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PETROLOGY OF THE HORNFELS CONTACT ZONE AROUND THE HROSSATUNGUR GABBRO, W-ICELAND

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ABSTRACT

This study focusses on a hornfels zone at the southern side of the Hrossatungur gabbro, W-Iceland. During contact metamorphism in response to this intrusion emplacement a hornfels contact zone was created by a recrystallization process of previously hydrothermally altered basalt. Here, the hydrothermal alteration and chemical composition of minerals is closely studied to evaluate the development during the contact metamorphism event forming the hornfels around the gabbro.

The hornfels mainly contains clinopyroxene compositions ranging widely from augite, salite, ferrosalite to hedenbergite in vesicle fillings, with minor orthopyroxene, while in the groundmass it ranges from diopside, augite to salite. The plagioclase composition ranges from andesine, labradorite to bytownite and occasionally to anorthite within the vesicles and veins, while the groundmass plagioclase ranges from labradorite to anorthite. Other minerals found in the hornfels are iron-titanium oxides (magnetite, ilmenite and titano-magnetite), garnet (andradite to about 20% grossular) and sulphides.

Loss-on-ignition measurements of hornfels compared with the LOI of Icelandic rocks in different alteration zones indicates that the water has been driven out of the hornfels rock by the replacement of hydrous minerals by non-hydrous minerals. The study shows that the formation of the hornfels is due to direct heat conduction, the expulsion of water from the rock and preventing a direct water-magma interaction.

1. INTRODUCTION

Hafnarfjall-Skardsheidi is a major extinct central volcano located about 100 km north of Reykjavík as shown in Figure 1. It is Tertiary in age and was active for over 1.5 Ma. The erosion of the central volcano has been estimated to range from a few hundred metres to ≤2 km unravelling the core and deep dissection into the high-temperature systems of the volcano. The intrusions include dyke and cone-sheet swarms along with larger intrusions such as gabbro and granophyre. The largest of these is semi-circular Hrossatungur Gabbro (HTG), which intrudes into a lava and pyroclastic caldera filling. High-temperature alteration is present around the gabbro intrusion which could be an evidence for the geothermal systems having developed by heat exchange between this heat sources and the surrounding groundwater systems. No intrusions are seen cutting through the Hrossatungur gabbro, and all evidence suggests that the gabbro is the last intrusive in this part of the central volcano (Franzson, 1979). The hornfels in the Hrossatungur area was brought about by the emplacement of the gabbro intrusion. As the depth of the hornfels occurrence is approximated as 800-1000 m (Brett et al., 2016), and the temperature of the gabbro can be estimated at 1000-1100°C. This approximates the maximum temperature of the hornfels nearest to the gabbro, but the temperature should diminish in a conductive way with distance from the gabbro. The hydrothermal alteration and chemical composition of minerals is studied in order to evaluate the development during the contact metamorphism event forming the hornfels around the gabbro.

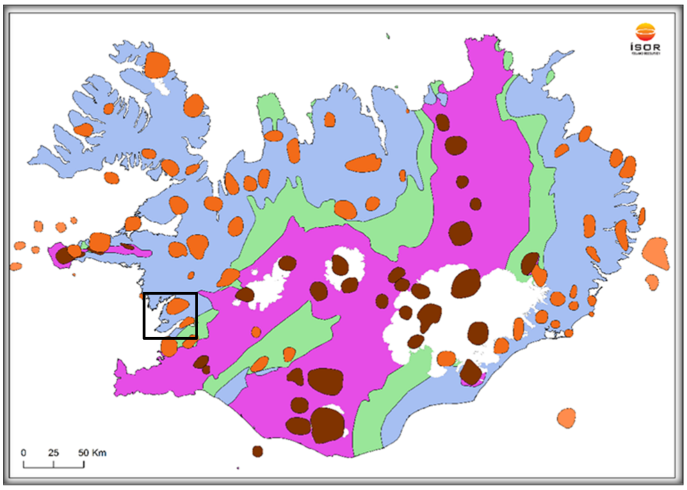

FIGURE 1: Active central volcanoes (dark red) and fossil central volcanoes (orange) across Iceland. The Hafnarfjall-Skardsheidi central volcano is in the area enclosed by the black square (Hjartarson and Saemundsson, 2014)

2. DESCRIPTION OF WORK

2.1 Objectives

This study is a part of a larger research project funded by GEORG which purpose was to study the deep roots of geothermal systems by geological and geophysical methods. This part involved the evaluation of the process of heat exchange between a molten magma body and the surrounding groundwater system. An important factor in this respect is the study of the hornfels contact rocks around the Hrossatungur gabbro heat source in order to find evidence either for the infiltration of the groundwater towards the magma or the outwards conduction of the heat from the magma into the surrounding rocks. This study focusses on the processes of the formation of hornfels and an evaluation of the role of water and heat in its formation.

2.2 Methodology and analytical methods

The sampling done specifically for this hornfels was threefold;

1. Individual samples from various hornfels locations around the gabbro;
2. Sampling of three specific profiles away from the gabbro boundary; and
3. A few samples from the roof of the intrusion in the eastern part as shown in Figure 2.

The methodology used in this study is a mixture of geochemistry, petrography and SEM/EMP mineral analyses. It was hoped that this combination would unravel the water-rock processes near the boundary of the gabbro. Therefore, the collected samples underwent several types of analysis as described below:

- ICP-OES chemical analyses were done to evaluate the chemical exchange and flux that may have taken place during the hornfels process and a potential magmatic contamination from the gabbro towards the hornfels zone (30 samples);
- Petrographic analyses of about 33 hornfels rock samples;
- Loss-on-ignition (LOI) analyses of about 30 hornfels samples to estimate the water and carbon content within the hornfels zone;
- SEM and partly electron microprobe analyses to identify the mineralogy of the hornfels.

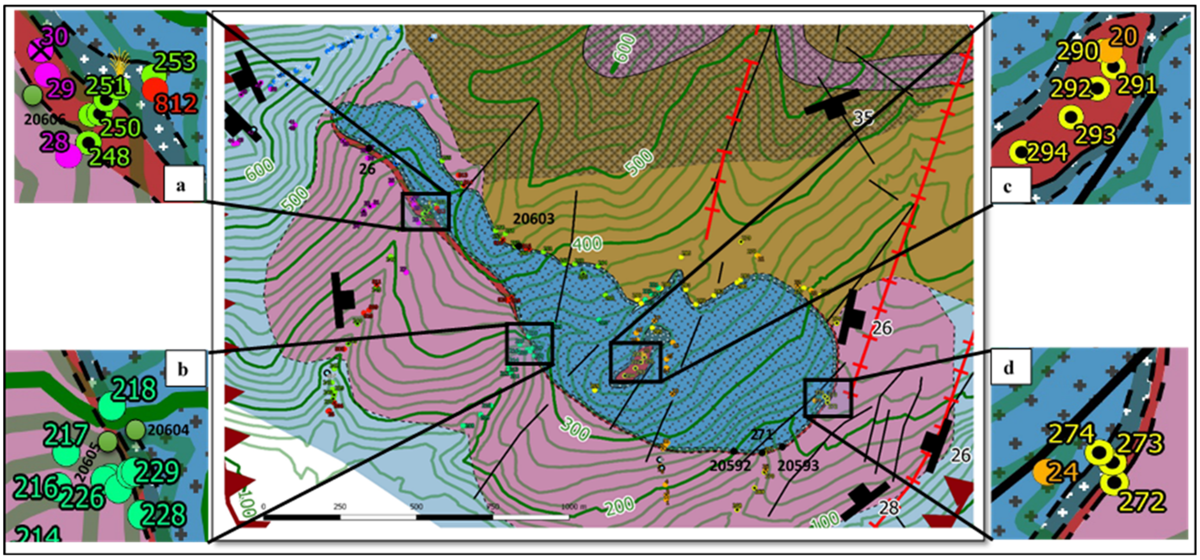

FIGURE 2: Geological map of the Hrossatungur gabbro and surroundings. Small squares enclose the locations of sampling profiles (a), (b), (c) and (d)

3. RESULTS

3.1 Whole-rock chemistry

The chemical analyses are used to evaluate what changes took place in the hornfels contact zone during the metamorphism process. For this purpose, samples from the hornfels zone around HTG were analysed for whole-rock composition (major and trace element concentration) and compared with the least altered equivalents from the Hafnarfjall-Skardsheidi central volcano. The major oxides include SiO_2, Al_2O_3, FeO (total), MgO, CaO, Na_2O, K_2O, MnO, TiO_2 and P_2O_5. Trace elements include Ba, Cu, Ni, Zn, Zr, Co, Cr, La, Sc, Sr, V and Y, as shown in Table 1.

The chemical analyses of the hornfels rock show that the overall compositional range is in many ways similar to the fresh-rock equivalent of the volcano. However, there seems to be an apparent overall depletion of Na_2O. SiO_2 content shows a wide range, which can to some extent be explained by dioritic to felsic veining from residual magmatic fluids injected from the gabbro, but also quartz veining and possibly even an andesitic protolith. A few samples show anomalously low values. These samples were taken from locations with a high sulphide content in the rock, which are superimposed on the hornfels. These suggest local late-stage sulphide volatile penetration through the hornfels, probably due to rock dissolution and formation of permeability within a very acidic environment. These samples also show elevated Fe and Al content. Furthermore, there

TABLE 1: Examples of major and trace element analyses of the hornfels contact zone around Hrossatungur gabbro based on ICP-OES

ICP No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sample No.	225	226	227	228	229	230	231	248	250	251	252	271	272A	272B	272C
Major elements in wt%															
SiO2	59.56	46.61	48.71	48.71	53.71	50.35	55.57	75.47	53.82	49.37	42.73	45.31	47.99	49.36	55.17
Al2O3	13.16	16.91	13.81	15.11	13.72	13.59	12.34	11.37	14.75	14.84	22.87	18.02	16.75	16.53	14.71
FeO	14.39	14.71	13.09	14.82	12.75	14.97	12.33	2.78	14.03	14.40	21.92	17.60	17.18	18.17	14.81
MnO	0.13	0.21	0.23	0.31	0.20	0.27	0.21	0.03	0.38	0.36	0.15	0.39	0.31	0.26	0.20
MgO	2.71	9.51	6.08	3.13	3.64	3.47	2.78	0.39	3.18	2.86	1.65	2.90	2.88	3.89	1.70
CaO	4.00	6.49	11.47	9.29	7.87	10.08	7.28	0.72	4.55	9.37	3.38	9.96	8.17	4.61	4.72
Na2O	2.31	2.70	2.96	2.90	3.22	2.78	3.59	0.85	4.67	4.12	0.72	0.41	1.24	1.08	3.39
K2O	0.63	0.19	0.25	0.83	1.03	0.26	1.97	7.81	0.16	0.11	0.66	0.10	0.43	1.21	0.09
TiO2	2.78	2.27	2.91	3.80	3.11	3.46	2.68	0.23	3.02	3.09	4.65	4.42	4.26	4.29	3.59
P2O5	0.19	0.20	0.34	0.95	0.59	0.62	1.04	0.02	1.29	1.34	0.98	0.72	0.63	0.42	1.49
Trace elements in (ppm)															
Ba	147.65	123.29	92.93	154.11	253.54	140.92	349.30	1833.87	50.23	43.58	134.48	41.39	152.66	237.53	28.92
Co	66.59	78.57	65.12	58.97	52.82	63.54	57.37	3.94	45.04	44.94	104.03	89.34	77.77	82.51	49.87
Cr	25.49	300.37	16.98	3.92	5.94	4.94	8.53	4.18	4.64	4.12	88.30	30.46	27.14	38.76	8.15
Cu	180.81	125.94	98.69	45.09	24.87	53.20	43.93	67.13	37.69	43.16	565.49	113.72	114.45	220.17	58.60
La	21.03	12.45	22.66	42.44	43.45	35.16	70.50	80.86	52.64	55.91	36.15	48.30	39.57	36.00	54.26
Ni	48.03	250.63	60.36	25.76	2.47	6.07	10.82	15.78	16.50	10.88	85.34	42.35	52.07	75.76	89.68
Sc	38.99	45.89	43.28	36.07	30.59	35.37	36.22	2.05	33.67	35.12	71.88	51.18	46.56	45.61	35.77
Sr	150.35	211.33	262.45	222.79	297.61	237.12	352.32	210.57	273.29	286.74	98.29	138.27	156.35	123.83	136.36
V	361.02	386.04	395.62	232.05	229.75	294.70	181.86	25.68	121.81	131.82	910.10	463.97	459.98	472.77	142.41
Y	36.16	26.33	34.93	81.18	64.08	66.23	107.20	115.00	104.45	108.01	64.70	74.74	60.98	55.26	106.81
Zn	129.13	157.45	105.04	166.31	119.53	174.96	174.45	76.31	177.92	183.57	277.03	224.49	187.95	180.30	116.89
Zr	224.78	173.74	196.36	368.44	415.28	294.30	636.25	634.77	485.80	488.11	376.48	415.41	334.69	286.94	475.92

appears to be an overall enrichment of Zn, Ni and Cu in the hornfels samples, probably due to the diffusion of sulphide vapour from the magma into the hornfels.

3.2 Loss on Ignition (LOI).

The results of the LOI analyses are very informative, in particular in comparison with LOI in other alteration zones. It shows that LOI increases towards the chlorite-epidote zone, but diminishes and reaches a minimum at the hornfels stage (see Figure 3). This decrease is mainly due to that the alteration minerals become less hydrous, and when reaching the proper hornfels, the mineralogy is dominantly composed of water-free minerals like pyroxene, plagioclase and oxides. Only minor garnet and amphibole are present. This minor amount of LOI is likely to be caused by remaining water and/or CO_2 in the rock since prior to the hornfels alteration. This indicates that thermal conduction around the gabbro has expelled the water from the rock and prevented the access of water/steam to the molten magma and associated heat-mining from the magma.

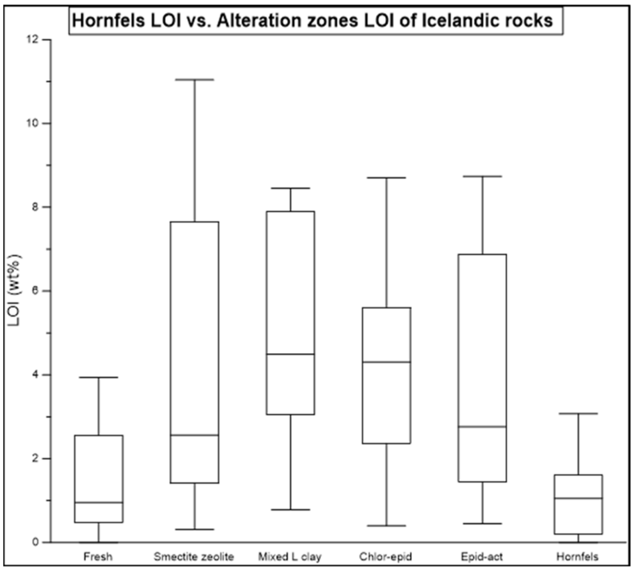

FIGURE 3: Comparison between loss on ignition (wt%) of different alteration zones in Icelandic rocks (Franzson, et al., 2001) and LOI of the hornfels around Hrossatungur gabbro.

3.3 Chemical variation of minerals in the hornfels

The main minerals analysed were pyroxene, plagioclase, oxides, garnet, and sulphides. The compositional range of pyroxene is dominantly salite-augite-ferrosalite, but may slightly extend into the diopside and hedenbergite fields as seen in Figure 4. Although compositions do vary from one sample to another, there seems to be a tendency for the composition of pyroxene analysed within veins and vesicle to extend more into the ferrosalite field compared to the groundmass. Secondly, the pyroxene in the hornfels nearest to the gabbro, where recrystallization is most pronounced, is more dominantly within the salite-augite field, while the composition of pyroxene further away from the contact falls more in the ferrosalite field. Furthermore, orthopyroxene is found in four samples. It is mostly Mg-rich, but one grain belongs to the ferro-hypersthene field. All grains of orthopyroxene are found within vesicle

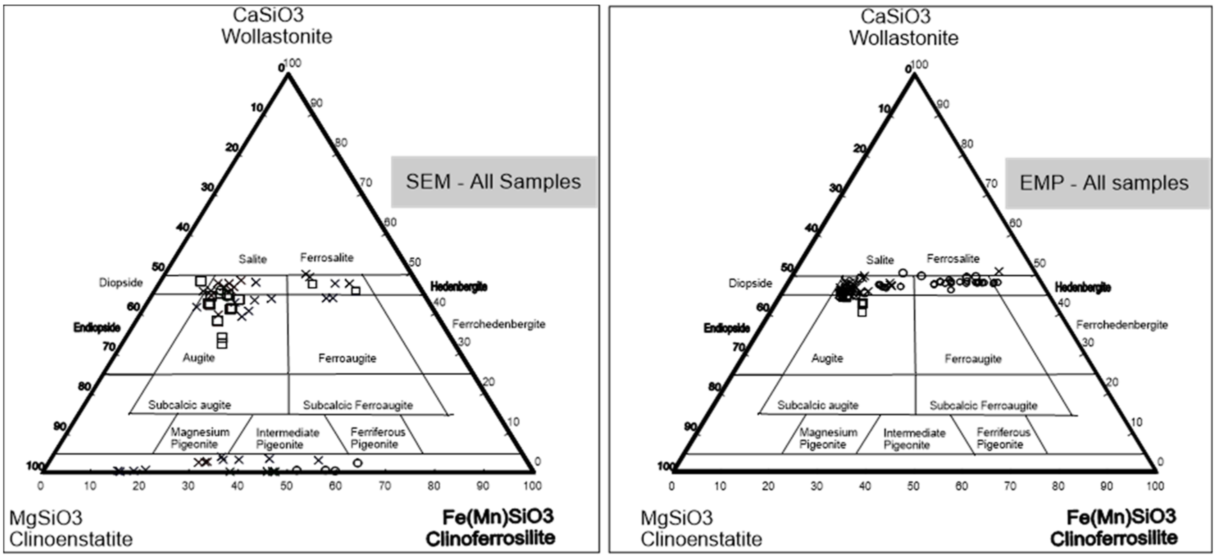

FIGURE 4: Compositional range of pyroxenes in the HTG hornfels analysed with SEM and EMP

fillings. Zoned pyroxene is found within the vesicle/vein domain with Fe enrichment towards the rim. Oxides are observed in some places in central parts of vesicles, suggesting abundance of Fe in this re-crystallization sequence.

Plagioclase shows a wide range of composition, but is dominantly found to be labradorite, but extends into the andesine field (Figure 5). Only one sample has oligoclase composition, but that sample has a high proportion of silicic veins, which could imply Na_2O contamination of the feldspar. One sample, which was taken at the hornfels/gabbro boundary (located separately out of the profiles), shows an anorthite composition. A comparison with the results of the analyses of pyroxene and plagioclase in a hornfels zone around a basalt dyke from well HE-42 at Hellisheidi high-temperature field is highly informative. There pyroxene is in general more confined within the salite-augite field and plagioclase is more Ca-rich labradorite and extends to nearly pure anorthite. Within vesicles and veins, there is a tendency for the pyroxene to be more Fe-rich (in particular in the EMP analyses), and for the plagioclase to be more anorthitic.

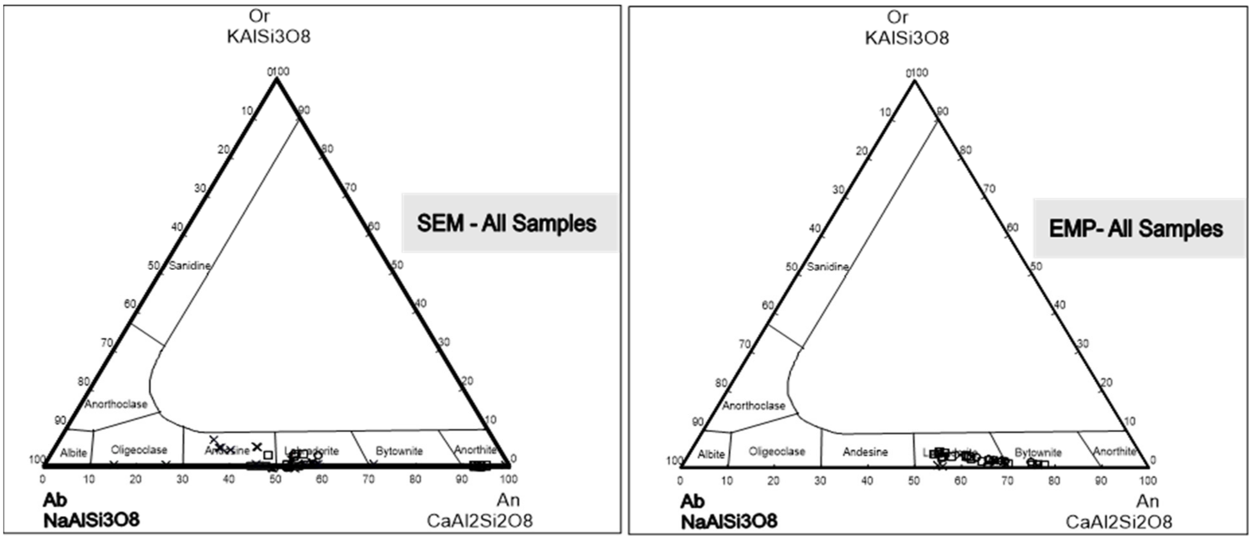

FIGURE 5: Compositional range of plagioclase in the HTG hornfels

The abundance of oxides is quite varied within the basalt range and is dependent on the iron content of the rock. The oxides were analysed in the same way as pyroxene and plagioclases. The oxides dominant in the HTG hornfels are magnetite and ilmenite, which are equally found in groundmass and void fillings, although the former seems to be more common within vesicles. Titano-magnetite is also observed in vesicle fillings.

Garnet is seen in the HTG hornfels through petrographic microscope observation in vesicle fillings more than in the groundmass and these analyses were confirmed by the electron microprobe. The end-member composition of the garnet is calculated as shown in Figure 6. The composition was around 65-97 mol%, andradite which is the dominant composition of the garnets in the hornfels around HTG. The grossular component ranges to about 17 mol% and almandine component to about 7 mol%. Sigurjónsson (2016) studied the garnet composition related to quartz veins in Hafnarfjall in a similar way within vesicles and veins. Many

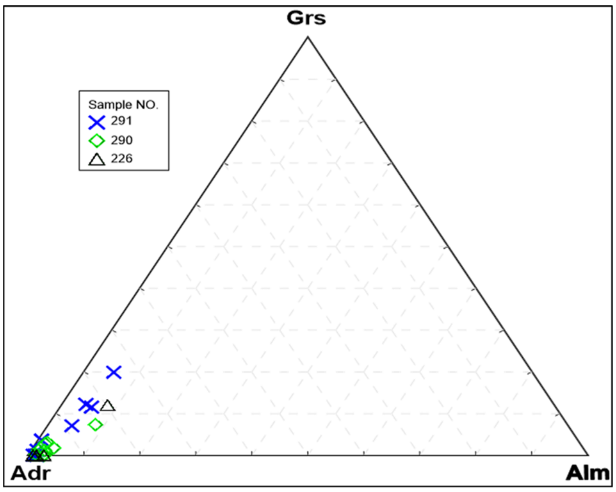

FIGURE 6: Triangular plot showing the distribution of garnet end-members; Adr-Andradite, Alm-Almandine, Grs- Grossular

of these samples were taken further away from the hornfels zone and indicate that the garnet had an alternating zoning of andradite- and grossular-rich bands with dominantly andradite-rich cores, which is different from the andradite-only garnet of the HTG hornfels (Sigurjónsson, 2016). Moreover, hedenbergite and garnet were the ideal secondary minerals for confirming the occurrence of supercritical condition or superheated steam at the time of the cooling of the gabbro body associated with the Geitafell geothermal system (Helgadóttir, et al., 2017).

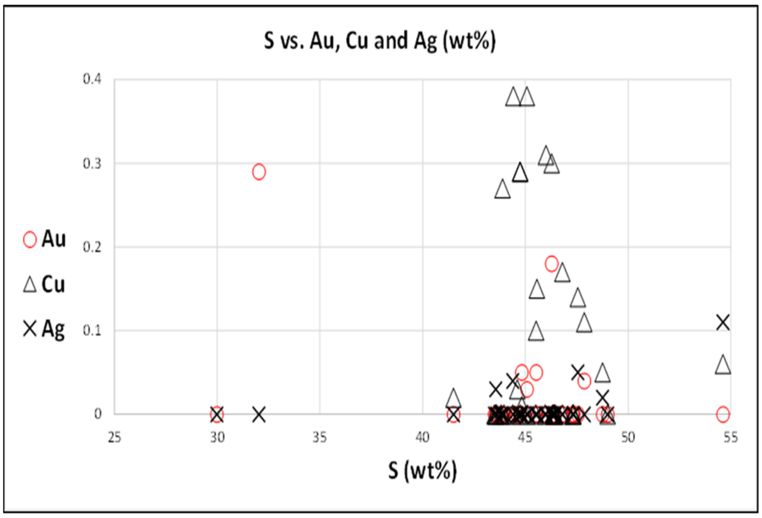

FIGURE 7: Variation of sulphide composition in HTG hornfels contact zone. (S vs. Au, Cu and Ag)

Sulphides are present in subordinate amounts in most of the hornfels but are quite frequent in the alteration zones further away from the gabbro. Specific patches of sulphides are observed within the hornfels are considered to represent late volatile degassing of the gabbro. Iron and sulphur are the dominant elements in the sulphide composition. Therefore, sulphide type in the hornfels zone around HTG is mainly pyrite, which contains <11% Pb as a major element, and As, Ti, Sb, Cu, Zn, Au and Ag as trace elements as shown in Figure 7. The hydrothermal sulphide types most commonly found in the cutting samples in the active Hellisheidi high-temperature area were pyrite, pyrrhotite and Cu-sulphides (Gunnarsdóttir, 2012).

4. CONCLUSIONS

Hrossatungur gabbro was the heat source for a high-temperature system and is surrounded by a hornfels contact zone. The evidence suggests that the gabbro is the last intrusive phase in this part of the Hafnarfjall-Skardsheidi central volcano. The hornfels is badly exposed on the northern side of the caldera, but well exposed on the southern side where it was closely studied. Loss-on-Ignition analyses show that the hornfels is the least hydrous part of the rocks around the intrusion, due to the mineral assemblage being dominantly water-free that was caused by thermal conduction from the gabbro intrusion. The hornfels rocks have a composition range that is almost identical to the equivalent fresh rocks of the volcano. The main minerals analysed were pyroxene, plagioclase and oxides. The pyroxene composition range is dominantly salite-augite (zone nearest the hornfels) and ferrosalite (further away from the gabbro) with slight diopside and hedenbergite. Orthopyroxene is mostly as Mg-rich vesicle fillings. Plagioclase shows a wide range of compositions dominantly with labradorite to andesine composition, which extends to anorthite composition in some cases. This is perhaps not surprising as the hornfels is a recrystallized rock with similar plagioclase and pyroxene compositions, although the pyroxene may shift a little towards Fe enrichment and the plagioclase towards the Ca end. Oxides are also similar to the primary ones.

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