally, to the above mentioned logs, several temperature and pressure profiles were measured (exemplified in Figure 5), CBL, gyros, MWD, injectivity and three spinner logs (3,158 m, 3,646 m, 4,420 m). In general the logs give valuable information on the formations physical properties, especially as no drill cuttings were obtained.

6. Lesson learned

There are several things that can be addressed here learned from the drilling of this deepest geothermal well drilled in Iceland. First to mention, we should avoid to directionally drill superdeep wells, as it involve a lot of problems as the depth increases to the end of drilling. This, however, was well known before we began drilling this well, and were discussing and designing IDDP wells (e.g. Thorhallsson et al., 2014; Friðleifsson (ed.), 2003). Necessity to reach the center of the up-flow zone at Reykjanes called for our decision to directionally drill RN-15/IDDP-2. Nevertheless, the biggest problems in our drilling related to keyholes that kept the string stuck for days, not enabling us to pull out of hole freely, and finally it can be blamed that we did not drill deeper. For the third time, we were stuck in a keyhole for almost 3 days, and
once on surface, the drill pipe showed to be dangerously damaged (Figure 6) and could easily have been twisted apart.

Figure 5. Temperature and pressure at end of drilling and after drilling out sacrificial casing and liner shoes. Injection 40-45 l/s and change in gradients indicate loss zones. At bottom indication of supercritical conditions. b) Example from image log showing large fracture at great depth.

Figure 6. Damaged drill pipes after having been stuck in keyhole for 3 days (photos AS)
Next to mention, is the mitigation we used for cleaning the well by bleeding HT polymer and Guargum continuously while drilling. That helped greatly keeping the well clean and the standpipe pressure much lower than when drilling with water alone. Then we can look at the coring problems that we had in the 8 ½” section. Coring with 8 ½” core bit and 7 1/8” core barrels clearly called for problems since the core barrel was far too stiff for smooth run into 8 ½” inclined bore hole. We should probably use 6” core bits on 4 ½ core barrel in 8 ½” inclined well for coring, and then ream out the hole to 8 ½” before continue drilling again. It can also be mention that cooling of the well while drilling was not a problem, as could be seen from the MWD drilling tool below 4,000 m, where temperature never exceeded 50-60°C.

Acknowledgement

Drilling of IDDP-2 is funded by HS Orka, Orkuveita Reykjavíkur, Landsvirkjun, the National Energy Authority in Iceland, Statoil, the EU H2020 (DEEPEGS, grant no. 690771), and science funding from ICDP and NSF. Funding from ICDP and the US NSF (grant no. 05076725) in 2005 for IDDP for spot cores at Reykjanes and elsewhere is all greatly appreciated. The drilling contractor was the Iceland Drilling Company (IDC) and we thank there drilling team and the managers for good jobs done and good cooperation throughout the drilling operation. Similarly, we acknowledge the ISOR team, the members of the IDDP science team, domestic and international, for teamwork and discussions throughout the years on this challenging IDDP/DEEPEGS project.

References


Next to mention, is the mitigation we used for cleaning the well by bleeding HT polymer and Guargum continuously while drilling. That helped greatly keeping the well clean and the standpipe pressure much lower than when drilling with water alone. Then we can look at the coring problems that we had in the 8 ½” section. Coring with 8 ½” core bit and 7 1/8” core barrels clearly called for problems since the core barrel was far too stiff for smooth run into 8 ½” inclined bore hole. We should probably use 6” core bits on 4 ½ core barrel in 8 ½” inclined well for coring, and then ream out the hole to 8 ½” before continue drilling again. It can also be mention that cooling of the well while drilling was not a problem, as could be seen from the MWD drilling tool below 4,000 m, where temperature never exceeded 50-60°C.

Acknowledgement
Drilling of IDDP-2 is funded by HS Orka, Orkuveita Reykjavíkur, Landsvirkjun, the National Energy Authority in Iceland, Statoil, the EU H2020 (DEEPEGS, grant no. 690771), and science funding from ICDP and NSF. Funding from ICDP and the US NSF (grant no. 05076725) in 2005 for IDDP for spot cores at Reykjanes and elsewhere is all greatly appreciated. The drilling contractor was the Iceland Drilling Company (IDC) and we thank there drilling team and the managers for good jobs done and good cooperation throughout the drilling operation. Similarly, we acknowledge the ISOR team, the members of the IDDP science team, domestic and international, for teamwork and discussions throughout the years on this challenging IDDP/DEEPEGS project.

References
www.deepegs.eu
www.iddp.is
Temperature Prediction by Multigeophysical Inversion: Application to the IDDP-2 Well at Reykjanes, Iceland

Ketil Hokstad and Kati Tänavsuu-Milkevičiene

Statoil Research Centre, Trondheim, Norway

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 °C 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.
Hokstad and Tänavsuu-Milkeviciene

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

![Bayesian network](image)

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.
Hokstad and Tännavsuu-Milkeviciene

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

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

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

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

where $F_i(T; \varphi)$ is the rock-physics relation for the dependence of model parameter $m_i$ on temperature, and $\Sigma_{el}$ 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 $m_1$ only if the forward model $F_i(T; \phi)$ 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 $F_1(T; \phi) = \sigma(T; \phi)$ and $F_2(T; \phi) = \rho(T; \phi)$.

Figure 2: Rock physics model for the temperature dependence of electric conductivity $\sigma_B(T)$ of dry basaltic rock. The data suggests that the conductivity can be modeled as a sum of two Boltzmann distributions. Data from Mostafa et al. (2003). The temperature is in Kelvin (K).

Electric conductivity (or resistivity) is the geophysical parameter that has the most direct response to temperature variations. The rock physics model for conductivity $\sigma(T; \phi)$ 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),

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

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.,...
Hokstad and Tänavsuu-Milkeviciene

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
Hokstad and Tänavsuu-Milkevičiene (2014). 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 $513 \pm 62$ °C at 5 km vertical depth. Reykjanes is in an active sea-floor spreading
zone, and earth quakes of magnitude 2 and less occur regularly. The earth quakes 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 earth quakes (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 multigophysical 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 earth quakes 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).
Hokstad and Tänavsuu-Milkeviciene

Figure 8: While-drilling update of temperature prediction with well description based on drilling parameters (left) and suggested geological model for the Reykjanes area (right).

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 Nielsson and Tobias Weisenberger (ISOR), and Robert Zierenberg (UC Davis).

We thank Ragna Karlsdóttir (ISOR) 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.deepegs.eu).

REFERENCES


Hokstad and Tännavu-Milkeviciene


A 300 Degree Celsius Directional Drilling System

Ari Stefánsson (HS Orka) | Ralf Duerholt (Baker Hughes, a GE company) | Jon Schroder (Baker Hughes, a GE company) | John Macpherson (Baker Hughes, a GE company) | Carsten Hohl (Baker Hughes, a GE company) | Thomas Kruspe (Baker Hughes, a GE company) | Tor-Jan Eriksen (Baker Hughes, a GE company)

DOI https://doi.org/10.2118/189677-MS
Document ID SPE-189677-MS
Publisher Society of Petroleum Engineers
Source: IADC/SPE Drilling Conference and Exhibition, 6-8 March, Fort Worth, Texas, USA
Publication Date 2018

Abstract
The typical rating for downhole measurement-while-drilling equipment for oil and gas drilling is between 150°C and 175°C. There are currently few available drilling systems rated for operation at temperatures above 200°C. This paper describes the development, testing and field deployment of a drilling system comprised of drill bits, positive displacement motors and drilling fluids capable of drilling at operating temperatures up to 300°C. It also describes the development and testing of a 300°C capable measurement-while-drilling platform.

The development of 300°C technologies for geothermal drilling also extends tool capabilities, longevity and reliability at lower oilfield temperatures. New technologies developed in this project include 300°C drill bits, metal-to-metal motors, and drilling fluid, and an advanced hybrid electronics and downhole cooling system for a measurement-while-drilling platform. The overall approach was to remove elastomers from the drilling system and to provide a robust “drilling-ready” downhole cooling system for electronics. The project included laboratory testing, field testing and full field deployment of the drilling system. The US Department of Energy Geothermal Technologies Office partially funded the project.

The use of a sub-optimal drilling system due to the limited availability of very high temperature technology can result in unnecessarily high overall wellbore construction costs. It can lead to short runs, downhole tool failures and poor drilling rates. The paper presents results from the testing and deployment of the 300°C drilling system. It describes successful laboratory testing of individual bottom-hole-assembly components, and full-scale integration tests on an in-house research rig. The paper also describes the successful deployment of the 300°C drilling system in the exploratory geothermal well IDDP-2 as part of the Iceland Deep Drilling Project. The well reached a measured depth of 4659m, by far the deepest in Iceland. The paper includes drilling performance data and the results of post-run analysis of bits and motors used in this well, which confirm the encouraging results obtained during laboratory tests. The paper also discusses testing and performance of the 300°C rated measurement-while-drilling components – hybrid electronics, power and telemetry - and the performance of the drilling tolerant cooling system.

This is the industry’s first 300°C capable drilling system, comprising metal-to-metal motors, drill bits, drilling fluid and accompanying measurement-while-drilling system. These new technologies provide opportunities for drilling oil and gas wells in previously undrillable ultra-high temperature environments.
Preliminary Description of Rocks and Alteration in IDDP-2
Drill Core Samples Recovered from the Reykjanes
Geothermal System, Iceland

Robert A. Zierenberg¹, Andrew P.G. Fowler¹, Guðmundur Ó. Friðleifsson², Wilfred A. Elders³, and Tobias. B. Weisenberger⁴

¹Department of Earth and Planetary Sciences, University of California, Davis CA, USA
²HS Orka Orkubraut 3, Svartsengi, 240 Grindavík, Iceland
³Department of Earth Sciences, University of California, Riverside CA, USA
⁴ÍSOR (Iceland GeoSurvey), Grensávegur 9, 108 Reykjavík, Iceland

Keywords
Iceland Deep Drilling Project, Reykjanes geothermal system, Drill Core, Lithology, Alteration, Supercritical, Enhanced Geothermal System.

ABSTRACT
The Iceland Deep Drilling Project (IDDP) well IDDP-2 was drilled to 4,659 m in the seawater-recharged and basalt-hosted Reykjanes geothermal system in Iceland. Spot drill cores were recovered between drilling depths of 3,648.00 m and 4,657.58 m. Temperature and pressure conditions at the base of IDDP-2 were over 426°C and 340 bar immediately following drilling, exceeding the critical point of seawater (406°C and 298 bar). The IDDP-2 cores are the first samples ever recovered from the supercritical roots of an active basalt-hosted hydrothermal system. We provide some preliminary hand sample descriptions, supplemented where possible by thin section petrography and mineral composition analyses for the IDDP-2 drill cores. The cores recovered between 3,648 m and the bottom of the hole at 4,659 m are from a sheeted dike complex and are generally pervasively altered. Despite the extensive alteration, veining is relatively minor and open space veins are very rare. Veins tend to be discontinuous and anastomosing and lack sharp wall rock contacts. They are interpreted as hydrothermal replacement veins formed in the transition zone between brittle and ductile deformation. Important initial findings include the transition from epidote-actinolite alteration to hornblende hornfels alteration at approximately 3,650 m, and the development of hydrothermal biotite in rocks below ~4,250 m. Felsic (plagiogranite) segregation veins are not common on the
Reykjanes peninsula west of the Hengill volcanic system, but are present in minor amounts in most of the dikes cored below ~4,300 m. Detailed petrographic and geochemical analysis of the samples is on-going. We have also sampled what appears to be hypersaline supercritical/magmatic brine trapped in pore spaces of porous felsite veins and adjacent wall rock, which manifests as a yellow potassium-iron chloride salt that precipitates on the cut edge of the core as pore fluid evaporates. Some of the core at these depths was stained by hematite that formed on the outer core surface by oxidation of ferrous iron in the formation fluid reacting at elevated temperature with oxygenated surface water used as drilling fluid. Further evidence for supercritical brine is apparent in complex fluid inclusions within quartz that contain multiple solid phases. The drill core samples are of immense scientific value for studying chemical conditions in the supercritical roots of high-enthalpy geothermal resources and submarine hydrothermal systems, with implications for improved understanding of ore-forming processes.

1. Introduction

The IDDP is a consortium of industries including Hitaveita Surdurnesja (now HS Orka), Landsvirkjun, Orkuveita Reykjavíkur, the National Energy Authority of Iceland (Orkustofnun), Alcoa Inc. (2007-2012), and Statoil (For a historical review of the IDDP project see Friðleifsson et al., 2010). The main IDDP goal is to determine the economic feasibility of energy and chemical extraction from supercritical brines, by drilling 4-5 km deep at a rifted plate margin and intercepting hydrous supercritical fluids (Friðleifsson et al., 2014).

On January 25th, 2017, IDDP successfully deepened well RN-15 (now RN-15/IDDP-2) to a depth of 4,659 m in the Reykjanes geothermal system of southwest Iceland. All primary drilling goals were met, which included intercepting supercritical fluids, encountering permeability below the presently exploited geothermal reservoir, and recovering drill core samples. The temperature at the base of the hole was 426°C at a pressure of 340 bars, measured during drilling after 6 days of heating at the bottom. This exceeds the critical point of seawater (406 °C and 298 bar), even though the well had not recovered from cooling during drilling. Complete circulation loss was encountered below 3,200 m, which precluded recovery of drill cuttings. Drill core was obtained in nine out of thirteen coring attempts from drilling depths between 3,648.00 and 4,657.58 m. This paper focuses on preliminary observations and analyses of the drill core.

Background on recent IDDP activities, drilling conditions, and future directions of IDDP are provided in a companion papers (Friðleifsson and Elders, this volume). The IDDP-2 cores are the deepest samples drilled from Iceland and the only rock samples ever recovered from supercritical conditions in an active, basalt-hosted and seawater-recharged hydrothermal system. Studies of the IDDP-2 cores are not only an opportunity to further our understanding of igneous processes, hydrothermal alteration and fluid characteristics in the roots of the Reykjanes geothermal system, but also provide insights into geochemical processes operating in the roots of active, basalt-hosted submarine hydrothermal systems that form massive sulfide deposits.
2. Geological setting

The Reykjanes geothermal system is the immediate onshore continuation of the submarine Mid-Atlantic Ridge, and is located on the seaward tip of the Reykjanes Peninsula in southwest Iceland (Figure 1). Fluids in the Reykjanes geothermal system are composed of seawater chemically modified by reaction with the host basaltic rocks (Arnórsson, 1978). Deep fluids in the Reykjanes geothermal system have major element and metal concentrations comparable to those from basalt-hosted submarine ‘black smoker’ fluids (Hardardóttir et al., 2013). An important difference from hydrothermal samples obtained from seafloor vents is that the Reykjanes fluids sampled at the well head have been altered due to boiling in the production wells, which results in the precipitation of well scale, including metal sulfides, that deplete the fluid in many trace metals (Hardardóttir et al., 2009; Hardardóttir et al., 2013) including rare earth elements (Fowler and Zierenberg, 2015).

The Reykjanes geothermal area is less than 40 m above sea level and is capped by ~120 m of lava flows emplaced subaerially during interglacial periods. The lava flows flood low points around subglacially emplaced hyaloclastite tuff and pillow basalt ridges that formed during the Late Pleistocene. Subaerially emplaced basalts are underlain by a sequence of hyaloclastite tuff formations that are in places intercalated with lava flows. Between about 500 and 1000 m below the surface, a series of reworked hyaloclastite tuff sediments with occasional marine fossils are periodically intercalated with submarine pillow basalts, and below 1000 m submarine pillow basalt formations and intrusive rocks dominate (Franzson, et al., 2002; Franzson, 2004; Marks et al., 2010) with dikes becoming increasingly abundant at depth.
There is a predictable sequence of alteration minerals that varies with depth and temperature in the Reykjanes geothermal system. With increasing depth and temperature this includes the: smectite-chlorite, chlorite, chlorite-illite, epidote-actinolite, and hornblende alteration zones (Tómasson and Kristmannsdóttir, 1972; Lonker et al., 1993; Franzson, et al., 2002; Marks et al., 2010; Weisenberger at al. 2016). Localized contact metamorphic granoblastic hornfels zones have also been identified below about 2,000 m (Marks et al., 2011).

3. Previous IDDP Drilling at Reykjanes

Prior to drilling the IDDP-2 well, IDDP recovered drill core from three Reykjanes drill holes and attempted to drill a deep geothermal well at the Krafla geothermal field. Details of rock samples and alteration recovered by the IDDP-1 drilling effort in the Krafla geothermal field, which was terminated at a depth of 2,104 m when a rhyolite melt was intersected, are provided elsewhere (Elders et al., 2011; Schiffman et al., 2012; Zierenberg et al., 2012).

IDDP intended to deepen the 3,082 m deep RN-17 production well in the Reykjanes geothermal field to meet project goals, however this idea was abandoned when the well became blocked during production testing in November 2005 (Friðleifsson and Richter, 2010). While RN-17 could not be used as an IDDP well of opportunity, studies of RN-17 drill cuttings by the IDDP science team improved models of the volcanic structure, hydrothermal alteration at depth in the Reykjanes geothermal and provided an important foundation upon which subsequent IDDP studies could be built (e.g. Marks et al., 2010; Marks et al., 2011). While drill cutting studies continue to provide important insights into Icelandic geothermal systems at conventional drilling depths, the IDDP team recognized the need to collect drill core during a future IDDP drilling attempt, in recognition of the limitations of drill cutting samples recovered from extreme depths (e.g. Fowler and Zierenberg, 2016b).

Prior to the IDDP effort, drill core had not previously been recovered from the Reykjanes system. Coring equipment tests were performed in well RN-19, RN-17B and RN-30. The RN-19 test produced 2.97 m of core from 2,245 to 2,248 m (Mortensen et al., 2006; Friðleifsson and Richter, 2010; Ottolini et al., 2012; Fowler and Zierenberg, 2016a). The RN-17B test recovered 9.3 m of core from a drilling depth of ~2,800 m in a 35º inclined sidetrack of hole of RN-17 (Friðleifsson and Richter, 2010; Fowler et al., 2015), and the RN-30 test recovered three sequential cores totaling 22.5 m in length from a drilling depth of ~2510 m a 35º inclined hole (Fowler and Zierenberg, 2016a).

4. The IDDP-2 Drill Cores

4.1 Descriptions of IDDP-2 Drill Core Samples

The following descriptions are primarily derived from hand sample descriptions completed onsite by the authors who comprised the IDDP-2 geologic team, supplemented where available by on-going petrographic and geochemical investigations, and should be taken as a preliminary report on the down hole geology. The intervals where drill core was recovered are provided on Table 1. More detailed descriptions of cores and core fragments will be made available in the IDDP-2 Scientific Drilling Reports.
Zierenberg et al.

Table 1: Drill cores recovered from IDDP-2. Core runs 1, 2, 4, and 9 did not recover intact core samples.

<table>
<thead>
<tr>
<th>IDDP-2 Core Run</th>
<th>Cored Interval (m)</th>
<th>Core Length (m)</th>
<th>Recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3,648.0 – 3,648.5</td>
<td>0.52</td>
<td>58</td>
</tr>
<tr>
<td>5</td>
<td>3,865.3 – 3,869.8</td>
<td>3.85</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>3,869.8 – 3,870.2</td>
<td>0.15</td>
<td>38</td>
</tr>
<tr>
<td>7</td>
<td>4,089.5 – 4,090.6</td>
<td>0.13</td>
<td>11</td>
</tr>
<tr>
<td>8</td>
<td>4,254.6 – 4,255.3</td>
<td>0.28</td>
<td>40</td>
</tr>
<tr>
<td>10</td>
<td>4,309.9 – 4,311.2</td>
<td>0.22</td>
<td>17</td>
</tr>
<tr>
<td>11</td>
<td>4,634.2 – 4,642.8</td>
<td>7.58</td>
<td>88</td>
</tr>
<tr>
<td>12</td>
<td>4,642.8 – 4,652.0</td>
<td>9.0</td>
<td>98</td>
</tr>
<tr>
<td>13</td>
<td>4,652.0 – 4,659.0</td>
<td>7.0</td>
<td>80</td>
</tr>
</tbody>
</table>

4.1.1 Core 3 (3,648.00 m – 3,648.52 m)

Core run 3 recovered segments of three medium-grained, greenish-grey diabase half dikes separated by chilled dike margins. The chilled margins are replaced by a very fine-grained mixture of epidote, actinolite, chlorite, albite, secondary clinopyroxene, magnetite and sphene. The diabase is pervasively altered with complete replacement of clinopyroxene by actinolite with less abundant hornblende, chlorite, and epidote. Igneous plagioclase is partly altered to albite, epidote and chlorite. Primary titanomagnetite is partly replaced by magnetite and sphene. The core is cut by several 1-5 mm thick discontinuous epidote-plagioclase-amphibole-quartz veins with dark amphibole-chlorite vein selvages (Figure 2A, 3A). The veins have irregular to gradational margins and lack clear open-space filling growth textures. Some veins show offsets where intersected by later veins while others merge together into anastomosing compound veins, but all veins have the same mineralogy. Sulfide minerals are present in the veins and groundmass alteration. The most abundant sulfide is intermediate solid solution (ISS) Cu-Fe sulfide with less abundant pyrrhotite and pyrite.

4.1.2 Core 5 and 6 (3,865.50 m – 3,869.95 m)

Core run 5 recovered 3.85 m of continuous core, with no missing intervals or coring gaps and no discernable systematic change in texture or mineralogy down core. The diabase recovered in Core 6 is identical in appearance and is interpreted to have sampled the same dike.
Figure 2: Drill core samples from the IDDP-2 well. See text for descriptions.

Zierenberg et al.
Figure 3: Representative rock textures from IDDP-2 drill cores, each image is a scan of a standard thin section (2.54 mm in short dimension). A. Core 3 3,648.28 m. Epidote-plagioclase-amphibole-quartz replacement veins cutting pervasively altered diabase dike. B. Core 5 3,865.50 m. Medium grained diabase dike. Clinopyroxene is completely replaced by actinolite and hornblende; plagioclase is generally unaltered. Hair-like amphibole vein cutting diagonally across (bottom left of center to top center) the sample is a typical expression of hydrothermal veining in this interval. C. Core 8 4,254.60 m. Fine grained basalt showing increasing grain-size away from the dark quenched margin (lower right corner). Early dark hornblende replacement veins developed in shear bands are cut by successive generations of hornblende-plagioclase+quartz veins. D. Core 11 4,636.32 m. Quenched margin of porphyritic diabase dike with flow alignment of plagioclase laths parallel to the margin. E. Core 11 4,637.79 m. Thin felsite vein network cutting partially altered diabase dike. Mafic minerals in the felsite are biotite > pyroxene pseudomorphed by hornblende. F. Core 13 4,653.25 m. Felsite vein cutting altered diabase with dark, fine-grained selvages of hornblende and magnetite.
Clinopyroxene is essentially completely replaced by dark green amphibole, which includes intergrown actinolite and hornblende. In contrast, plagioclase and titanomagnetite appear essentially unaltered. There are a few <1 mm hairline veins of dark-green to black amphibole (Figure 2B, 3B) that cut the core at various angles, with large changes in vein direction along a single vein. A few discontinuous and diffuse 1-3 mm wide veins and patches of lighter colored, more felsic, diabase are present. Plagioclase is more abundant in these veins and some has a cloudy appearance due to symplectic intergrowth of plagioclase and quartz. Clinopyroxene (replaced by amphibole) is less abundant compared to the surrounding diabase and anhedral quartz is present as a minor phase. The textural relationships and the mineralogy suggest these are late-stage differentiated igneous segregations as opposed to hydrothermal alteration features.

4.1.3 Core 7 (4,090.00 m – 4,090.12 m)
Core run 7 recovered 120 mm of fine-grained altered diabase dike generally similar in texture and composition to the dike recovered in Cores 5 and 6. The recovered core was broken into 4 disk-like fragments along planer fracture perpendicular to the core axis. There is a weak lineation on the fracture surfaces that is roughly parallel on each fracture surface when the core is pieced back together. Clinopyroxene is generally 2 x 2 mm in cross section, with some grains more elongated, up to 4 mm. The elongated clinopyroxene and the 2-4 mm, slightly elongated plagioclase laths show weak aligned that apparently define the lineation on the core fractures. There are sparse blocky plagioclase phenocrysts/glomerocrysts up to 5-6 mm. This dike is pervasively altered, but igneous clinopyroxene is still present, although subordinate to hydrothermal amphibole. Examination of the cut surfaces of core pieces shows that some plagioclase is slightly cloudy and greenish, apparently due to incipient alteration. The finer-grained interstitial patches show more pervasive greenish-blue patchy alteration and/or late-stage plagioclase-quartz symplectic intergrowth. There are some sparse 1-2 mm patches of sulfide, dominantly pyrrhotite, but including some Cu-Fe sulfide that appears to be authigenic rather than immiscible magmatic sulfide.

4.1.4 Core 8 (4,254.60 m – 4,254.88 m)
The core, and majority of fill fragments collected on top of the core, consist of fine- to medium-grained basalt completely replaced by very fine-grained hornblende, secondary calcic plagioclase, and subordinate metamorphic titanomagnetite and ilmenite (Figure 3C). The veining, sheering and recrystallization suggest this interval may be a screen between younger dikes, but it is not clear if the protolith was a submarine lava or an older, fine-grained dike margin. A thin quench zone is present in two of the core pieces, but subsequent alteration and deformation make it unclear if this is a dike margin or the glassy rind on a pillow. This unit is composed of approximately 60% black to dark green, equant to slightly elongate hornblende with a ~1 mm grain-size that replaces original clinopyroxene, and locally, plagioclase. Approximately 30-35% of the rock is calcic plagioclase, most of which pseudomorphs igneous plagioclase. There are minor Na-rich plagioclase patches that are likely relict albite replacement, but this plagioclase now has intermediate compositions with sub equal Na and Ca. Plagioclase in the matrix tends to be equant and coarser grained (~2 mm). A weakly defined foliation approximately perpendicular to the core axis is developed locally. The earliest vein set consists of discontinuous monomineralic green amphibole replacement veins. These veins are offset by dark hornblende-magnetite replacement veins developed in shear-bands. The shear bands include abundant fine-grained calcic plagioclase and fine-grained disseminated magnetite and ilmenite.
The early shear bands are cross cut by at least three generations of amphibole-plagioclase-magnetite-quartz veins. The later veins contain proportionally more plagioclase and quartz, and at least one of these veins contains trace mm-size biotite books. Cu-Fe sulfides are present, especially in earlier shear-bands and later quartz bearing veins.

Figure 3. A. Felsite vein cutting diabase. The cut surface of the core shows hematite staining. Yellow KFeCl salts precipitated on the top cut surface of the core. B. Chilled dike margin. C. Euhedral hydrothermal biotite, approximately 1 mm in diameter, coating fracture surface shown in Fig. 2D. Exposed crystals were stained red by hematite during the coring operation. D. Open-space filling quartz overgrowing hydrothermal biotite (black and reflective, approximately 1 mm across) coating the fracture shown in Figure 2D.

4.1.5 Core 10 (4,309.90 m – 4,310.12 m)

Core run 10 recovered a fine-grained basaltic intrusion with a texture suggesting emplacement as a dike, but the limited recovery precludes determination of the orientation of this intrusion. The protolith contained sub equal amounts of elongated tabular plagioclase up to 2 mm with interstitial subhedral clinopyroxene about 1 mm across, and a few percent anhedral 1 mm titanomagnetite grains. The lower two core pieces are weakly porphyritic due to the presence of

Zierenberg et al.
less than 1% blocky plagioclase phenocrysts up to 3-4 mm and rare pyroxene phenocrysts up to 2-3 mm. The rock is extensively, but not completely, altered. Phenocrysts and coarser groundmass plagioclase laths are more often clear and glassy, but much of the matrix feldspar is cloudy white to light bluish-green. Clinopyroxene is greenish due to extensive replacement by amphibole, but brown glassy clinopyroxene is preserved in places. The interstitial material is completely replaced by amphibole, which is locally intergrown with biotite and secondary plagioclase. Disseminated fine-grained anhedral sulfide is common, with Cu-Fe sulfide more abundant than pyrrhotite and pyrite.

Locally, the core is cut by plagiogranite segregation veins and patches, the best developed of which is a 2 cm thick band dipping at approximately 70° to the core axis. Given the ~30° inclination of the drill hole, the vein may have originally been approximately horizontal. Where best developed, the plagiogranite is approximately 70% feldspar, most of which is anhedral and cloudy white due to symplectic intergrowth with quartz. However, there are some euhedral, 2 mm blocky plagioclase crystals that are relatively clear. The plagiogranite contains approximately 20% green amphibole, which replaces original pyroxene that show a range of grain size from < 1 mm equant crystals to acicular crystals < 1 mm in cross section and up to 3-4 mm long. There is ~5% fine-grained sub-euhedral titanomagnetite disseminated through the rock. Healed fractures cutting through some of the plagiogranite have a small amount of subhedral grey quartz.

4.1.6 Cores 11, 12, and 13 (4,634.20 m – 4,657.58 m)

The IDDP-2 hole was drilled to a depth of 4,626 meters using a 216 mm bit and recovered 102 mm diameter core. The open hole was logged from the base of the casing shoe (2,940 m) to the bottom of the hole at 4,623 m using a suite of logging while tripping tools. A pressure-temperature log was run to a depth of 4,560 m following 6 days of heating at the bottom of the hole. The major feed zone in the open section of the hole occurs at about 3,450 m, with several smaller feed zones, the deepest of which is at 4,550 m (Friðleifsson and Elders, this volume). The bottom hole temperature was ~426° C (Friðleifsson and Elders, this volume), but the well had clearly not thermally equilibrated, so this is a minimum estimate of the in situ temperature, yet clearly above the critical temperature for fluid with seawater salinity (406° C). Following insertion of a 178 mm lining, three consecutive core runs were conducted using a 152 mm bit that cut 67 mm core. Core run 11 recovered 7.58 m of continuous core, with no missing intervals or coring gaps. Core run 12 recovered 9.00 m of continuous core, and Core run 13 recovered 5.58 m of continuous core.

The interval cored at the bottom of the hole contains four half dikes separated by three chilled dike margins. A chilled margin at 4,636.25 m indicates the dike in the upper part of Core 11 chilled against the underlying dike (Figure 4B). Plagioclase phenocrysts define a flow alignment parallel to the dike margin (Figure 3D). The upper dike in Core 11 is a porphyritic basalt with a groundmass that consists of 1 mm euhedral to subhedral glassy (where unaltered) green-brown clinopyroxene (65-70%) separated by 1 mm long euhedral plagioclase laths (20-25%), and less than 5% 1 mm euhedral titanomagnetite. Phenocrysts include elongate plagioclase (5%) up to 5 mm, and occasional 3 mm euhedral, greenish, partially altered olivine. Plagioclase typically shows igneous textures and zoning, but the crystals have a dusty appearance, suggesting subtle alteration, that follows compositional zoning in the plagioclase. Pyroxene is partially to completely replaced by hornblende. The upper part of Core 11 is cut by conjugate veins less than
1 mm wide filled with dark hornblende (Figure 2C). Hornblende, intergrown with biotite, forms dark selvages and as well as irregular diffuse alteration patches. Hydrothermal mineral veins are not common down core, and those present are predominantly hairline fractures filled with hornblende. There is little to no sulfide associated with the alteration.

Felsite segregation veins are more prominent in the deeper cores. The veins range in width from 2 to 30 mm wide (Figure 4A). They commonly branch and intersect with no offset margins. The dominant minerals are subhedral plagioclase and rounded quartz set in a matrix of fine, sugary intergrown quartz and plagioclase. In contrast to the dusty appearing plagioclase in the host rock, the plagioclase in the felsite veins appears clear. The symplectic intergrowths of plagioclase and quartz that characterize the more felsic zones in shallower core are lacking. Some of the felsite veins contain up to 5% mafic minerals, including pyroxene, which is generally replaced by hornblende, and biotite. The ratio of pyroxene to biotite is variable and either phase can dominate. The contacts of the felsite veins with the wall rock are very sharp (Figure 2D, 3E), but in some instances euhedral plagioclase crystals cross the boundary. In some instances, fragments of wall rock are included within the felsite vein. The veins are typically (but not ubiquitously) stained red with a thin hematite film that is only present on the outer, drill-cut surface and rare pre-coring open fractures (Figure 2C, 2D); the core interior, exposed by fracturing or cutting the core after recovery, are not hematite stained. Cut felsite vein surfaces are often stained yellow due to post-coring/post saw-cut evaporation of pore fluid that precipitates yellow potassium-iron chloride salt as the core dries (Figure 4A). Open fractures are rare, but one open fracture bounding a felsite vein was coated with coarse-grained, euhedral hydrothermal biotite (Figure 2D, 4C). Euhedral, prismatic quartz crystals, including some that are doubly terminated, overgrow the biotite (Figure 4D). This represents the sole occurrence of open space filling quartz in the recovered core. The quartz contains sparse fluid inclusions that range from vapor-dominated, to nearly filled with precipitated salts. The facture surface and adjacent core surface were coated by a thick film of hematite, and deep-red hematite-bearing fluid oozed out of the fracture when the core was first recovered. A second mineralized fracture coated by hydrothermal biotite occurs down core and is associated with crystals of a Cu-Fe sulfide mineral (ISS?), and euhedral prismatic crystals tentatively identified as hydrothermal pyroxene.

The lower intrusion in Core 11 is glomeroporphyritic with both plagioclase and clinopyroxene glomerocrysts. Clinopyroxene is more abundant than plagioclase. Some plagioclase occurs as 1-2 mm elongated crystals, but generally the plagioclase is somewhat irregular shaped and forms a weakly felted matrix that is interstitial to clinopyroxene. The lower intrusion has ~5-8% equant titanomagnetite crystals, which appears to be more abundant than in the upper dike. Some plagioclase has what appears to be greenish alteration in hand specimen. Clinopyroxene in the lower intrusion appears more altered than in the overlying (and younger) dike. The lower dike is typically homogeneous and appears to coarsen down hole in Core 12. Felsite veins are less common than in the overlying dike. Locally, there are irregular-shaped plagioclase-rich ‘felsite’ patches and small networks of thin branching veins, usually with width and length dimensions less than 10 mm, but up to 50 mm (Figure 3E). The patches are dominated by plagioclase and quartz, with minor mafic minerals that include biotite and black pyroxene.

The glomeroporphyritic half dike is the thickest dike recovered, with a downhole extent of 14.4 m. Given the ~40° inclination of the drill hole at this depth, the dike would have a minimum
thickness greater than 9 m, assuming the dike is vertical. At the base of the dike there is a rapid
decrease in grain-size and the dike is chilled against the underlying half dike.

The older, underlying dike at the base of Core 12 is a medium- to fine-grained intrusive with a
heterogeneous texture with irregular patches that are coarser, finer, or richer in interstitial
material. Based on hand sample observations, this intrusion is classified as a two-pyroxene
diabase. The dominant texture consists of 2-3 mm elongate plagioclase (55%) with occasional
pheno/glomerocrysts of blocky plagioclase up to 4 mm. Plagioclase is generally clear and appears
unaltered. Clinopyroxene (15%) appears as blocky, black, 2 mm euhedral crystals that are rarely
elongated, up to 4 mm. Orthopyroxene (20%) is beer bottle brown, euhedral, and 1-2 mm. Patches of fine-grained, late-stage interstitial material make up 7-8% of the rock, and consist of
concentrated irregular shaped 5-10 mm patches of fine-grained plagioclase, orthopyroxene, and
clinopyroxene that appear slightly greenish and slightly altered. There are occasional 1-2 cm
patches of coarser grained rock with the same composition. There is patchy overprinting
alteration where some of the pyroxene is altered to amphibole, but other patches where all
crystals appear fresh. Titanomagnetite (2-3%) is fine grained and not abundant in coarse-grained
patches, but occurs as fine-grained aggregates in the fine-grained interstitial material, and often
occurs with sulfide, which appears to be pyrrhotite.

The uppermost core fragments in Core 13 contain a chilled dike margin, but the orientation of
these core fragments is uncertain, so the age relationship of the lowermost half dike to the
overlying half dike remains to be determined by more detailed petrographic analysis. The
intrusion in Core 13 is characterized by a heterogeneous texture and composition with patchy
alteration. Euhedral plagioclase (60 to 65%) forms a matrix of thin, elongated and felted crystals
2-3 mm long, with 30% 1-2 mm interstitial dark clinopyroxene, and 5-8% 1-2 mm subhedral
titanomagnetite. There is patchy development of coarser, blocky to glomerocrystic plagioclase
up to 3-4 mm. Plagioclase appears generally fresh, but pyroxene is partly altered to amphibole.
Variation in grain size is difficult to discern due to the ubiquitous hematite staining coating the
cored surface. Diffuse, centimeter-scale clots of coarser-grained material appear throughout the
dike and are separated on the scale of centimeters (a 10 cm length of core may contain two to
four cm-sized clots) giving the cut core a spotted appearance. The boundaries of the clots are
indistinct and gradational and may suggest partial assimilation or magma mixing/incorporation
of crystal mush. The coarser-grained clots tend to have slightly more pyroxene, and the
plagioclase and pyroxene can approach 4 mm in size. Fine-grained, sugary textured mm-wide
feldspar + quartz zones with indistinct boundaries may represent healed fractures or thin zones
thermal recrystallization. A few cm-scale felsite segregation veins are present in this half dike. In
contrast to felsite veins at shallower depths, amphibole pseudomorphing pyroxene is the
dominant mafic phase and biotite does appear to be present either in the veins or in the altered
wall rock. The wall rock adjacent to the felsite veins is typically flooded with abundant fine-
grained hornblende and secondary magnetite (Figure 3F). The dark selvedge can extend outward
from the felsite vein edges to distances similar to the vein width.

4.2 Mineral Compositions

Here we present preliminary results for electron microprobe analyses of key primary and
secondary minerals in the IDDP-2 drill cores. Data is currently available for samples from cores
3 through 10; analysis of minerals in cores 11 through 13 is in progress.
Primary and hydrothermal pyroxene in the Reykjanes geothermal system are compositionally distinct; primary pyroxene is augitic in composition while hydrothermal pyroxene ranges in composition from diopside to hedenbergite (Figure 5A), consistent with observations from RN-17 drill cuttings (Marks et al., 2011). Both primary and secondary pyroxenes are present in the IDDP-2 cores, and fall in the compositional ranges reported for pyroxene in shallower portions of the system. Hydrothermal clinopyroxene is most abundant in the quenched margins of the sheeted dikes recovered in Core 3 (Figure 5A), both replacing the glassy margin and in veins cutting the glassy margin. Veins crossing from the quenched margin through the older wall rock change from dominantly clinopyroxene to dominantly amphibole at the dike contact. Formation of hydrothermal clinopyroxene may be favored by initial alteration of the glass to low-aluminum Mg-Fe smectite.

Primary and hydrothermal plagioclase in the IDDP-2 drill cores are often distinguishable based on the petrography relations, e.g. hydrothermal plagioclase in veins. They also appear to be distinguishable geochemically with hydrothermal plagioclase extending to very high anorthite number (percent anorthite), but with relative low MgO concentration (Figure 5B). Electron microprobe analyses confirm the presence of primary igneous plagioclase in cores 3 through 10, although cores 5, 6 and 7 are dominated by primary igneous plagioclase and cores 3, 8 and 10 contain a significant proportion of secondary plagioclase.

Amphibole in cores 3 through 10 ranges from actinolitic/ferroactinolitic through hornblende/ferrohornblende in composition, while cores 5&6 include edenite/ferroedenite amphibole (Figure 5C). Cores 5, 7 and 10 largely contain hornblendic amphibole. In many cases early actinolite amphibole is overgrown by and/or replaced by hornblende.

As mentioned earlier, a post-drilling yellow salt precipitate is prevalent on saw-cut surfaces and is related to samples that have an intense hematinic stain on the outer core surface. The iron stained zones are often spatially associated with felsite veins. Semi-quantitative analyses of the salts using energy dispersive X-ray spectroscopy suggest that the most abundant phase is a potassium-ferrous iron chloride with the composition of Javorieite (KFeCl₃). Other phases detected include halite and morphologically distinct K-Fe chloride salts with appreciable concentrations of Mn, Cu, Zn or Al. Aqueous solutions of the salt retain a yellow ferrous chloride color and do oxidize to precipitate ferric oxides when stored at room temperature in containers open to the atmosphere. The salt appears to precipitate in the lab due to evaporative concentration of hydrothermal brine trapped in the intergranular pore space of the rocks, and seems to be most prevalent in the felsite veins and the deepest half dikes. Mixing of the hydrothermal brine and oxygenated surface waters used as cooling fluid at elevated temperatures down hole appears to be responsible for the hematite staining that coats the surface of the deep cores. Efforts to further characterize the deep hydrothermal brine are on going.
Figure 5. Mineral compositions based on electron microprobe analyses. A=pyroxene; B=plagioclase; C=amphibole
5. Conclusions

Our investigation of the recovered drill cores is in the preliminary stages, but the following conclusions seem to be supported by the observations at hand. The IDDP-2 cores include the first samples recovered from active, supercritical geothermal conditions in a seawater-recharged hydrothermal system similar to deep-sea black smokers. The lithological section underlying the presently exploited hydrothermal system at Reykjanes is typical of sheeted complexes in oceanic crust and ophiolites. Logging measurement confirm that permeable feed zones are present at temperature and pressure conditions in excess of the critical point of seawater in the deepest section of the well. The alteration assemblage in the shallowest recovered core includes albite chlorite, epidote, actinolite and quartz; the typically assemblage of epidote-actinolite facies alteration that characterizes production reservoir at Reykjanes. However, rocks at this depth are cut by veins with hornblende and anorthite, indicating that these rocks have not fully equilibrated to amphibolite facies alteration. Below this depth, veins become relatively uncommon and open space veins are nearly absent, consistent with transition from the brittle to the ductile regime. Despite the lack of veining and the excellent preservation of igneous textures, most rocks are pervasively altered with most pyroxene replaced by hornblende, and less apparent alteration of plagioclase. Albite, epidote and chlorite are not present as alteration phases below ~3,450 m, and quartz is at best only a minor phase. The alteration is characterized by hornblende and calcic plagioclase, but actinolite persists as a metastable alteration mineral in the amphibolite alteration facies. Hydrothermal biotite has been identified for the first time in the Reykjanes system and is commonly observed in the deepest drill cores. Felsic segregation veins become increasingly common in the sheeted dikes with depth, and some contain igneous biotite and zircon. We appear to have sampled hyper saline supercritical (magmatic?) brine in the intergranular pore space of the deepest drill cores, and these fluids are the target of future fluid sampling and fluid inclusion investigations. The IDDP-2 cores provide an unprecedented opportunity to investigate geochemical reactions occurring under supercritical conditions, and should provide continued insight into fluid/rock reactions that control the composition of fluids that form basalt-hosted massive sulfide systems.

Acknowledgement

The IDDP-2 was funded by HS Orka, Landsvirkjun, Orkuveita Reykjavíkur, and the National Energy Authority in Iceland, together with Statoil, the Norwegian oil and gas company. The IDDP has also received funding from the EU H2020 (DEEPEGS, grant no. 690771. Funding for IDDP to obtain spot cores at Reykjanes and elsewhere was provided by ICDP and the US NSF (grant no. 05076725). RAZ would also like to acknowledge the support of the U.S. Fulbright Scholar Program, which allow his participation during the drilling.

REFERENCES


Fowler, A.P.G. and Zierenberg, R.A., 2016a. Elemental changes and alteration recorded by basaltic drill core samples recovered from in-situ temperatures up to 345°C in the active, seawater-recharged Reykjanes Geothermal System, Iceland. Geochemistry, Geophysics, Geosystems, 17.


Processing of magnetotelluric data for monitoring changes in electric resistivity during drilling operation

Nadine Haaf1,2, Eva Schill1,2

1. ABSTRACT

Long-term magnetotelluric monitoring of different injection and production experiments at the Rittershoffen geothermal site in Alsace (France) provided a first continuous data set over several month, covering the end of drilling phase of GRT2 (Abdelfattah et al. 2018), mostly, production from, but also injection into this well, injection into GRT1 and a circulation experiment. Transfer functions showed particular variation pattern for different operations, i.e. an increase in uncertainty, conductivity and phase during test operation with a preferential direction sub-parallel to Shmin, i.e. perpendicular to the expected extension of the fractures controlling the reservoir. In particular fluid injection, either into GRT2 or GRT1 causes a strong decrease in resistivity by up to one order of magnitude in the XY component between about 8–25 s of period. Here, we present particularities of processing of continuous magnetotelluric monitoring for the example of deepening of the RN-15 well on the Reykjanes peninsula (Iceland) to 4665m (IDDP-2 well) with a magnetotelluric dataset from November 2016 to January 2017. The drilling progress during this period was accompanied by partial and up to total circulation loss (Friðleifsson et al. 2017). Two continuous running MT stations, GUN and RAH, were installed on the Reykjanes peninsula. RAH and GUN are located about 6 and 1 km away from IDDP-2. Both MT stations are equipped with two electric dipoles in N-S and E-W direction, as well as three magnetic sensors oriented in N, E and vertical direction. MT monitoring was carried out with a sampling frequency of 512 Hz. Processing revealed the bad data quality of RAH. Consequently, MT data were processed using single site method with the code Bounded Influence Remote Reference Processing (Chave and Thomson 2004). Due to a temporally noise signal in the time series, they were down filtered to get the lower frequency bands and hence to clean the time series. Additionally, a remote station from Germany has been tested to improve the data quality in the dead band. First results might suggest a temporal correlation between low resistivity in the MT data, fluid loss, and induced seismicity.

2. INTRODUCTION

An increasing interest in magnetotelluric (MT) monitoring of hydraulic stimulation experiments results from soft stimulation techniques that reduce induced seismicity to a minimum. MT is a passive electromagnetic method that records the ambient electric and magnetic field to gain information about the electric conductivity of the subsurface. Used for monitoring, the directional evolution of the reservoir, e.g., during reservoir engineering, can be traced.

MT monitoring proved to be useful to trace the directional development of the Paralana and Cooper basin reservoirs during massive hydraulic stimulation experiments by relative phase tensor changes (Peacock et al. 2012; Peacock et al. 2013; Didana et al. 2017). In these experiments, volumes of 3100 m³ and 36,500 m³ were injected at up to 60 L/s and 53 L/s resulting in reservoir pressures of up to 62 MPa and 48 MPa in the wells Paralana-2 and Habanero-4, respectively. Long-term magnetotelluric monitoring of different low-volume and -pressure injection and production experiments at the Rittershoffen geothermal site in Alsace (France) provided a first continuous data set over several month, covering the end of drilling phase of GRT2 as well as production and injection into both wells GRT1 and 2 (Abdelfattah et al. 2018). Transfer functions showed operation dependent variation, i.e. variation in uncertainty, conductivity and phase with a preferential direction sub-parallel to Shmin, i.e. perpendicular to the expected extension of the fractures controlling the reservoir. In particular fluid injection, either into GRT2 or GRT1 causes a strong decrease in resistivity by up to one order of magnitude in the XY component between about 8–25 s of period.

Similar long-term monitoring during deepening from 2500 to 4659m and development of the RN-15/IDDP-2 well on the Reykjanes peninsula (Iceland) was carried out from November 2016 to January 2017. In this well, the H2020 project DEEPEGS (https://deepegs.eu) aims at demonstrating advanced engineering technologies. A deep Enhanced Geothermal System at Reykjaness aims injection of fluid underneath the conventional geothermal field to support production. The drilling from August 2016 until January 2017 was accompanied by partial and up to total circulation loss. Earlier MT exploration in the area reveals a typical resistivity structure of a high temperature geothermal system with a low resistive cap layer, here, with up to 2 km thickness. In the vicinity of the well vertical conductive structures hint to a dyke swarm or a sheeted dyke complex as heat source (Friðleifsson et al. 2014). Besides anthropogenic noise, the challenge of processing continuous MT monitoring data are the relatively high-frequency changes in the "perturbed" MT signal. Perturbation in the reservoir are caused during drilling by partial and up to total circulation loss and induced seismicity (Friðleifsson et al. 2017). Here, we present the necessary processing procedure and first results from the final drilling phase.
In a first field campaign in September 2016, eight stations were tested to identify an optimal location for continuous MT monitoring with respect to the expected electric noise (Darnet et al. 2018). During this period a temporary remote station was operated in the region Höfuðborgarsvæðið, 20 km South of Reykjavik. This remote station cannot be accessed during the winter period, when the target depth was reached and main stimulation of the well occurred. For practical operation and maintenance regarding power supply and data transfer and for reasons of data comparability, the two continuous monitoring stations, GUN and RAH, were selected close to seismic stations (Figure 3.1). The GUN station represents the main monitoring site and is located about 750 m SE of the wellhead of RN-15/IDDP-2 well and beeline about 1 km to the E of the bottom of the well the away from the well. The MT station, RAH, is located at about 5 km to the NE. RAH was planned to operate as a second continuous monitoring station with the potential of being a local remote reference.

Figure 3.1 Geological map of the Reykjanes peninsula with the MT test (blue triangles) and monitoring stations (red triangles) and the Wellhead of RN15 (black cross).

Both stations were installed with a controlling unit ADU07e from Metronix Inc. to measure orthogonal and time dependent components of the Earth's magnetic field and the corresponding electric response. The so-called time series were measured by two horizontal electric components, $E_x$ and $E_y$, and three magnetic components, $H_x$, $H_y$ and $H_z$. The three MFS07e coils were aligned perpendicular in north-south, east-west and vertical direction, respectively. The electric horizontal dipoles were aligned with the horizontal magnetic coils in N-S and E-W direction. The stations and the cables were buried to about 10 cm depth protect them from the weather.

At GUN, continuous monitoring was carried out between November 30th, 2016 and July 21st, 2017. The sampling frequency was 512 Hz and it was measured in 24-hour blocks. Measurements at RAH were stopped in May 2017 due to continuing bad data quality after mid of December 2016. The MT monitoring covers the last third of the drilling period of the RN-15/IDDP-2 well and the successive stimulation of the well.
4. PROCESSING AND DISCUSSION OF MT DATA

The processing of MT data is carried out using the bounded influence remote reference code, birrp, (Chave and Thomson 2004) to process the data. Remote referencing is included in the advanced mode of birrp.

4.1 Types of noise and perturbation

Figure 4.1 reveals different types of noise. To better visualize the noise peaks in the spectrum, the power spectral density was calculated and the whole window length is shown. Most prominent peaks appear in all five channels were observed at 14 Hz for the time period between November 30th and 18th, 2016 and 50 Hz and harmonics across the entire monitoring period. This 14 Hz noise signal occurs roughly every 30 minutes with a duration of about 90s. The source of noise could not be identified.

Figure 4.1 Noise spectra in the five channels from a) January 13th, 2017 and b) December 11th, 2016 (decimated to 128 Hz) of GUN MT station.
In the following, we introduce that variability of the single-site processed transfer functions (calculated for 48 h) over the time period of November 30th, 2016 to December 1st, 2016 at the GUN station (Figure 4.2). Typically, temporal variations in electric resistivity occurs between $10^{-1}$ and 10 s. Changes in the phase are not observed. One end-member type shows apparent resistivities down to about $10^{-2}$ Ωm at periods of a few tens of seconds (Figure 4.2a). The opposite end-member type reveals apparent resistivities down to 1 Ωm at periods up to 10 s (Figure 4.2b). Note that such decrease in resistivity has been attribute in other geothermal projects such as Rittershoffen (France) to fluid injection (Abdelfettah et al. 2018).

![Figure 4.2](image)

**Figure 4.2** Representative end-member types of transfer functions (top: apparent resistivity, bottom phase) with a) a resistivity low ($>10^{-2}$ Ωm) at periods of a few tens of seconds from December 18th to 19th, 2016 and b) a resistivity low ($>1$ Ωm) at periods of up to 10 s from November 30th to December 1st, 2016.

### 4.2 Remote Referencing

Following the approaches of Gamble and Clark (CLARKE et al. 1983; GAMBLE et al. 1979) uncorrelated noise can be eliminated from the measured data using remote referencing, when a high degree of correlation between the naturally-induced electromagnetic fields at local and remote site is reached. Thus, the remote reference must be sufficiently distant to the local station, i.e. a few skin depths (Chave et al. 2012), to ensure possible bias errors due to correlated noises to be small compared to the random errors (Chave et al. 2012; GAMBLE et al. 1979).

Note that for MT monitoring the period of the perturbation is crucial for the applicability of remote referencing. Perturbations at the well bottom are caused by changes in the engineering process, i.e. changes in flow rate, pressure or even related seismicity. If of low period with respect to the measurement period and causing an electromagnetic signal, these changes may contribute to uncorrelated noise. Thus, when applying conventional remote referencing, this signal of interest may be weakened or eliminated. For this reason, several remote stations were tested during the project period, a temporary remote reference for the test measurements in September 2016, the RAH station at a distance of 5 km from the drilling platform and the Wittstock remote site in the Northwest of the federal state Brandenburg in Germany. Since the coherency needs to be high for the remote referencing, the transfer functions are averaged over 48 hours to obtain a reasonable resolution for the depth of investigation.

#### 4.2.1 Remote referencing with the temporary remote station

In the following, transfer functions calculated over a period of 48 h from September 25th to 26th, 2016 are discussed. The following operations were carried out at the drilling site during these two days. On September 25th, the loss zones in the well were cemented down to 2950 m with mainly with flow rates of 15 and up to 30 L/s. At 3:10 p.m., a seismic event of magnitude 0.86 occurred in the reservoir zone. On September 26th, drilling was performed from 2945-2950 m with flow rates up to 45 L/s and high frequency changes (Figure 4.3).
Figure 4.3 Changes in injection flow rate during cementation and drilling from September 25th to 26th, 2016 at the RN15/IDDP2 well.

The single-site processed transfer function of the temporary remote station from September 25th to 26th, 2016 is given in Figure 4.4. Differences in XY and YX components in both apparent resistivity and phase are relatively small indicating a well-layered 1-D underground. Relatively large error bars in the phase between 2 and 10 s reveal some issue of this station being used as remote reference.

Figure 4.4 Single site processed XY (blue) and YX (red) components of apparent resistivity (a) and phase (b) of the temporary remote reference MT station from September 25th to 26th, 2016.

Figure 4.5 compares the transfer function of the same date using single-site and remote referenced processing. Single-site processing shows comparably small error bars and relatively smooth changes in resistivity and phase over most of the periods. Small outliers are observed at $2.5 \cdot 10^{-1}$ and 1 s in the apparent resistivity and at 1 and 2.5 s in the phase. Between $1.5 \cdot 10^{-1}$ and 1 s the resistivity of the YX component decreases from about 6 $\Omega$m down to 1 $\Omega$m compared to 2 $\Omega$m in the XY component. Both, the small outliers and the decrease in resistivity disappear with remote referenced processing. A clear decline in quality of the transfer function is observed for the low periods down to $3 \cdot 10^{-2}$ s.
4.2.2 Remote referencing with the RAH station

For completeness, we present here (Figure 4.6) the remote-referenced transfer functions of the GUN station from January 10th to 11th, 2017 using the RAH station. As mentioned above, these measurements of this station were of bad quality and consequently, the obtained transfer functions reveal unrealistic results ranging from apparent resistivity values of $10^4$ to $10^4$ $\Omega$m and extreme error bars for the phase.

Figure 4.6 Remote reference processed transfer functions using the RAH reference station, XY (blue) and YX (red) components of apparent resistivity (top) and phase (bottom) of GUN MT station from January 10th to 11th, 2017.

4.2.3 Remote referencing with the Wittstock station

The Wittstock station is located in the Northwest of the federal state Brandenburg in the Northeast of Germany and operated by the Geo Research Center, GFZ since 2010 as continuous MT reference station. It is equipped with different sensors to measure both, middle to high frequency variations of the horizontal magnetic field components as well as slow magnetic variations, at sampling rates of 1 Hz to 6 kHz (Ritter et al. 2015a; Ritter et al. 2015b). Representative time series of the horizontal magnetic components of Wittstock from December 11th 2016 are compared in Figure 4.7 to the measurements of the GUN monitoring station revealing specific noise in the period between November 30th to December 18th 2016. In the latter, peaks are observed regularly in the $H_x$ component. Its baseline, however, reveals a smaller amplitude compared to the data from Wittstock. Here, random noise is observed in both channels.
Figure 4.7 Horizontal magnetic components Hx and Hy of representative time series of December 11th 2016 from the Wittstock remote station (black) and the GUN monitoring station (blue).

Due to different sampling frequencies of 250 Hz in Wittstock, compared to 512 Hz at GUN, the data of Wittstock were resampled using interpolation. In Figure 4.8 a comparison between single site and remote referencing processed transfer functions of a representative example from December 17th to 18th 2016 that is comparable to the sample in Figure 4.5 is shown. The single-site processed transfer function reveals low error bars across the entire period range, including the anomaly observed between about 0.2 and 1 s that is pronounced in the YX component of the apparent resistivity. The anomaly disappears in the remote referenced transfer function, leading, however, to a strong increase in error bars at periods > 0.2 s and < 0.008 s in both, apparent resistivity and phase.

Figure 4.8 Remote reference processed transfer functions using the Wittstock reference station, XY (blue) and YX (red) components of apparent resistivity (top) and phase (bottom) of GUN MT station from September 25th to 26th, 2016.
Given short wavelength of the perturbations introduced by drilling and reservoir engineering (Figure 4.3) as well as even shorter wavelength of seismicity with respect to the period of integration of 48 h, we can consider the sought-after electromagnetic appearing as uncorrelated signal with the distant remote reference station. As shown in Figure 4.6, the local station RAH is not applicable for remote referencing due to bad quality. Thus, in the following, we will address the elimination of noise from the measured data without eliminating the sought-after electromagnetic signal from the introduced perturbations.

4.3 Noise sources

Anthropogenic electromagnetic noise may result from many sources that are often difficult to identify and may occur at significant distance. In Figure 4.9, we present parameters over time that indirectly indicate major possible sources of electromagnetic noise that can arise from activities on the drilling platform, i.e. the pump rates of the three pumps used for mud circulation during drilling, the drill bit’s torque, the number of rotations, and the rate of penetration of the drill bit. The torque is the rotational force between the drill string and the formation. The rounds per minute is the frequency of rotations performed by the drill bit whereas the rate of penetration is a measure of the speed at which the drill bit can break the rock under it and thus deepen the wellbore. The drill bit parameters are mainly active until end of December 2016 and then shortly again before end of drilling. In addition, high frequency changes in amplitude are shown in Figure 4.9 for certain time intervals.

In the following, the correlation between changes in the apparent resistivity in the frequency range of interest and these drilling parameters is analyzed. Representative examples for the resistivities of 5 and 10 Hz are shown Figure 4.10 for both polarizations, XY and YX. These frequencies are in the interval between 0.1-4 s, in which significant changes in the transfer functions were observed. Correlation coefficients between the drilling parameters and the resistivities range between 0.27 and 0.5 indicate no correlation. Note that it is not excluded that other sources influence the signal. However, an influence of the operations at surface seem not to be responsible for the resistivity changes in the investigated frequency range.
Haaf et al.

Figure 4.9: Drilling parameters versus time during the final drilling periods: the pump rates of the three pumps on site (left top), number of rotations (rounds per minutes RPM, left bottom), torque (deci-Newton meter, right top), and rate of penetration (meters per hour, right bottom) of the drill bit.

(a) Torque

Corrcoeff: 0.34088; 0.27481; 0.47605; 0.47605

(b) Rounds per minute

Corrcoeff: 0.3891; 0.33224; 0.50374; 0.50374
Figure 4.10: The correlation between apparent resistivity at 5 and 10 Hz for both polarizations XY and YX and the drilling parameters presented in Figure 4.9 for a) torque, b) number of rotations, c) rate of penetration, and d) the total pumping rate.

4.4 Single Site processing with data filtering

Since e.g. the 14 Hz noise (Figure 4.1) with a duration of about 60-90 s occurs approximately every half hour between November 30th and December 18th 2016, deletion of the noise from the data would result in a data loss of about 50-70 minutes per day. To better visualize the noise peaks in the spectrum, the data were decimated to lower frequency bands (128 Hz). Pre-filtering using notch filter for the respective bandwidths were applied to the 128. The results are presented in Figure 4.11. The spectra indicate a significant elimination of the 14 Hz noise signal and a clear reduction in amplitude is shown in the time series. However, a complete elimination of the peak is not obtained.
Figure 4.11 a) Comparison of a) noise spectra and b) time series of the measured (decimated to 128 Hz for frequencies < 1 Hz) and filtered data of the electric and magnetic components from December 11th, 2016 of GUN MT station.

Finally, the processed transfer functions are now composed of 512 Hz for the high frequency range down to 10 Hz and 128 Hz for the low frequencies > 1 Hz. Between 1 and 10 s (including the dead band), the sampling frequency with lower error bars is used.

5. DISCUSSION AND CONCLUSION
Due to the high frequency of the perturbations applied during drilling and reservoir engineering and the therefore presumed high frequency of changes in the electromagnetic field, in MT monitoring, conventional processing of MT data as applied in exploration with the aim to obtain smoothest distribution must be questioned in our case.

Here we demonstrated that low perturbations represented by low error bars in the transfer functions are not improved by remote referencing. The data uncertainties in the transfer functions were computed using the robust statistical Jackknife approach (Chave and Thomson 2004). In contrast, the changes in electric resistivity, which have been related to fluid injection in comparable studies (e.g. (Abdelfettah et al. 2018), appear as uncorrelated noise in the remote referenced processing. To eliminate only the uncorrelated noise that originates from operations at the surface, we propose to apply notch filters of the respective frequencies. In the case of high frequency signal an improvement of filtering is achieved by decimation of the sampling frequency prior to the filtering.

ACKNOWLEDGEMENTS
The DEEPEGS project has received funding from the European Union’s HORIZON 2020 research and innovation program under grant agreement No 690771. We would like to thank P. Saillhac (EOST) for providing processing software in the framework of the Labex G-Eau-Thermie Profonde, which is co-funded by the French government under the program “Investissements d’Avenir”. Furthermore, we thank Albert Borbergson and Stefán Audunn Stefansson for surveying the MT stations. In addition, we would like to thank Anne Neska for her helpful input about this work. The Geophysical Instrument Pool Potsdam (GIPP) provided data from permanent magnetotelluric reference station. This work is partly supported through the Helmholtz-Portfolio project Geoenergy and the Helmholtz renewable energy program.

PUBLICATION BIBLIOGRAPHY


Haaf et al.


Ritter, Oliver; Muñoz, G.; Weckmann, Ute; Klose, Reinhard; Rulff, Paula; Rettig, St. et al. (2015a): A Permanent Magnetotelluric Remote Reference Station in Wittstock, Germany.

Ritter, Oliver; Muñoz, Gerard; Weckmann, Ute; Klose, Reinhard; Rettig, Stefan; Schüller, Manfred et al. (2015b): Permanent Magnetotelluric Reference Station Wittstock, Germany. With assistance of Oliver Ritter, Gerard Muñoz, Ute Weckmann, Reinhard Klose, Stefan Rettig, Manfred Schüller et al.
Improving Geothermal Economics by Utilizing Supercritical and Superhot Systems to Produce Flexible and Integrated Combinations of Electricity, Hydrogen, and Minerals

Wilfred A. Elders (1), James Shnell (2), Guðmundur Ó. Friðleifsson (3), Albert Albertsson (3), and Robert A. Zierenberg (4)

(1) Department of Earth Sciences, University of California, Riverside, California, USA
(2) Ocean Geothermal Energy Foundation, California, USA.
(3) HS Orka, Svartsengi, Grindavik, Iceland
(4) Dept. of Earth and Planetary Sciences, University of California, Davis, California, USA.

Keywords
Geothermal Economics, Supercritical, Superhot, Hydrogen, Mineral Extraction

ABSTRACT

In 2017, a 4.5 km-deep well in SW Iceland reached supercritical conditions with a bottom hole temperature probably >600°C) and a pressure of 35MPa. This paper discusses the potential significance of this achievement. Supercritical wells could produce up to ten times more power than normal high-temperature geothermal wells. Although the cost of drilling supercritical wells is greater than the cost of drilling conventional wells, this should be offset by the much higher power output per well, yielding more favorable economics. Producing higher temperature working fluids creates other possibilities to improve economics by making downstream processes more efficient. To improve earnings, the geothermal industry could improve returns on investments by taking a fully integrated and flexible approach that uses the electricity generated to extract value from supercritical and superhot fluids (i.e., above supercritical temperatures but at pressures below supercritical). Where the conditions permit, this can be done by selling electricity when demand is high, and at times of lower demand using electricity to produce hydrogen as a fuel by electrolysis of hot or supercritical water. Electrolysis is more efficient at high temperatures, but electrolytic cells require clean water, so heat exchangers and/or desalination would be necessary. Similarly, when the chemistry of geothermal brine is suitable, salable products such as lithium, base metals and other mineral products could be extracted from the brines. Shnell et al. (2018) discuss new technological approaches to these processes in an accompanying paper. The future of utilizing supercritical and superhot geothermal systems lies in CUSGER (Combined Use of Supercritical Geothermal Energy Resources), the name suggested for flexible integration of the production of electric power, hydrogen, minerals, renewable methanol, and desalinated water. A new chapter in the development of alternative energy could be about to begin.
Elders, Shnell, Friðleifsson, Albertsson, and Zierenberg

1. Introduction

Compared to the phenomenally fast growth of electricity generation by carbon-free sources such as solar and wind, the worldwide rate of growth of installed geothermal generating capacity is very modest. According to a recent global status report on electric power generation, renewable power generation reached 70% of the net additions to installed capacity in 2017 (Ren21, 2018). An estimated 0.7 GW of new geothermal power came online in 2017, bringing the global total to an estimated 12.8 GW. However, this represents only ~1% the worldwide renewable power capacity (excluding hydro) of 1,081 GW, whereas solar PV capacity was 402 GW or 37% of this renewable power capacity. Unlike the intermittent generation from solar and wind power, geothermal generation has the advantage of being a source of baseload power. However, in certain circumstances this is not an advantage. For example, in California, USA, the rapid development of solar power is causing problems in balancing the grid. In the early evening, when the sun goes down, the demand for electricity remains high. (“The Duck Curve”, see Figure 1). In such an environment it is clearly desirable that any large new sources of electrical generation should be flexible with respect to time of day, for example by incorporating battery or pumped storage, or other means of flexibility that respond to the daily changes in the ratio of supply to demand.

![Figure 1: Projected daily electricity demand, minus wind, and solar generation, on a typical spring day in California. There is a risk of overgeneration in the middle of the day and early afternoon, followed by a steep ramp where an additional 13 GWe is needed (Source: California Energy Commission, Annual Report 2017, Figure ES-4).](image)

Recent cost comparisons between various types of renewable power generation indicate that, even without subsidies for renewable energy, in the appropriate circumstances geothermal electric power can be cost competitive. For example, the unsubsidized cost of community PV generation is estimated to be between $76/MWh and $150/MWh, while geothermal generation is estimated to cost between $77/MWh to $117/MWh (Lazard, 2017). However, development of geothermal resources has the disadvantage of requiring large front-end investments, including...
surveys to select drilling sites, drilling exploration wells, and if the exploration phase is successful, drilling production and injection wells, before building a plant for generation of electric power. Lazard (2017) estimates that the capital cost per installed megawatt for geothermal power lie in the range of $4,000 to $6,000/kWh whereas the capital costs for installing community solar PV are only $1,550/kWh to $3,100/kWh. Furthermore, where land and permitting are available, solar PV can be installed rapidly, whereas a “greenfield” geothermal development can take eight to ten years to produce revenue. Obviously, reducing costs and improving the reliability of exploration and drilling would directly address this problem. However, with the Iceland Deep Drilling Project (IDDP), an international consortium is taking a different approach, that is to produce supercritical geothermal resources that should greatly increase the power output per well. Currently interest in developing supercritical geothermal resources is increasing worldwide (Reinsch et al., 2017).

This paper discusses the implications of the IDDP for the future development of the geothermal industry and the potential it creates for enhancing revenues by downstream use of supercritical or superhot resources for production of hydrogen, methanol, metals and minerals, desalinated water, and various direct uses. We are using the term “superhot” for fluids that are above supercritical temperature but below supercritical pressure. An accompanying paper submitted to this meeting discusses promising newer technologies that could be applied to these downstream processes (Shnell et al., 2018).

2. Supercritical Geothermal Resources

Figure 2. The boiling point curve and critical point curves for water. The critical point for pure water is indicated by the open circle at 374°C and 22.1 MPa. As shown by the relevant critical point curves for H2O-NaCl and H2O-CO2, dissolved salt increases the temperature and pressure of the critical point whereas dissolved gas reduces the temperature and elevates the pressure of the critical point (Hashida et al., 2001).

The main motivation of the IDDP is to investigate the power potential and economics of the temperature-pressure regime of supercritical geothermal fluids (Elders et al., 2001). The critical
Elders, Shnell, Friðleifsson, Albertsson, and Zierenberg

point for pure water occurs at 374°C and 22.1 MPa, but it is higher for solutions that contain dissolved salts (Figure 2). For example, the critical point for seawater is 407°C and 29.8 MPa (Bischoff and Rosenbauer, 1988). Not only do such fluids have higher enthalpy than conventional geothermal reservoir fluids, but they also exhibit extremely high rates of mass transport due to the greatly enhanced ratios of buoyancy forces to viscous forces in the supercritical state (Fournier, 1999; Fournier, 2007; Hashida et al., 2001; Friðleifsson, Elders, and Albertsson, 2014).

3. The Iceland Deep Drilling Project (IDDP)

The IDDP is a long-term project by a consortium of Icelandic energy companies aimed at greatly increasing the production of usable geothermal energy by drilling deep enough to reach the supercritical conditions believed to exist beneath existing high-temperature geothermal fields in Iceland (Friðleifsson and Elders, 2005; Friðleifsson, Elders, and Albertsson, 2014). Modeling indicates that a well penetrating a supercritical geothermal reservoir could produce an order of magnitude more usable energy than that produced by a conventional high-temperature (~300°C) geothermal well. The fewer wells needed for a given power output result in a smaller environmental footprint. When the IDDP consortium was formed in 2003, three geothermal fields in Iceland were chosen as suitable to search for supercritical resources, Krafá in the northeast of Iceland, and Hellisheiði and Reykjanes in the southwest. The first attempt to drill into a supercritical reservoir was made in 2009 in the Krafá caldera, but the well (IDDP-1) did not reach supercritical fluid pressures because drilling had to be suspended at a shallow depth (Elders et al., 2009). This was because 900°C rhyolite magma flowed into the well at only 2,100 m depth. However, the IDDP-1 well was completed with a liner set above the rhyolite intrusion. When the well was tested, it produced superheated steam at 452°C at a flow rate and pressure sufficient to generate about 35 MWe. While flowing, this was the world’s hottest production well, but after two years of flow testing repair of the surface installations was necessary, and the well had to be quenched due to failure of the master valves. This caused collapse of the well casing and premature abandonment of the well. The IDDP-1 well is described in 14 papers in a special issue of Geothermics, 2014, volume 49, (http://iddp.is/2014/01/15/geothermics-special-issue-on-iddp-january-2014/).

IDDP-2, the second well in the series, was drilled to a vertical depth of 4.5 km in the Reykjanes high-temperature geothermal field in SW Iceland, on the landward extension of the Mid-Atlantic Ridge (Friðleifsson et al., 2017). This was done by taking over an existing 2.5 km deep well and deepening it and directionally drilling towards the main up flow zone of the system. The Reykjanes field is unique among Icelandic geothermal systems in being recharged by seawater. In January 2017, following only six days of heating, a temperature of 426°C at 34.0 MPa pressure was logged, confirming that supercritical conditions exist at 4,560 m measured depth. Inflection points in the temperature log occurred at ~3,400 m due to cooling at a major loss of circulation zone and at smaller loss zones at ~4,375 m and ~4,500 m. Whatever the fluid composition at 4.5 km depth, it is hard to argue that the measured temperatures and pressures are not supercritical. A several months-long program of injecting cold water at 50 l/s was then begun to enhance the permeability of these deeper loss zones. A second series of temperature/pressure logs run from May 23-29, 2017 indicated that the permeability of the deepest loss zone had increased and yielded an estimated bottom hole temperature of 536°C, which is consistent with other estimated formation temperatures based on extrapolation of a joint
Elders, Shnell, Friðleifsson, Albertsson, and Zierenberg

geophysical inversion of earlier wireline logs obtained at shallower depths (Hokstad and Täniavsuu-Milkeviciene, 2017). Unfortunately, a constriction subsequently developed in the production casing at a depth of ~2400 m that at present is preventing deployment of logging tools deeper.

Additional information on the downhole conditions of the IDDP-2 comes from the drill cores obtained. These sampled a series of dolerites (diabases) with chilled margins that are interpreted to come from a sheeted dike complex (Zierenberg et al., 2017; Friðleifsson et al., 2017). Alteration mineral assemblages indicate a complex history of response to dike emplacement and variable hydrothermal conditions. The shallowest IDDP-2 rocks are extensively altered to greenschist facies mineral assemblages that include epidote, actinolite, plagioclase, quartz, and chlorite. Deeper than 3,825 m, igneous clinopyroxene is pervasively altered to hornblende, and amphibolite facies mineralogy prevails that includes, in addition to hornblende, calcic plagioclase, hydrothermal olivine, orthopyroxene, clinopyroxene and biotite. Such assemblages require a minimum of 400°C to form. Unfortunately, fluid inclusions are sparse in the amphibolite facies rocks and difficult to work with as they consist of only vapor, or vapor plus daughter crystals. Study of these inclusions is still under way, and the results will be published elsewhere. Despite the extensive hydrothermal alteration, primary igneous textures are usually quite well preserved. As these dolerites lack microscopic porosity, the textures and minerals observed are consistent with alteration by high-temperature, very low viscosity, supercritical fluids (Zierenberg et al., 2017).

Another study of these cores to estimate downhole temperatures is also underway that when concluded will also be published elsewhere (R. A. Zierenberg and P. Shiffman, personal communication, April 2018). It applies petrological geothermometry to the alteration by measuring the partitioning of specific elements between pairs of minerals that appear to have equilibrated together under hydrothermal conditions. The mineral pairs being analyzed are hydrothermal clinopyroxene-orthopyroxene, the Fe-Ti oxides magnetite and ilmenite, and the feldspars plagioclase and orthoclase (Davidson and Lindsey, 1989; Ghiorso and Evans, 2008; Putirka, 2008). Titanium contents of biotite and quartz provide an additional constraint on these temperatures. Samples from the currently producing reservoir (<3,000 m) have temperature estimates that lie on the boiling point to depth curve for seawater, as might be expected. The hydrothermal mineral pairs in the deepest cores indicate that hydrothermal alteration occurred over a range extending from ~1,000°C down to 600°C. The minerals are recording hydrothermal alteration by seawater-derived fluids at supercritical conditions above 600°C. However, the actual present-day temperatures deep in the IDDP-2 still require to be determined by direct measurements.

The more than year-long experiment of injecting cold water to stimulate the deep permeable zones in the IDDP-2 ended in May 2018, and the well began to heat up. In the summer of 2018 the plan is to attempt to insert a 4-inch drill pipe past the constriction to allow deployment of a downhole fluid sampler at the bottom of the well, concurrent with design and construction of the surface installations necessary for a long-term flow test, planned to begin in the first quarter of 2019. Whatever the outcome of these planned flow tests, it is evident that the IDDP-2 has achieved its primary objectives of demonstrating, for the first time anywhere, that it is possible to drill into supercritical conditions and that permeability exists even approaching the transition
Elders, Shnell, Friðleifsson, Albertsson, and Zierenberg

from brittle to ductile behavior. It is also evident that, if the flow tests are successful, IDDP-2 should be the world’s hottest producing geothermal well.

4. Implications for the Energy Market in Iceland and Beyond

If the flow tests planned for the IDDP-2 live up to expectations and lead to development of supercritical resources in the principal geothermal fields in Iceland, how would this new electricity be used in Iceland and elsewhere?

Iceland has the highest electricity production per capita in the world, (19,000 GWh/year for a population of ~300,000) and is in the unique position of producing entirely “green” electricity. Approximately 73% comes from hydroelectricity (1,986 MWe) and 27% (655 MWe) is produced by conventional flashed steam geothermal plants. The geothermal companies also provide hot water to heat 97% of the buildings in Iceland, and for other uses such as drying fish, greenhouses, and bathing (Albertsson and Jonsson, 2010). Favorable electricity prices have attracted energy-intensive industries, such as aluminum smelting and production of ferro-silicon, that together use 77% of the electricity produced. The cost is between 25-30 USD/MWh for contracts negotiated 10 to 15 years ago. For future contracts, Landsvirkjun, the Icelandic National Power Company, is proposing long-term contracts at a fixed price of 43 USD/MWh for 12 years, with discounts in the first 5-7 years for “greenfield” projects (source: http://askjaenergy.com//iceland-introduction/energy-data/).

In addition to developing new energy intensive industries, Iceland has an even larger potential electricity market that could be developed within the next few years. “IceLink” is a plan to build a 1,200 km long, submarine, high-voltage DC cable to Scotland to interconnect Iceland’s electric grid to those of the UK and beyond. The additional annual generation required is estimated to be 5,000 to 6,000 GWh. Landsvirkjun estimates that 3,900 GWh of this would require construction of new hydroelectric, geothermal, or wind power plants, an increase of >20% in the total installed generating capacity (Askja Energy - Report posted April 18, 2018). There is clearly a market in Iceland for electricity generated by more efficient superhot and supercritical geothermal resources. A first step could be to decarbonize Iceland’s fishing fleet by converting to use hydrogen as a fuel.

However, if Iceland is successful in developing supercritical geothermal energy it could impact high-temperature geothermal resources worldwide. The potential advantages of the approach of accessing hotter and deeper geothermal resources include:

(1) Improvement in the ratio of drilling costs to power output per well. Although deeper wells would be more expensive, this should be offset by much higher power output per well. (2) Improvement in the power output of existing geothermal fields without increasing their environmental footprints. (3) Improvement in the lifetime of existing geothermal fields by increasing the size of the producible resource by extending production downward. (4) Accessing deeper, hotter, environments for fluid injection. (5) Improvement in the economics of geothermal power production. Higher-enthalpy aqueous working fluids in a turbine have a higher heat-to-power efficiency and therefore should potentially yield more favorable economics. Higher temperatures of the working fluid result in higher exergy (availability of maximum electrical power production potential for a given flow rate).
Elders, Shnell, Friðleifsson, Albertsson, and Zierenberg

5. CUSGER (Combined Use of Supercritical Geothermal Energy)

The marketability of new electrical capacity from more efficient supercritical (or superhot) geothermal resources depends upon both the local geology and the prevailing economics of electricity production and distribution. However, one thing they have in common is that pricing needs to be competitive. The unique feature of geothermal resources compared to other kinds of alternative energy is that geothermal wells produce combinations of heat and water. The flashed steam passes to a turbine-generator, but the still hot separated brine goes to a disposal well. In this regard, the very high enthalpy of supercritical and superhot systems creates new opportunities to add value by (1) allowing flexibility in sales of electricity depending on time of day, and (2) more importantly adding revenue from downstream use of the hot fluids by, for example, making hydrogen and methanol, extracting dissolved metals and minerals, desalinating water, and finally direct use of the spent fluids. The CUSGER scheme proposed here begins with negotiating contracts for power sales that have prices depending on the time of day. A CUSGER plant could sell electricity to the grid when demand is high and when demand is lower could use all or part of the electricity on site to make salable products.

5.1 Electrolysis and Desalination

The key part of the proposed CUSGER scheme is, at suitable times of day, to use all or part of the electricity produced for electrolysis to separate hydrogen and oxygen from clean water. Hydrogen is mainly used in industrial chemical and refining processes, in metallurgy, glass production and electronics, and more recently as a transportation fuel. Currently, production by electrolysis of water is only a minor source of hydrogen as the dominant source of commercial hydrogen production uses industrial steam to reform methane or natural gas. The availability of supercritical water would improve the economics of electrolysis relative to reforming natural gas. This could also be helped by carbon credits as reforming methane releases CO2, whereas hydrogen fuel releases only water. But the main point is that, at supercritical conditions, electrolysis is much more efficient, and so the electricity needed is much less (Shnell et al., 2018). Similarly, the use of very high enthalpy geothermal fluids in heat exchangers should make desalination more cost effective. The accompanying paper by Shnell at al. (2018) describes new technical developments in electrolysis and desalination that promise to improve the economics even more.

5.2 Renewable Methanol

Another proposal included in CUSGER is production of renewable methanol. The carbon footprint of generating electricity from geothermal flashed steam is small compared to generation using fossil fuels. For example, geothermal plants produce an amount of CO2 that is typically less than 30% of that produced by combined cycle gas turbines generating the same amount of electricity. IDDP-2 was drilled in the Reykjanes geothermal field, which currently has an installed capacity of 100 MWe. This plant provides the CO2 from its gas extractors to a methanol plant, built and operated by an independent company, Carbon Recycling International, where 5 MWe of power is used to purify the CO2 and combine it with hydrogen (produced by electrolysis) in a catalytic reaction to make more than 5 million liters of methanol a year. This renewable methanol is sold to be blended with gasoline and used in the production of biodiesel in Iceland and abroad (see: Carbon Cycling International at www.cri.is.-info@cri.is). As hydrogen
production by electrolysis is an integral part of CUSGER, capturing the CO₂ for methanol production should be even more efficient.

5.3 Mineral and Metal Extraction

An additional source of revenue included in the CUSGER concept is the extraction and refinement of metals and salable minerals from supercritical and superhot geothermal fluids. Many geothermal brines contain high concentrations of such potential products. For example, historically Laderello in Italy was first developed as a source of borax, but today the worldwide geothermal industry has very little commercial production of metals and minerals.

Table 1. Some metal concentrations (mg/kg) in the well State 2-14, in the SSGF, calculated to reservoir conditions at >300°C (data from the Salton Sea Scientific Drilling Project, Elders and Sass, 1988).

<table>
<thead>
<tr>
<th>Element</th>
<th>Li</th>
<th>Rb</th>
<th>Cs</th>
<th>Mn</th>
<th>Fe</th>
<th>Zn</th>
<th>Cu</th>
<th>Pb</th>
<th>Cd</th>
<th>As</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>209</td>
<td>132</td>
<td>142</td>
<td>1500</td>
<td>1710</td>
<td>507</td>
<td>6.8</td>
<td>102</td>
<td>2.3</td>
<td>5</td>
</tr>
</tbody>
</table>

This is true even for the Salton Sea Geothermal Field (SSGF) in southern California, which, among currently producing geothermal systems, has the most concentrated brines (up to 25 weight % TDS - more than eight times the salinity of seawater). The SSGF currently has an installed generating capacity of ~400 MWe, but the latest published estimate of its geothermal reserves, to 3 km depth, indicated that it could generate 2,950 MWe for 30 years (Kaspereit et al., 2016). Despite its huge heat content, development of the SSGF resource was slow because of its very high salinity. This problem was overcome by creative chemical engineering in designing the power plants operating today. Although these brines contain unusually high concentrations of metals (Table 1), previous attempts by the principal operator of the SSGF (CalEnergy), using solid-liquid ion exchange to extract zinc from ZnCl₂, proved to be uneconomic at that time.

A simple calculation indicates that the lithium in solution in the SSGF, at current prices (recent reported to be >$13,000 USD/tonne) in this large geothermal system to a depth of 4 km could be worth several billion USD (not considering costs of extraction and price elasticity). The accompanying paper, by Shnell et al. (2018), describes some of newer technology that could be applied to this hitherto intractable problem by using supercritical or superhot geothermal fluids. In appropriate circumstances in the CUSGER scenario, along with power production, part of future developments would be extraction of valuable metals, such as lithium, providing an additional revenue stream, that, in favorable cases, could possibly exceed the revenues from power sales.

5.4 Combination and Integration
Elders, Shnell, Friðleifsson, Albertsson, and Zierenberg

Figure 3: Possible schemes for CUSGER processes using supercritical or superheated fluids with integrated and flexible production of industrial steam, electricity, industrial gases, methanol, hydrogen and hot water and desalinated water for direct uses. Figure 3A: using supercritical or superhot fluids directly in turbines in two stages. Figure 3B: Using clean water, heated by supercritical or superhot fluids, as the working fluid in the turbine.
Elders, Shnell, Friðleifsson, Albertsson, and Zierenberg

The overarching principle of the CUSGER scheme is the synergism of integrating different technologies that use supercritical fluids to improve the economics of geothermal resources. Figure 3A and 3B present diagrams of how this integration could occur for two different scenarios: (1) where the chemistry allows using the supercritical or superhot geothermal fluid directly in turbines with minimal treatment such as removing condensate, non-condensable and acid gases, and (2) where the supercritical or superhot geothermal fluid is not suitable for direct introduction in a turbine and so heat exchangers are used to heat a clean working fluid, most likely water (but Shnell et al., 2018 discuss using CO2 turbines). Many other combinations are possible, depending on the local conditions.

6. Conclusions

The economics of utilizing such supercritical and superhot geothermal fluids could be greatly enhanced by using a flexible and integrated approach. Using superhot water and electricity on site to make hydrogen fuel obviates the need to use electricity storage such as batteries or pumped storage at times when electricity demand is low, while keeping flow rates from the wells constant. Similarly, the higher enthalpy should improve the economics of extracting metals and minerals from the brines and making renewable methanol and desalinated water. Of course, not all these techniques will be applicable in any given case and a great deal of technology development will be necessary. The CUSGER approach will likely evolve in a step-wise fashion at different sites.

Supercritical conditions are not restricted to Iceland, but should occur deep in any young, volcanic-hosted geothermal system. Recent numerical simulations of magma-heated, saline, hydrothermal systems indicate that phase separation is the first-order control on the dynamics and efficiency of heat and mass transfer near intrusions (Scott et al., 2017). Above deep intrusions emplaced at >4 km depth, where fluid pressure is >30 MPa, phase separation occurs by condensation of hypersaline brine from a saline intermediate-density fluid. The fraction of brine remains small, and advective and vapor-dominated mass and heat fluxes are therefore maximized for exploitation of supercritical geothermal resources.

Similarly, superhot fluids at less that supercritical pressures have been encountered in wells in several volcanic geothermal fields. Deep wells drilled in Kakkonda in NE Japan (Muraoka et al., 1998), Laderello in Italy (Bertini et al., 1980), Los Humeros in Mexico (Gutiérrez-Negrín and Izquierdo-Montalvo, 2010), Menengai in Kenya (Mbai et al., 2015), Puna, Hawaii, USA (Teplow et al., 2009) and Salton Sea in USA (Kaspereit et al., 2016) have all encountered temperatures above 374°C. By drilling deeper to reach higher pressures, development of supercritical geothermal resources could be possible there and in many other volcanic areas worldwide. For example, in Japan the Japanese Beyond Brittle Project (JBBP) is an ambitious EGS project to extract geothermal energy from >500°C neogranites (Muraoka et al., 2014). Another future possibility, when the technology and economics permit, is to produce useful energy directly from the worldwide submarine mid-ocean ridge systems (Elders, 2015). Vents discharging supercritical water on the sea floor have been directly observed at 5°S on the Mid-Atlantic Ridge (Koshchinsky et al, 2010). Similarly, if the technology can be developed, very high temperature energy could be extracted directly from magmas (Eichelberger et al., 2018).

Until the series of flow tests are concluded we will not know the economic potential of the IDDP-2 experiment. However, despite all the problems encountered, we are encouraged by the
Elders, Shnell, Friðleifsson, Albertsson, and Zierenberg

results of the IDDP-1 and IDDP-2 so far. We know where to drill at Krafla and Reykjanes and have learned much about drilling and completing very hot wells. This knowledge will be applied in planning and drilling the IDDP-3 at Hellisheidi in the next few years. Having drilled what appears to be the world’s hottest geothermal well, and by demonstrating that it is possible to drill into supercritical conditions, we believe that we are on the threshold of a new era of geothermal development with the potential to yield very large new sources of environmentally friendly, alternative energy.

Acknowledgements

The IDDP-2 was funded by HS Orka, Landsvirkjun, Orkuveita Reykjavíkur, and the National Energy Authority in Iceland, together with ALCOA (for IDDP-1) and Statoil (for IDDP-2). The IDDP has also received funding from the EU H2020 (DEEPEGS, grant no. 690771), and science funding from ICDP and NSF (grant no. EAR – 05076725 to Elders), which are greatly appreciated.

REFERENCES


Elders, Shnell, Friðleifsson, Albertsson, and Zierenberg


Elders, Shnell, Friðleifsson, Albertsson, and Zierenberg


Elders, Shnell, Friðleifsson, Albertsson, and Zierenberg


Thermal stimulation of the deep geothermal wells: insights from the H2020-DEEPEGS project

Mariane Peter-Borie¹, Annick Loschetter¹, Arnold Blaisonneau¹, Van Hieu Tran¹, Emmanuel Gaucher², Omar Sigurdsson³, Gudmundur Omar Fridleifsson³, Pierre-Clément Damy⁴, Morgan Le Louis⁵, Helga Tulinius⁵

¹ BRGM, 3 Avenue Claude Guillemin, 45060 Orléans, France
² KIT, Adenauerring 20b, D-76131 Karlsruhe, Germany
³ HS Orka, Svartsengi, 240 Grindavík, Iceland
⁴ FONROCHE Géothermie, 2 av. P. Angot, 64053 Pau Cedex 9, France
⁵ ISOR, Grensásvegur 9, 108 Reykjavík, Iceland

Contact: m.peter-borie@brgm.fr

Keywords: DEEPEGs, EGS, stimulation, thermal, Iceland, France

ABSTRACT

Enhanced/Engineered Geothermal System (EGS) generally requires well stimulation to enhance the injectivity to commercial levels. This stimulation step still constitutes a challenge to permit large-scale deployment of this renewable energy.

The present work is focused on thermal stimulation, which is often underestimated, and very little investigated. However, it may constitute a key effect especially in geothermal wells, for which temperature differences between the fluid and the formation are expected (either intentionally during dedicated stimulation, or less intentionally during drilling and operations).

Thermal stimulation can lead to both thermal shearing and thermal fracturing. We model both processes, respectively through analytical and numerical modelling, applied to two EGS demonstrators in the frame of the H2020-DEEPEGs project. The first demonstrator, located in Iceland, is characterized by very high rock temperature, and is likely to encounter high thermal stimulation (both by shearing and by fracturing). The second demonstrator, located in France corresponds to lower rock temperature. In spite of uncertain context (stress state, rock properties, etc.), it appears that thermal stimulation is likely to lead to the re-opening of the pre-existing sealed fractures.

1. INTRODUCTION

The Enhanced/Engineered Geothermal System (EGS) constitutes a promising renewable energy technology to produce heat and/or electricity from deep geothermal resources. White Paper published under the IPGT partnership (International Partnership for Geothermal Technology) states the following (IPGT, 2012): "Reservoir stimulation is the single most critical research area for enabling the development of commercial EGS technology. Stimulation also provides a method to increase production in conventional geothermal wells and low permeability regions of otherwise productive geothermal systems." The H2020-DEEPEGs project (grant agreement No 690771) aims at demonstrating the feasibility of EGS for delivering energy from renewable resources in Europe. In this framework, two deep geothermal wells in Iceland and in France were drilled to demonstrate the EGS technology in different geological contexts.

The first demonstrator (RN-15/IDDP-2) located in Reykjanes (Iceland) targets the sheeted dyke complex in a magmatic field. It is a high temperature reservoir (more than 450°C expected) at 4460 m TVD. The second demonstrator located in Vendenheim (France) targets a normal fault in the plutonic basement, in the Upper Rhine Graben, with temperature around 200°C. In both cases, short time injectivity index was estimated lower or equal to 3.1 L.s⁻¹.bar⁻¹ at the end of the drilling operation. This confirms the necessity of stimulation methods to enhance the injectivity to commercial levels.

Stimulation operations are commonly part of the completion programs of conventional geothermal wells worldwide, both in high-temperature volcanic environments and in lower temperature fracture-controlled convective systems and deep sedimentary systems. The purpose of such operations is to enhance the output of the wells, either by improving near-well permeability that has been reduced by the drilling operation itself, or to open up hydrological connections to permeable zones not directly intersected by the well in question. The methods generally used are based on the activation of mechanical, thermal and/or chemical mechanisms that drive to rock permeability enhancement (modified from Axelsson and Thorhallsson, 2009).
In this paper, we will focus on the thermal stimulations that can lead to pre-existing-fracture shearing and/or rock fracturing. We will discuss its effects on both demonstrators. Indeed, this potentially mixed-mechanism stimulation (using the term defined by McClure and Horne, 2014) has been used on the Icelandic well and it is planned for the French wells. Note that other technologies have been used or are planned for both demonstrators such as hydraulic stimulations (both demonstrators), chemical stimulations and dual-laterals drains (French demonstrator). Within the set of available technology, thermal fracturing is very attractive compared to the other options for cases for which flow can be restored or enhanced by the generation of a relatively near wellbore fracture network that will (hopefully) reconnect to a main reservoir flow system. The fluids commonly used during thermal stimulation of geothermal wells are indeed harmless, easy-to-prepare, with simple chemistry (compared to those used for hydraulic stimulations), low demanding in terms of equipment and usually low cost (Flores et al., 2005). Flores et al. (2005) claim that thermal fracturing is potentially the most attractive, but least understood, stimulation technique and that no well-founded methodology to design such well treatments was available at that time. For instance, a standard procedure for conducting thermal stimulation operations has not been established yet, and the mechanism of cold-water stimulation is still poorly understood. Even though some time has passed since the publication of their paper, a well-founded methodology is still lacking.

In this paper, after a state of the art on thermal stimulation, we present the method and the tools used for a first assessment of the efficiency of the stimulation depending on the suspected involved geomechanisms. In the fourth and fifth paragraphs, after a brief description of the demonstrators, we present the thermal stimulations (done or planned) and the results of the assessment of thermal stimulation potential efficiency. The results are then discussed.

2. THERMAL STIMULATION: STATE OF THE ART

2.1 Mechanisms

Covell (2016) describes what is involved in thermal stimulation, according to the most recent understanding: thermal stimulation is driven by thermal contraction caused by the significant temperature difference between cold injection of fluid and hot reservoir rock formation, which can enhance near wellbore permeability.

Several mechanisms that may enhance reservoir permeability through thermal stimulation include (modified from Covell, 2016): 1) the widening or reopening of pre-existing fractures due to thermal (cooling) rock contraction, 2) the shearing of pre-existing fractures after widening/reopening, 3) the creation of new fractures due to thermal contraction (thermal fracturing), or 4) the development of secondary fractures due to the contrast in the thermoelastic properties of the mineral components of reservoir rocks. In-situ permeability increase linked to thermal stimulation is difficult to associate to fracturing or shearing. However, from a theoretical point of view, both mechanisms can be distinguished.

From a physical point of view, the injection of a fluid colder than the rock mass into a deep reservoir could potentially cause thermo-mechanical disturbances resulting in rock weakening. Indeed, the thermal solicitation induces differential strains at the origin of thermo-mechanical stresses. When these stresses exceed the mechanical resistance of the rock, microcracks and failures could appear (thermal fracturing). Strains at the origin of this process can be mainly due to (Siratovich et al., 2015): 1) microcracks between grains with different thermoelastic moduli or between similar, but misaligned anisotropic grains (differential and incompatible thermal expansion); 2) microcracks may also be initiated within individual grains at internal boundaries which are sites of thermal gradients; 3) thermo-chemical mechanisms may also be involved, such as bursting of fluid inclusions, mineral decomposition, devolatilization.

Thermal shearing is the shearing of a fracture (natural or induced by previous stimulation processes) due to thermal loading. This phenomenon is very understudied as most authors attribute shear slip on fractures to an increase in the pore pressure field linked to water flow. But the pore pressure increase does not necessarily correspond to the existence of flow and several authors show that injection pressure in geothermal reservoirs is often insufficient to open a fracture, pointing the importance of thermal stresses as reported by Ghassemi et al. (2007). Under typical EGS field conditions, a substantial increase in fracture slip is observed when thermal stresses are taken into account. Theoretically, two physical processes can lead to thermal shearing: 1) fluid expansion (fluid warming; highlighted in Delage, 2013; Delaney, 1982; Palciauskas and Domenico, 1982 among others); 2) wall contraction (rock cooling).

2.2 Experience in geothermal fields

Thermal stimulation has already proven to be effective on several EGS and conventional geothermal fields. One of the oldest publications available explicitly discussing thermal stimulation of geothermal wells is written by Benson and Daggett (1987). They highlighted that three wells of the Los Azufres (Mexico) high temperature geothermal field indicated an increase in permeability during cold water injection. They could also model an increase in permeability by a factor of approximately 5 in the near-bore region after 2-3 h of injection. They also concluded that thermal contraction and thermal stress cracking of the formation were responsible for the permeability enhancement.

Flores et al. (2005) analysed field results and performed preliminary modelling to calculate effective
permeability changes, with the objective to compare thermal stimulations with other stimulation methods. They concluded that thermal fracturing is fully applicable to geothermal environments, and is highly cost effective. Grant et al. (2013) developed an empirical formula to estimate the injectivity increase of geothermal wells with time when cold water is injected. They found that injectivity of a geothermal well generally increases with time at a rate proportional to $t^n$ where $n$ ranges between 0.4 and 0.7. The increase in permeability with time can be up to two orders of magnitude. Regarding time scale, they state that the increase cannot continue indefinitely, but has been observed to continue for a few years.

The increase is also strongly dependent on the temperature difference between the formation vicinity of the wellbore and the injected fluid. Authors gathered information on a large number of wells (34) in New-Zealand and Iceland, and proposed statistical analysis to highlight the effect of temperature on injectivity. They show that the permeability ratio (defined as the permeability in cold conditions to the permeability in hot conditions) increases with the temperature difference ($\Delta T$). The authors note that there is a strong variation but nevertheless detect a trend: the variation is close to $\Delta T^3$. They also observed that most wells drilled with cold water were greatly stimulated through the effects of drilling and through operations at the end of drilling. According to them, the increase is due to thermal contraction of the rock, and causes permeability changes much greater than those due to pressure changes.

Within the literature, experience feedbacks are mainly from high temperature magmatic fields: in Iceland (Héóinsdóttir, 2014, Axellsson and Thorhallsson, 2009), at Los Humeros (Mexico, Flores-Armenta and Tovar-Aguado, 2008, and Luviano et al., 2015), at Bouillante (Guadeloupe, France, Tulinius et al., 2000), in Costa Rica (Zúñiga, 2010), in Japan (Kitao et al., 2008, and Luviano et al., 2015), at Bouillante (Guadeloupe, France, Tulinius et al., 2000), in Costa Rica (Zúñiga, 2010), in Japan (Kitao et al., 2008, and Luviano et al., 2015). The main conclusions of these stories are that it was generally not possible to identify whether the permeability increases were due to mode-1 opening, i.e. contraction of existing fractures or thermal fracturing, or shear initiation, because of the absence of sufficient experimental control, such as a repeat injection after the well had been allowed to fully recover to determine whether the improvements persisted. It was also impossible to distinguish between shearing and cleaning of drill cuttings, both of which are expected to produce irreversible increases in injectivity. It was found that thermal stimulation has a major influence in close vicinity of the wellbore. The case studies analysed show permeability enhancements caused by thermal effects, both through fracturing and shearing. The dominating mechanism caused by the thermal effects for short-term injections of cold fluid is believed to be shearing. It may furthermore be noted that fracture-filling material, near a wellbore, may crack during thermal stimulation, which may facilitate its removal with the fluid injected.

### 3. ASSESSMENT OF THE SHEARING AND FRACTURING UNDER THERMAL STIMULATION

#### 3.1 Assessment of fault plane vulnerability to shear

One initial approach to assess if discontinuities are likely to shear or not is based on analysis of the normal and shear stress applied on a given discontinuity with regard to a failure criterion (e.g.: Moeck et al., 2009; Cuss et al., 2015). The three-dimensional Mohr diagram is plotted in Figure 1, and the in-situ effective stress field is displayed. For a given discontinuity, the shear and normal stresses on a discontinuity applying on it can be plotted (on the Figure 1, by a red dot and by a blue dot). A Mohr-Coulomb failure criterion (characterised by a friction angle and a cohesion) is defined for this discontinuity and plotted in this system. The points lying above the Mohr-Coulomb failure criterion are critically stressed and are likely to shear in the current state. In case of thermal loading, we can state:

1. that the normal stress on the discontinuity decreases if the fluid expansion drives the phenomenon (displayed by green arrows on Figure 1 shifting the dots; when the cold injected fluid goes through the discontinuities, it warms up, and then it expands) or,

2. that the internal friction angle decreases if the wall contraction drives the phenomenon (displayed by a black arrow and dashed failure criterion on Figure 1; true when the rock mass is cooled down).

**Figure 1: Three-dimensional Mohr diagram.** The effective stress state is displayed by black semicircles; the red and blue dots display the shear and effective normal stresses on two discontinuities; the failure criterion is displayed by a pink line delimiting the stable and the unstable areas. Under thermal loading, the dots corresponding to discontinuities can cross the failure criterion if the normal effective stress decreases (green arrow) or if the criterion changes (black arrow and dashed failure criterion). See the text for more details.

In both cases, it leads to a further step towards the unstable area. Note that considering the high level of uncertainties, this study is qualitative (see below).
3.2 Assessment of thermal fracturing potential

Numerical simulations are performed to assess if thermo-mechanical stresses induced by thermal loading exceed the mechanical resistance of the rock. As strains at the origin of this process can be mainly due to thermal gradient in the rock mass and also to the heterogeneity of the grain contraction in the rock matrix, Discrete Element Method (DEM) has been chosen. Indeed, it is a useful approach to capture the cracking around a wellbore under stresses (e.g.: Karatala et al., 2016, Peter-Borie et al., 2018), as well as the physical phenomena at the granular phase level (micro scale), and to analyse their impact on the mechanical behaviour of the near-wellbore zone (macro scale). This approach is implemented using the code PFC2D (Particle Flow Code - 2 Dimensions, Itasca Consulting Group Inc. 2008). The proposed numerical approach enables quantifying the depth and shapes of damages. Complementary information on the approach are available in Peter-Borie et al. (2018) and references therein.

The calculation set-up consists of a two dimensional cross-section perpendicular to the well or to a pre-existing discontinuity. The numerical simulations focus on the deepest part of the well. As far as possible, the conditions observed at the bottom of each well are used in the numerical simulations (rock and injected fluid temperatures, wellbeing/discontinuity orientation, stress state if known…).

We focus our study on the behaviour of the matrix of the grained-textured rock. The description of the rock mass in the reservoir is used as a reference for the numerical rock model: dolerite for the Icelandic demonstrator and plutonic formation for the French demonstrator. The numerical simulation is performed stepwise. The aim is to reproduce, as far as possible, the state of the rock in the vicinity of the wellbore or of a pre-existing fracture before the thermal stimulation. The main steps are the borehole drilling (if any), which is simulated by removing the particles located on the wellbore surface, and the thermal loading, which is subjected to a hydraulic pressure (if any) and to a thermal loading. As a result of the thermal and mechanical loadings, cracks between numerical particles may appear. They are interpreted as rock damages; once cracks coalesce, a “macro”-discontinuity develops. If this discontinuity is connected to the borehole, then the injection pressure and the fluid temperature can penetrate into it.

If coalesced-crack discontinuity connects to the borehole, the permeability of the rock mass in the surrounding of the wellbore increases. Here, we propose a method to estimate the permeability evolution in the near-wellbore due to modelled thermal fracturing based on the investigations of Jobmann et al. (2010), Zhou et al. (2016), and Tran et al. (2018). Assuming a given initial permeability of the intact rock mass constant, we can estimate that the permeability gain is proportional to the porosity gain in the rock mass. This porosity gain is estimated from the space gain between two particles separated by a coalesced crack (more details in Tran et al., 2018).

4. THERMAL STIMULATION OF THE ICELANDIC DEMONSTRATOR

4.1 Context

The Reykjanes geothermal system is located at the tip of the Reykjanes peninsula, SW Iceland at the landward extension of the Reykjanes Ridge (NNE-striking). From the surface to around 2.5 km depth, the lithology consists of sub-aerial basaltic lavas and to a lesser degree of hyaloclastites. Below, a typical sheeted dyke complex of an ophiolite is assumed, including a swarm of tectonic vertical to subvertical fractures and faults. Most of these discontinuities strike parallel to the ridge axis (Palmason 1970; Gudmundsson 2000; Foulger et al. 2003; Karson 2016; Stefanson et al. 2017; Friðleifsson and Elders 2017).

Within the Reykjanes peninsula, the stress state evolves laterally from normal to strike-slip regime. At depth, the strike-slip regime seems to dominate (Sæmundsson et al., 2018, Keiding et al., 2009). Keiding et al. (2009) as well as Kristjánssdóttir (2013) found that $\sigma_{\text{max}}=\sigma_{\text{min}}$. It appears that the admissible ratio $\sigma_{\text{max}}/\sigma_{\text{min}}$ may be very high at 1.5 km depth ($\approx 2$) (Batir et al., 2012). The major horizontal stress is oriented NNE-SSW to NE-SW. Note that the directions of stress at depth and the strain rate observed at the surface are in a good agreement (all seems to be driven by plate motion; Keiding et al., 2009).

4.2 The Reykjanes EGS demonstrator

The drilling of RN-15/IDDP-2 has been successfully completed in January 2017 (see more in Friðleifsson et al., 2019). The final measured depth of the well is 4650 m from the ground level (True Vertical Depth: 4460 m). Cores in the sheeted-dyke complex show mainly rocks with fine-grained igneous texture: microgabbro/dolerite to fine-grained basaltic intrusive, with heterogeneous grain size (Friðleifsson et al. 2017). The temperature measured at depth under disturbed conditions was 426°C, which gives an order of magnitude of the high temperature reached. Short time injectivity index was estimated to be around 3.1 L/s/bar at the end of the drilling operation (Weisenberger et al., 2017). Like the other shallower geothermal wells of the Reykjanes geothermal field (see Axelsson and Thorhallsson, 2009), thermal stimulation was performed after the end of drilling of RN-15/IDDP-2 by cold-water-injection-and-warm-up cycles, for several months (Sigurdsson, 2019).

4.3 Investigation of the potential thermal shearing

The set of discontinuities crossing the rock mass around the RN-15/IDDP-2 well has been characterised by Khodayar et al. (2014). Figure 2 shows these discontinuities within the expected stress state. Regarding the uncertainties on the stress state, two extreme regimes are considered, a normal regime (Figure 2A) and a strike-slip regime (Figure 2B). In the case of a normal regime (A), the swarm of...
discontinuities does not seem prone to shear, unless the failure criterion is lowered. In the strike-slip regime (B), most of the discontinuities of the swarm lie in the unstable area, and thus should have sheared. Note that considering a non-zero cohesion would lead to reinforcement of the failure criterion, and would thus reduce the unstable area.

Seismic activity has been closely followed during this stimulation period, as discontinuities close to the wellbore seem to be prone to shear under thermal and/or mechanical loading. Indeed, during drilling considerable induced seismicity has been observed in connection with fluid losses (Blanck et al., 2019). This seismic activity can be considered as an indirect proof of discontinuity shearing. However, due to uncertainties on the stress state, on the level of hydraulic stimulation (that shifts the Mohr’s circles to the left), and on the effects of thermal loading, it remains difficult to identify precisely the origin of this discontinuity shearing.

Figure 2: Three-dimensional Mohr diagram (for legend detail and explanation see Figure 1. The discontinuities plotted by coloured dots are from Khodayar et al. (2014). A: Result for a regional normal faulting regime; B: Result for a strike-slip regime.

4.4 Investigation of the potential thermal fracturing by numerical modelling

In this section, we present the results of the numerical investigations on the potential rock mass fracturing around the borehole under thermo-mechanical loading (more details available in Peter-Borie et al., 2018 and Tran et al., 2018).

A thermal difference of 400°C at the bottom hole is considered in this study. No overpressure is considered in the well as a first evaluation of the impact of the thermal loading. The normal and strike-slip regimes are still considered and give insights on the shape of the potential induced damaged. In both cases, induced fractures develop under thermal loading (Figure 3). In the most isotropic cases (Figure 3A), fractures develop around the wellbore without preferential direction, following the path of least resistance defined by the local mineral distribution. With the largest 2D deviatoric stresses (Figure 3B), the fracture propagates in the direction of the 2D maximum stress. In the vicinity of the wellbore, and still under thermal loading, permeability of this induced discontinuity can be estimated (Figure 4). Fracture permeability has a downward trend from the wellbore (main branch permeability up to $10^{-11}$ m$^2$) to the tip of the induced fracture.

Figure 3: Thermal fracturing modelled after 4 hours of thermal loading. The front colour corresponds to the temperature (see legend). Each dot corresponds to a crack between two grain-modelling particles. Grey uniform colour corresponds to the area connected to the wellbore (penetration of thermal loading). A: Result for a regional normal faulting regime; B: Result for a strike-slip regime (modified from Peter-Borie et al., 2018).

Results from numerical modelling argue in favour of potential permeability increase around the wellbore due to thermal cracking and subsequent fracture development.
5. PERSPECTIVES FOR THERMAL STIMULATIONS OF THE FRENCH DEMONSTRATOR

5.1 Context and reservoir model

The second demonstrator located in Vendenheim (France) targets a N10°E-striking and 82°W-dipping fault in the plutonic basement in the Upper Rhine Graben (URG).

The targeted fault zone in the basement of Vendenheim has probably been created during Permo-Carboniferous times (sinistral shearing assumed) and submitted to a repeatedly changing stress field leading to its reactivation since then (Schumacher, 2002; Edel et al., 2007, among others). A conceptual model of the fault zone is proposed in Figure 5; it is based on drilling data and cutting analyses. This regional fault of order 2 is composed of a damaged zone (in the upper part of the hole) and of a fault core, that can be split in a low permeability zone (probably gauge), and in a heavily fractured zone. Euhedral quartz has been found in the cuttings, probably linked to hydrothermal sealing of discontinuities.

Currently, the URG is assumed to be globally an Andersonian system, i.e. the vertical stress is a principal stress. The faulting regime varies from normal faulting (mostly in the sedimentary part) to strike-slip regime. Vendenheim is located in the permutation area between a strike-slip-regime farthest North and a normal regime farthest South (e.g. Meixner et al., 2016); it is a quite area in term of natural seismicity. The main horizontal stress is roughly oriented NW–SE, with local variations from N130°E to N180°E (Meixner et al., 2016, Cornet et al., 2007). It is well-admitted that the orientation of the main horizontal stress is closer to N130°E in the Northern part of the URG and to N145° to N160° in the Southern part/Northern Switzerland (Plenefisch and Bonjer, 1997). First analyses of the breakouts observed in the Vendenheim well are consistent with a major horizontal stress between N150° and N170° (unpublished data and analyses).

5.2 The Vendenheim demonstrator

The drilling of the well doublet has been successfully completed in February 2019. The final measured depth of wells are respectively 5308 m (True Vertical Depth: 4426 m) and 5393 m (True Vertical Depth: 4650 m). The temperature measured at depth under disturbed conditions was around 200°C. The injectivity at the end of the drilling operation and after a first chemical stimulation is less than the targeted injectivity, which confirms the necessity of stimulation methods.

5.3 Investigation of the potential of thermal shearing

In this paper, we assume that the fault has been created under the Palaeozoic-time stress state. Assuming a Riedel-shear zone (main direction Y-Shear), main discontinuities subsets are the synthetic R-shears and the antithetic R’-shears as plotted in Figure 6. In this study, we also considered the traction subset bisecting the R-shears and the R’-shears.

Figure 5: Conceptual model of the geometry of the targeted fault zone based on the drilling data

Figure 6: Plot of the targeted fault on a Wulff net (in red). Theoretical sub-fractures (Riedel shear structure) in the main fault zone assuming a structuration based on a sinistral faulting in the basement during the Permo-Carboniferous time: Synthetic R-shears (blue), antithetic R’-shear (green), and traction direction at the bisecting line (black). The estimated direction of the major horizontal stress is plotted in green (arrow and thick line).
Figure 7 displays the three-dimensional Mohr diagram for this fault and the associated subsets of discontinuities for a current normal regime (Figure 7A) and current strike-slip regime (Figure 7B). For the selected failure criterion of the discontinuities (friction angle between 35° and 45°), all the discontinuities are in the stable area. It is consistent with the absence of natural seismicity. However, the R-shear planes, T-traction planes and Y-shear planes are close to the chosen lower failure criterion. Consequently, the discontinuities appear likely to shear with a slight decrease of the normal effective stress or of the failure criterion. This is even more critical for a strike-slip regime. The micro-seismic events (with magnitude lower than 1.4) that have been recorded during injection in the first well in March 2018 and localised in the reservoir area are likely an evidence of the proximity to failure of the discontinuities. This micro-seismicity may have been induced by hydro-mechanical effects due to the overpressure and/or of the thermal loading. Note that quantifying the stress induced by the cooling remains very uncertain.

Figure 7: Three-dimensional Mohr diagram (for the legend details and explanation see Figure 1; legend of the colour of the dot is in Figure 6). A: Result for a normal faulting regime; B: Result for a strike-slip regime.

5.4 Investigation of the potential of thermal fracturing by numerical modelling

First insights in the potential of plutonic formation fracturing within the context of the central part of the URG is based on the numerical modelling performed for the neighbouring Soultz-sous-Forêts EGS (Peter-Borie et al., 2015). In both cases the nature of the rock mass, the bottom-hole depth (4.5 to 5 km depth) as well as the stress state are so far comparable. Peter-Borie et al. (2015) investigated the thermo-mechanical failure in the granite at 2 km-depth and 5 km-depth for several temperature differences between the injected fluid and the granite. The main conclusion is that the temperature difference expected in the reservoir (up to 150°C) is insufficient to create new fractures at 5 km depth in the granite. Note that thermal fracturing has been obtained in simulations at shallower depth (2 km depth), for a temperature difference at least equal to 120°C without overpressure in the well, and less when overpressure is considered.

Present data from the first well drilled in Vendenheim suggest that discontinuities are more or less sealed by hydrothermal quartz. Simulation of the cooling of such a discontinuity is performed to assess its cracking potential. Figure 8 displays the thermally induced cracking around a discontinuity perpendicular to the minimum horizontal stress, with quartz sealing (Figure 8A) and without sealing (Figure 8B, plutonic walls lie directly around the discontinuity).

Figure 8: Thermal failure in a quartz vein (A) and in the plutonic formation (B) at 4775 m depth from the tip of a discontinuity perpendicular to the minimum horizontal stress. The temperature difference between the rock mass and the fluid in the fracture is 150°C. The colour scale refers to the simulated time from the cold fluid injection in the discontinuity (M. Peter-Borie, unpublished results from Soultz-sous-Forêts investigations).

The temperature difference between the rock mass and the fluid in the fracture is 150°C. In the presence of a
quartz vein partially sealing the discontinuity, numerous coalescing cracks are induced, while in the other case, only few cracks are induced in the vicinity of the discontinuity. These numerical simulations argue in favour of a localised induced thermal fracturing within the sealed discontinuities. Thermal stimulation appears to be source of a potential enhancement of fluid circulation and/or creation of new fluid paths within the sealing, while it seems that no fracturing can be induced in the granite at the considered depth.

6. DISCUSSION AND CONCLUSION

The thermal stimulation efficiency is assessed on the two demonstrators of the H2020-DEEPEGS project. The two demonstrators target fractured/faulted tight reservoirs at similar depth, but the geological contexts and the formation temperatures are different.

Within the “young” rock mass of Reykjanes, all conditions are met to an efficient thermal stimulation because:

- the current stress state drives the discontinuities creation and these discontinuities are likely to shear under a slight stress increase that can be induced by thermal loading;
- the high temperature of the rock mass allows high temperature difference with the injection fluid, then thermal fracturing is possible within the rock at the considered depth.

As a result, the Reykjanes demonstrator can quite easily develop a mixed-mechanism stimulation involving both shearing and fracturing under thermal loading. In this context, both new discontinuities and pre-existing ones would be involved in the development of the geothermal fluid flow path. McClure and Horne (2014) suggest that in this case, propagating new fractures may terminate against pre-existing fractures, preventing the formation of large, continuous fractures. Note that the induced fractures are from a tensile mechanism, and need then to be propped to stay open when the fluid warms up.

The case of Vendenheim demonstrator is more complicated:

- this plutonic basement has been structured under a stress state quite different from the current one. There is currently low natural seismicity, due to lack of natural loading. Nonetheless, the basement is prone to shear if the pore pressure increases. In this context and considering high uncertainties, it is difficult to assess the potential effect of thermal stimulation, and if it would lead to induced seismicity or not. Further analyses and feedbacks are needed.
- the temperature of the reservoir is, comparatively to the Icelandic demonstrator, twice lower. It appears to be insufficient to create large induced fractures as in Iceland. However, the plutonic basement undergone numerous hydrothermal phases and quartz seals currently a part of the discontinuities of the reservoir. Veins of quartz appear to be prone to crack under “low” thermal loading. The flow path in the pre-existing sealed discontinuities can consequently be enhanced.

Hence, the Vendenheim demonstrator can also be enhanced by thermal stimulation, however, for a similar stimulation implementation, involved mechanisms will be different. The thermal loading will principally result in the unsealing of pre-existing discontinuities by cracking the quartz veins. This process should enhance the flow path within the subsets of discontinuities of the fault zone. At first, minimal shearing mechanisms are expected, leading to few and low micro-seismic events. However, more investigations are needed to prove this point.

To conclude, this first insight on the efficiency of the thermal stimulation, we can say that, unsurprisingly, the knowledge of geological context is necessary to assess the involved mechanisms and their efficiency. Beyond the two main processes dealing with thermal stimulation, shearing and fracturing, the way to enhance the reservoir can differ a lot: in our cases, the fracturing in the Icelandic reservoir will create new paths while in the French context it leads to the re-opening of the pre-existing sealed fractures.

In the different cultural and societal contexts of Iceland and France and considering the associated sensibilities to induced seismicity or to fracturing, knowing which mechanism will be involved during stimulation and at which scale is key for an EGS success story. In France especially, the thermal stimulation plan and induced mechanisms are likely to lead to the re-opening of the pre-existing sealed discontinuities in a soft way. However, further investigations are in progress to quantitatively assess the impact of all the possibly involved mechanisms.

REFERENCES


and Geothermal Research, 2019


Peter-Borie et al.


Pálmason G. Crustal structure of Iceland from explosion seismology, Science Institute, University of Iceland, Reykjavik, 1970.


Sigurðsson O., Stimulation of the RN-15/IDDP-2 well at Reykjanes in an attempt to create an EGS system, Confidential deliverable (D6.5) H2020-DEEPEGs project, 2019.


Acknowledgements

This study was part of the DEEPEGs project, which received funding from the European Union HORIZON 2020 research and innovation program under grant agreement No 690771.

The authors would like to thank the two anonymous reviewers of the abstract for advising to focus on one stimulation type for this paper.
The Iceland Deep Drilling Project at Reykjanes - 4.5 km Deep Drilling into Supercritical Conditions

Tobias B. Weisenberger1, Björn S. Harðarson1, Kiflom G. Mesfin2, Gunnlaugur M. Einarsson1, Steinþór Nielsson1, Robert A. Zierenberg3 and Guðmundur O. Friðleifsson1

1ÍSOR, Iceland GeoSurvey, Grensávegur 9, 108 Reykjavik, Iceland; 2HS Orka, Svartsengi, 240 Grindavík, Iceland; 3Department of Earth and Planetary Sciences, University of California, Davis, CA 95616, USA
tobias.b.weisenberger@isor.is

Keywords: Iceland, Reykjanes, Drilling, IDDP, supercritical

ABSTRACT

In 2016 and 2017 the geothermal well RN-15/IDDP-2 was drilled in the Reykjanes geothermal field, in southwest Iceland. With a total measured depth of 4650 m the well RN-15/IDDP-2 marks the deepest well drilled in Iceland to date and the hottest geothermal well (more than 426°C) reaching supercritical fluid conditions. Drilling was completed in 168 days by deepening the pre-existing production well RN-15, which was drilled in 2004 to a depth of 2507 m. In total 13 core runs were conducted during drilling of phase 4 and 5. Nine core runs retrieved core material with a total core length of 27.31 m and a core recovery of 63%. The high-temperature conditions of the predicted amphibolite facies was confirmed by a temperature and pressure log that was carried out on January 3rd, 2017, yielding a minimum temperature of 426°C at a pressure of 340 bar, but the well had not recovered from cooling during drilling.

1. INTRODUCTION

The drilling scheme is part of the Iceland Deep Drilling Project (IDDP), which aims to drill deep wells down to 4–5 km depth into geothermal systems in Iceland (Friðleifsson and Albertsson, 2000; Friðleifsson et al., 2014a, b). The IDDP consortium was established in 2000 (Friðleifsson and Albertsson, 2000) to investigate the feasibility and economics of deep, high-enthalpy geothermal resources, and especially supercritical hydrothermal fluids, as possible energy sources. The first well in the series, IDDP-1, was drilled in 2008–2009 within the Krafla geothermal field in NE Iceland (Hölmgírsson et al., 2010; Pálsin et al., 2014). However, the drilling of the IDDP-1 well had to be terminated at a depth of 2104 m when it intersected >900°C magma (Hölmgírsson et al., 2010; Pálsin et al., 2014).

It was decided to drill the second well in the series, IDDP-2, in the Reykjanes geothermal field, which is exploited by HS Orka for power production. The chief motivation of HS Orka to undertake such a challenging drilling operation was to address several basic questions for commercially viable reasons (Friðleifsson et al., 2014b): (i) Where is, and what is the nature of the base of, the Reykjanes hydrothermal reservoir? Is it possibly heated by superheated steam from below? (ii) Can the deep heat sources be exploited by injecting fluid into the hot rocks beneath the most productive part of the well field? (iii) Will productive permeability be found at such great depths within the reservoir? Is it possibly heated by superheated steam from below? (iv) Can the deep heat sources be exploited by injecting fluid into the reservoir or does it lie deeper still? (v) What is the nature of the ultimate heat source of this saline seawater recharged hydrothermal system; is it a sheeted dike complex or a major gabbroic intrusion? Individual dikes may cool to ambient temperatures in a few years, depending on thickness, while large gabbro intrusions may act as a heat source for thousands of years.

Well RN-15 was selected as target well for the IDDP-2 project, as it had already been drilled to a depth of 2507 m. Well RN-15 is located on the northeast side of the Reykjanes production field (Figure 1) and was drilled vertically in the year of 2004 down to its final depth of 2507 m (reference level rig-floor; 6.86 m above ground level, Table 1).

Table 1: Drilling and casing depths of well RN-15 and RN-15/IDDP-2. The drilling depths are measured from the rig floor (RF) of each drill rig. Bör: 9.0 m above ground level, Jötunn: 8.66 m above ground level, Saga: 2.0 m above ground level.

<table>
<thead>
<tr>
<th>Drill rig</th>
<th>Phase</th>
<th>Bit size</th>
<th>Casing type</th>
<th>Casing depth</th>
<th>Casing depth reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saga</td>
<td>Bit</td>
<td>2½&quot;</td>
<td>5½&quot;</td>
<td>84.4</td>
<td>Ground surface</td>
</tr>
<tr>
<td>Jötunn 1</td>
<td>Phase 2</td>
<td>4½&quot;</td>
<td>8½&quot;</td>
<td>292.8</td>
<td>Ground surface</td>
</tr>
<tr>
<td>Jötunn 1</td>
<td>Phase 1</td>
<td>7&quot;</td>
<td>13½&quot;</td>
<td>793.8</td>
<td>Ground surface</td>
</tr>
<tr>
<td>Jötunn 2</td>
<td>Phase 3</td>
<td>8½&quot;</td>
<td>12½&quot;</td>
<td>445</td>
<td>Ground surface</td>
</tr>
<tr>
<td>Jötunn 3</td>
<td>Phase 4</td>
<td>8½&quot;</td>
<td>9½&quot;</td>
<td>2871.2-4591.2</td>
<td>Ground surface</td>
</tr>
<tr>
<td>Bör</td>
<td>Phase 5</td>
<td>8½&quot;</td>
<td>7½&quot;</td>
<td>1303.7</td>
<td>Ground surface</td>
</tr>
</tbody>
</table>

Well RN-15 was selected as target well for the IDDP-2 project, as it had already been drilled to a depth of 2507 m. Well RN-15 is located on the northeast side of the Reykjanes production field (Figure 1) and was drilled vertically in the year of 2004 down to its final depth of 2507 m (reference level rig-floor; 6.86 m above ground level, Table 1).
Figure 2: Geological map of the Reykjanes geothermal field showing the location of the well-head of RN-15/IDDP-2 and the red line shows the well path extrapolated to the surface. Black lines show well paths extrapolated to the surface (map based on Sæmundsson et al., 2016).

Figure 2: Drilling progress during the deepening of well RN-15/IDDP-2. Core runs #1 to #13 are marked by black circles. The dashed line and open circles show the planned progress (adapted from Weisenberger et al. 2017).
2. DRILLING OPERATION

On August 11th, 2016, the deepening of well RN-15 was initiated in the Reykjanes geothermal field (Figure 1), now known as well RN-15/IDDP-2. The well was drilled by Iceland Drilling (Jarðboranir) using the rig Þór, which is a Bentec 350-ton drill rig with an electric top drive (MH PTD-500-AC). After 29 workdays, drilling phase 3 (Figure 2) was completed at a depth of 3000 m on September 8th, 2016 (Weisenberger et al., 2016). Due to total loss of circulation during the deepening to 3000 m, no cutting samples were retrieved and therefore, no direct information about the lithological and the mineralogical inventory is available. The kick-off point is located at a depth of 2750 m, and the aim was to build up an inclination of about 16° with an azimuth of about 210°. Well RN-15 had an existing production casing of 13 ¾” cemented from 0–793.8 m. During continuation of phase 3 in August 2016 an additional production casing (anchor casing) of 9 ¼” (0–445 m) and 9 ¾” (445–2932.4 m) was run into hole and cemented.

Drilling activity of phase 4 started on September 8th (workday 29) and partial circulation loss was almost immediately encountered at the beginning drilling of phase 4. Drilling was very challenging and although 12 successive attempts to seal the loss zone with cement were carried out, total loss of circulation below about 3200 m could not be avoided. One side tracking was necessary at a depth of about 3040 m (measured depth). Direct information on the nature of the drilled formation is restricted to the depth interval between 3000 and 3200 m, the only area were cuttings were retrieved. Drilling into formation commenced again on workday 66 with a total loss of circulation and continued with variable progress during the next weeks (Figure 2), but on December 17th phase 4 reached its total depth at 4626 m. During phase 4, 10 spot core runs were carried out (see below). Drilling phase 4 was followed by “logging while drilling”, carried out by Weatherford logging engineers. Subsequently a 7” perforated liner was run into hole on December 29th and 30th (2880.2–4600.2 m, reference to rig floor of Þór). On January 3rd, 2017, a temperature and pressure log was carried out after five days of heating-up, which resulted in a maximum temperature of 426°C and a pressure of 340 bar (Figure 3) about 30 m above the liner shoe (4591.2 m from the ground level). Subsequently a sacrificial 7” casing (0–1303.7 m, referenced to the ground level) was inserted and cemented and with that phase 4 was completed on workday 152 (Figure 2).

Drilling of phase 5 with a 6” tricone drill bit commenced on workday 157. In total 8 meters were drilled as pilot hole for core run #11, which was followed by core runs #12 and #13. On January 19th core run 13 was completed at a measured depth of 4659 m (referenced to the rig floor) and marked the total depth of RN-15/IDDP-2. The final depth of RN-15/IDDP-2 is 4650 m (measured depth, referenced to ground level) or about 4469 m total vertical depth. The horizontal displacement is about 730 m with an azimuth of about 220° (Figure 1). After stimulation of the well, drilling activity was terminated on January 25th, 2017 (workday 168, see figure 2) and the string was left in the well for stimulation.

Figure 3: Temperature and pressure logged inside the 7” liner on January 3rd, 2017.
Weisenberger at al.

2.1 Coring

In total 13 core runs were carried out during the drilling of RN-15/IDDPP-2. A summary of all core runs is shown in Figure 4. Core runs #1 to #10 were carried out by using an 8½” coring assembly specifically designed for IDDP (Skinner et al., 2010). However, the coring attempts yielded rather disappointing results and during coring activities of RN-15/IDDPP-2, several adjustments were made to the coring assembly to improve the coring results. These included the use of three different bit types, which were specially designed by Rok-Max Drilling Tools Ltd. for the IDDP Project. Core runs 1 to 4 were carried out with a 10 m long core barrel. However, problems occurred while running into the long core barrel, which included the use of collars and stabilizer in the bottom-hole assembly. Therefore, it was decided to shorten the core barrel to 5 m, step it of reamers to minimize the bottom-hole assembly and diminish its stiffness and this assembly was used for core runs 6 to #10. The main problem seemed to relate to running an 8½” coring assembly inside a directionally drilled 8½” hole, which called for extensive reaming while tripping. Core runs 1 and 2 were conducted under the supervision of ACS Coring Service. Core runs 3 to 10 were accomplished by Iceland Drilling. In addition to the coring with the 8½” core barrel, a 6” core barrel was used for core runs 11 to 13, which was carried out by coring engineers from Baker Hughes.

Figure 4: Overview of all core runs conducted in RN-15/IDDPP-2. The pie charts provide information about the core recovery (adapted from Weisenberger et al., 2017)

3. WELL DESIGN

The well design as it was built is shown in Figure 5 and Table 1 with all depth information referenced to the ground level. The casing program of RN-15/IDDPP-2 was designed by Mannvit. The casings already installed in the well of opportunity, RN-15, were 22½” surface casing, 18⅝” anchor casing and 13¾” production casing. These casings now serve as surface casing and intermediate casings 1 and 2. A new production casing was installed in RN-15/IDDPP-2. It also acts as an anchor casing as the well-head is attached to it. Its top 445 m are made of 9⅞”, 62.8 lb/ft, T95 grade casing with GEOCONN connections, and the lower section is made of 9⅝”, 47 lb/ft, L80 grade casing with GEOCONN connections. A 7”, 26 lb/ft, L80 grade perforated liner with buttress threaded connections (BTC) hangs inside the production casing (anchor casing) at about 2871.2 m measured depth and reaches down to 4591.2 m measured depth. Finally, a 7”, 26 lb/ft, specially selected grade Tenaris High Collapse and Sour Service TN 80HS liner with TenarisHydril Blue® connections, was installed from ground level to a measured depth of 1303.7 m.
Figure 5: Schematic drawing of well RN-15/IDDP-2 as it was “built”.

4. GEOLOGY

4.1 General geology

The Reykjanes area is largely covered by sub-aerial basalt lavas erupted in postglacial times (<12.5 ka) along with low-rise hyaloclastite ridges from the last glacial stage. A study of the stratigraphy shows a dominance of pillow basalt formations below about 1100 m b.s.l. (below sea level) that gradually change to a succession of tuffaceous volcanic formations of Surtseyan type above about 1000 m depth, with intervening shallow water fossiliferous tuffaceous sediments. Shallow marine tuffaceous rocks predominate up to about 100 m depth where sub-aerial lavas top the sequence. Intrusions are commonly found in the succession below about 800 m depth. These are mostly fine- to medium-grained basalt dikes and/or sills. An abundance assessment suggests they may reach up to 60% of the succession at deeper levels. Younger dikes can act as heat sources and dikes provide a significant control on the permeability structures at depths (Franzon et al., 2002; Franzon, 2004).
4.2 Lithologies

4.2.1 Cutting analysis

Due to the total loss of circulation within the entire drilling phase 3 and below a measure depth of 3200 m within drilling phase 4 cuttings were only retrieved within the depth interval between 3000 and 3200 m. The lithological descriptions for the well before side tracking (from 3000 to 3069 m) indicate the presence of dense medium-grained, grayish basaltic intrusions that are intercalated with fine- to medium-grained dense basaltic rocks which are, in contrast, black in color. A large quantity of secondary minerals, including epidote, quartz and pyrite/chalcopyrite, are found, which also appear as fracture fills. At 3021 m a garnet-filled fracture was observed. Formation after side tracking from 3040 to 3200 m consists exclusively of an alternating sequence of crystalline basaltic rocks which most likely represent a sheeted dike complex. Fresh, grayish to reddish medium- to coarse-grained plutonic rocks that are lighter color due to the abundance of plagioclase are the dominate the lithology, and are intercalated with finer-grained dark (more mafic) fresh dolerite.

The high content of epidote and quartz and lesser amount of actinolite, garnet and sulfides (pyrite and chalcopyrite) indicates significant porosity and permeability. The intrusive rocks are quite dense and the secondary minerals are most likely related to pore-space, associated with fractures. Mono-mineralic fragments of secondary phases can reach up to several millimeters in size. However, the grains are anhedral. The lack of euhedral secondary minerals, characteristic of open space veins, indicates that most of the fractures are totally sealed with secondary minerals. The intrusive rocks are in general fresh. Nevertheless, minor amounts of altered igneous grains are present. This implies that the alteration is not pervasive. It is most likely related to the fracture and selvage zones adjacent to the fracture pore space. The occurrence of epidote, actinolite (amphibole) and garnet indicates high temperature conditions characteristic of upper greenschist facies alteration.

4.2.2 Core observation

Because of the total loss of circulation in RN-15/IDDP-2 below 3200 m depth, spot cores are the only rock samples available from the deeper section of the well. Coring was difficult, and in total only 27.3 m were recovered (Weisenberger et al., 2017). The IDDP-2 cores include a series of dolerite dikes with chilled margins interpreted to originate from a sheeted dike complex (Friðleifsson et al., 2018; Zierenberg et al., 2017). Many of the rocks were found as “rollers” on top of cores from unknown depths above coring intervals. These include dolerites, basalts, and a few hyaloclastite and volcanic sandstone/siltstones with alteration similar to the RN-17B and RN-30 cores (Friðleifsson et al., 2018; Zierenberg et al., 2017). The lowermost cores of altered dolerites, contain thin felsic veins that are the first identification of evolved rocks within the volcanic rock series within the Reykjanes geothermal field. Cross cutting veins are relatively uncommon and open space filling veins are nearly absent, although the rocks appear to be pervasively altered (Friðleifsson et al., 2018; Zierenberg et al., 2017).

4.2.3 Drilling parameters

Drilling parameters show only minor variations and are indicative for drilling into relative hard formations. However, small variations did occur, which may reflect changes in lithology or penetration into soft formations, and could be related to fracture zones. Within the shallower part (3000–3185 m), which was cemented multiple times due to the high fluid loss, the drilling crew reported a large variation in the fluid circulation as well as in the stand-pipe pressure, which may indicate the penetration of narrow fracture zones. However, no indications are observed on the temperature logs which were carried out during drilling, of any major feed points within this depth interval. While drilling from 3305 to 3312 m a drop in the stand-pipe pressure (95–80 bar) was observed, which may indicate the penetration of a permeable zone. While drilling from 3373 to 3375 m, the weight on bit decreased while the rate of penetration increased. This is at a similar depth where a larger fracture zone was detected. Drilling parameters indicate that in general the formation from 3400 to about 3750 m consists of a relative uniform, hard formation, which is most likely represented by the core retrieved during core run 3. The peak in rate of penetration at a depth of 3710 m indicates a thin soft layer, or possibly a fault zone. A thicker soft zone occurs between 3751 and 3754 m, as indicated by the drastic change in drilling parameters (e.g. rate of penetration). From 3755 to 3816 m the drilling parameters show significant fluctuations which may indicate the penetration of a heterogeneous units, where hard and soft layers intercalate. Below 3816 m, drilling parameters show only minor variations except for a significant increase in the rate of penetration between 3884 and 3887 m. This may reflect a formation boundary. Another sharp peak in the rate of penetration is observed at a depth of 3990 m. The spike in the torque just below 4000 m indicates the penetration of an open structure. In addition, at 4000 the MWID showed a drop in the inclination of about 2.5°. Between 4118 and 4160 m the rate of penetration is quite high (8–15 m/h), which indicates a rather soft formation in comparison to the unit above and below. Within this interval, the well inclination built up, which may indicate the penetration of a fault/fracture zone. Subsequently, the rate of penetration declined, but at about 4210 m, the rate of penetration increased again with an outstanding spike at about 4240 m indicating again a weak/softer formation. Below about 4250 m the rate of penetration dropped back to lower numbers and does not indicate any major variations in lithology. It should be mentioned that the temperature log carried out on December 6th shows a similar undulating pattern as the rate of penetration pattern between 4100 and 4250 m and may reflect the different cooling behavior of the formations (Weisenberger et al., 2017).

4.3 Alteration

A regular progression in hydrothermal alteration with increasing depth was noticed from the alteration mineral assemblage in well RN-15. Such depth and temperature controlled mineral alteration zoning is well known in Icelandic hydrothermal systems (e.g. Kristmannsdóttir and Tómasson, 1978; Weisenberger and Selbekk, 2009). Low-temperature minerals, like fine-grained clay (smectite) and zeolites occur at shallower levels (Gautason et al., 2004). High-temperature minerals, like epidote and coarse-grained chlorite appear at deeper levels in the well. Epidote was first observed at a depth of 716 m (Gautason et al., 2004; Jónsson et al., 2010). The 13/14°
production casing of well RN-15 was set at 793.8 m (reference to ground level) and based on the mineral assemblage, the production casing of RN-15 extends well into the geothermal reservoir, where abundance of epidote (>230–250°C) was noticed in cutting samples. Furthermore, garnet and actinolite (>280°C) were first observed at 1378 m and 1560 m respectively.

Based on cutting analysis in the depth range from 3000 to 3200 m in RN-15/IDDP-2, high-temperature minerals, like epidote, garnet and actinolite, could be identified, but epidote was the dominant secondary mineral. Visual core inspection, accompanied by initial thin section observations of the retrieved cores reveals that epidote is common in a sample of core 3 (3648.0–3648.52 m), locally accompanied by minor amounts of chlorite. Epidote and chlorite are absent in core run 5 and below (Friðleifsson et al., 2018; Zierenberg et al., 2017). In contrast, calcite-plagioclase and hornblende were identified by microscopic observation. Biotite was observed as minor mineral phase in core 8 (4254.6–4254.88 m) as well as in core 11 (4634.20–4641.78 m).

The mineral assemblage plagioclase-hornblende is a characteristic mineral assemblage found in metabasaltic rocks of amphibolite facies rocks. The presence of hydrothermal biotite is consistent with this high temperature alteration of intermediate to felsic rocks, but biotite alteration is unusual in low K tholeiitic basalts. Pyroxenes are a common part of the alteration assemblage in the deepest part of hole. However, a detailed pressure-temperature estimation requires a more thorough mineralogical and petrological study, as well as considerations of the effects of mass transport and metasomatic alteration.

Figure 6: Map view showing the well path of RN-15/IDDP-2 (red) and the location of feed zones and their relative sizes (blue).

4.4 Feed zones

Permeable zones in RN-15/IDDP-2 are summarized in Table 2 and marked along the well path in Figure 6. The zones with high fluid permeability have been identified by circulation losses during drilling and the evaluation of geophysical logging data, which was carried out during the drilling activity. Minor permeable zones have also been detected by detailed studies of drilling parameters. After the production phase had been cemented and drilling phase 3 was completed, temperature logs revealed a small feed zone between the casing shoe and the final depth of drilling phase 3 at 3000 m. While drilling the top part of drilling phase 4, from 3000 to 3185 m, the drilling crew observed a constant increase in circulation loss. Furthermore, circulation losses fluctuated as drilling progressed.

The most prominent loss zone is located at about 3350 to 3380 m. All temperature logs, which were executed after this depth had been achieved, indicate that most of the pumped fluid disappears at a depth of about 3365 m and only a small portion of the pumped fluid travels further down the well. This indicates that a major fracture or fault is located at this depth. However, a temperature log carried out on January 3rd, 2017, indicates that small loss zones are present in the well at even deeper levels. For example, at about 4375 and 4550 m, minor loss zones may be present. Although fluctuations in some drilling parameters (e.g. stand-pipe pressure, torque) seem to indicate some softer zones that possibly indicate higher permeability (e.g. 4000 m), temperature logs do not reveal any indications of feed or fracture zones at those depths.

It should be emphasized that during the blind drilling from 3200 to the final depth at 4659 m a minimum volume of 53 m³ rocks was extracted. The total loss of circulation implies that the large volume of cuttings was transferred from the wellbore into the rock formation. This probably occurred along fracture zones. Considering the large estimated volume of cuttings, it may be assumed that major permeability exists in the vicinity of the wellbore.
Weisenberger et al.

Figure 7 shows the well path of RN-15/IDDP-2 and the location of fracture and feed zones along the well path in relation to the tectonic model of Reykjanes based on Khodayar et al. (2016a). It seems that the major fracture zones in RN-15/IDDP-2 are related to compartments as defined by Khodayar et al. (2016a, b).

Table 2: Fracture and feed zones in well RN-15/IDDP-2 after Weisenberger et al. (2017).

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Fluid loss (L/s)</th>
<th>Relative size*</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>Small</td>
<td>Gautason et al. (2004)</td>
<td></td>
</tr>
<tr>
<td>280</td>
<td>Small</td>
<td>Gautason et al. (2004)</td>
<td></td>
</tr>
<tr>
<td>900</td>
<td>1</td>
<td>Jónsson et al. (2010)</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>Small/medium</td>
<td>Jónsson et al. (2010)</td>
</tr>
<tr>
<td>1300</td>
<td>12</td>
<td>Small</td>
<td>Jónsson et al. (2010)</td>
</tr>
<tr>
<td>1720</td>
<td>9</td>
<td>Small</td>
<td>Jónsson et al. (2010)</td>
</tr>
<tr>
<td>2395</td>
<td>23</td>
<td>Medium</td>
<td>Jónsson et al. (2010)</td>
</tr>
<tr>
<td>2941-3185</td>
<td>5 to &gt;45</td>
<td>Small</td>
<td>permeable interval, based on circulation losses during drilling</td>
</tr>
<tr>
<td>3160-3170</td>
<td>20 to &gt;45</td>
<td>Small</td>
<td>Spinner 28.10.2016, 23.01.2017</td>
</tr>
<tr>
<td>3210</td>
<td>&gt;45</td>
<td>Small</td>
<td>temperature log 27.10.2016</td>
</tr>
<tr>
<td>3330-3380</td>
<td>&gt;45</td>
<td>Large</td>
<td>temperature log 28.10.2016, 03.01.2017</td>
</tr>
<tr>
<td>3820</td>
<td>&gt;45</td>
<td>Small</td>
<td>temperature log 03.01.2017</td>
</tr>
<tr>
<td>3990</td>
<td>&gt;45</td>
<td>Small</td>
<td>based on drilling parameters and drillers report</td>
</tr>
<tr>
<td>4100</td>
<td>&gt;45</td>
<td>Small</td>
<td>temperature log 03.01.2017</td>
</tr>
<tr>
<td>4200</td>
<td>&gt;45</td>
<td>Small</td>
<td>temperature log 03.01.2017</td>
</tr>
<tr>
<td>4375</td>
<td>&gt;45</td>
<td>Small</td>
<td>temperature log 03.01.2017</td>
</tr>
<tr>
<td>4550</td>
<td>&gt;45</td>
<td>Small</td>
<td>temperature log 03.01.2017</td>
</tr>
</tbody>
</table>

* Well RN-15 was a moderate producing well and the estimated size of the feed zones was probably underestimated in drilling reports.

Figure 7: Well path RN-15/IDDP-2 and the location of feed and fracture zones along the path in relation to the tectonic model of the Reykjanes geothermal field (Khodayar et al., 2016a).
5. SUMMARY

Drilling of well RN-15/IDDP-2 was commissioned by HS Orka in 2016. Drilling was performed by the drill rig Þór (Iceland Drilling, Jarðboranir) and drilling was completed in 168 days (August 11th, 2016 to January 25th, 2017). The well represents the second well of the Iceland Deep Drilling Project (IDDP). It is the deepest (4659 m measured depth, referenced to the rig floor Þór) and hottest (>426°C) geothermal well drilled in Iceland. For this purpose, well RN-15 was deepened, but it had previously been drilled in 2004 down to 2507 m (reference rig floor Jötunn). Drilling of RN-15/IDDP-2 commenced with continuation of drilling phase 3 using a 12½" drill bit from 2509 to 3000 m (reference rig floor of Þór). Subsequently, phase 4 was drilled with an 8½" drill bit from 3000 to 4626 m and finally, phase 5 was drilled with a 6" drill bit from 4626 to 4659 m. All depth information of RN-15/IDDP-2 refer to the rig floor of Þór. Drilling of phase 3 commenced with a total loss of circulation. After completion of phase 5, a production casing (anchor casing) (9⅞" down to 454 m and a 9⅝" down to 2941.4 m) was installed. Minor circulation losses were encountered when drilling of phase 4 started. The loss increased and a total circulation loss was encountered at about 3185 m. Several cement jobs were carried out in attempt to plug the circulation losses. However, the cement jobs did not limit the circulation losses and therefore, drilling was blind (total loss of the circulation) below 3200 m until the end of drilling. Phase 4 was completed with the installation of a 7" liner (2880.2 to 4600.2 m, reference to rig floor of Þór) and a 7" sacrificial casing (from the surface to 1312.7 m, reference to rig floor of Þór). Subsequently, the well was completed at a final depth of 4659 m in phase 5, drilled with a 6" drill bit. The well was drilled vertical down to 2750 m where the kick-off point is located. The well was deviated in a southwest direction (220°), and an inclination angle of about 40° was eventually built up, which is higher than originally planned (16°).

Figure 8: Summary sketch of the RN-15/IDDP-2. a) A simple model that shows the geology of the Reykjanes geothermal system. Sketch is not scaled. b) Temperature-pressure diagram showing the nature of supercritical conditions of the fluids within RN-15/IDDP-2 (CP: critical point; CPSW: critical point of seawater; yellow star: logging results of the temperature-pressure log carried out on January 3rd, 2017).
During drilling, a total of 13 core runs were conducted. Nine core runs retrieved core material; in total 27.31 m of core was recovered. The core recovery was 63%.

During most of the drilling, a total loss of circulation was persistent and no cuttings were retrieved at the surface apart from the beginning of phase 4. Therefore, the information about the lithology is very limited and needs to be constrained from the limited cuttings (3000–3200 m) and from the retrieved core material. Mineralogical and petrographic observations yield that the rocks of the deeper parts in the well are equilibrated at amphibolite facies conditions. The high-temperature conditions of amphibolite facies conditions are confirmed by the temperature and pressure logs that indicates the presence of a supercritical fluid (Figure 8).

Lithological and textural observations, in particular the occurrence of chilled margins and the grain-size of the rocks indicate that the lithology is consistent with the existence of a sheeted-dike complex (e.g. Friðleifsson and Elders, 2005; Khodayar et al., 2016b; Weisenberger at al., 2016b). Figure 8a shows a simple geological sketch of the Reykjanes geothermal field, which is equivalent to an ophiolite model (Friðleifsson and Elders, 2005). The heat is most likely transferred by primitive magma that is emplaced in the lower oceanic crust by dike injections within the sheeted-dike complex, and by dike and sills injections within the shallower volcano-sedimentary sequence.

Textural observations of core 3 and interpretation of the cutting analysis suggests that the lithology at the top most part in drilling phase 4 (3000 to 3650 m) experienced high brittle deformation, which can be deduced by the high fracture density. Detected circulation losses at this depth are evidence for the brittle behavior, which results in a significant permeability.

Based on circulation losses and temperature logs, several permeability zones are identified. A minor permeable zone is located just below the casing shoe. Increased circulation losses below that zone, finally resulting in a total loss of circulation at about 3200 m, indicate the high permeability at this depth. The most prominent permeable zone is found at 3350 to 3380 m and most likely reflects a major fracture zone into which most of the injected pumped fluid disappear. Smaller feed zones or permeable zones are identified at 4375 m and 4550 m.

6. ACKNOWLEDGMENTS
The preparation of this report was carried out as part of the DEEPEGS Project, which received funding from the European Union “HORIZON 2020 Research and Innovation Programme” (grant agreement No. 690771). The paper benefited from contributions by several colleagues including people from Iceland Drilling, HIS Orka, the IDDP science team, STATOIL and ÍSOR.

REFERENCES


Imaging and monitoring the Reykjanes supercritical geothermal reservoir in Iceland with time-lapse CSEM and MT measurements

M. DARNET1, N. COPPO1, P. WAWRZYNIAK1, S. NIELSSON2, G.O. FRIDLEIFSSON1, E. SCHILL1

1BRGM, France, 2ISOR, Iceland, 3HS-ORKA, Iceland, 4KIT, Germany
m.darnet@brgm.fr

Keywords: Controlled-Source Electro-Magnetic, Magneto-Telluric, monitoring, time-lapse, geothermal reservoir, MT, CSEM

ABSTRACT
We have investigated the benefits and drawbacks of active EM surveying (Controlled-Source EM or CSEM) for monitoring geothermal reservoirs in the presence of strong industrial noise with an actual time-lapse survey over the Reykjanes geothermal field in Iceland before and after the thermal stimulation of the supercritical RN-15/IDDP-2 geothermal well.

It showed that a high CSEM survey repeatability can be achieved with electric field measurements (within a few percent) but that time-lapse MT survey is a challenging task because of the high level of cultural noise in this industrialized environment. To assess the quality of our CSEM dataset, we inverted the data and confronted the resulting resistivity model with the resistivity logged in the RN-15/IDDP-2 well. We obtained a good match up to 2-3km depth, i.e. enough to image the caprock and the liquid-dominated reservoir but not deep enough to image the reservoir in supercritical conditions. To obtain such an image, we had to jointly invert legacy MT data with our CSEM data.

On the monitoring aspects, the analysis of changes in electric fields did not allow to identify any CSEM signal related to the thermal stimulation of the RN-15/IDDP-2 well. One possible explanation is the weakness of the time-lapse CSEM signal compared the achieved CSEM survey repeatability as a result of a limited resistivity change over a limited volume within the reservoir.

1. INTRODUCTION
Surface geophysical monitoring techniques are important tools for geothermal reservoir management as they provide unique information on the reservoir development away from boreholes. For magmatic environments, electromagnetic (EM) methods are attractive monitoring tools as they allow to characterize the reservoir and hence potentially monitor changes related to fluid injection/production. Indeed, the electrical resistivity of reservoir rocks is highly dependent on the volume, chemistry and phase of the in-situ geothermal brine (e.g. liquid, vapor, supercritical). Passive EM techniques (e.g. magnetotellurics or MT) are traditionally used for geothermal exploration and a few recent studies have demonstrated its potential for monitoring reservoir development. One of the main challenges is though the presence of cultural noise and/or variability of the Earth magnetic field that can obfuscate the EM signals of interest.

In the framework of the H2020-DEEPEGS project, we have investigated the benefits and drawbacks of active EM surveying (Controlled-Source EM or CSEM) to tackle this challenge, first with a synthetic study and subsequently with an actual time-lapse survey acquired in 2016 and 2017 over the Reykjanes geothermal field in Iceland before (baseline) and after (monitor) the thermal stimulation of the supercritical RN-15/IDDP-2 geothermal well.

2. CSEM AND MT SENSITIVITY STUDY
2.1 Reykjanes conceptual resistivity model
In order to study the sensitivity of the CSEM and MT methods for the characterization and monitoring of high-enthalpy geothermal reservoir, we have first designed a simplified 1D resistivity model of the Reykjanes reservoir based on the existing conceptual geological models (Flovenz et al. (1985), Kristinsdottir et al. (2010), Khodayar et al. (2016)), resistivity logs and MT soundings (Karlsdottir and Vilhjalmsson (2016)). It consists in a relatively unaltered and hence resistive (100 Ohm.m) layer overlying a more conductive (1 Ohm.m) smectite-zeolite rich zone (Figure 1); then, follows a more resistive (30 Ohm.m) chlorite-epidote rich zone until supercritical conditions are met (at 4km depth in RN-15/IDDP-2 well). At this point, only a handful of studies have measured in laboratory conditions the behavior of the rock electrical resistivity but it is likely that it increases due to the drop of the brine electrical conductivity (Reinsch (2016), Nono et al. (2018)). A factor three increase of the resistivity on different Icelandic rock samples has been observed (Reinsch (2016)), most likely caused by the combination of lower viscosity reduction, thermal expansion and decrease of the dielectric constant (Kummerow and Raab (2015), Nono et al. (2018)). We therefore assumed that the chlorite-epidote rich zone in supercritical conditions is three times more resistive than the chlorite-epidote rich zone (i.e. 100 Ohm.m). Depths of the different interfaces have been defined...
based on the existing conceptual geological models of the Reykjanes geothermal field and well data. To study the sensitivity of the CSEM and MT methods to resistivity changes at the reservoir depth, we assumed that its resistivity drops by a factor three over a 1km thick section at 4km depth, simulating a change of geothermal fluid from supercritical to liquid due thermal cooling, as expected during the thermal stimulation of the RN-15/IDDP-2 well.

Figure 1: Simplified resistivity model of the Reykjanes geothermal field. Depth scale is arbitrary.

2.2 MT sensitivity study

We have first computed the MT impedance tensor on the aforementioned 1D resistivity models and subsequently calculated the detectability $D$ of a time-lapse MT signal between two surveys A and B as 

$$D_{MT} = |\rho_B - \rho_A|/\sqrt{\epsilon_A + \epsilon_B}$$

where $\rho$ is the MT apparent resistivity (Ohm.m) and $\epsilon$ is the measurement error (Ohm.m). Frequencies are logarithmically distributed from 0.001Hz until 100Hz.

Figure 2 displays the apparent resistivity curves for the simplified 1D resistivity model of the Reykjanes geothermal field as well as the detectability D of the signal caused by the 100 Ohm.m to 30 Ohm.m resistivity drop at 4km depth. Here, we assumed a 1% measurement error on the apparent resistivities on the base and monitor surveys (Ogaya et al. (2016)). Detectability is maximum at low frequencies (< 1Hz) and tops around 5.

2.3 CSEM sensitivity study

Similarly to the MT case, we have first computed the CSEM impedance tensor on the aforementioned 1D resistivity models based on the CSAMT formulation (Zonge et al. (1991)) and subsequently calculated the detectability $D$ of a time-lapse CSEM signal between two surveys A and B as:

$$D_{CSEM} = |\rho_B - \rho_A|/\sqrt{\epsilon_A + \epsilon_B}$$

where $\rho$ is the CSEM apparent resistivity (Ohm.m) and $\epsilon$ is the measurement error (Ohm.m).

CSEM fundamental frequencies range from 1/32s until 32Hz and increase by a factor 4, as typically used during CSEM field surveys (Coppo et al. (2016)). We also calculated the CSEM response for the first fourth odd harmonics of the aforementioned fundamental frequencies to obtain a well sampled spectrum from 1/32s until 100Hz. Figure 2 displays the CSEM apparent resistivity curves for the simplified 1D resistivity model of the Reykjanes geothermal field (figure 1) as well as the CSEM detectability D of the signal caused by the 100 Ohm.m to 30 Ohm.m resistivity drop at 4km depth. Here also, we assumed a 1% error on apparent resistivities as observed on our actual measurements. Detectability is high at low frequencies (< 1Hz) and long transmitter-receiver offset (10km). Detectability tops around 10 at intermediate frequencies (0.1 - 1Hz) i.e. in the transition zone between the far and near-field CSEM response (Zonge et al. (1991)).

2.4 MT vs CSEM sensitivity

The CSEM and MT detectability computed on the simplified 1D resistivity model of the Reykjanes geothermal field (figure 2) shows that for a similar noise level over the whole frequency band, the sensitivity to a resistivity change within the resistive reservoir is likely to be higher on CSEM data than on MT data, most likely due to the superior sensitivity of the CSEM technique to resistors compared to MT (Constable and Weiss (2006); Weidelt (2007); Constable et al. (2009); Commer and Newman (2009)).
In addition, the use of a CSEM transmitter allows to control and hence potentially decrease the measurement error on apparent resistivities. This provides an unique opportunity to increase the detectability and hence sensitivity of the EM monitoring method to resistivity changes at the reservoir level (Siripunvaraporn et al. (2018)).

3. REYKJANES TIME-LAPSE EM SURVEYS

3.1 Time-lapse EM data acquisition

Time-lapse CSEM surveys have been acquired in September 2016, while drilling of RN-15/IDDP-2 well and in August 2017, after the thermal stimulation of the well. It used a double orthogonal horizontal electric dipole for the transmitter (figure 3), 3km north of the geothermal field providing two polarizations called POL1 (900m-long dipole between E1 and E2) and POL2 (900m-long dipole between E2 and E3). Its position is such that the mid-point of the longest transmitter-receiver offsets (7km) is located in the vicinity of the target of interest and such that injection electrodes can be installed in conductive superficial material (here, a swamp) to ensure a good electrical coupling of the transmitter with the ground. In the end, we managed to inject repeatably a current of about 30A at 560V with a Metronix TXM22 during both baseline and monitor CSEM surveys. This signal was successfully picked up by all our CSEM stations deployed over the Reykjanes peninsula (figure 3). To adequately characterize the subsurface, a broad band set of CSEM frequencies (from 1/32s up to 1024Hz) was acquired with a minimum set of 50 cycles at low-frequencies to ensure proper stacking of any random noise. The waveforms were seven square waves of fundamental frequencies ranging from 1/32s up to 128Hz increasing with a factor 4. A total number of 22 CSEM recording stations were deployed during the baseline and monitor surveys. They were Metronix ADU07 acquisition systems, MFS07 or MFS06 magnetic coils and two orthogonal 100m long electric dipoles oriented North-South and East-West. MT data have been acquired with the same equipment during the night shifts of the baseline survey i.e. when the CSEM transmitter was off. Given the results of the baseline MT survey (see section MT analysis), MT stations were only deployed a couple of hours during the monitor survey, not long enough to provide reliable low-frequency MT data. All recording equipment (electrodes, magnetometers, recording units) have been positioned with a differential GPS with a centimeter accuracy and replaced at the same position during the monitor survey to minimize positioning errors. When possible, electrodes and magnetometers have been put back in the same holes into the ground. Similarly, the transmitter electrodes and cables have been dGPS positioned and re-installed at the same position during the monitor survey.

3.2 MT data analysis

Seven stations were used for MT acquisition during the baseline survey (Figure 3). Each MT station dataset consists in one hour of recordings at 4096Hz sampling frequency and at least 12 hours at 512 Hz. A distant synchronous MT station, located 80 km away, was used as a remote reference (hereafter site 100). MT sounding consistency quality assessment was performed using apparent resistivity and phase curves inter-comparison between single site and combinations of remote reference results. Phase tensor consistency analysis was performed, as advocated by Booker (2014): “Smooth variation of the phase tensor with period and position is a strong indicator of data consistency.”.

In order to assess the quality of the MT data in the [1 mHz-128 Hz] band, we show the normalized phase tensor (hereafter PT), i.e the phase tensor with longer axis Phimax normalized to 1, is displayed for all frequency and RR combination. Ellipses are filled with a color bar indexed either on their their ellipticity value (left panel on figure 4) or their beta angle (right panel, same figures). Low values of ellipticity diagnose a 1D medium (Bibby et al. (2005) while beta angles absolute values below 3° diagnoses a 2D medium (Booker (2014)).

In any remote reference combination (indexed by vertical scale ticks on figure 4), discontinuous PT behavior are observed for 4 soundings (sites 9 10 11 and 24), leading to rejection of those data for interpretation. Site 13 display a smoother and coherent behavior in the high frequency (above 1 Hz) when combined with sites 10 and 100. Site 15 display smooth PT behavior at frequencies below 0.1 Hz and above 5 Hz.
Darnet et al.,

Figure 4: Multiple remote reference two-stage bounded influence processing results. Comparison of normalized phase tensor (PT) for each possible combination of remote reference. PT are filled with color bar indexed on their ellipticity value (left panel) and their beta angle value (right panel).

"Best" soundings 00, 13 and 15 are displayed on figure 5 for single site (SS) processing and maximum number of RR two-stage processing. Error bars on both phase and apparent resistivity are significantly larger on multiple RR curves. Consistently with figure 4, MT soundings are inconsistent in the [0.1-5] Hz frequency band for site 15, and below 1 Hz for site 13. SS curves show non physical apparent resistivity decreases (up to 3 order of magnitude decrease on rhoxy for site 13) in the [0.05-5] Hz band, which tends to disappear on the RR curves. Still RR curves are scattered. On site 00, MT curves are smoother in SS mode.

Figure 5: MT soundings for Single Site (blue curves) and maximum number of remote reference processing for sites 00, 13 and 15 (red curves). Apparent resistivity curves rhoxy and rhoyx and phases phixy and phiyx are shown in continuous lines, components xx and yy in dashed lines.

Due to intense anthropogenic activity in the area during RN-15/IDDP-2 drilling phase, MT soundings are of bad quality and cannot be used for interpretation. Despite the use of combinations between local and distant remote reference and bounded influence processing, a signal incoming from a near-field source persists in the data and creates either fake resistivity variations or large amplitude scatter in the frequency curves. MT imaging and subsequently monitoring with such EM noise conditions will not lead to reliable enough results. Since the baseline MT were of poor quality, we did not deem necessary to acquire MT data during the monitor time-lapse survey.

3.3 CSEM data analysis

To assess the CSEM survey repeatability of the time-lapse surveys, we have compared the amplitude and phase variations of the PE major axis of the horizontal electric field at station 18 between the baseline and monitor surveys (figure 6). We define the repeatability R of electric field measurements as:

$$R_{AB} = \frac{|E_B - E_A|}{(|E_A| + |E_B|)/2}$$

where E is the amplitude of the electric field normalized by the transmitter dipolar moment (V/Am2), A and B refers to the baseline and monitor surveys, respectively. Over the whole frequency band, repeatability is within 2-3% and 2-3° for the amplitudes and phases, respectively but the presence of strong external noise on the baseline or monitor surveys on some specific frequency bands (e.g. 1/32s at low frequencies, 50Hz and harmonics at high frequencies) degrades again significantly the repeatability up to 10% and 10° on the amplitudes and phases, respectively. Although weather was humid during the baseline and dry during the monitor survey, the change of the top soil water saturation and hence resistivity seems to have a limited influence on survey repeatability.
Figure 6: Left: amplitudes (top) and phases (bottom) of the PE major axis of the horizontal electric field measured at station 18 during the baseline (black) and monitor (red) surveys as a function of the CSEM fundamental frequencies and associated first fifth odd harmonics. Noise estimates are displayed as errorbars. Right: Repeatability R of the amplitudes (top) and phase difference (bottom) of the PE major axis of the horizontal electric field between station 18 measured during baseline and monitor surveys as a function of the CSEM fundamental frequencies and associated first fifth odd harmonics.

Interestingly, similar conclusions hold for the entire time-lapse dataset. Indeed, when comparing the repeatability of the amplitudes of the PE major axis of the horizontal electric field with the baseline and monitor signal to noise ratio (figure 7), the trend is a clear decrease of the repeatability R with increasing signal to noise ratio i.e. with decreasing level of external noise. Since the frequencies of interest for deep reservoir monitoring are low, we have limited our analysis to frequencies less than 10Hz. This observation demonstrates that for our time-lapse CSEM procedure, the signal to external noise ratio of the repeated EM measurements is the most important parameter to control in order to achieve a good survey repeatability. Contrary to MT monitoring experiments where the practitioner has limited control on the source strength and hence on the achievable survey repeatability, the CSEM signal to noise ratio can be controlled and increased at will by simply increasing the transmitter dipolar moment (e.g. longer electric dipole transmitter and/or stronger power generator) and/or recording signals for longer periods of time to increase the chance of stacking-out random external noise.

Figure 7: Repeatability R of the amplitudes of the major PE axis of the horizontal electric fields between the baseline and monitor surveys as a function of the combined baseline and monitor signal to noise (S/N) ratios on their amplitudes. Only CSEM fundamental frequencies and associated first fifth odd harmonics less than 10Hz are displayed.

In order to identify time-lapse signals in our dataset related to the thermal stimulation of the RN-15/IDDP2 well, we have calculated the amplitude and phase change of the polarization ellipse of the horizontal electric field between the monitor and baseline surveys (figure 8, phase not shown). We focused on the stations located along the aforementioned profile as it crosses the producing reservoir and the RN-15/IDDP-2 well. For the stations with a high signal to noise ratio and therefore high repeatability (stations 09, 14, 18, 19), no clear and consistent time-lapse anomaly related to the RN-15/IDDP-2 thermal stimulation can be identified. Indeed, observed time-lapse anomalies are random and stay within the measurement error. The only significant anomalies occur at frequencies where the signal to noise and hence repeatability is poor (e.g. 0.03125Hz, 50Hz) and are likely to be related to external sources of noise.

Figure 8: Relative amplitude change of the major axis of the polarization ellipse of the horizontal electric field for the stations 09, 14, 18, 19, 22 and 24 between the monitor and baseline CSEM surveys as a function of frequency. Vertical bars indicate the estimated time-lapse amplitude measurement error.

4 CSEM AND MT INVERSIONS

In this section, we have performed an inversion CSEM and MT data to confront and validate the CSEM and MT results with the logged resistivities in the RN-15/IDDP-2 well. For this calibration, we only inverted stations along a profile running from the transmitter and crossing the producing geothermal reservoir (figure 3). For the inversion, we used the 2.5D MARE2DEM inversion code (Key (2016)).

4.1 CSEM inversion

We inverted the amplitudes of the PE major axis of the horizontal electric field from seven CSEM stations located in the vicinity of the selected profile (stations 05, 09, 14, 18, 22 and 24). Inverted frequencies were 1/32s, 1/8s, 1/2s, 2Hz, 8Hz, 32Hz and associated first fifth odd harmonics up to 50Hz. Both POL1 and POL2 transmitter polarizations were inverted. Data from either the baseline or monitor survey were used depending on their signal to noise ratio. We limited the
frequency band on the high side to 50 Hz due to the presence of strong external noise (e.g. 50Hz and harmonics, industrial noise). The starting model of the CSEM inversion was a homogeneous 2 Ohm.m half-space. Numerical simulations of the impact of the land/ocean interface showed that stations nearby the coast may be affected by the presence of the conductive sea over a large frequency band but since the area of interest (RN-15/IDDP-2 well) is located far away from the coast (at least 2km), we did not include it. Future 3D inversions will however require to include such an interface.

To assess the convergence of the inversion and quality of the data fit, we calculated RMS misfits based on measurement errors (Key (2016)). Measurement errors have been estimated from the external noise levels calculated at the processing stage. The target misfit is set to 1 and we consider the data fit to be satisfactory when misfits are small (as close as possible to unity) and have been significantly reduced during the inversion process (typically several units). Here, initial misfits were in the 10-20 range and dropped into the 2-5 range after 15 iterations, leading a satisfactory data fit over the whole frequency band (figure 9). Only station 14 has a RMS misfit great than 10, most likely due to a remaining static effect as evidenced by the similar shapes of the modelled and observed amplitude curves.

The resulting resistivity model as well as the average resistivities logged in the RN-15/IDDP-2 well are displayed on figure 10. The shallow conductive smectite-rich caprock is well imaged in the vicinity of the RN-15/IDDP-2 well, with a resistivity (<5 ohm.m) and thickness (approximately 1200m) in good agreement with the logged values. The underlying more resistive chlorite/epidote rich layer is also imaged but deeper than 2km, the recovered resistivities are too low (20 Ohm.m vs 50/100 Ohm.m in the well). To explain this discrepancy, we have computed the Jacobian or sensitivity matrix at the last iteration of the inversion (figure 11). Higher values indicate areas where the dataset is highly sensitive to a change in resistivity. The sensitivity of the CSEM setup is clearly non-uniform with the highest sensitivity towards the mid-point between the CSEM transmitter and receiver grid (around 3km from the transmitter) i.e. in the vicinity of the RN15/IDDP-2 well (located at 3.7km distance from the transmitter), confirming that the transmitter and receiver layout is adequate for imaging resistivity variations in this area. It however also shows that the sensitivity at 4.5 km depth is low (at least two orders of magnitudes less than in the first 1.5km), possibly explaining why the resistivity values recovered from the CSEM inversion are too low compared to the logged ones. Finally, figure 11 also shows that the CSEM sensitivity is poor underneath the transmitter and the most distant receivers (distances greater than 5km from the transmitter). These low sensitivity areas explain most likely the unexpected absence of the conductive layer at large distances from the transmitter (greater than RX18) and its unexpected thickening at negative distances from the transmitter. Similarly, at shallow depth (< 1.5km) between the transmitter and first receiver (RX05), artefacts may be present due to the low sensitivity of the CSEM setup. This illustrates the difficulty of imaging complex resistivity variations with only CSEM transmitter and the need for multiple transmitter positions to obtain a more homogeneous sensitivity matrix.

---

**Figure 9:** Observed (dots) and modelled (solid lines) after 2.5D inversion of the amplitudes of the major axis of the polarization ellipses of the horizontal electric field as a function of the CSEM frequencies for POL1 (red/magenta) and POL2 (blue/cyan) transmitter polarizations for stations 05, 09, 14, 18, 22 and 24. Each panel corresponds to a different CSEM receiver along the inversion line. Measurement errors are displayed as vertical bars. Thin and thick solid modelled curves corresponds to the CSEM only and joint CSEM and MT inversions, respectively.

**Figure 10:** Resistivity model (log scale) obtained after the 2.5D inversion of the CSEM data only from CSEM stations 05, 09, 14, 18, 22 and 24.

**Figure 11:** Sensitivity model (Jacobian matrix in log scale) obtained after the 2.5D CSEM inversion of the stations 05, 09, 14, 18, 22 and 24.

---

4.2 Joint MT and CSEM inversion

To compensate for the low sensitivity at depth of our CSEM setup, additional constraints (e.g. structural, petrophysical) and/or datasets (e.g. MT, resistivity logs) may be necessary (Scholl et al. (2010)). In an
attempt to increase the resolution of the resistivity image at depths greater than 2/3 km, we have looked into the possibility of jointly inverting CSEM and MT over the area of interest (Abubakar et al. (2011)). Since our MT dataset is of poor quality, we used the legacy MT dataset collected over the Reykjanes geothermal field instead (Karlsdottir and Vilhjalmsdottir (2016)).

We first inverted the apparent resistivities and phases of the non-diagonal components of the MT impedance tensor for seven MT stations nearby our CSEM stations along the profile of interest (figure 3). Frequencies range from 0.001 Hz until 100 Hz. Final RMS misfits are close to unity, providing a satisfactory data match (figure 12). The resulting resistivity model as well as the average resistivities logged in the RN-15/IDDP-2 well are displayed on figure 13. Here also, the shallow conductive smectite-rich caprock is well imaged with inverted resistivities (<5 Ohm.m) in good agreement with the logged values. Nevertheless, the depth of the base of this conductive layer does not match well with the well observations (a few hundreds of meters difference). Contrary to the CSEM inversion, the underlying more resistive chlorite/epidote rich layer is well imaged with highly resistive layers (up to 100 Ohm.m at 5 km depth).

Figure 12: Observed (dots) and modelled (solid lines) after 2.5D inversion of the amplitudes and phases of the non-diagonal components of the MT impedance tensor as a function of frequency for MT stations 77, 76, 74, 78, 79, 70 and 139. Each panel corresponds to a different MT station along the inversion line. Thin and thick solid modelled curves correspond to the MT only and joint CSEM and MT inversions, respectively.

Figure 13: Resistivity model (log scale) obtained after the 2.5D inversion of the MT data only from MT stations 77, 76, 74, 78, 79, 70 and 139. To take advantage of both CSEM and MT datasets, we have jointly inverted the amplitudes of the electric field for the CSEM stations 05, 09, 14, 18, 22 and 24 with the apparent resistivities and phases of the non-diagonal components of the MT impedance tensor for MT stations 77, 76, 74, 78, 79, 70 and 139. CSEM and MT data fit are displayed on figure 9 and figure 12. Overall, misfits are small and similar to the CSEM only and MT only cases, providing a satisfactory data fit. However, RMS misfits are slightly larger than the standalone cases, simply due to the fact that additional constraints have been introduced in the inversion process by the addition of new data. The resulting resistivity model as well as the average resistivities logged in the RN15/IDDP2 well are displayed on figure 14. Interestingly, both the shallow conductive smectite-rich caprock and the underlying resistive chlorite/epidote rich layer are now well imaged in good agreement with the logged values. Furthermore, the depth of transition zone between the caprock and the deeper and more resistive material fits now very well with the well observations. This good match demonstrates the validity of CSEM and MT measurements for estimating and hence monitoring resistivity variations within the Reykjanes geothermal reservoir.

Figure 14: Resistivity model (log scale) obtained after the joint 2.5D inversion of CSEM data from CSEM stations 05, 09, 14, 18, 22 and 24 and MT data from MT stations 77, 76, 74, 78, 79, 70 and 139. Resistivity model (log scale) obtained after the 2.5D inversion of the MT data only from MT stations 77, 76, 74, 78, 79, 70 and 139.

5 DISCUSSION

Despite the high degree repeatability of the CSEM measurements between the Reykjanes baseline and monitor (a few percent on the amplitude of the electric field), no clear and consistent time-lapse anomaly related to the RN-15/IDDP-2 thermal stimulation has been identified. A most likely explanation is related to the weakness of the time-lapse CSEM signals in comparison to the achieved repeatability. To demonstrate this, we have calculated the detectability of time-lapse CSEM signals based on electric field amplitudes as a function of the size of the stimulated zone (here, width) and measurements errors for the 2.5D Reykjanes conceptual model (figure 15). It clearly shows that the amplitude of the time-lapse signal is strongly related to the volume of the stimulated area (here, its width as its height is kept fixed at 1 km). For the repeatability achieved during the actual Reykjanes time-lapse survey (a few percent), it indicates that a time-lapse signal can be observed (D greater than 1) only if the stimulated area is larger than 500 m in width. During the drilling of RN-15/IDDP-2 well, high-
permeability circulation-fluid loss zones were detected below 3 km depth to bottom. The largest one occurred at around 3.4 km depth with permeable zones encountered below 3.4 km accepting less than 5% percent of the injected water. It is therefore likely that most of the fluid injected during the thermal stimulation leaked into this zone between 3 and 3.4 km depth. Since the total volume of injected cold water was roughly 100000m³ in one month and the porosity of the in-situ rock is low (a few percent), the lateral extent of the stimulated zone does not exceed a couple of hundreds meters and most likely well below the detectability threshold achieved for our actual survey. To pick such a small signal up, even more repeatable measurements would be required (less than a percent, figure 15) or alternatively, a more sensitive CSEM layout would need to be deployed (e.g. a borehole to surface CSEM configuration, Tietze et al. (2015)). Our CSEM time-lapse analysis is based on the amplitude and phase of the electric field measurements but it is possible that other parameters are actually more sensitive to resistivity changes than the raw electric field measurements, like the distortion (Rees et al. (2010), Thiel (2017)) show that only resistivity simulations (figure 15, Orange et al. (2009), Wirianto et al. (2010), Thiel (2017)) show that only resistivity changes happening over a significant reservoir volume (e.g. after long periods of fluid injection/production) may lead to detectable EM signals. Time-lapse MT measurements alleviate this logistical constraint but as shown with our particular example, significant efforts have to be made to ensure sufficient data quality during both baseline and monitor MT surveys, especially when performed in highly industrialized areas with high levels of electromagnetic noise.

**ACKNOWLEDGEMENTS**
The IDDP-2 was funded by HS Orka, Landsvirkjun, Orkuveita Reykjavíkur, and the National Energy Authority in Iceland, together with Statoil, the Norwegian oil and gas company. The IDDP-2 has also received funding from the DEEPEGS project, European Union’s Horizon 2020 research and innovation program under grant agreement No 690771. We would like to thank HS-ORKA for providing access to the MT dataset over the Reykjanes geothermal field.

**REFERENCES**


The Reykjanes DEEPEGS Demonstration Well – IDDP-2

Guðmundur Ómar Friðleifsson1, Albert Albertsson1, Ari Stefánsson1, Geir Þórofésson1, Kiflom G. Mesfin1, Kristján Sigurðsson1, Ómar Sigurðsson1, Þór Gíslason1

1 HS Orka, Svartsengi, 240 Grindavík, Iceland
go@hsorka.is

ABSTRACT

The DEEPEGS demonstration well at Reykjanes, SW Iceland, was drilled to a depth of 4,659 m and cased with a production casing to almost 3,000 m depth. The well was angled towards the main up-flow zone of the Reykjanes high temperature geothermal system. Based on alteration mineral assemblages, the bottom hole temperature is estimated to be approaching 600°C. The DEEPEGS project, supported by the EU Horizon 2020 research and innovation programme, has the principal aim to demonstrate the feasibility of Enhanced Geothermal Systems (EGS) for delivering renewable energy for European citizens. The DEEPEGS project was meant to demonstrate advanced technologies in three types of geothermal reservoirs, a high enthalpy system at Reykjanes with temperatures up to 550°C, and in two deep hydrothermal reservoirs in southern France with temperatures up to 220°C. The Reykjanes demonstrator is just about to be flow tested at TRL level 6 in expected environment. The flow testing and pilot study is expected to begin in June 2019 and is of value to find out if the deep fluid is fit for direct use, with or without chemical mitigation, for producing electricity, and/or for other geothermal usage in the Reykjanes geothermal resource park. Drilling proceeded without recovering any drill cuttings and consequently several spot cores provided the only deep rock samples from the well. These cores are characteristic of a basaltic sheeted dyke complex, with hydrothermal alteration mineral assemblages that range from greenschist to amphibolite facies, enabling investigation of water-rock interaction in the active roots of an analogue to submarine hydrothermal systems, as the Reykjanes geothermal fluid is of oceanic origin. Earthquake activity is monitored with a local seismic network during drilling of the deep well detected abundant small earthquakes (M≤ 2) within the depth range of 3-5 km. A zone at 3-5 km depth below the producing geothermal field, generally aseismic prior to drilling, became seismically active during the drilling.

The drilling of this deep IDDP-2 well achieved several scientific- and engineering firsts. It is the deepest and hottest drill hole so far sited in an active mid-ocean spreading center. It penetrated an active supercritical hydrothermal environment at depths analogous to those postulated as the high temperature reaction zones feeding black smoker systems. The total loss of circulation throughout the drilling and subsequent 1.5 year of re-injection tests demonstrate that an EGS system will simply be created with further reinjection down to the 400-600°C hot environment. The DEEPEGS demonstrator well at Reykjanes, IDDP-2, had an immediate impact on the accepted and used geothermal reservoir model at Reykjanes – and thereby the size of the geothermal reservoir, which increased in exploitable volume by some 40-50%.

A second major impact already resulting from the deep IDDP-2 drill hole, is the connectivity to the surrounding production wells, which allows us to conclude that we have already proven that the EGS concept will work for the Reykjanes demonstrator.

For the first time drilling into an active supercritical regime in an ocean floor setting has succeeded. Such an active system has never been drilled into before and the resulting scientific impact is beyond the state of the art. The scientific work currently undertaken will have exceptional visibility and socio-economic impact.

1. INTRODUCTION

The Iceland Deep Drilling Project (IDDP) was established in year 2000 (www.iddp.is). IDDP has the main goal to find supercritical hydrothermal fluids by deep drilling and test the utilization of such fluids which develop in the roots of high-temperature systems in vicinity of cooling magmatic intrusions. Supercritical geothermal wells could produce up to ten times more power than the usual subcritical geothermal wells, which evidently is appealing for the geothermal industry. The IDDP program was established by a
Consortium of three the largest energy companies in Iceland, Landsvirkjun (National Power Company), Reykjavik Energy and HS Orka (formerly Hitaveita Suburnesja), and Orkustofnun (National Energy Authority of Iceland). Later Alcoa (international aluminum company) and Statoil (the Norwegian oil and gas company) joined the consortium for several years during the drilling of IDDP-1. And few years later Statoil (now Equinor) joined the consortium again with a contract extending to 2020. From the beginning the IDDP consortium program has been to investigate three high temperature systems in Iceland (figure 1).

Since 2005, the International Continental Scientific Drilling Program (ICDP) and the USA National Science Foundation (NSF) provided grants for scientific coring and academic water-rock studies of drill cores. The ICDP and NSF grants have now been used up while the IDDP consortium continues in its effort and intends to complete flow testing and pilot tests of well IDDP-2 and is already preparing ahead for the drilling of well IDDP-3, which may be drilled after 2020.

**Figure 1:** Simplified geological map of Iceland showing the location of the three high-temperature geothermal fields attended by IDDP, namely Krafla in NE-Iceland and Reykjanes and Hengill in SW-Iceland, hosting wells IDDP-1, IDDP-2 and IDDP-3 respectively. The detailed drill site of IDDP-3 remains to be dealt with.

IDDP intended to drill the first well in 2005-2006 at Reykjanes in SW-Iceland (figure 1). In 2005 HS Orka offered the IDDP consortium to deepen to 5 km depth, a 3 km deep production well, RN-17, which was just being drilled at that time. Before deepening and casing of the well, the HS company decided to flow test the well without a casing support (barefoot) and during that flow test the rock formation collapsed into the well. Despite severe attempts with a drill rig to recondition the well, the well finally needed to be abandoned and the IDDP consortium had to look for another opportunity to drill the first superdeep well.

In 2009 the well IDDP-1 was drilled by Landsvirkjun in Krafla in NE-Iceland (figure 1), into an aphyric 900°C hot rhyolitic magma at only 2.1 km depth. The well had to be completed at that depth and was finished with a sacrificial casing, partly cemented towards the surface, with ~100 m long perforate liner next to the bottom, closest to the magma heat source. The idea was that the IDDP consortium should “take over” and fund the deep well section together below 3.5 km depth to completion, but this well never progressed to that stage because of the magma intervention. However, IDDP consortium participated in the finishing of the well above the magma and in subsequent testing, while majority of the cost was born by Landsvirkjun. During the subsequent flow tests, which extended to 2012, the well yielded 452°C hot superheated steam at surface. At a max flow rate at 20 bar pressure it could have generated up to 36 MWe, while it was extensively flow tested the following years at much higher pressures (~140 bar), leading to a conclusion that the world’s first magma enhanced geothermal system had been created (Fridleifsson et al., 2015, and references therein). IDDP-1 well was the world’s hottest production well for a while, but in 2012 the well had to be terminally abandoned due to valve failures and was cemented up. Nevertheless, the lesson learned was significant - similar wells can be drilled again towards shallow magma bodies in high temperature systems and magma-EGS systems created. At Krafla, however, the current idea is to establish an extensive volcanological and geothermal research program called Krafla Magma Testbed (KMT) ([www.kmt.is](http://www.kmt.is)).

In 2017 the world’s first supercritical well, IDDP-2, was drilled to 4.659 m slant depth at Reykjanes in SW-Iceland (figure 1). This corresponds to about 4.5 km vertical depth from the surface (figure 2). Its bottom hole temperature is believed to be close to 600°C, while during drilling after only 6 days heating, 426°C was measured at 4.550 m depth at 340 bar pressure, which is truly a supercritical for both fresh water and saline. The critical point for fresh water is 374°C at 221 bar pressure, while it is elevated for saline water to 406°C and 298 bar pressure (Bischoff and Rosenbauer, 1988). From the scientific point of view, this location at Reykjanes is of great interest because the Reykjanes Peninsula is the landward extension of the Mid-Atlantic Ridge. Furthermore, the geothermal reservoir fluid in the Reykjanes system is modified seawater, with similar chemical composition as some sampled ocean floor geothermal systems. Therefore, it is possible at Reykjanes to test a subaerial analogue of the mid-ocean ridge “black smokers”, some of which yield supercritical fluid at the ocean floor at great depths (e.g. Koschichinsky et al., 2008). Drilling deep enough into a saline geothermal system on land at a ridge crest like at Reykjanes, which is recharged by seawater, could yield fluids at similar P-T conditions and in analogue settings as in the ocean floor ridge systems, geologically speaking, from within a sheeted dyke complex. This makes the Reykjanes system unique and appealing for research.

In 2015 a part of the IDDP consortium members joined in a consortium of 10 partner organization from the geothermal industry, technical and oil- and gas sectors,
coming from five European countries, and submitted a proposal to the European Union’s Horizon 2020 research and innovation programme. The project was called DEEPEGS (www.deepegs.eu) received funding for 4 years under grant agreement No 690771, beginning 1st December 2015 (Fridleifsson et al., 2016, Bogason et al., 2019).

Figure 2: Schematic model of well IDDP-2 at Reykjanes. The IDDP-2 well basically began at 3.5 km depth, involving deepening of an existing production well, RN-15, which was first deepened to 3.5 km by HS Orka and Statoil (Equinor), and then finished by IDDP consortium participation to final depth, 4659 m from rig floor. DEEPEGS participates in the deepening effort and the well completion, including stimulation, flow test and pilot test.

The DEEPEGS project’s total budget of 44 million Euro received an EU grant of about 20 million Euro making it one of the larger publicly funded H2020 projects. The ambition of the project is to explore the possibilities of producing energy from deep geothermal systems in Iceland and France, systems which are enhanced by stimulation following drilling to depths of 4-5 km. The project was meant to demonstrate advanced technologies in three types of geothermal reservoirs, a high enthalpy system at Reykjanes with temperatures up to 550°C, and in two deep hydrothermal reservoirs in southern France with temperatures up to 220°C. However, for administrative reasons within France the location of the two originally suggested demonstrators there had to be moved twice within France, involving considerable delay in the project execution (Bogason et al., 2019). When this paper is written, a request from the French energy company, Fonroche Geothermie, to move the France demonstrator site to Vendenheim in Alsace is hopefully just about to be accepted by EU. There, two deep wells have already been drilled, the first one reaching record temperature for central Europe of ~200°C in a granite basement close to 5 km depth. The present paper, however, will not discuss the French demonstrator much further, while figure 3 is used to schematically describe different scenarios for potential energy outputs from different high-temperature geothermal systems.

Figure 3: Schematic model showing comparative energy output of different high temperature well scenarios including current EGS systems. Super-Hot EGS systems are yet to be established, while the IDDP-1 magma drilling at much shallower depth surely resulted in one such system. (diagram borrowed from NNDP proposal).

IDDP-1 could be grouped with the Super-Hot EGS systems, while only drilled to 2.1 km into magma. Well IDDP-2 could also be grouped in that category too as a clear connection between the deep reservoir and the overlying shallower reservoir has already been demonstrated as will be described below.

2. THE IDDP-2 WELL AT REYKJANES

The drilling and key results of the of the IDDP-2 well at Reykjanes have been extensively described and publicized by Fridleifsson (2017), Fridleifsson and Elders, (2017 a, b), Fridleifsson et al., (2017, 2018) and Stefánsson (2017), Stefánsson et al. (2018), and others. In this chapter a short summary is presented based on the referred publications and additional new data and information.

The drilling began by deepening an existing 2.5 km, well RN-15 to 3 km, and case it with 9 7/8”-9 5/8” casing and cementing to surface. To reach the main up-flow zone of the Reykjanes system it was necessary to build the well inclination from 2,750 m with an azimuth of 210°deg (figure 4). Total loss of circulation was experienced most of the time to the end of drilling. An exception to this was just after casing and repeated plug cementing below 3 km to about 3.2 km, after which the well was drilled totally blind to final depth. A 7” perforated liner was run into hole and then a 7” production (sacrificial) casing to 1,300 m and cemented to surface. This was followed by running in with 6” rotary assembly to drill out casing shoes for the sacrificial casing and the liner. A 6” pilot hole was then...
drilled for 8 m before pulling out for 3 successive 6" spot coring runs to final depth. The well was left with 3 1/2" drill pipe to 4,590 m for long term stimulation and tracer injection.

The existing 2.5 km deep production well, RN-15 was drilled by HS Orka in 2010. First it was cooled down slowly and then deepened and cased to almost 3 km depth in 2016. Equinor funded that effort with HS Orka, including further deepening to 3.5 km depth. From there on to final depth of 4,659 m depth, completed January 2017, the IDDP consortium funded the drilling itself. DEEPEGS participated in the funding through all this effort apart from the drilling itself, but including materials, loggings and miscellaneous research including extensive stimulation efforts. Drill coring with spot coring equipment was attempted 13 times from 3 km depth to the bottom, resulting in some 27 m of valuable drill cores. All the spot core drilling was funded by ICDP and NSF. The funding overview here is just made to stress the fact that many geothermal stakeholders and research agencies are supporting this R&D program for enhanced geothermal energy by deep drilling.

As the well was directionally drilled, from 2.7 km depth to bottom, the vertical depth from surface to bottom is close to 4.5 km. The well track is shown in figure 4. Supercritical conditions were measured during drilling at ~4,550 m depth of 426°C at 343 bars. Prior to this temperature log Ketil Hogstad from Equinor had used Bayesian inversion of available geophysical data from Reykjanes to model the bottom hole temperature distribution, which reached over 500°C (Hokstad and Reyna to 2017). This prediction of very high temperatures was later supported by petrological and fluid inclusion studies of the drill cores.

After the temperature logging January 6th, 2017 during drilling, the well was deepened by additional 100 m, a liner inserted, and a 6" pilot hole and 3 successive drill cores retrieved from the very bottom of the well.

Altogether some 27 m of drill cores, from 13 coring attempts below 3 km depth, were retrieved from the well (Table 1). As the well was drilled with total circulation loss most of the time these core samples comprise almost the only rock samples from the entire well deeper than 2.5 km depth. An exception to this is from the interval below the cemented production casing at 3.0-3.2 km depth from where some drill cutting samples exist (Weisenberger et al. 2017). A major problem encountered during drilling the IDDP-2 well was the total loss of circulation below 3.2 km to final depth. The temperature logs showed the largest feed zone to be at about 3.4 km depth, while several smaller feeds were detected towards the bottom of the well (figure 4). The drilling operation took 168 days and during most of that time some 40-60 l/s of cold water were pumped through the drill string, including cooling water injected on the annulus to keep the casings cool, as the water table was at about 1 km depth. During the following stimulation effort cold water was injected continuously through a stimulation string for 1/2 year (see below) and on the annulus as well, and for more than a year after the stimulation pipe had been removed. The total amount of injected cold water is in the order of 1.5-2.0 million tons of fresh water. Evidently this fresh water had to mix in with the saline geothermal reservoir fluid if the IDDP-2 feed zones were connected to the conventional reservoir, see further discussion in chapter 2.3 below.

2.1 Core drilling and petrological studies

Table 1 shows an overview on core recovery in 10 core runs with the IDDP 8 1/2" coring tool and 3 successive core runs with 6" Baker Hughes tool at the bottom of IDDP-2, beneath the 7" liner. Prior to coring with the 6" tools, an 8 m deep 6" pilot hole had been drilled with tri-cone bit from 4,626-4,634 m, to clean out the bottom fill after casing and to condition the well.

Figure 4: A map showing the track of the inclined well IDDP-2, towards SW from the RN-15 wellhead in the NE. Main feed points are shown by brown, yellow and blue dots on the track line. Partly open fracture (not shown as blue dot) was seen in the one of the lowermost drill cores at the bottom.

The cores recovered were extremely valuable as they indicate that the IDDP-2 drilled through a basaltic sheeted dike complex that shows progressive metamorphism from greenschist facies to lower amphibolite facies, consistent with hydrothermal alteration at temperatures up to 450-600°C. A detailed

<table>
<thead>
<tr>
<th>Core run</th>
<th>Start</th>
<th>Coring interval</th>
<th>Cored length [m]</th>
<th>ROP [m/h]</th>
<th>Core recovery [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.9.2016</td>
<td>3006.7-3079.4</td>
<td>5.4</td>
<td>7.12</td>
<td>1.8</td>
</tr>
<tr>
<td>2</td>
<td>4.10.2016</td>
<td>3177.2-3279.0</td>
<td>1.4</td>
<td>2</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>10.11.2016</td>
<td>3695.0-3948.9</td>
<td>0.9</td>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>21.11.2016</td>
<td>3864.9-3950.7</td>
<td>1.8</td>
<td>10.25</td>
<td>0.2</td>
</tr>
<tr>
<td>5</td>
<td>12.12.2016</td>
<td>3825.3-3921.8</td>
<td>4.3</td>
<td>1.8</td>
<td>0.8</td>
</tr>
<tr>
<td>6</td>
<td>12.13.2016</td>
<td>3805.3-3870.2</td>
<td>0.4</td>
<td>2.5</td>
<td>0.2</td>
</tr>
<tr>
<td>7</td>
<td>22.11.2016</td>
<td>3905.5-4006.6</td>
<td>1.1</td>
<td>2.25</td>
<td>0.5</td>
</tr>
<tr>
<td>8</td>
<td>13.11.2016</td>
<td>4296.6-4355.9</td>
<td>0.7</td>
<td>5.5</td>
<td>0.1</td>
</tr>
<tr>
<td>9</td>
<td>6.12.2016</td>
<td>4368.7-4380.9</td>
<td>1.2</td>
<td>3</td>
<td>0.4</td>
</tr>
<tr>
<td>10</td>
<td>7.12.2016</td>
<td>4390.0-4512.2</td>
<td>2.2</td>
<td>8.25</td>
<td>0.2</td>
</tr>
<tr>
<td>11</td>
<td>16.1.2017</td>
<td>4612.6-4642.6</td>
<td>8.6</td>
<td>1.25</td>
<td>0.9</td>
</tr>
<tr>
<td>12</td>
<td>17.1.2017</td>
<td>4612.6-4652.0</td>
<td>0.2</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>13</td>
<td>16.1.2017</td>
<td>4652.0-4698.0</td>
<td>7</td>
<td>9.75</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Total 45.3  27.33

Core recovery about 65 %
The seismic network had revealed an aseismic body about 6 km depth, while observations from the local boundary at Reykjanes is generally believed to occur at 3-5 km. The regional brittle-ductile occurred within the depth range where drilling activity took place, between 3-5 km depth, starting at 3 km depth, during the drilling progress, indicating that induced earthquakes appeared to follow the drill bit with time. Earthquake activity mainly was closely monitored during the IDDP-2 stimulation phase that followed the drilling contains over 2300 earthquakes. The detailed results of the seismic monitoring during the DEEPEGS project will be described in detail by Zierenberg et al. (2020) and Bali et al. (2020).

2.2 Seismicity during drilling and stimulation

The active rift crossing Iceland from Reykjanes through the country is seismically active while variable over time, with scattered activity and occasional short-term earthquake swarms. Since 2013, a dense local seismic network of seven seismic stations has been operated at around the Reykjanes geothermal field, with an average spacing of ~0.5 km. In addition, on-line data from four seismic stations in the regional seismic network of Iceland (the SIL network) are available. Seismic activity was closely monitored during the IDDP-2 drilling from the 12th of August 2016 to the 25th of January 2017. During that period 650 earthquakes occurred in the field and more than 200 of them were located within less than 1 km of the IDDP-2 wellhead. The seismic catalogue, however, covering the timespan from the start of drilling to the end of the main stimulation phase that followed the drilling contains over 2300 earthquakes. The detailed results of the seismic monitoring during the DEEPEGS project will be reported, interpreted and discussed by Guðnason et al. (2020), and undoubtedly in follow-up papers.

Comparison of hypocentral depths with daily reports covered from 0.5 to 1.5 ML. This earthquake monitoring results was described by Peter-Borie et al., (2017). Fluid inclusions in the stained quartz from the open mineral vein were studied in detail by Enikő Bali and described briefly at GGW-2018 (GEORG Geothermal Workshop), confirming homogenization temperatures close to 600°C. The petrological and fluid inclusion details of the unique core samples from IDDP-2 will be described in detail by Zierenberg et al. (2020) and Bali et al. (2020).

2.3 Stimulation, tracers and chemistry

At end of drilling short stimulation with thermal cycling and pressurization was carried out. That increased the indicated injectivity index for the well to about 3.1 L/s per bar (Sigurðsson, 2019). The drilling operation was completed on January 25th, 2017 by installing a 3 ½” pipe to about 4589 m depth for deep stimulation, and the idea was also to inject gas tracer through the stimulation string. In planning the deep drilling, it was expected that permeability would decrease with depth in a similar manner as predicted reduction of porosity from MT-resistivity profiles in the area. Therefore, it was considered likely that the well could be “dry” below 3000-3500 m depth. It was also predicted that temperature would increase with depth so for a soft stimulation it was planned to put in a stimulation pipe and circulate cold water through it for several months in order to create enough temperature difference for contraction fractures to form. The plan was described by Peter-Borie et al., (2017).

The deep stimulation was completed in July 2017, and after that cold-water stimulation was continued for more than a year, with relatively low flow rate on the annulus. The reason for the extension related to a casing damage between 2.3-2.4 km, briefly discuss elsewhere. The stimulation effort was concluded with hot condensate water injection for about 2 months. A short step rate injection test was carried out during that stage in September 2018, just over a month into the warmup period. The injection to the well from the injection system had by then been increased to about 50 L/s at temperature about 130°C. The test was done by shutting off the injection for some time and then open for the injection again. The results for the injectivity test yielded an estimated injectivity index of 2.7 to 2.9 L/s per bar which is not much lower than at end of the first stimulation stage. Bearing in mind that considerable amount of fluid blocker material had been put into the well, which does not break down until temperature is 180°C or higher, the injectivity was deemed reasonably between 3 and 6 km depth beneath the center of the production field. The uppermost part of this apparent asemic body, from 3-5 km depth, became seismically active during the deep drilling. A possible explanation for the absence of natural earthquakes in this body is that its temperature is very close to the brittle-ductile boundary for normal strain rates (Guðnason et al., 2016). Most likely the primary cause for the induced seismicity related to the introduction of cold water into the zone of total circulation loss below 3.0 km depth, increasing the strain rate sufficiently to induce seismicity. These induced earthquakes were predominantly small, with magnitudes ranging from 0.5 to 1.5 Mₛ, with 95% of located earthquakes ranging from 0.5 to 1.5 Mₛ. This earthquake monitoring results for Reykjanes are of paramount importance for the development of EGS geothermal systems in general and thereby the DEEPEGS project (Friðleifsson et al. 2018).
good. The details will be described by Sigurðsson (2020).

During the blind drilling and subsequent stimulation efforts, over 1.5 m³ of cold water was injected to the IDDP-2 drill hole as said above. The plan was to inject gas tracers (FS, and Ar) and a liquid tracer deep into the system through the stimulation string in order to demonstrate connectivity to the overlying exploited geothermal reservoir. For several reasons the injection of the tracer proved unattainable once on drill site. However, connection to the surrounding production wells was pleasantly detected because of the fresh water injection. Regular chemical monitoring since 2006 of neighboring wells, like RN-11 and RN-12, showed clear chemical influence from the fresh water drilling fluid. Their salinity decreased temporarily during drilling and subsequent stimulation effort, and influx of atmospheric gas like nitrogen, carried with the cold drilling fluid, appeared as well as significant changes were seen in oxygen and hydrogen isotopes reflecting the freshwater dilution of the geothermal brine. The details of it will be described by Borgljisson et al. (2020).

2.4 Flow test preparation

Design of the IDDP-2 flow testing equipment had already been done by an IDDP working group prior to the drilling of the well. That design, however, needed to be re-addressed as the drilling proceed, and once finished a “Way Forward Workshop” helped setting the likely P-T condition to be dealt with on surface (SAGA report 11, available at www.iddp.is). The working group then completed the final design last autumn and most of the needed bidding and purchasing orders have already been made. The equipment construction on surface is expected to be completed in May 2019. The details of the design and proceeding will be described by Jóhannesson et al. (2020)

The original flow testing plan from 2017, was delayed by more than one year due to a casing damage at 2.3-2.4 km depth detected by downhole logging after the 3½” stimulation pipe had been removed from the well in July 2017. A small leak had been detected there and potential mitigation actions needed to be inspected carefully and decided upon. Finally, a decision was reached to leave it be and flow test the well under current condition. Heating up of the well began in September 2018 and the flow test was expected to begin in April 2019 but is already delayed to June. The outflow from the well will be a mixture of fluids from several feed zones at different depths, while majority of the flow is expected from the 3.4 km feed zone. Minor inflow to the well is expected from the leaky casing zone below 2.3 km, depending on flow rate. At low flow rate fluids may possibly flow out though the damaged casing, and possibly block it up by precipitates? Speculations on differential flows from different feed points continues in the flow test working group. According to calculations (Sturla Sæther, pers. com.) the lowermost and hottest feed zones could contribute to the total outflow from ~ 2% to 20%, again pending on flow rate, larger at low flow rates.

2.5 Scientific and engineering firsts in IDDP-2

Just to list up several scientific and engineering firsts related to the IDDP-2, we include this chapter. Amongst such „firsts”, was our decision to try to cement in several thermocouples outside the production casing. The manufacturer was Petrospec which also supervised its insert. The thermocouples worked well for a while but then started to fail. Only 3 of 9 are still working.

Also amongst first attempts was our decision to use reverse cementing method for the entire 3 km length of the production casing, which was done in one go cementing operation. The operation appeared successful, while we have still some concerns about the cement mixture and its integrity in the lower part of the well below the casing damage zone.

Prototype high-temperature downhole motor from Baker Hughes, tolerating up to 300°C, was also used during part of the directional drilling with good success, later described at an IADC/SPE technical conference in Texas by Stefánsson et al. (2018), including prototype high-T drill bits.

As total circulation loss, but very high temperature at the bottom of the well prevented conventional downhole geophysical logging in the IDDP-2 hole, a logging while drilling LWD (LWT) tool from Weatherford was hired and used for the first time in an Icelandic hole. Thereby we got proper geophysical logs almost to the bottom of the well (yet to be published), excluding the final core section at the bottom. Those cores however, were still geophysically logged on the surface with a MSCL scanner from ICDP to be described by Mesfin et al. (2020).

More than 2.1 km of blind drilling involved losing of about ~ 60 m³ of cuttings into the rock formation. Such a blind drilling to a record depth of 4,659 m into a formation at supercritical temperature is evidently a noteworthy achievement. The drilling operation could have been extended an bit deeper while repeated blockages and increased torque left us deciding to stop the drilling operation.

Last but not the least, the IDDP-2 is the deepest and hottest drill hole so far sited in an active mid-ocean spreading center. It penetrated an active supercritical hydrothermal environment at depths analogous to those postulated as the high temperature reaction zones feeding black smoker systems.

3. CONCLUSIONS AND DISCUSSION

The DEEPEGS demonstrator well at Reykjanes, well IDDP-2, had an immediate impact on the accepted and used geothermal reservoir model at Reykjanes – and thereby the size of the geothermal reservoir, which
increased in exploitable volume by some 40-50 % (almost doubled). Since 2006 high temperature fluid, from 220-320°C, has been harvested from some 18 production wells at Reykjanes to produce about 100 MW, in two turbines. Most of the feed zones are located between 0.8 km to 2.3 km, i.e. below the production casing towards the bottom of the conventional production wells (2.2-2.8 km deep). The currently used reservoir model has set the bottom of the reservoir system at 3.0 km depth, assuming dense impermeable rocks below that depth. In the new IDDP-2 well the production casing was cemented in at 2,941 m depth, while the drilling suffered massive total circulation loss from that depth to the bottom of the well at 4,650 m. Twelve times cement plugging was attempted in attempts to heal the loss zones but proved unsuccessful so at 3.2 km depth no further plug cementing was attempted. Accordingly, the rest of the well was drilled with temporary isolation of the loss zone (blast drilling). During temperature downhole logging during and after drilling the main feed zone proved to be at about ~3.4 km depth in the temperature logs, screening off the apparent feed zones mentioned above, and then revealing several smaller feed-points down to bottom of the well. The massive loss zone at 3.4 km depth is about 1 km below the deepest significant feed points in other wells within the Reykjanes drill field, indicating that the exploitable reservoir needs to be sized up to at least that depth and the “floor” of the reservoir for modelling calculations to be set about 1 km deeper that in the current estimates. Irrespective of all other impact the deep IDDP-2 well may have, this is probably the most economic information resulting from the DEEPEGS demonstrator at Reykjanes. While it is too early to speculate on a significant impact from the remaining flow test of the IDDP-2, the primary goal of the IDDP project is to gain significant power output from such deep wells. The DEEPEGS primary goal of creating a workable enhanced geothermal system (EGS) however, has already been accomplished at Reykjanes.

A second major impact already resulting from the deep IDDP-2 drill hole, is the connectivity to the surrounding production wells. Regular chemical monitoring since 2006 of neighboring wells, like RN-11 and RN-12, showed clear chemical influence from the fresh water drilling fluid. Their salinity decreased temporarily during drilling and subsequent stimulation effort, and influx of atmospheric gas like nitrogen, carried with the cold drilling fluid, appeared as well as significant changes were seen in oxygen and hydrogen isotopes reflecting the freshwater dilution of the geothermal brine. This means that by drilling deep under the currently harvested geothermal reservoir, into much hotter rocks (500-600°C hot), and by re-injecting whatever fluid we like such as condensate water at some temperature, both temperature and pressure support will result in the overlying geothermal reservoir. In other words, we have already proven that the EGS concept will work for the Reykjanes demonstrator.

The third significant impact concerns the deepest part of the DEEPEGS demonstrator at Reykjanes, namely the extremely high temperatures in the lowermost 1 km, currently assumed to be close to 600°C at the bottom of the well. During drilling 426°C at 343 bar pressure was measured at 4,550 m depth after only 6 days heating. Most recent petrological studies of the IDDP-2 drill cores, including mineral geothermometry and fluid inclusion studies, all indicate that the bottom hole temperatures should be close to 600°C. All imply that we drilled into an active supercritical regime in an ocean floor settings of a sheeted dyke complex in a saline fluid system. Such an active system has never been drilled into before and the resulting scientific impact is beyond the state of the art. The scientific work currently undertaken will have exceptional visibility and socio-economic impact. Part of this impact data has already been published in peer reviewed journals, in Scientific Drilling (2017) and Journal of Volcanology and Geothermal Research (2018) (Fridleifsson et al., 2017, 2018), and there are more to be expected during this year and next (e.g. Zierenberg et al., 2020, Bali et al., 2020).

REFERENCES


Fríðleifsson et al.


Sigurðsson, Ó., Stimulation of the RN-15/IDDP-2 well at Reykjanes in an attempt to create an EGS system. DEEPEGS Deliverable 6.5 (internal report) (2019).


Acknowledgements

The IDDP-2 drilling was funded by HS Orka, Statoil (Equinor), Landsvirkjun, Orkuveita Reykjavíkur, and the National Energy Authority in Iceland. The IDDP-2 well has also received funding from the European Union’s HORIZON 2020 research and innovation programme under grant agreement No 690771. Funding for obtaining spot cores at Reykjanes and elsewhere was provided by ICDP and the US NSF (grant no. 05076725). Robert A. Zierenberg, Wilfred A. Elders, UC Davis and UC Riverside, and other US collaborators have worked expeditiously on the petrological details of the drill cores, and Enikó Ball at University of Iceland and her co-workers on fluid inclusions. All these are greatly acknowledged.
DEEPEGS project management - Lessons learned

Sigurdur G. Bogason¹, Gudmundur Ömar Fridleifsson², Hjalti P. Ingolfsson¹

¹ GEORG Geothermal Research Cluster, Grensásvegur 9, 108 Reykjavik, Iceland
² HS Orka hf, Svartsengi, 240 Grindavik, Iceland

sigurdur@georg.cluster.is

Keywords: Deep drilling, geothermal, enhanced geothermal systems (EGS), H2020 funded project, DEEPEGS, licensing, lessons learned.

ABSTRACT

The DEEPEGS Horizon 2020 Innovation action project “Deployment of deep enhanced geothermal systems for sustainable energy business” was selected for funding in 2015, and its official launch was in December 2015. The project’s total budget of 44 million Euro received an EU grant of about 20 million Euro for its four years duration, making this one of the larger publicly funded H2020 projects. The consortium of 10 partner organisations is from the geothermal industry, technical and oil- and gas sectors, and research organisations coming from five European countries. The main objective was to test and demonstrate Enhanced Geothermal System (EGS) technology in three different geothermal systems and geological settings with the goal of facilitating the transferability of the expected results to other deep geothermal sites throughout Europe and worldwide.

The project has over its life cycle encountered several hurdles that have needed to be addressed by the consortium management. Number of these directly link to policy actions or sometimes inaction or slow administrative processes that clearly do not facilitate evenly the successful implementation across the European Economic Area (EEA), and market considerations are not equal across the common EEA market zone.

1. INTRODUCTION

The project management lessons learned from the DEEPEGS project will be addressed in this paper. Project management perspective from within a complex collaborative international publicly funded research and innovation action will be shared, as well as insights gained from the policy environment. The aim is to share the experience gained and discuss how the barriers encountered might be addressed to enable geothermal developments to be deployed more widely. The knowledge and technical developments from DEEPEGS need to be more actively facilitated and transferred to the geothermal sector across Europe and around the world. The public research funding for this and other geothermal projects makes it an obligation to exploit the innovations developed, and share lessons learned in the project.

The successful drilling in Reykjanes for the deep well is thoroughly described by G. O. Fridleifsson et. al (2017, 2018), and the background geology and structure of the volcanic Reykjanes system in Iceland by K. Sæmundsson, et al. (2018). The drilling of the well began in August 2016 and the well was completed at a depth of 4659 m MD (Measured Depth, 4.5 km vertical depth) in January 2017. Supercritical conditions were encountered at the bottom (measured temperature: 426 °C and estimated to be around 500–530 °C at 340 bar pressure (Fridleifsson et al., 2017; Stefanson et al., 2017). The high-enthalpy well in DEEPEGS, is commonly referred to as RN-15/IDDP-2, and a recent paper from Peter-Borie et al. (2018) describes the borehole damaging under thermo-mechanical loading. The research work at Reykjanes well site provided the project consortium with opportunities to deploy monitoring tools at the geothermal field and improve the knowledge base for future work and other projects (Darnet et al., 2018). Fridleifsson et al (2019) discusses the impacts generated from the deep IDDP-2 (DEEPEGS) well in Reykjanes and how this work provides improved understanding of the geothermal reservoir and connectivity to the other production wells in the geothermal field.

This paper presents a current overview from an ongoing active project, and the following list of issues and lessons learned are among those that can be presented and discussed now by this paper:

- Licensing of geothermal projects under different policy regimes,
- Project management and disruptive decision-making barriers,
- Funding mechanism, partner commitments and lessons learned,
- Transparency and trust among actors,
- Public relations and outreach communications.
2. DEEPEGS PROJECT

The H2020 call Topic: LCE-3: Demonstration of renewable electricity and heating/cooling technologies for this project had specifically requested the following geothermal coverage:

Deep geothermal energy: Testing of enhanced geothermal systems in different geological environments – Widespread deployment of enhanced geothermal systems (EGS) needs new and improved models and innovative solutions are needed to routinely create EGS reservoirs with sufficient permeability, fracture orientation and spacing. Cross-fertilisation with hydrothermal fields and cross-fertilisation with tight oil and gas fields can be explored.

The DEEPEGS project consortium, coordinated by the Icelandic energy company HS Orka, brings together geothermal research organisation, companies from both the geothermal and oil and gas energy industry sectors. The 10 partner organisations (Fig. 1) jointly mobilise the required expertise and cross-fertilisation required to demonstrate the feasibility of creating EGS reservoirs for wider future deployment in Europe and elsewhere.

The project planning streamlines as well inputs from previous geothermal projects through earlier work by some of the partners (Fig. 2). The vision presented had an original ambition of two demonstrator countries, two sites in France, and one in Iceland.

The work has been progressing very well on deep drilling into the high-enthalpy volcanic rock formation in Reykjanes, but only recently in the Vendenheim demonstrator that currently is pending a grant amendment by the Innovation and Networks Executive Agency (INEA) of the European Commission that
manages the H2020 grant agreement for DEEPEGS. The drilling of two wells in Vendenheim down to about 5 KM depth is completed, and currently the EGS demonstrator is undergoing multi drain drilling and later stimulation which will be followed by flow testing later this year, 2019.

In Reykjanes the casing damage (Peter-Borie et al, 2018) has once more showed the importance of new flexible couplings technology development (GEOWELL H2020 project1). Testing ending in GEOWELL at TRL4 (Ingolfsson et. al. 2016, 2017), but will be continued as progressive work in DEEPEGS to advance this further to TRL6 level.

Another technological development in the project is a drilling tool technology manged by partner Herrenknect Vertical GmbH, and field testing. at TRL5-6 could take place during latter half of 2019.

The DEEPEGS project management has in place monitoring, quality and risk management procedures. Also, project management bodies like the Executive Board, a Project Office and a qualified and experienced coordination team. This proved to be crucial in moving the project forward and enabled the mitigation of risks. The consortium worked jointly to seek solutions and during 2018 a number of extraordinary management meetings were required to progress the consortium plans. Several meetings with INEA were also organised to provide the funding agency with up to date information on the situation.

2. LICENSING POLICY OBSERVATIONS

In Iceland the regulatory and policy framework for geothermal projects is linked to similar processes and licencing processes as found in some EU countries. Environmental assessments and planning licences are required for new fields prior to their development. Orkustofnun (2019) is responsible for the licensing process. The ownership of resources inside the ground is attached to a private land, while on public land resources inside the ground are the property of the State of Iceland, unless others can prove their right of ownership. Even though the ownership of resources is based on the ownership of land, research and utilisation is subject to licensing according to the Act on Survey and Utilisation of Ground Resources, No. 57/1998 and the Electricity Act No. 65/2003. Survey, utilisation and other development pursuant to these Acts are also subject to the Nature Conservation Act, Planning and Building Act and other acts relating to the survey and utilisation of land and land benefits.

In France the regulatory framework and licencing process has been recently described by Dumas et al, and Fraser (2013), and that the French mining law distinguishes two steps in every mining project, including geothermal: the first one is exploration and the second one production. Therefore, the rules of licensing consist in two permits: the exploration license or the production license. Boissavy (2015) confirms that the main barrier in France remains administrative constraints and delays to get the permission for drilling.

In the DEEPEGS project two geothermal demonstration sites were planned in France and the company Fonroche Geothermic2 had secured the exploratory licenses for the two planned geothermal sites. However, the drilling licences are managed under the French mining code and regional approval process was required separately for both the sites. This licencing process was very time consuming and several hurdles had to be overcome step by step. Repeatedly, the company needed to delay planned drillings due to the slow progress at the regional level. The timeline in the French sites slipped continually, and finally in 2018 an alternative solution was needed within the DEEPEGS project. An alternative demonstrator site in Alsace, France that Fonroche had obtained all licences for is through a pending grant amendment being brought into the project, replacing the original two planned demonstrators in the H2020 project. The drilling work in Vendenheim started by Fonroche in 2018 and in first half of 2019 two deep wells have been drilled and becomes the DEEPEGS project’s alternative French demonstration site. Currently the work in Iceland and France demonstrators is focused on the EGS part and flow testing of the wells is to be carried out in 2019 and continuing into 2020. Data on geothermal fluids and energy potential will be available for reporting during 2019 and presented at the WGC 2020 event.

The lessons learned regarding policy environment and geothermal project licensing was a truly difficult and uphill journey for the French industrial energy partner. This delayed significantly the planned work in DEEPEGS and put the project at a significant risk for achieving the main objective of demonstrating successful EGS outcomes.

- Regional governance and regulatory barriers,
- Slow processing of licensing issues, in part due to lack of experienced government officials in France,
- As the mining code regulates the process for geothermal, few staff available with required expertise on geothermal,
- In France, some regions have very limited background on geothermal, exception being Alsace and Aquitaine region
- Geothermal is possibly the “GREAT-Unknown, or a know-how mystery, therefore, caution takes charge and slow actions become the current norm.
- All licenses for the geothermal site need to be confirmed prior to launching the project,


2 Visted by Internet 6 March 2019, https://www.fonroche-geothermie.com/
actors and transparency of timely information sharing. Learned at the DEEPEGS Reykjanes geothermal funded project. At project management level the core communications regarding outcomes from the expectations are for wider dissemination and coming much later through in the project, but delayed work in the French demonstrator is now will be available, following the end of the project. The 2020 as at this time the core outcomes from DEEPEGS World Geothermal Congress in Reykjavik in April Vendenheim demonstrator site as well. Many of these are targeting the knowledge for deep wells in volcanic regions like Iceland that will be applicable in other regions, like e.g. Iceland Deep Drilling Project at Reykjanes: Drilling into the root zone of a black smoker analog. Journ.Volc. and Geoth. Research (2018).


For risk mitigation, an alternative site needs to be identified should any unforeseen issues arise for the site,

More flexible arrangement for realigning H2020 funding within a project, should mitigation actions be required,

Strong internal communications among partners,

High-level of collaborative trust between partners is crucial and willingness to share timely information,

The DEEPEGS project consortium is currently working on the preparation of numerous scientific papers and reports. These are being prepared for publication in open access formats to communicate the significant scientific know-how generated and the crucial lessons learned at the DEEPEGS Reykjanes geothermal demonstrator site. Many of these are targeting the World Geothermal Congress in Reykjavik in April 2020 as at this time the core outcomes from DEEPEGS will be available, following the end of the project. The delayed work in the French demonstrator is now coming much later through in the project, but expectations are for wider dissemination and communications regarding outcomes from the Vendenheim demonstrator site as well.

3. CONCLUSIONS

The DEEPEGS project has provided significant new knowledge for deep wells in volcanic regions like Iceland that will be applicable in other regions, like e.g. Italy and internationally. The complex and slow acting licensing processes in France have presented unforeseen effort on project risk mitigation actions. The key lesson learned is that all licenses for the geothermal sites need to be confirmed prior to launching a H2020 funded project. At project management level the core lesson learned is on the core importance of trust among actors and transparency of timely information sharing.

REFERENCES


Acknowledgements

The DEEPEGS project is funded by the European Union’s HORIZON 2020 research and innovation program under grant agreement No 690771.
Testing Flexible coupling for Geothermal Wells GRC 2019

Conference Paper - October 2019

CITATIONS: 0
READS: 12

3 authors:

I.O. Thorbjornsson
Iceland GeoSurvey (ÍSOR)
29 PUBLICATIONS, 104 CITATIONS

Gunnar Skúlason Kaldal
Iceland GeoSurvey (ÍSOR)
14 PUBLICATIONS, 40 CITATIONS

Árni Ragnarsson
Iceland GeoSurvey (ÍSOR)
36 PUBLICATIONS, 315 CITATIONS

Some of the authors of this publication are also working on these related projects:

Nonlinear Finite-Element Analysis of Casings in High-Temperature Geothermal Wells View project
OptiCast View project

All content following this page was uploaded by I.O. Thorbjornsson on 04 October 2019.
The user has requested enhancement of the downloaded file.
GRC Transactions, Vol. 43, 2019

Testing Flexible Couplings for Geothermal Wells
I.O. Thorbjornsson, G.S. Kaldal, A. Ragnarsson

Keywords
Flexible Couplings, Strain mitigation, Geothermal wells, Buckling, Collapse, Strain reduction, Production casing.

ABSTRACT
Flexible Couplings (FC) as a solution to mitigate thermal straining of casings in geothermal wells have been tested, where its function to allow intermittent displacement of the production casing during warm-up has been verified both for straight and deviated wellbore. During warm-up, free thermal expansion of the steel used for casing in geothermal wells is blocked in conventional design, resulting in high stresses that are often above the yield strength of the material. This stress can both damage the casing as it will release the stress by permanently deforming the casing plastically. The proposed solution allows the casing to expand into the FC that replace conventional connections, and by that ensure that the stress level will remain below the yield strength of the material. Chance of generating plastic strains will therefore be lowered reducing the risk of casing failures. Testing in two, third party, laboratories have been performed within the EU funded projects, GeoWell (www.geowell.eu) and DEEPEGS (www.deepeg.eu) and the plans are to make the first full scale testing in a high-temperature geothermal well in the end of 2019.

1. Introduction
The Flexible Coupling concept has been under development since 2015. The concept, to mitigate plastic strain in the production casing during warm up by allowing the casing to expand axially, has been tested and verified in two independent testing laboratories. The axial displacement, designed according to the difference between cementing temperature and operational conditions can be adjusted to operational temperatures up to 600°C. The design criteria for the FC is to fulfill all requirements for drilling, cementing and completion of the geothermal well, meaning that the anchor casing and drilling diameters are the same as with use of conventional connections. With the release of the axial stress in the production casing it is expected that the risk for buckling/collapse will be reduced significantly and plastic strains minimized. Therefore, the risk of tearing the casing out of couplings during cooling, e.g. for well workovers, should be lowered significantly.
Thorbjörnsson et al

The European Union-funded Horizon 2020 research and development program has funded two projects (www.geowell.eu, www.deepelts.eu) where the FC has been designed, tested and verified. The next step is final tests in laboratory followed by production of FCs for full length of the production casing. The plan is to have it ready for a high enthalpy well in Iceland by the end of the year 2019 – early 2020.

2. Failure modes and mitigation.

Thermal expansion of the constrained casing material is one of the major issues causing failures in high-temperature geothermal wells. While it is well documented and standardized how to tackle thermal expansion in surface installations, no solution has been available for casings in drilled wells both in oil and gas as well as in geothermal applications. The casings are made of steel of grades chosen according to standards API 5CT and ANSI/NACE MR0175/ISO 15156. Carbon steel commonly used for geothermal casings has a thermal expansion coefficient around 0.012 mm/m°C. The material strain often well above yield has been linked to statistical studies of well failures in an unpublished paper at ISOR (Iceland geoSurvey) by Björn Sveinbjörnsson (Figure 1). Around 250 geothermal wells in Iceland were analysed, whereof 136 have been regarded as production wells, reveal that 75 wells or 55% have reported incidents. The number could be higher as not all the wells have been analysed or in some cases logged since production started.

![Pie chart](image)

**Figure 1:** Reported failures in a series of 136 high temperature geothermal wells in Iceland. In total 75 wells, out of the 136, have reported failures (Lohne et al. 2017).

Mitigation of the axial load for the production casing with Flexible Coupling allow each casing segment to expand axially into the FC, thereby enabling design where the stress level of the...
casing material is controlled to be lower than the yield strength of the material. This allows for the first time, a well design following the same design criteria as used for surface installations, i.e. to be designed elastically. The allowed axial movement is according to expected temperature in the well and more specifically temperature difference between cementing temperature and operational temperature. Flexible Couplings are therefore designed in, but not limited to, several temperature intervals as shown in Table 1.

<table>
<thead>
<tr>
<th>Flexible Coupling</th>
<th>Operational temperature: [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>200-300</td>
</tr>
<tr>
<td>300</td>
<td>250-350</td>
</tr>
<tr>
<td>400</td>
<td>300-400</td>
</tr>
</tbody>
</table>

Design work and related parameters have been reported by Kaldal et al (2011), Kaldal and Thorbjornsson (2016) and Thorbjornsson et al (2017).

3. Testing and verification of Flexible Couplings.
Flexible Couplings were made as prototypes in two casing dimensions, 9¾" and 13¾". The prototypes were made of medium carbon steel type AISI 4140-4, commonly known in the geothermal industry as L80. Three of the 9¾" prototypes were tested at SINTEF (www.sintef.no) laboratories in Trondheim, Norway, and one 9¾" and one 13¾" prototype were tested at NORCE (www.norce.no) laboratories in Stavanger, Norway. Test setup in SINTEF and NORCE can be seen in Figure 2 and Figure 3, respectively. The test procedure was based on the ISO/PAS 12835:2013(E) testing standard for premium connections, but as the standard is intended for connections with no moving parts, modifications were made. Test loads for the 9¾" FC was 1000 and 2000 kN in compression, and 1000 kN in tension. In all load cases as well as unloaded, pressure tightness with water at ambient temperature was measured. Finally, the ultimate tensile load capacity was measured.

Figure 2: Test setup for testing 9¾" Flexible Coupling in SINTEF laboratories in Norway.
Thorbjørnsson et. al

Test loads for the 13¾" FC were 1400 and 2800 kN in compression, as well as the ultimate tensile load. Sliding forces and start up force for sliding were measured in both straight and bended position. For the first three prototypes in 9¾ a bending curvature of 2,5° and 5° pr. 30 m length was applied and sliding forces measured.

![Figure 3. Test setup for testing 9¾" Flexible Coupling in NORCE laboratories in Norway.](image)

Table 2 shows result from testing three 9¾" FC in SINTEF, one 9¾" and one 13¾" in NORCE.

<table>
<thead>
<tr>
<th>Prototype:</th>
<th>Start force [kN]</th>
<th>Sliding force [kN]</th>
<th>2,5° bending: Sliding force [kN]</th>
<th>5° bending: Sliding force [kN]</th>
<th>Ultimate tensile load [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 9¾</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>1837</td>
</tr>
<tr>
<td>2 - 9¾</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>1926</td>
</tr>
<tr>
<td>3 - 9¾</td>
<td>320</td>
<td>320</td>
<td>320</td>
<td>320</td>
<td>3135</td>
</tr>
<tr>
<td>4 - 9¾</td>
<td>247</td>
<td>176-219</td>
<td>-</td>
<td>-</td>
<td>3032</td>
</tr>
<tr>
<td>5 - 13¾</td>
<td>267</td>
<td>189-229</td>
<td>-</td>
<td>-</td>
<td>3922</td>
</tr>
</tbody>
</table>

4. Conclusion

Testing of five prototypes of Flexible Couplings have been performed whereas four tests for 9¾" casing diameter and one for 13¾" casing diameter. Results show that the concept of the FC with sliding mechanism is working well, for straight as well as deviated test setup. Sliding forces have been recorded and are consistent during several runs of opening and closing the couplings.
Thorbjørnsson et. al

Sliding forces have been slightly adjusted between prototypes as well as improvements to the ultimate tensile strength. Leakage has been recorded to be over given limits by the standard for premium connections. Part of the improvements between prototypes have been focusing on pressure tightness of the FC. Prototype 4 in 9½" casing diameter showed pressure tight connection in all positions up to 110 bar water pressure at ambient temperature. Two international patent applications have been filed to the European and USA patent agency, both have now been accepted as Icelandic patents.

Schedule for the next steps in the verification process is to test 2-3 more prototypes of the 13¾" diameter and thereafter the plan is to make a full demonstration by producing up to 100 pcs of the 13¾" FC for production casing in a well to be drilled in Iceland late 2019 or early 2020.

Acknowledgement

The authors want to acknowledge the unpublished work done by Mr. Björn Már Sveinbjörnsson who sadly passed away in 2018. His work on damage analyses of Icelandic high-temperature geothermal wells will be continued and finalized by others in due time. Also, we would like to express our gratitude to the European Commission for the support in the H2020 projects GeoWell under grant agreement No 654497 and DEEPEGs under grant agreement No 690771.

REFERENCES


# Index

<table>
<thead>
<tr>
<th>#</th>
<th>Article</th>
<th>Authors</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SCIENTIFIC PAPERS</strong></td>
<td></td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>1</td>
<td>The Iceland Deep Drilling Project geothermal well at Reykjanes successfully reaches its supercritical target</td>
<td>Friðleifsson, G.O.; Elders, W.A.;</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>The Iceland Deep Drilling Project 4.5 km deep well, IDDP-2, in the seawater-recharged Reykjanes geothermal field in SW Iceland has successfully reached its supercritical target</td>
<td>Friðleifsson G.O.; Elders W.A.; Zierenberg R.A.; Stefánsson A; Fowler A.P.G.; Weisenberger T.B.; Harðarson B.S.; Mesfin K.G.</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>Geology and structure of the Reykjanes volcanic system, Iceland</td>
<td>Sæmundsson K.; M.Á. Sigurgeirsson; G.O. Friðleifsson</td>
<td>47</td>
</tr>
<tr>
<td>5</td>
<td>Monitoring geothermal reservoir developments with the Controlled-Source Electromagnetic method — A calibration study on the Reykjanes geothermal field</td>
<td>Darnet M.; Wawrzyniak P.; Coppo N.; Nielsson S.; Schill E.; Friðleifsson G.Ö.</td>
<td>60</td>
</tr>
<tr>
<td>6</td>
<td>Borehole damaging under thermo-mechanical loading in the RN-15/IDDP-2 deep well: towards validation of numerical modeling using logging images</td>
<td>Peter-Borie, M.; Loschetter, A.; Merciu, I.A.; Kämpfe, G.; Sigurðsson, O.</td>
<td>77</td>
</tr>
<tr>
<td>7</td>
<td>Temperature log simulations in high-enthalpy boreholes</td>
<td>Wang, J.; Nitschke, F.; Gholami K.M.; Kohl, T.</td>
<td>110</td>
</tr>
<tr>
<td>8</td>
<td>The need for integrated valuation tools to support decision-making – The case of cultural ecosystem services sourced from geothermal areas A cascade model and initial exploration of co-production processes underpinning the ecosystem services of geothermal areas. Renewable Energy.</td>
<td>Cook, D.; Fazeli, R.; Davidsdóttir, B.</td>
<td>131</td>
</tr>
<tr>
<td>9</td>
<td>Reykjanes, Iceland: Structure and dynamics of mid-oceanic ridge geo/hydrothermal systems</td>
<td>Jousset P.; Mortenssen, A.K.; Friðleifsson, G.Ö.; Ágústsson, K.; Gudmundsson, M.T.</td>
<td>137</td>
</tr>
<tr>
<td>10</td>
<td>Materials investigation of the high temperature IDDP-1 wellhead</td>
<td>Thorbjörnsdóttir, I.O.; Kjeldal, G.S.; Krogh, B.C.; Palsson, B.; Markussson, S.H.; Sigurðsson, P.; Einarsen, A.; Gunnarsson, B.S.; Jonsson S.S.</td>
<td>140</td>
</tr>
<tr>
<td><strong>CONFERENCE PROCEEDINGS</strong></td>
<td></td>
<td></td>
<td>157</td>
</tr>
<tr>
<td>11</td>
<td>Successful drilling for supercritical geothermal resources at Reykjanes in SW Iceland</td>
<td>Friðleifsson, G.Ó.; Elders, W.A.</td>
<td>158</td>
</tr>
<tr>
<td>12</td>
<td>The drilling of RN-15/IDDP-2 research well at Reykjanes in SW Iceland IDDP-2 research well at Reykjanes in SW Iceland</td>
<td>Stefánsson, A.; Gíslason, Þ.; Sigurðsson, Ö.; Friðleifsson, G.Ö.</td>
<td>171</td>
</tr>
<tr>
<td>13</td>
<td>Temperature Prediction by Multigeophysical Inversion: application to the IDDP-2 Well at Reykjanes, Iceland</td>
<td>Hokstad; K.; Tánavsúu-Mikleviciene; K.</td>
<td>182</td>
</tr>
<tr>
<td>14</td>
<td>A 300 Degree Celsius Directional Drilling System.</td>
<td>Stefánsson, A.; R. Duerholt; J. Schroeder; J. Macpherson; C. Höhl; T. Kruspe; T.J. Eriksen</td>
<td>194</td>
</tr>
<tr>
<td>15</td>
<td>Preliminary description of rocks and alteration in IDDP-2 drill core samples recovered from the Reykjanes Geothermal System, Iceland.</td>
<td>Zierenberg; R.A.; Fowler; A.P.G.; Friðleifsson; G.Ö.; Elders; W.A.; Weisenberger; T.B.</td>
<td>195</td>
</tr>
<tr>
<td>16</td>
<td>Processing of magnetotelluric data for monitoring changes during drilling operation</td>
<td>Haaf; N.; Schill; E.</td>
<td>212</td>
</tr>
<tr>
<td>17</td>
<td>Improving Geothermal Economics by Utilizing Supercritical and Superhot Systems to Produce Flexible and Integrated Combinations of Electricity, Hydrogen, and Minerals</td>
<td>Elders W.A.; Shneli; J.; Friðleifsson; G.O.; Albertsson, A; Zierenberg; R.A.;</td>
<td>224</td>
</tr>
<tr>
<td>18</td>
<td>Thermal stimulation of the deep geothermal wells: insights from the H2020- DEEPEGS project</td>
<td>Peter-Borie; M.; Loschetter A.; Blaisonneau A.; Hieu Tran V.; Gaucher E.; Sigurðsson O.; Friðleifsson G.Ö.; Damy PC.; LeLous M.; Tuliníus H.</td>
<td>238</td>
</tr>
<tr>
<td></td>
<td>Title</td>
<td>Authors</td>
<td>Page</td>
</tr>
<tr>
<td>---</td>
<td>----------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>19</td>
<td>The Iceland Deep Drilling Project at Reykjanes - 4.5 km Deep Drilling into Supercritical Conditions</td>
<td>Weisenberger; T.B.; B.S. Harðarson; K.G. Mesfin; G.M. Einarsson; S. Nielsson; R.A. Zierenberg; G.Ó. Friðleifsson.</td>
<td>248</td>
</tr>
<tr>
<td>20</td>
<td>Imaging and monitoring the Reykjanes supercritical geothermal reservoir in Iceland with time-lapse CSEM and MT measurements</td>
<td>Darnet; M.; N. Coppo; P. Wawrzyniak; S. Nielsson; G.O. Fridleifsson; E. Schill;</td>
<td>259</td>
</tr>
<tr>
<td>21</td>
<td>The Reykjanes DEEPEGS Demonstration Well–IDDP-2</td>
<td>Friðleifsson GÓ; Albertsson A.; Stefánsson A.; Párlófsson G.; Mesfin K.G.; Matthíasdóttir K.V.; Sigurðsson K.; Sigurðsson Ó.; Gíslason R.; Elders W.A.; Zierenberg R.A.; Bali E.; Guðnason E.Á.; Óskarsson F.; Weisenberger T.B.;</td>
<td>268</td>
</tr>
<tr>
<td>22</td>
<td>DEEPEGS project management - Lessons learned</td>
<td>Bogason, S.G.; Fridleifsson, G.Ó.; Ingolfsson, H.P.</td>
<td>276</td>
</tr>
<tr>
<td>23</td>
<td>Testing flexible couplings for geothermal well.</td>
<td>Thorbjørnsson I.O; Kaldal G.S.; Axelsson R.</td>
<td>282</td>
</tr>
</tbody>
</table>

Index 287