

Classification of Lithology and Minerology using Icelandic Rock Properties

Cari D. Covell¹, Samuel Scott¹, Agust Valfells¹, Juliet Newson¹, Egill Juliusson², Halldor Palsson³, Birgir Hrafnkelsson³, Maria Gudjonsdottir¹

¹Reykjavik University, School of Science and Engineering, Menntavegur 1, 101 Reykjavik, Iceland

²Landsvirkjun, Haaleitisbraut 68, 103 Reykjavik, Iceland

³University of Iceland, School of Engineering and Natural Sciences, Saemundargata 2, 101 Reykjavik, Iceland

cari14@ru.is

Keywords: database, alteration, classification, clustering, grain density, total porosity, Klinkenberg permeability

ABSTRACT

Rock properties such as density, porosity, and permeability govern the mechanical behavior of rocks and productivity of aquifers. However, heterogeneity in rock properties contributes to uncertainty in reservoir modeling; and it may be best to provide ways to make data easier to work with. This study examines variability in rock properties by classification of lithology and minerology in Icelandic geothermal systems. Databases used include the IMAGE database, Valgardur database, and data collected by Levy and Covell for the Krafla area. The aim is to find the best way to represent data through proper cohesion of grain density, total porosity, and Klinkenberg permeability measurements based on lithology and minerology.

1. INTRODUCTION

The mechanical behavior of rock units and the productivity of aquifers is controlled by petrophysical, chemical, and thermal rock properties. For simplicity in reservoir characterization, rock properties tend to be assigned uniformly over a large-scale volume. However, rock property measurements reveal high variability both on the field and hand-sample scale (Aladejare & Wang, 2017). In Iceland specifically, this high variability is also present in several databases related to similar geological fields. Therefore, proper classification methods are needed to provide a more cohesive representation of data that is easy to work with, yet still accounts for specific variabilities.

Goals in this paper include ways to understand proper cohesion and fill in gaps where necessary. This is done by creating clusters within lithologies and mineralogies. These clusters are based on grain density, total porosity, and Klinkenberg permeability, given that two out of the three are present in a given database per sample at minimum. We hope to expand overall knowledge of working geologic fields.

2. DATABASES

In Iceland, measurements on rock properties began in the early 1990s and statistical analyses began in the early 2000s. There was a focused interest to determine the effects of grain density, total porosity, and permeability in hyaloclastites based on hydrothermal alteration (Sigurdsson et al., 2000; Franzson, Gudlaugsson, & Fridleifsson, 2001; and Frolova et al., 2005). In the later 2000s, interest in hydrothermal alteration evolved into analyses of chemical compositions and changes (Franzson, Zierenberg, & Schiffman, 2008; Franzon et al., 2010; and Franzson et al., 2011). The interest in hyaloclastite rock property research stems from the hyaloclastite formations tending to be highly porous, which promotes circulation both of cold groundwater and geothermal fluids, but with increasing alteration, the permeability tends to decrease significantly (Franzson et al., 2011). However, hyaloclastites and altered hyaloclastites make up only a portion of rock types observed in Iceland (Gudmundsson, Franzson, & Fridleifsson, 1995).

The Valgardur database is designed to be a source of all rock property data from samples collected throughout Iceland. Currently, the status of the database contains surface samples and drill cores obtained between the years 1992-2004. More specifically, the majority of the database includes surface samples in south-west Iceland; such as Geitafell, Hafnarfjall, Hveragerdi, Reykjanes, Hengill, and Thjorsardalur. The database specifically includes drill cores only from Krafla. There are 802 samples in the database, of which 786 samples are surface observations in south-west Iceland, and 16 samples are drill cores from Krafla. Most of the samples include a description of the rock types observed, measurements of various chemical characteristics, and measurements of the petrophysical properties of density, porosity, and permeability. However, every sample does not include a rock type description or every type of measurement. In total, 19716 measurements were conducted.

The Integrated Methods for Advanced Geothermal Exploration (IMAGE) database aims at providing easily accessible information on physical rock properties relevant for geothermal exploration and reservoir characterization in one single compilation (Bar et al., 2017). Data include hydraulic, thermophysical, and mechanical properties as well as electrical resistivity and magnetic susceptibility (Bar et al., 2017). Similar to the Valgardur database, samples have corresponding sample location and petrographic description. In theory, everything from the Valgardur database should be in the IMAGE database, and vice versa. However, there are several missing information within both databases. Therefore, a cross examination was performed between the Valgardur database and the IMAGE database and further analyses indicate this cohesion.

Another set of data was published by Levy (2018) which details drill core samples of wells KH-1, KH-3, KH-5, and KH-6 in the Krafla geothermal field. Three types of properties have been measured in the laboratory on 88 Icelandic core samples: chemistry

(Cation Exchange Capacity), mineralogy (X-ray Diffraction, or XRD), and petrophysical properties including porosity, grain density, and electrical impedance measurements at six distinct pore water conductivities (Levy, 2018).

Finally, an additional 32 samples were measured by the first author of this paper for the purposes of expanding petrophysical and mineralogical data for the Krafla geothermal area as part of the Data Fusion project for Geothermal Reservoir Characterization (Covell et al., 2017). Half the measurements were from well KH-3 in Krafla and the other half were from well THR-7 in Theistareykir. Measurements include density and porosity, as well as electrical impedance and XRD mineralogical quantification.

3. CLASSIFICATIONS

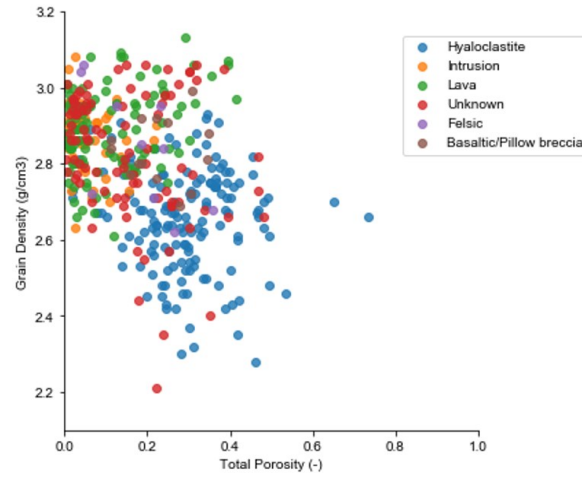
3.1 Based on Lithology

To begin the process of merging the databases together, a simple lithological code was made based on a list of keywords, as shown in Table 1. The keywords were chosen based on English and Icelandic translations into five categories. There was good cohesion within the Valgardur and IMAGE databases to keep the lithologies into three categories: hyaloclastite, lava, and intrusion. From the Levy data, felsic was also included in addition to the previous three lithologies. Also in the Levy data, a category of Basaltic/Pillow breccia was listed and was kept in a separate category due to its ambiguity with hyaloclastite and lava. In addition, if a sample had no lithology detailed, but met the requirements of having at least two out of the three rock property values of grain density, total porosity, and Klinkenberg permeability, the sample was classified into an unknown category.

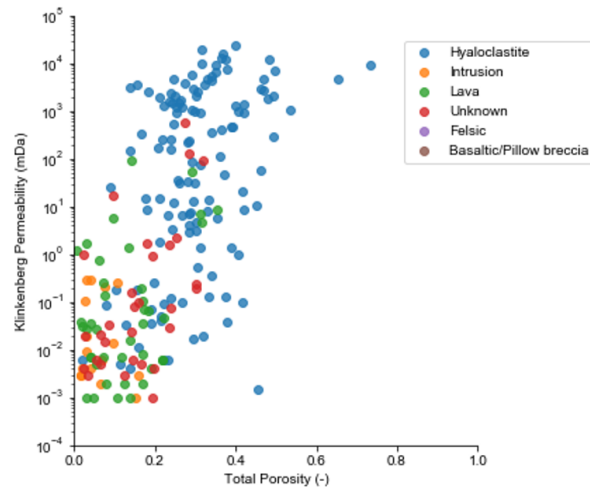
Table 1: List of keywords used to identify lithology assignments.

Keyword(s)	Assigned Lithology
Basalt	Lava
Basaltic lava	Lava
Basaltic/Pillow breccia	Basaltic/Pillow breccia
Breccia	Hyaloclastite
Breksía	Hyaloclastite
Crystalline basalt, dolorite, gabbro	Intrusion
Dolerit	Intrusion
Dolorite dyke	Intrusion
Felsic	Felsic
Gabbró	Intrusion
Gangur	Intrusion
Hraun	Lava
Hyaloclastite	Hyaloclastite
Intrusion	Intrusion
Keilugangi	Intrusion
Lava flow	Lava
Móberg	Hyaloclastite
Pillow Basalt	Hyaloclastite
Poorly altered hyaloclastite	Hyaloclastite
Tuff	Hyaloclastite
Unaltered lava	Lava
Very altered hyaloclastite	Hyaloclastite
Very altered lava	Lava
Vesicular basalt	Lava

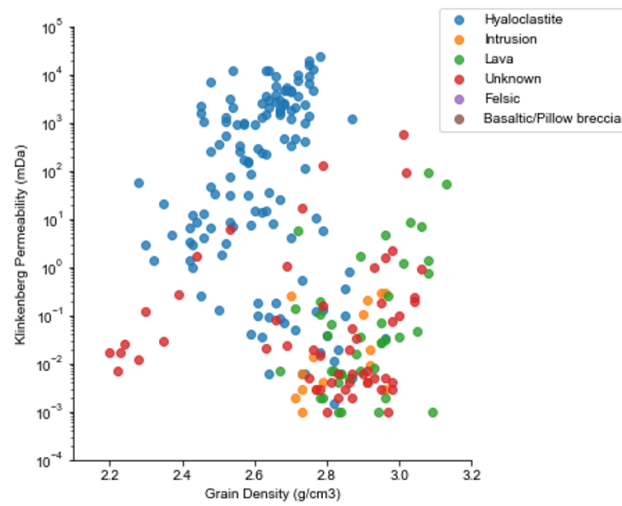
Three different comparisons were made between grain density, total porosity, and Klinkenberg permeability, based on lithology as shown in Figure 1. Each dot represents a sample with its corresponding paired rock property measurement. By visual inspection, Figure 1[A] shows the hyaloclastites with the majority of porosity measurements $> 10\%$ and at grain densities $< 2.8 \text{ g/cm}^3$. Many of the unknown samples are on trend with intrusion measurements, i.e. high grain density and low porosity, but several are hard to distinguish, especially between hyaloclastite and lava flow. In Figure 1[B], there is fairly clear separation of hyaloclastite and lava, where hyaloclastite have high porosity and high permeability (majority $> 10^1 \text{ mDa}$) compared to lava having lower porosity and lower permeability. Intrusion also follows lava pattern, so it may be interesting to see how the unknown samples will be categorized. Finally in Figure 1[C], hyaloclastite follow the trend of low grain density and high permeability. However, lava and intrusion seem to be mixed but together follow the trend of higher grain density and lower permeability than hyaloclastite. The unknown samples are also quite mixed and scatter throughout the dataset.



[A]



[B]



[C]

Figure 1: Scatter plots of petrophysical properties categorized by lithology. [A] Total porosity versus grain density. [B] Total porosity versus Klinkenberg permeability. [C] Grain density versus Klinkenberg permeability.

In addition, Table 2 shows the frequency and mean values with respect to the scatter plots in Figure 1. These values are of importance for classification work, for example, in the unknown category to classify into known lithologies.

Table 2: Frequency and mean values in respect to Figure 1 for [A] Total porosity versus grain density. [B] Total porosity versus Klinkenberg permeability. [C] Grain density versus Klinkenberg permeability.

[A]

		Mean Value	
Lithology	<i>Frequency</i>	<i>Grain Density</i>	<i>Total Porosity</i>
<i>Hyaloclastite</i>	151	2.65	0.2956
<i>Lava</i>	115	2.89	0.1095
<i>Intrusion</i>	44	2.87	0.0635
<i>Felsic</i>	10	2.84	0.1773
<i>Basaltic/Pillow breccia</i>	14	2.83	0.2292
<i>Unknown</i>	90	2.83	0.1546
Total	424	2.82	0.1716

[B]

		Mean Value	
Lithology	<i>Frequency</i>	<i>Total Porosity</i>	<i>Klinkenberg Permeability</i>
<i>Hyaloclastite</i>	125	0.3026	2.45E+05
<i>Lava</i>	40	0.1275	1.77E+02
<i>Intrusion</i>	16	0.0614	7.58E-02
<i>Unknown</i>	30	0.1598	8.26E+02
Total	211	0.16	6.15E+04

[C]

		Mean Value	
Lithology	<i>Frequency</i>	<i>Grain Density</i>	<i>Klinkenberg Permeability</i>
<i>Hyaloclastite</i>	132	2.63	1.99E+03
<i>Lava</i>	40	2.91	4.43E+00
<i>Intrusion</i>	16	2.83	7.58E-02
<i>Unknown</i>	53	2.77	1.57E+01
Total	241	2.79	5.03E+02

3.2 Based on Minerology

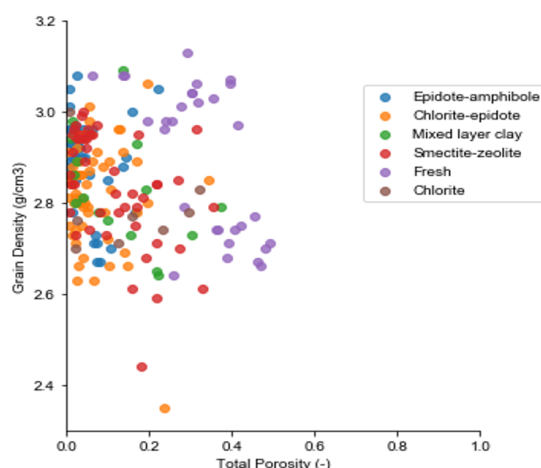
Unfortunately, the minerology within each database is not as consistent as the lithology previously outlined. Therefore, in the initial stages, minerology will be looked at separately, to see if any cohesion is possible for further clustering analyses.

The Valgardur database exclusively outlines minerology by showing a generalized type of alteration per sample, if applicable. Table 2 shows the frequency of the amount of samples in the Valgardur database that have an alteration zone listed, based on lithology. The idea of showing this breakdown of alteration zone by lithology is to provide a baseline for comparison once the unknown lithologies are classified. There are about one quarter of the samples with alteration that have an unknown lithology (50 out of 203), hence a significant amount of information that is not as useful now in geologic modelling as it has potential to be once the lithology is known.

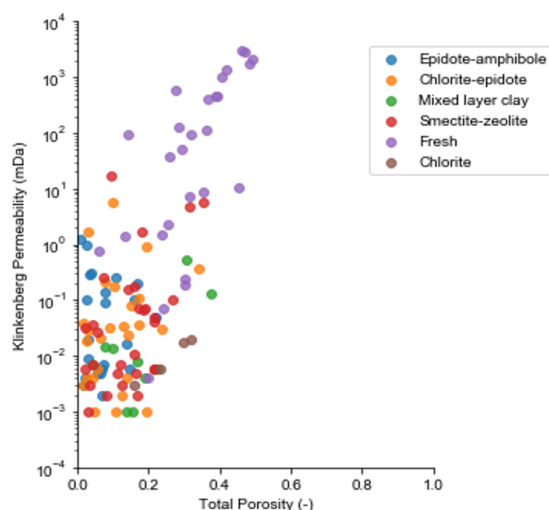
Table 2: Frequency tabulation of alteration zones present in the IMAGE and Valgardur database with respect to lithology.

Lithology	Alteration Zone						Total
	Fresh	Smectite-zeolite	Mixed layer clay	Chlorite	Chlorite-epidote	Epidote-amphibole	
Hyaloclastite	12	10	4	3	8	1	38
Lava	9	24	8	2	29	13	85
Intrusion	0	1	2	1	10	16	30
Unknown	9	11	2	2	18	8	50
Total	30	46	16	8	65	38	203

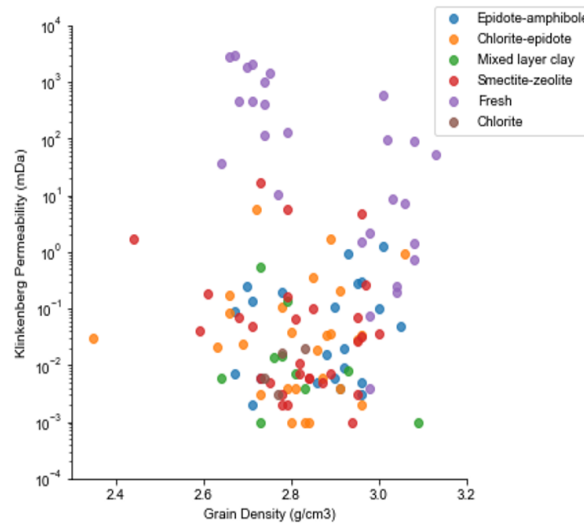
Similar to the scatter plots based on lithology in Figure 1, three different comparisons were made between grain density, total porosity, and Klinkenberg permeability, based on alteration zone, as shown in Figure 2. Overall, the clusters are difficult to distinguish, perhaps except for freshly altered samples. Trends show samples with fresh alteration having higher porosity ($> 20\%$) and higher permeability (> 1 mDa), but mixed values on the range for grain density. About one third of this category has unknown lithology (9 out of 30), therefore there seems to be a mix of potential categorization between hyaloclastite and lava, due to the fact that no intrusion values are present. Additionally, smectite-zeolite alteration shows good clustering for total porosity, where porosity is very low ($< 10\%$) when compared to grain density. However, in samples where total porosity and Klinkenberg permeability are present, the cluster is more spread out over the range of values. The mixed layer clays also have good clustering for total porosity ($< 20\%$) when compared to both grain density and Klinkenberg permeability, however not as much cohesion when comparing grain density and Klinkenberg permeability side by side. Here, these differences show variability in best comparisons of petrophysical measurements to alteration zones.



[A]



[B]



[C]

Figure 2: Scatter plots of petrophysical properties categorized by alteration zone. [A] Total porosity versus grain density. [B] Total porosity versus Klinkenberg permeability. [C] Grain density versus Klinkenberg permeability.

The IMAGE database contains 223 samples different to those in the Valgardur database, where mineralogy is separated into different categories per sample. These categories include glass, primary crystals, altered glass, clay, zeolites, calcite, altered crystals, and other (miscellaneous). There are notes in the database that detail the discrepancies within specific mineralogical categories, as these samples were point counted, rather than using XRD. Therefore, the percentages don't add up to 100% for every sample. As alteration is the highlight in this study, we move forward with analyzing only those categories that are known to contain completely altered minerals, and those are altered glass and altered crystals. Furthermore, all the altered glass in the database has a known lithology, and they are all consistent with being categorized as hyaloclastite. Hence, altered crystals are those that need lithology classification. Figure 3 shows the altered crystals weight fraction with respect to total porosity, categorized by lithology.

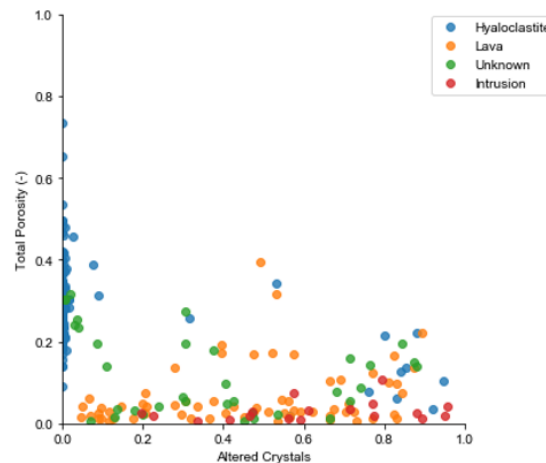


Figure 3: Scatter plot of altered crystals (weight fraction) in IMAGE database with respect to total porosity, categorized by lithology.

The Levy data were combined with the additional 32 samples from Krafla (now called Covell data). Mineralogy was determined through XRD measurements. As the categories of mineralogy were diverse, a summation was made that includes the following alteration minerals: Zeolites, Laumontite, Wairakite, Pyrite, Iron Oxides, Titanite, Amphiboles, Epidote, Prehnite, Albite, Diopside, Anatase, Saponite, Chabazite, Mordenite, Analcime, Labradorite, Yugawaralite, Heulandite, Anorthite, Kanoite, Microcline, Enstatite, Hedenbergite, Magnetite, Clinoptilolite, Hyalophane, Chamosite, Ilmenite, Monalbite, Hematite, Maghemite, Crystobalite, Tridymite, HydroMagnetite, Sudoite, Pigeonite, and Braunitz. Figure 4 shows the quantity of alteration (weight fraction) with respect to total porosity, classified by lithology. Interestingly, intrusion are not highly altered here, but basaltic/pillow breccia is highly altered. As this cluster is visually closer to the hyaloclastite cluster (compared to the lava cluster), perhaps many of these samples are highly altered hyaloclastites.

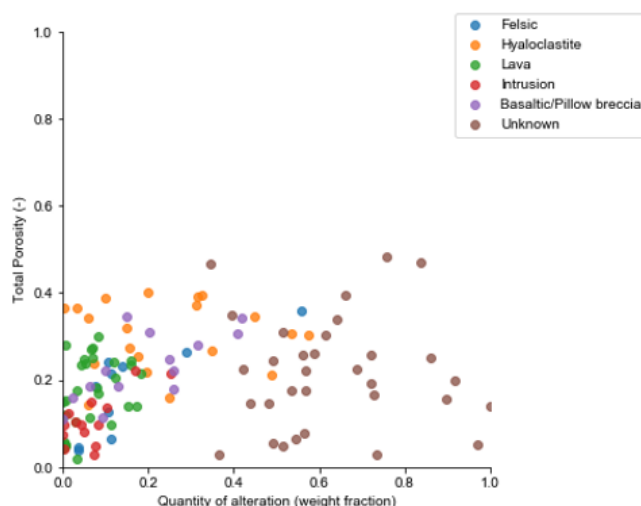


Figure 4: Scatter plot of quantity of alteration (weight fraction) in Levy and Covell data with respect to total porosity, categorized by lithology.

4. CONCLUSIONS

The main lithologies present in each of the databases overall are hyaloclastite, lava, and intrusion. However, many lithologies are unknown, but show promise to be either hyaloclastite or lava flow. In terms of mineralogy, chlorites and mixed layer clays have some trend of good cohesion within the Valgardur and IMAGE database collaboration. Within altered crystals, no trends could be made based on lithology as there is much variation, except for hyaloclastites where all alteration is actually altered glass. For overall alteration within the Levy and Covell data, many of the unknown samples could belong to their own category, or perhaps be a portion of highly altered hyaloclastites. As this is a work in progress, further studies will detail K nearest neighbors analyses for the unknown category, and potentially the basaltic/pillow breccia category.

ACKNOWLEDGMENTS

The authors listed in this paper work together under the Operations Research in Subsurface Modeling (ORSM) group based at Reykjavik University. The work presented here is part of a larger project entitled Data Fusion for Geothermal Reservoir Characterization, funded by RANNIS under the Technology Development Fund. The Valgardur Database was used with permission from Landsvirkjun, with clarifications made by Hjalti Franzson of Iceland GeoSurvey (ISOR). Hjalti Franzson also aided in cross checking the Valgardur and IMAGE databases. Access to the IMAGE database was with permission from Kristian Bär of Technische Universität Darmstadt. The additional 32 samples at Krafla collected by the author was made possible with funding from Landsvirkjun, in cooperation from Benoit Gibert of the University of Montpellier and Lea Levy as short-term post-doctoral researcher for Reykjavik University.

REFERENCES

- Bar, K., Reinsch, T., Sippel, J., Strom, A., Mielke, P., & Sass, I. (2017). P³-International PetroPhysical Property Database. In Proceedings, 42nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (pp. 1-6).
- Covell, C., Valfells, A., Gudjonsdottir, M., Stefansson, H., Juliusson, E., Palsson, H., & Hrafnkelsson, B. Data Fusion for Hydrothermal Reservoir Characterization through use of Bayesian Statistical Inference and MCMC Maximum Likelihood Models. In Proceedings, 42nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA.
- Gudmundsson, A., Franzson, H., & Fridleifsson, G. (1995). Fordafræðistudlar: sofnun syna. OS-9517-JHD-11 B, 73 pp. In Icelandic.
- Franzon, H., Gudfinnsson, G., Helgadóttir, H., & Frolova, J. (2010). Porosity, density, and chemical composition relationships in altered Icelandic hyaloclastites. Birkle & Torres-Alvarado (ed), Water-Rock Interaction (pp. 199-202). London, England, United Kingdom: Taylor & Francis Group.
- Franzon, H., Gudfinnsson, G. H., Frolova, J., Helgadóttir, H. M., Pauly, B., Mortensen, A. K., & Jakobsson, S. P. (2011). Icelandic Hyaloclastite Tuffs, Petrophysical Properties, Alteration and Geochemical Mobility. Reykjavik: Iceland GeoSurvey (ISOR-2011/064).
- Franzon, H., Gudlaugsson, S., & Fridleifsson, G. O. (2001). Petrophysical Properties of Icelandic Rocks. 6th Nordic Symposium on Petrophysics. Trondheim, Norway.
- Franzon, H., Zierenberg, R., & Schiffman, P. (2008). Chemical transport in geothermal systems in Iceland: Evidence from hydrothermal alteration. *Journal of Volcanology and Geothermal Research*, 217-229.

- Frolova, J., Ladygin, V., Franzson, H., Sigurdsson, O., Stefansson, V., & Shustrov, V. (2005). Petrophysical Properties of Fresh to Mildly Altered Hyaloclastite Tuffs. World Geothermal Congress. Antalya, Turkey.
- Levy, L., Gibert, B., Sigmundsson, F., Flovenz, O. G., Hersir, G. P., Briole, P., & Pezard, P. A. (2018). The role of smectites in the electrical conductivity of active hydrothermal systems: electrical properties of core samples from Krafla volcano, Iceland. *Geophysical Journal International*, 215(3), 1558-1582.
- Sigurdsson, O., Gudmundsson, A., Fridleifsson, G. O., Franzson, H., Gudlaugsson, S., & Stefansson, V. (2000). Database on Igneous Rock Properties in Icelandic Geothermal Systems: Status and Results. World Geothermal Congress. Kyushu-Tohoku, Japan.