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Use of Automated QEMSCAN Technique for Mineral Quantification in Reykjanes Geothermal Field, Iceland

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ABSTRACT

Mineralogical analyses have been performed on 36 core samples and 4 cuttings samples from the RN-15/IDDP-2 well that was deepened by the Iceland Deep Drilling Project (well IDDP-2). RN-15/IDDP-2 drilled to 4659m depth, is the deepest geothermal well drilled in Iceland. The samples analyzed in this study are from the three depth intervals 3021m to 3870m, 4090m to 4310m and 4634m to 4656,99m. Polished thin sections were prepared from all the core samples. To identify the mineralogy of the samples both light microscopy analyses and QEMSCAN (Quantitative Evaluation of Minerals by Scanning Electron Microscopy) have been applied. The advantage of utilizing the QEMSCAN technique is the possibility of both quantitative mineral analyses and mineral mapping at microscale. In addition, SEM/BSE mapping have been performed to reveal the micro-porosity of the metamorphic rock samples from the thin section material. The rock samples analyzed show a change in mineralogy with depth corresponding to granulite facies in the deepest depth interval through amphibolite facies and into greenschist facies in the shallowest depth interval. Ore mineralogy in veins was detected on all depth levels. This study is part of a multidisciplinary study that aims to better understand all aspects of geothermal drilling and production. The mineralogical data will be applied in evaluating the effect of mineralogical processes in well production and well stability. Further, the results from this study give a better understanding of mineral processes and properties that are important in the process of identifying risks when utilizing oil industry knowledge and equipment in geothermal drilling processes.

1. INTRODUCTION

Iceland is situated on the boundary of the Eurasian and North American tectonic plates, a dynamic position as it produces volcanic eruptions and earthquakes. Also, a unique position as it provides geothermal heat which is the base of Iceland being supplied with almost all stationary energy derived from renewable resources. Iceland is a pioneer in utilizing the geothermal resources and has had an impressive growth in geothermal electricity production the last decades.

Equinor, developing as an energy company, joined the Iceland Deep Drilling Project (IDDP) consortium several years ago. The consortium was formed about 20 years ago to determine if utilizing supercritical geothermal fluids would improve the economics of power production from geothermal fields. The RN-15/IDDP-2 well reached supercritical conditions as it was drilled to 4659m measured depth, with a bottom hole temperature of ~535°C estimated from temperature logs and a Horner plot (Friðleifsson et al., 2018).

In this study, conventional mineral analytical methods have been applied to samples from the RN-15/IDDP-2 well. The mineral analyses have been obtained utilizing polarized light microscopy and electron microscope with the QEMSCAN software installed for mineral detection. The great advantages of QEMSCAN is the possibility of quick analyses of rock fragments and the ability to present the results in a very visual way. A known risk in doing QEMSCAN analyses is the possibility of not being able to separate minerals with similar chemistry. To mitigate that risk, the mineral reference database of the QEMSCAN software was calibrated using other mineral analyses methods, light microscopy being most suitable in this case. Comparison of the QEMSCAN mineral identifications with more spatially limited mineral chemistry obtained by electron microprobe (Zierenberg, et al., 2020) provides a means to evaluate the effectiveness of automated mineral identification.

The mineralogical data from this study will be applied to the evaluation of how mineralogical processes will affect well production and well stability over time. Secondary minerals precipitate along open cavities, in vesicular structures, and in fracture zones. There are many factors that play a role in the formation of secondary minerals, including permeability, time, rock composition, temperature, pressure, composition of the hydrothermal fluid, overprinting, and hydrology (Pendon, 2006 and references therein). An important question to consider is how the drilling and well production becomes a factor affecting the creation of secondary minerals.

2. GEOLOGICAL SETTING

The RN-15/IDDP-2 well is drilled in the Reykjanes high temperature geothermal field on the Reykjanes Peninsula in SW Iceland. The Reykjanes Peninsula is the landward extension of the Mid-Atlantic Ridge (Figure 1). The Reykjanes geothermal field differs from almost all the inland geothermal fields, like Nesjavellir and Krafla on Iceland, in being recharged by seawater instead of meteoric water.

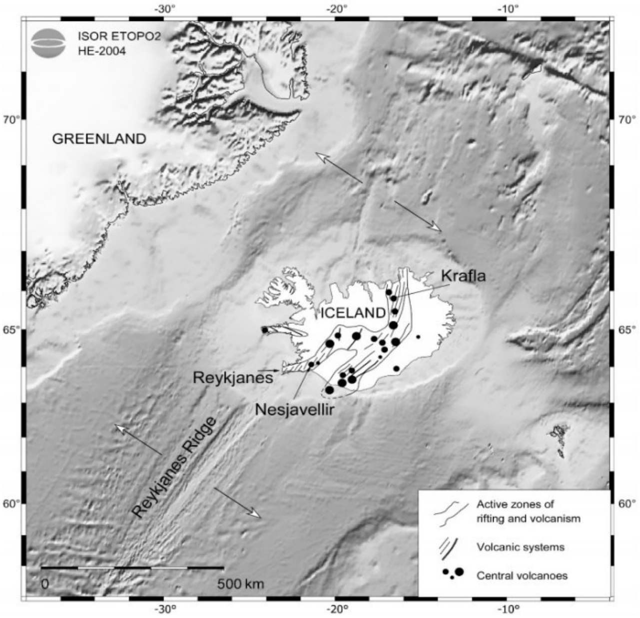

Figure 1: The Reykjanes high temperature hydrothermal system is one of the three fields in Iceland considered by IDDP (figure from Friðleifsson et al., 2017a).

3. SAMPLING AND METHODS

3.1 Sampling depths and sample material

In the RN-15/IDDP-2 well, 13 cores runs were attempted, with various amount of material recovered in the different core runs (Friðleifsson et al., 2018). In this study, the samples are from core runs 3, 5, 7, 8, 10, 11, 12, and 13. Both the core material and cuttings material analyzed represent the sheeted dike complex of the crust (Figure 2).

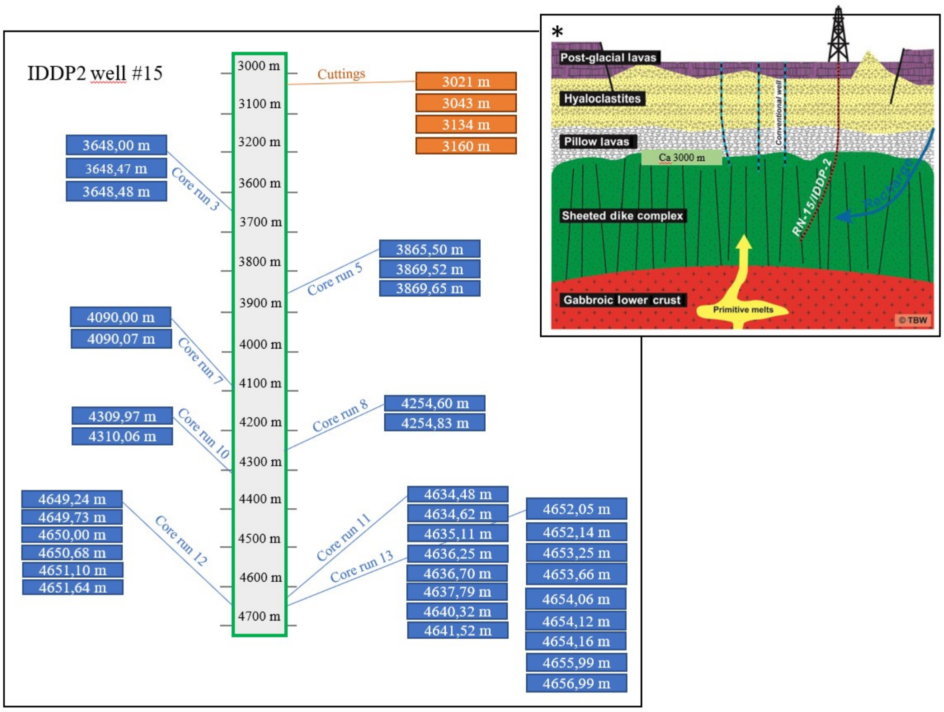

Figure 2: Depth and type of samples from well RN-15/IDDP-2 analyzed in this work (lower left), and the schematic lithological model including the trajectory of RN-15/IDDP-2 into the crust indicating that the samples are from the sheeted dike complex (upper right, from Friðleifsson et al., 2017a).

3.2 Methods

3.2.1 QEMSCAN

Fully automated QEMSCAN technology has been used for mineral quantification and high-resolution mapping of thin section material. QEMSCAN is an acronym for Quantitative Evaluation of Materials by SCANning Electron Microscopy (SEM). The

QEMSCAN analyses have been performed on a Quanta FEG 650F equipped with two Bruker XFlash 5030 EDS detectors. Measurements were performed with an acceleration voltage of 15kV and a current of 10nA ±0.5. Sample points were collected every 8µm. The program iMeasure v5.2 was used for data acquisition, and iDiscover v.5.2 was used for spectral interpretation and data processing. Thin section material was coated with carbon before QEMSCAN analyses. The QEMSCAN software utilizes both the back-scattered electron (BSE) signal intensity as well as the energy dispersive spectra (EDS) signal. These data are used to assign mineral identities to each measurement point (pixel by pixel) by comparing the signals against a database.

High resolution backscattered electron (BSE) mapping have been performed for porosity analyses. The mapping was performed on carbon coated samples with an acceleration voltage of 5kV and a current of 3.5nA±0.5. Sample points were collected every 2.5 µm. To determine the porosity of the high-resolution BSE maps, the program ImageJ was used.

3.2.2 Optical microscopy

Conventional polarizing microscopy method was applied to all the samples mounted on thin sections. The instrument in use was a Nikon Eclipse LV100 Pol.

4. QEMSCAN APPLIED TO ANALYSES OF MAGMATIC ROCKS

4.1. Overview of the mineralogical composition of RN-15/IDDP-2

The analyzed rock samples represent a basaltic sheeted dike complex that shows progressive metamorphism (Friðleifsson et al., 2017b). The basalts have undergone ocean floor metamorphism ranging from greenschist facies to granulite facies (Friðleifsson et al., 2017a, Friðleifsson et al., 2017b, Friðleifsson et al., 2018, Weisenberger et al., 2019, Zierenberg et al., 2017).

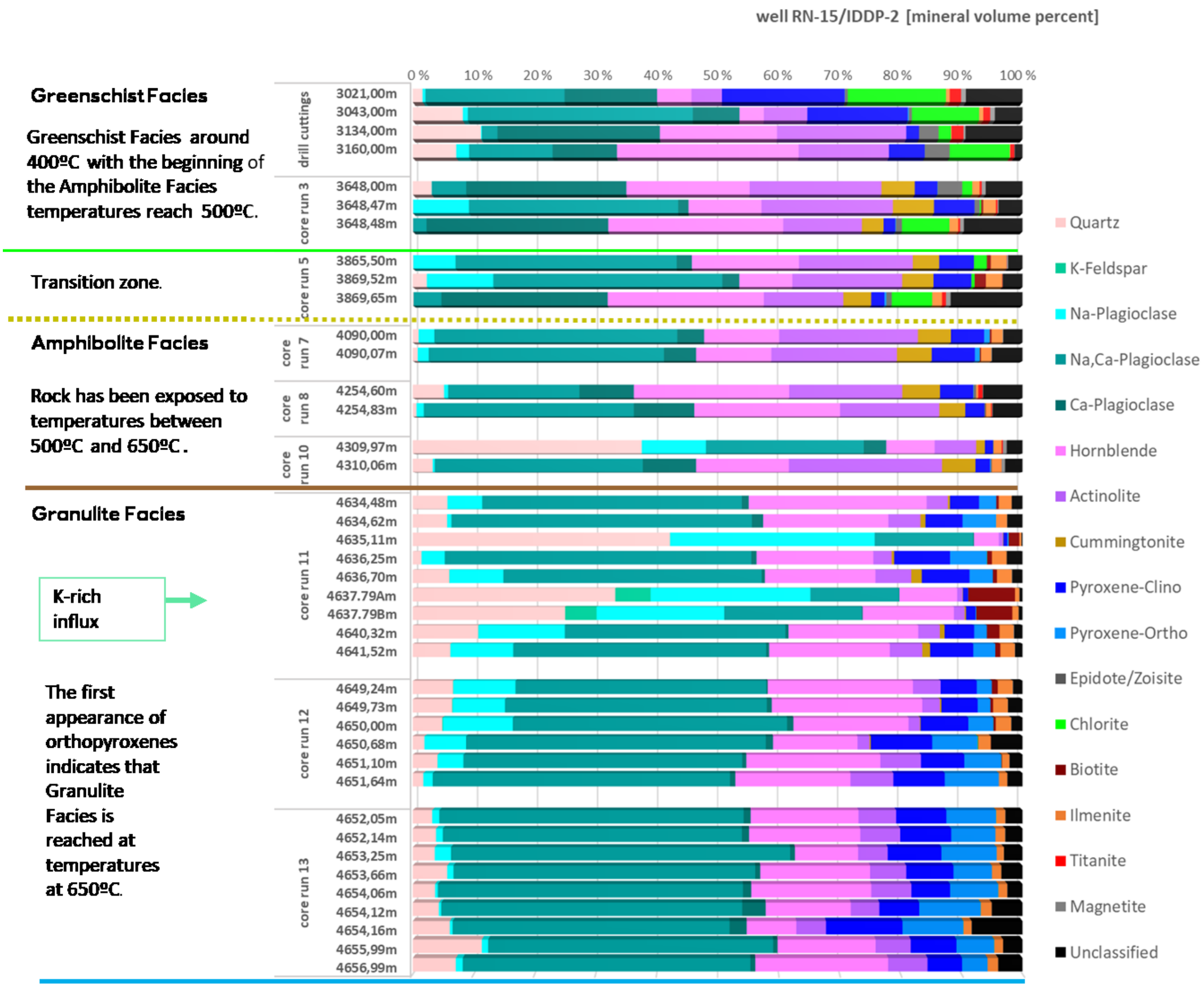

Figure 3: Overview of the mineralogical composition of well RN-15/IDDP-2. Note that minerals at each depth are represented in the same order.

The QEMSCAN analyses provide quantification of the mineral composition. The plagioclase series is divided into three components, presented as Na-plagioclase (albite and oligoclase), Na,Ca-plagioclase (andesine and labradorite), and Ca-plagioclase (bytownite and anorthite) (Figure 3). Minerals in the amphibole group represented are ferro-magnesio-hornblende (hornblende), the tremolite-actinolite series (actinolite) and cummingtonite. Hornblende is defined by the general chemical formula

$(Ca,Na)_{2\text{-}3}(Mg,Fe,Al)_5(Al,Si)_8O_{22}(OH,F)_2$, actinolite as $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$ and cummingtonite $(Mg,Fe)_7Si_8O_{22}(OH)_2$. Clinopyroxenes are identified as augite, Fe-rich-augite and diopside, and the orthopyroxene identified is ferrosalite.

The greenschist facies, with its indicator mineral chlorite, is observed down to 3869,65m by QEMSCAN methodology. Petrographic analyses by Zierenberg et al. (2017) of the same sample material report the presence of chlorite not deeper than 3450m. Epidote/zoisite is present in the shallowest samples from 3021m until 3648,48m. Zierenberg et al. (2017) describes epidote not deeper than 3450m. A transition zone between greenschist and amphibolite facies is identified between 3648m until 3865,5m. Zierenberg et al. (2017) describes, in core 3, that minerals characteristic of greenschist facies have been replaced by amphibolite facies minerals, suggesting a transition between greenschist and amphibolite facies between core 3 and 5. Cummingtonite, an indicator mineral for the amphibolite facies, occurs from 4090m until 4310m before orthopyroxenes are identified. QEMSCAN mapping shows very finely distributed cummingtonite precipitation. Between 4310m and 4634,48m, no sample material is available. With the presence of orthopyroxene from 4634,48m until 4656,99m, the metamorphic rocks belong to the granulite facies.

Biotite and potassic feldspar are observed in sample 4637,79A (Figure 3). They have earlier been described by Zierenberg et al. (2017). Both minerals can only form when potassium is present. A solid solution containing potassium could have been in contact with the rock at the respective depth, resulting in the formation of biotite and alkali-feldspar. Biotite has been in addition identified in minor amounts at 3865,92m in whole core run 11 and in the upper parts of core run 12. Single crystals of olivine have been observed at 4636,25m. Minor amounts of pyrite, pyrrhotite and Cu-Fe sulfides are present in all core samples from 3648,47m until 4656,99m but not in the cutting material from 3021m until 3160m. Minor biotite precipitation, Fe- and Cu-Fe sulfides, and olivine have also been reported (Friðleifsson et al., 2017a, Weissenberger et al., 2019, Zierenberg et al., 2017).

4.2 Detailed mineralogical description of (A) plagioclase and (B) pyroxene in well RN-15/IDDP-2

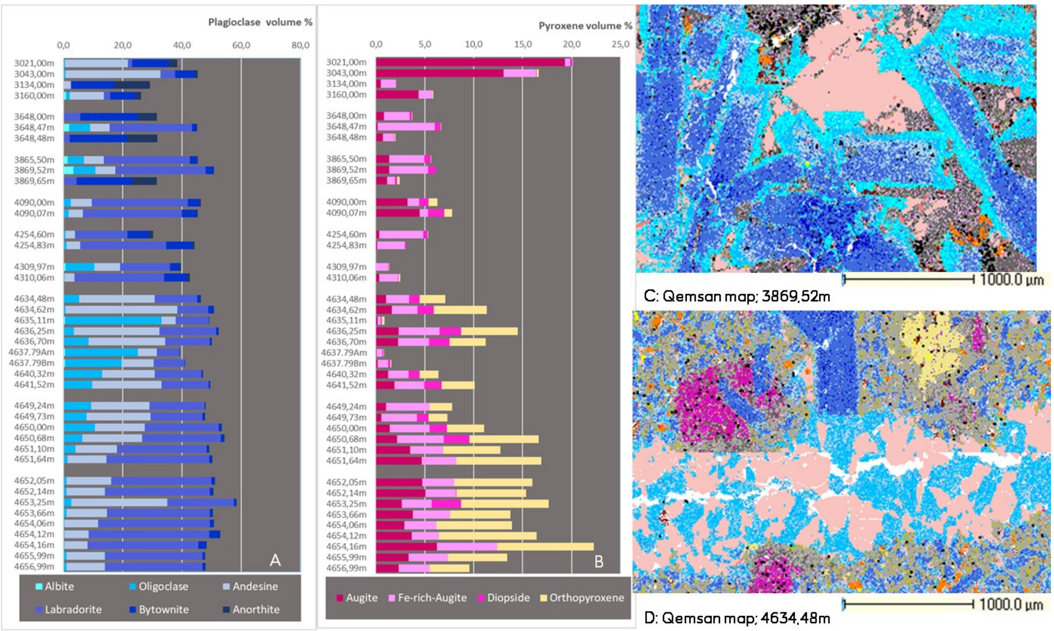

Figure 4: Detailed mineralogical composition of (A) plagioclase and (B) pyroxene of well RN-15/IDDP-2 and mineralogical maps from (C) 3869,52m and (D) 4634,48m.

Detailed analyses of the plagioclase feldspar series and clinopyroxene subgroup are presented in Figure 4. Plagioclases present in the shallowest samples from 3021m to 4310m are mainly Na,Ca-plagioclase, while also minor amounts of Na-plagioclase and Ca-plagioclase are present. Below 4635,11m an increase of oligoclase is observed that gradually decreases with depth. Plagioclases become more Ca-rich and less Na-rich downward from 4634,48m until 4656,99m. The amount of labradorite increases while andesine and oligoclase decreases. Figure 4C shows zonation of a plagioclase. The most Ca-rich part is in the core of the plagioclase crystal, and the amount of Na increases towards the rim of the mineral. From core to rim of the plagioclases the following order is shown: bytownite, labradorite, andesine, oligoclase and albite at the outermost rim (Figure 4C). During plagioclase alteration, the crystal morphology has been preserved (Figure 4C), which illustrates an interface-coupled dissolution-reprecipitation mechanism as described in Hövelmann et al., 2009. Figure 4D shows an QEMSCAN map revealing an oligoclase (light blue) and quartz (pink) vein as a prominent feature across the field of view, in contrast to the surrounding host rock that contains a more Ca-rich plagioclase (dark blue) (bytownite). The clinopyroxene subgroup has also been studied in detail. Augite/Fe-rich augite is the predominant subgroup clinopyroxene while diopside is present in minor amounts and only in some samples (Figure 4B). The amount of augite/Fe-rich augite is highest in the material from 3021,00m and 3043,00m. The deepest samples from 4653,66m until 4656,99m, and the shallowest samples from 3021m until 3160m, do not contain diopside. Figure 4D reveals an augite (dark pink) and an orthopyroxene (yellow). Fe-rich augite is very fine distributed (not shown) and is observed together with augite. Orthopyroxene (Figure 4D) is observed from 4634,48m, and the amount of orthopyroxene increases with depth.

The plagioclases feldspar series have distinct chemical differences. Hence, detecting the different feldspar composition is well within the QEMSCAN software capacity. More challenging is the distinction of the clinopyroxene subgroup minerals due to their similar chemical composition. In this study, the QEMSCAN reference database was calibrated with results from the optical microscopy technique to get an optimal QEMSCAN analyses of minerals with similar chemistry.

4.3 Porosity measurements by high resolution BSE mapping

Depth (m)	Porosity
3648,45	3,041
3648,45	3,016
3648,47	2,7
3648,48	0,15
3865,5	0,2
3865,58	3,706
3869,65	0,5
3865,72	1,959
4090	2,2
4090,03	3,05
4254,6	0,1
4254,68	0,947
4309,97	1,4
4310,06	1,811
4649,24	2,58
4649,3	3,715
4654,06	0,74
4654,12	1,74
4654,16	0,65
4654,25	2,081
4654,25	1,919
4654,25	0,766
	SEM/BSE porosity this study
	He porosity Friðleifsson et al. 2017b

Table 1: Porosity (%) of the thin section and cutting material done by SEM/BSE high resolution mapping of well RN-15/IDDP-2 (green), and He-porosity measurements of core material from well RN-15/IDDP-2 (grey) (Friðleifsson et al. 2017b).

First choice method for porosity analyses is the He-porosity method on core material. Benoit et al. (2020) present detailed petrophysical data on whole round mini-cores drilled from some of the same sample core intervals as the thin sections analyzed here. Porosity, and its relation to permeability, is a primary control on fluid rock interaction. Limited access to core material appropriate for physical properties makes it of interest to investigate whether porosities can be analyzed by the SEM/BSE mapping method. SEM/BSE mapping on thin section and cuttings have been performed with an acceleration voltage of 5kV. The electron beam has with an acceleration voltage of 5kV and a penetration depth of 160nm (standard for Fe). Hence, pores larger than 160nm in diameter are detected. The porosity analyses done in this study are presented in Table 1 and compared to He-porosity data from the nearest depths reported in Friðleifsson et al. (2017b). Cracks have not been filtered out and are included in the porosity. Some of these cracks have formed during the coring process (Benoit et al., 2020), so this method provides an upper limit on *in situ* porosity. The numbers in Table 1 are comparable, and support SEM/BSE as a tool to determine porosity when pores are larger than 160nm. However, the small difference between the He-porosities and the SEM/BSE porosities might also indicate limited number of pores in nanometer size in the analyzed crustal rock samples.

5. CONCLUSION

This study is part of a multi-disciplinary project including HS Orka, Landsvirkjun, Orkuveita Reykjavíkur, the National Energy Authority of Iceland, Alcoa Inc, and Equinor. The consortium is dealing with many questions and challenges in the process of drilling and producing a geothermal well. Investigating the mineralogy of the drilled rock provides input to evaluating the effect of mineralogical processes in well production and well stability. In this study, the QEMSCAN software has proven to be a very efficient and suitable tool for the purpose of doing advanced and detailed mineral analyses of magmatic rocks, plus porosity, both on core and cutting material.

6. ACKNOWLEDGEMENTS

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