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Exceptionally High-Grade Surface Alteration in the Vonarskard Active Central Volcano, Mid-Iceland

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ABSTRACT

Exceptionally high-grade surface alteration has been observed in hyaloclastite within the caldera of the active Vonarskard central volcano. This surface alteration includes the high-temperature mineral assemblage: actinolite-epidote-wollastonite-quartz (act-ep-wo-qtz), which is assumed to be formed at temperatures above 300°C and pressures above 100 bars. Pits after recently cooled hot springs or mud pits, presumably of early Holocene age, are found within the outcrop, which covers an area of some 2.5 km^2. No active geothermal surface manifestations are found within the outcrop itself, while vividly active fumaroles and boiling hot springs field occur in an area of 6 km^2 adjacent to the outcrop of the high-grade alteration. The active geothermal field, in the highlands above 950 m a.s.l., is unusual in being characterized by numerous colourful hot springs and permanently running warm streams, instead of the more normal fumarole type of fields, with seasonal variation in hot spring activity and limited runoff in this type of settings. This character of the Vonarskard geothermal field relates to high watertable, which presumably is kept up by heavily altered rocks at shallow depths below the active field, supported by the high-grade alteration outcrop.

Seeking explanation for the high-grade surface alteration containing act-ep-wo-qtz on the surface of a volcanically active area, the first one that comes in mind is erosion, which in this case can be ruled out apart from some few metres to tens of metres at the most. The second, and the more likely explanation, is that the high-grade alteration took place on the bottom of a subglacial lake, under at least 1 km thick ice sheet of late Weichselian age. This is the first finding of high grade surface alteration of this type in Iceland. It might be more commonly formed in subglacial settings than hitherto recognized, even globally. Black smokers on the ocean floors are likely candidates for this type of surface alteration. However, our attempt scanning the literature for descriptions of similar curiosities, proved unsuccessful.

1. INTRODUCTION

Vonarskard is located in the centre of Iceland and within the Northern Rift Zone (Figure 1, Johannesson and Saemundsson 1999). In the region are three active central volcanoes (Saemundsson 1982). To the west is the Tungnafellsjokull central volcano which is slightly eroded. It has not erupted in Postglacial time (i.e. last 9000 years). In the centre is the Vonarskard central volcano with its 8 km wide caldera and active high-temperature field. To the east of Vonarskard is the majestic Bardarbunga central volcano which is one of the more active volcanoes in Iceland. It is located in the northwestern part of the Vatnajokull glacier and has a relatively small caldera. Towards south is the fourth central volcano named Hagongur volcano with an active high-temperature field.

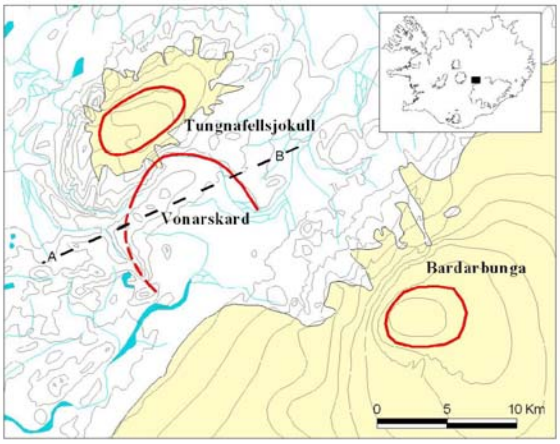

Figure 1: Map showing the location of three central volcanoes in Mid-Iceland, including the Vonarskard central volcano. The Vonarskard caldera is indicated, open towards the southeast and approximately 9 km across. The stippled line A-B indicates a cross section used for the schematic model shown in Figure 2. The high-grade hydothermal alteration site described in text is exposed on the surface along this line in the centre of the caldera. See text or discussion on the Tungnafellsjokull and Bardabunga central volcanoes, both of which are partly covered by ice caps.

The Vonarskard volcano is clearly a slightly younger structure than Tungnafellsjokull volcano. Subglacial volcanics from the younger Bardarbunga volcano cover the eastern part of the Vonarskard volcano. It is not clear, however, if the Tugnafellsjokull caldera and Vonarskard caldera should be considered as two calderas within the same central volcanic complex, or considered to belong to two separate central volcanoes. Tungafellsjokull forms a ridge-shaped mountain reaching elevation of 1500 m, and as such separates itself topographically from the lower altitude Vonarskard complex on the east side. While detailed geological mapping is needed, reconnaissance survey by the present authors, seems to suggest that the two volcanoes should be considered as a part of the same central volcanic complex. For the present discussion, however, it is more convenient to discuss them as two separate volcanoes.

The subglacial central volcano Bardarbunga reaches an elevation above 2000 m, and is one of the most vividly active central volcanoes in Iceland, located just above the centre of the Icelandic hot spot. The fissure swarm attached to the Bardabunga volcano extends more than 100 km to both directions from the center, and involved extremly voluminious eruptions in early Holocene time, like that of the Thjorsarhraun lava in the south, and the Trolladyngja shield volcano in the north.

The authors of this article had the opportunity to visit the hydrothermal system of Vonarskard in relation to geothermal and geological exploration and mapping of the Hagongur geothermal system south of the Vonarskard system, first in 1995 (Fridleifsson et al. 1996) and then in 2001 and 2002. In 1995 the hydrothermal surface manifestations were briefly looked at and a fumarole sampled. The application of gas geothermometry indicated subsurface temperatures there around 300°C (Fridleifsson et al. 1996, see also Oskarsson 1984). The high-grade greenschist facies hydrothermal surface manifestation was first observed in the 2001 survey within the Vonarskard caldera. Hitherto, this has not been desribed. The purpose of the present paper is to announce and discuss this unususal and exceptional geothermal phenomenon of greenschist facies surface alteration.

2. NOTES ON THE GEOLOGY OF VONARSKARD

The oldest rock formations which can be related to the Vonarskard volcano may be 300.000-500.000 years old and are exposed at the northern caldera rim. These older formations consists of interglacial lava flows intercalated with subglacial hyaloclastites and tillites.

The caldera is about 8 km in diameter but only the western half of it is exposed at the surface (Figure 1). The caldera escarpment is well exposed on the northern rim and inward dipping slabs are seen on the lower eastern slopes of Tungnafellsjokull volcano. The southern rim is marked by arched subglacially erupted rhyolite extrusions.

Continued volcanic activity has filled in the caldera. The presently exposed caldera filling consists mainly of subglacial basaltic hyaloclastites and pillow lavas. The rocks are generally aphyric in character contrasting the Bardarbunga system where nearly all formations are highly plagioclase porphyritic and easily distinguished. Some of the youngest pillow lavas within the caldera are of special interest because they resemble pillow lavas of fast spreading ridges of the ocean floor. Their surface is ropy like in subaerial pahoe-hoe flows but their interior comprise typical pillows. This type of pillow lava flows presumably form in relatively shallow but widespread subglacial caldera lakes. The hyaloclastite pillow basalt ridge, containing the high-grade greenschist facies alteration discussed in this paper, however, is slightly older and presumably erupted in a more confined subglacial lake above the eruptive fissure in Weischelian time. It is composed of a more tuffaceous pillow breccia and forms an oval shaped hill elongated in NE-SW direction. Figure 2 shows a schematic cross section of the situation during this subglacial volcanic eruption, roughly along line A-B in Figure 1.

In Figure 2, the ice sheet is shown as being thicker than 1 km, which would be sufficient to explain over 300°C hot hydrothermal alteration in the hyaloclastite pillow breccia newly erupted on the caldera floor. During the culmination of the Weischelian period the ice sheet may even have been much thicker than this, possibly 1.5-2 km. The hyaloclastite formation under consideration rises to 1000 m elevation, only some 60 m above the present caldera floor, while the adjacent ice-covered Bardarbunga volcano reaches an elevation above 2000 m (Fig. 1). Therefore a 1-2 km thick ice sheet during glacial time would not be surprising.

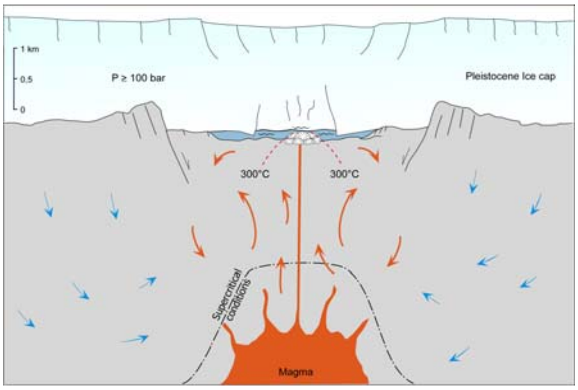

Figure 2: Schematic model of the Vonarskard caldera during late Pleistocene, roughly along line A-B in Fig. 1. Within the centre of the caldera, a brecciated pillow lava formation erupted subglacially in late Pleistocene time (Weichelian), and only insignificant erosion occurred within the caldera upon subsequent glacial retreat. Apparently the eruption took place within and on top of an active subglacial hydrothermal system. Apparently, a vivid hydrothermal activity followed the eruption and extensive hydrothermal alteration of the pillow basalt took place on the caldera floor. This occurred at exceptionally high temperatures and pressures – above 300°C and at above 100 bar pressure.

Quite surprising, however, was the unexpected discovery in 2001of finding epidote and wollastonite bearing rocks on the surface of this young and little eroded caldera floor, a curiousity which needed an immediate explanation.

3. THE VONARSKARD HYDROTHERMAL SYSTEM

A simplified map showing the distribution the active hydrothermal manifestation in the Vonarskard caldera is shown in Figure 3. Fumaroles, boiling mud pits and flowing hot springs are shown in red colour; hot steaming ground as surrounding orange areas, while extinct Holocene surface alteration is show as dark green areas and the older Pleistocene alteration as light green areas. The light green area more or less embraces the exposed hydrothermal active area and surface alteration within the caldera, appart from the high-grade greenschist facies alteration, which is shown by the yellow hatched area north-east of the active hydrothermal manifestations.

The active area needs to be discussed to some extent here. It shows reasonably normal surface manifestation for an active high altitude, high-temperature hydrothermal system within an Icelandic central volcano, especially at higher elvations. And as such it is comparable to hydrothermal systems recently mapped in the huge Torfajokull central volcano (Saemundsson and Fridleifsson, 2001) and the Hagongur hydrothermal system (Fridleifsson et al. 1996). However, what distinguishes the Vonarskard system from those systems mention is the unusual amount of boiling runoff water, and the exceptionally extensive growth of colourful algaes in many of the hot springs, ranging in colour from blackish red through green to white. The extenisve growth of algae in the Vonarskard system undoubtedly relates to the high groundwater table and reasonably steady runoff, which is unusual for a high altitude hydrothermal system. The colour variation presumably reflects differences in temperature, pH and chemical composition of the hot springs, the details of which were not studied.

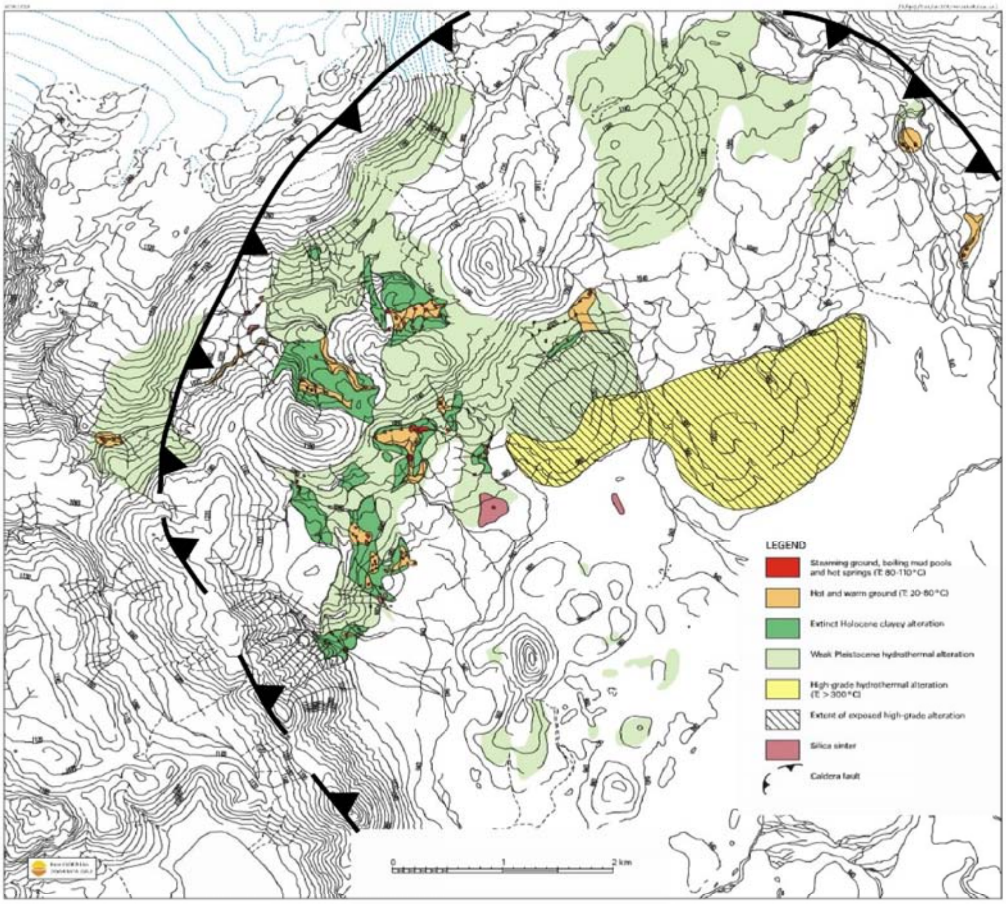

Figure 3: A simplified map of the active high-temperature field within the Vonarskard caldera, showing fumaroles, steam vents, boiling mud pits and hot springs in red; hot ground in orange; Holocene surface alteration in dark green, and late Pleistocene alteration in light green. The distribution of high-grade greenschist facies surface rocks is shown hatched and in yellow, covering an area of ca. 2.5 km^2.

However, it was pretty clear that sulphuric steam escaping into some of the springs turned smoky black upon contact with runoff waters, due to pyrite formation, while CO_2 rich mineral springs were reflected in reddish algae and red earth, and so forth. At first the reason for the high watertable was not at all obvious. However, after observing the high-grade alteration of greenschist facies rock on the surface in the adjacent aera, the most likely reason for relatively dense rocks close to the surface in the active hydrothermal field may relate to high-grade alteration at shallow depths there as well.

The distribution of the high-grade greenschist facies altered rocks in shown in Figure 3, covering an area of some 2.5 km^2. The altered rock is composed of basaltic pillow breccia and tuff, mostly light greenish to yellow or light gray in colour, due to heavy alteration (Fig. 3 and Figs. 4 & 5). Epidote, wollastonite and quartz amydales are easily recognized in a handlense, as well as actinolite, and presumable albite and adularia as well. Actinolite forms at temperatures above ~300°C, while the epidote-wollastonite may form at temperatures above ~250-260°C. The other minerals form at temperatures above 200°C upwards. Mineral temperatures are based on estimates from drillhole research in Iceland (e.g. Kristmannsdottir 1979, Fridleifsson 1990). In the field the lighter the colours the more intense the alteration. Also occuring within the most altered area, are patches of less altered brownish pillow basalts, containing monomineralic amygdales of laumontite, formed at much lower temperatures, 110-180°C, and chabacite, formed at lower temperatures still (ca. 40-70°C) can be seen in other amygdales. The occurrence of high-temperature mineral assemblages in amygdales and as rock replacement minerals in some rocks, and much lower grade alteration and less intensive rock replacement by lower grade mineral assemblages in adjacent rocks, is interpretated as reflecting extreme variation in formation temperatures within the hyaloclastite formation. The temperature variation can be explained by the presence of abundant supplies of melt-water in the ice cave formed by the basaltic volcanic eruption.

Moving outwards, to the flanks of the high-grade alteration, the greenish colours fade and brownish colours and lower grade alteration become more prominent, and only patches of light green epidote containing rocks are seen at the fringe of the high-grade zone in the hills towards the west. Towards the south and east the high-grade rocks disappear under the sandur plain.

In thin sections, the high-temperature mineral assemblage observed in the field were confirmed, and rock replacement also proved to be quite extensive in many of the samples. Elongated albites completely replacing primary labradorite, and actinolite replacing pyroxene in the subophitic pillow lava matrices, is quite common. Titanite is likely to be present as well and adularia. Chlorite is also found in amygdales. Garnet, presumably andratite, is also observed as well as calcite. The calcite seems to overprint the higher-grade mineral assemblages. Typical feature of the amphiboles is a prominent pleochroism.

Turning back towards the field again, another prominent feature on the surface within the heavily altered rocks, is the presence of numerous pits, presumeably remnants of early Holocene hot springs. This feature together with the total lack of glacial tillites or any other extensive erosional features, led us to conclude that erosion of the oval shaped hyalocastite pillow basalt formation had been insignificant. And thereby – that the greenschist facies alteration had taken place, so to speak, on the surface of the caldera.

Figure 3: Intensively altered hyaloclatite mound in the Vonarskard caldera, Mid-Iceland.

Following the hydrostatic boiling point curve from the surface down, 300°C would not be reached until at about 1 km depth within an active field. In the case of the Vonarskard caldera, 1 km of ice would yield similar pressure, approaching 100 bar, on the caldera floor, and thicker ice would evidently yield higher pressures. Thus, as far as pressure is concerned, 300°C hot fluid could be expelled directly into a subglacial lake without boiling, and a kind of a subglacial “black smoker” would have formed. Vigorous mixing of hot and cold water would have taken place under such conditions, especially during the pillow basalt eruption, but eventually the abundantly replenished melt-water from the ice sheet source should have dominated the hydrous system – one would think. Why then the extensive alteration of high-grade alteration above 300°C in an area of more than 2 km^2, literally speaking on the surface of the caldera? Black smokers thrive under high pressures on the ocean floor, and presumably seal themselves from the cold ocean above, and so could a subglacial “black smoker” under a thick ice sheet. However, one does not see any sealed caprock in the case of the Vonarskard, unless it is was completely removed by the insignificant erosion of few metres at the most. Exactly why 300°C hot hydrothermal fluid trived at the surface of the caldera floor for long enough time to almost completely alter and recrystallize 2 km^2 of tuffaceous pillow basalt formation is not known. Most likely an active hydrothermal system thrived at the caldera floor just below the volcanic vent area at the time of the subglacial eruption. This may have triggered voluminous upflow of hydrothermal fluid from the underlying hydrothermal system. Due to high fluid pressure the temperature in the underlying system may have been close to or above 300°C at the time of the eruption. Thereby the excess heat contained within the heap of newly formed pillow basalts and tuffs may have been sufficient to maintain temperatures above 300°C for long enough time to cause the extensive high-grade alteration within the formation.

Alteration of this type is simply unknown as a surface phenomena within the Icelandic central volcanoes. In geothermal drillholes, however, the presence of high temperature minerals, like chlorite and epidote, at relatively shallow depths, and much shallower depths than accounted for by the hydrostatic boiling point curve from the present day surface, has been explained by higher water pressures during glacial times allowing for the higher temperatures to form high-T minerals at shallow depths. A similar explanation is used here to explain the greenschist facies surface alteration in Vonarskard, the difference being that the surface temperature in Vonarskard seems to have been much higher, which may relate to thicker ice sheet.

Scanning the international literature, with the aid of computer search tools, surface alteration of this type is also unknown elsewhere – even within the ocean floor black smoker basalts at great depths – as far as the authors are aware. If anywhere – one would expect high-grade rock alteration of simlar grade as that of Vonarskard to occur almost at surface of the ocean floor in the black smokers’ vicinity – or at least in some of them. As yet though, only a few of the black smokers of the deep oceans have been sampled sofar, and most are unexplored. Only shallow drilling has been undertaken into some of them by ODP or others in recent years. While the black smokers of the oceans involve brine fluids, the Vonarskard hydrothermal system involves dilute fluid of metoric origin, which may explain the lack of abunant sulphides in Vonarskard, which are characteristic surface phenomena of the ocean floor black smokers.

Figure 4: A view of an extinct hydrothermal pit in the Vonarskard caldera, Mid-Iceland.

Turning to the Icelandic systems – still seeking explanation for the unusual high-grade surface alteration phenomenon of Vonarskard – most of the subglacially formed hyaloclastite ridges of Iceland are more or less unaltered, and only low grade alteration in the vent areas is known in some of them. Still, one should only seek an analog situation to that in Vonarskard in the interiors of other calderas of the Icelandic central volcanoes. Perhaps the Vonarskard situation is more common within the calderas of Iceland that hitherto acknowleged, while the tickness of an ice sheet during volcanic eruptions within them is likely to have been quite variable in Plio-Pleistocene times.

One of the presently active central volcanoes covered by the present-day Vatnajokull ice sheet, is the Grimsvotn central volcano. The volcano erupts frequently, several times each century in historic times, and has frequently caused catastrophic floods on the Skeidararsandur plain upon drainage of the caldera. The last of such floods occurred in 1996, sweeping off several bridges and roads. The caldera drains regularly, either as a consequence of volcanic activity, or steady infilling of meltwater into the caldera due to vigorously active hydrothermal system on the caldera floor. Bjornsson et al. (1982) estimated that for a given time period a mean steady output of thermal energy, equalling about 5000 MW thermal over about four decades, was needed to explain the steady replenishment of meltwater in the caldera during that given time period, since 1934. An effective water penetration into a cooling major intrusion allowing for rapid heat exchange (Bjornsson et al. 1982) was considered possible explantion. The example from the Vonarskard high-grade caldera floor surface alteration phenomenon might be an alternative to explain the extreme yield of thermal energy into a subglacial caldera lake, while the hydrothermal temperatures on the caldera floor in the present Grimsvotn caldera need to have been somewhat lower than the Vonarskard temperatures, due to much thinner ice cap of perhaps 500 m at present. Bjornsson and Gudmundsson (1993) estimated the mean steady state output of thermal energy over several hundreds of years in the Grimsvotn caldera to be about 1500-2000 MW.

4. CONCLUDING REMARKS

The occurence of the Vonarskard high grade greenschist facies alteration in surface rocks of the Vonarskard caldera, is explained as having been formed under a thick ice cap of at least 1000 m in Weischelian times, and is considered to have yielded high enough pressure of 100 bars to account for temperatures above 300°C. The maximum temperature is not known, but a study on fluid inclusions in quartz or the amphiboles could possibly give a closer estimate of the maximum temperature. Exactly why 300°C hot hydrothermal fluid thrived at the surface of the caldera floor for long enough to almost completely alter and recrystallize 2 km^2 of tuffaceous pillow basalt formation is not known. An explanation suggested here is, that an active hydrothermal system existed just below the volcanic vent area at the time of the subglacial eruption. This may have triggered voluminous upflow of hydrothermal fluid from the underlying hydrothermal system into the newly erupted heap of pillow basalts and tuffs. Analog hydrothermal situations may be active in the wake of subglacial eruptions at present within the Grimsvotn caldera, which is covered by several hundred metres thick ice sheet.

One last point worth mentioning – given the surface temperatures above 300°C in Vonarskard. Viewing the model presented in Figure 2, the 300°C isotherm was elevated by at least 1 km compared to a normal situation in a present-day hydrothermal system open to the surface. Similarily, an isotherm marking the boundary between subcritical to supercritical condition could have been elevated by 1 km or more. The higher the temperature in the surface high-grade rocks the more elevated the supercritical boundary conditions could have been. Thus, a closer study of the high grade alteration and its maximum temperature should be undertaken. While drilling for economic purposes is unlikely to take place in the Vonarskard caldera for decades to come, the unusal high-grade alteration there might warrant scientific drilling in this magnificent place.

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REFERENCES

Bjornsson, H, Bjornsson, S. and Sigurgeirsson Th.: Penetration of water into the hot rock boundaries of magma at Grimsvotn. Nature 1982. 295, 580-581.

Bjornsson, H. and Gudmundsson M.T.: Variations in the thermal output of the subglacial Grimsvotn caldera, Iceland. Geophysical Research Letters 1993. 20, 2127-2130.

Fridleifsson, G.O.: Hydrothermal systems and associated alteration in Iceland. In: Third Symp. On Deep-Crust Fluids: High Temperature Acid Fluids and Associated Alteration and Mineralization. (1990). 81-87. Geological Society of Japan.

Fridleifsson, G.O., Olafsson M. and Bjarnason J.O.: Geothermal activity in Koldukvislarbotnar (in Icelandic). Orkustofnun (National Energy Authority) report. 1996. 38 p.

Johannesson, H. and Saemundsson K.: Geological map of Iceland 1.500.000. Bedrock geology. 1999. Icelandic Institute of Natural History. Reykjavik. 2nd. edition.

Kristmannsdottir, H.: Alteration of basaltic rocks by hydrothermal activity at 100-300°C. In: Developments in Sedimentology (eds. Mortland, M. & V. Farmer), (1979). 359-367.

Oskarsson, N.: Montitoring of fumarole discharge during the 1975-1982 rifting in Krafla volcanic center, North Iceland. Journal of Volcanology and Geothermal Research 1984. 22. 97-121.

Saemundsson, K.: Calderas in the active volcanic belts of Iceland (in Icelandic). Eldur er í Nordri. Sogufelagid, Reykjavik, 1982. 221-239.

Saemundsson, K. and Fridleifsson G.O.: In Torfajokull. Geological and geothermal maps of the Torfajokull area (in Icelandic). Orkustofnun (National Energy Authority) report. 2001. 118 p & maps.