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Quenched Silicic Glass from Well KJ-39 in Krafla, North-Eastern Iceland

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ABSTRACT

In the fall of 2008 well KJ-39 was directionally drilled to a depth of 2865 m (2571 m TVD) into the Suðurhlíðar field in Krafla geothermal field, north-eastern Iceland. Quenched silicic glass was found among the cuttings retrieved from the bottom of the well suggesting that magma had been encountered and high temperatures of 385.6°C were measured, while drill string was stuck in the well. The silicic glass contained resorbed minerals of plagioclase, clinopyroxene and titanomagnetite and was subalkaline, peraluminious in composition; containing 4-5% corundum in the norm. The composition of the silicic glass resembles magma that has formed by partial melting of hydrated basalt during initial stages of contact metamorphism. The melt was encountered among cuttings from impermeable, coarse basaltic intrusives at a depth, where the well was anticipated to penetrate the Hólseldar volcanic fissure. The disclosure of melt at such shallow depths within Krafla geothermal system conform with the existence of a two phase reservoir, where temperature have reached 340-350°C at 2000 m depth.

1. INTRODUCTION

Being a segment of the N-Atlantic rift-system Iceland is composed of oceanic basaltic rocks dominated by olivine tholeiites. The occurrence of silicic rocks is confined to central volcanoes, which are distributed along the neo-volcanic rift zone and flank zones of Iceland. Evolved basalts and silicic rocks, therefore, make up about 10% of the Icelandic lava plateau. The proposed hypotheses for the genesis of silicic rocks in Iceland may roughly divide into two; fractional crystallisation of basaltic magmas (Carmichael 1964, Macdonald *et al.*, 1990) or partial melting of hydrothermally altered basaltic crust (O´Nions & Grönvold, 1973; Sigvaldason, 1974; Oskarsson *et al.* 1982, Condomines *et al.*, 1983; Sigmarsson *et al.*, 1991, Jónasson, 1994, 2007).

In the autumn 2008 fresh silicic glass was retrieved from well KJ-39 while drilling into the geothermal system within Krafla central volcano, north-eastern Iceland. The glass provides further insights into the geological circumstances under which petrogenesis of silicic rocks occurs in Iceland.

2. GEOLOGICAL SETTING

The Krafla central volcano is located within the neovolcanic zone in north-eastern Iceland (figure 1). It is estimated that the volcano has been active for at least 300000 years (Sæmundsson, 1991). The volcano is approximately 20 km in diameter and within it is an eroded and partly filled caldera 8x10 km in diameter. A N5-15°E oriented and 90 km long rifting fissure swarm extends through Krafla volcano, while a prominent NW-SE elongated geothermal area covering ca. 10 km^2 is present within the caldera structure (Sæmundsson, 1991, 2008). The geothermal area appears to be closely coupled to an inferred underlying magma chamber, since seismic studies during the Krafla Fires 1975-84 indicate a S-wave shadow delineating a NW-SE elongated magma domain at 3-7 km depth (Einarsson, 1978).

The Krafla rock suite shows a bimodal distribution in composition, basaltic lavas and hyaloclastite ridges are predominant, while minor volumes of subglacial rhyolitic ridges are found mainly at or outside the margins of the caldera (Sæmundsson 1991, 2008; Jónasson, 1994). Drilling into the geothermal field in Krafla for geothermal development has revealed a similar compositional distribution of the volcanic and plutonic rocks in the substrata, where silicic rocks are also more abundant towards the caldera margin (Gudmundsson, 1983; Ármannsson *et al.*, 1987).

2.1 Volcanic Activity in Krafla in the Past 3000 Years

Volcanic activity has been confined to the eastern flank of the Krafla fissure swarm for the past 3000 years (Sæmundsson, 1984, 1991). During this time there have been six rifting events with associated volcanic fissure eruptions, but they have been unevenly distributed in time at intervals of 300-1000 years. The last three eruption periods, Krafla Fires (1975-1984), Mývatn Fires (1727-1729) and Dal Fires (~900 AD) extruded mainly along fissures to the west or at the western margin of the developed geothermal field in Krafla. In contrast, the 2200-2500 year old Hólseldar Fires (~2200-2500 AD) erupted along cone sheets at the northern margin of the caldera, but fissures extended to the south along the Krafla mountain and across the eastern margin of the Suðurhlíðar geothermal field (figure 1).

2.2 Krafla Geothermal Field

Geothermal development of Krafla geothermal field began in 1974. Since then the field has been developed in stages and currently the installed capacity at Krafla Power plant is 60 MWe. Four well fields, Leirbotnar-Vítismór, Suðurhlíðar, Hvíthólar and Vesturhlíðar, have been developed within the Krafla caldera (figure 1) and they are characterised by distinct physical conditions (Stefánsson, 1981; Böðvarsson *et al.*, 1984; Ármannsson *et al.*, 1987). The Leirbotnar-Vítismór area is divided into an upper 1000-1400 m thick, water saturated reservoir with temperature within 190-220°C and a lower boiling reservoir with temperatures reaching up to 350°C. Suðurhlíðar area is characterised by a boiling system, while Vesturhlíðar define the border zone between Leirbotnar-Vítismór and Suðurhlíðar areas, where a major up-flow zones in the Krafla system is believed to be located. The Hvíthólar field is located at the southern caldera rim, where the reservoir is characterised by boiling conditions to 900 m depth, but with temperature reversal below.

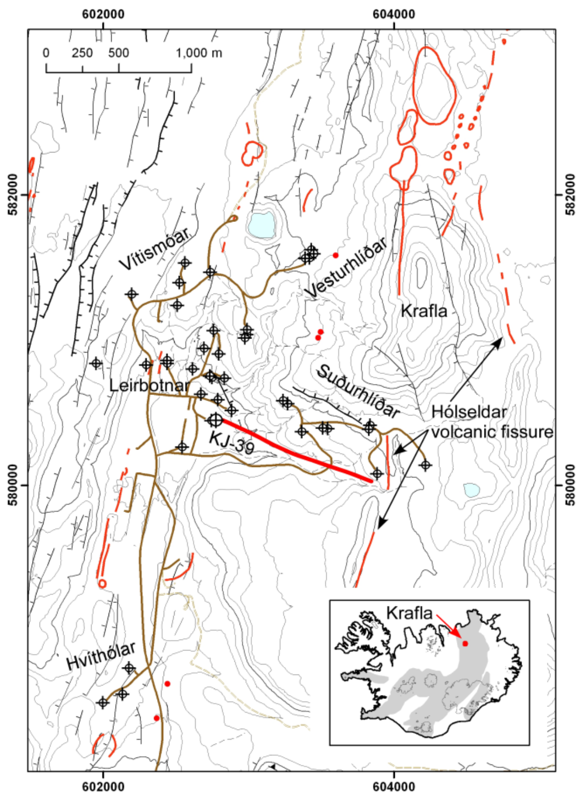

Figure 1: Location of Krafla within the neovolcanic zone in north-eastern Iceland and a close-up of Krafla geothermal well field with the well path of KJ-39 highlighted

3. STRATIGRAPHY OF WELL KJ-39

Well KJ-39 is located in the southern part of Leirbotnar-Vítismór field, but was directionally drilled to the east (115°) into the Suðurhlíðar field, where it aimed at permeability associated with felsic intrusions, an explosion crater and the Hólseldar volcanic fissure (figure 1). Drilling was completed to a depth of 2865 m (2571 m TVD) in the fall of 2008. Recovery of drill cuttings was 100% to 1404 m depth, from 1404-2654 m depth the cutting recovery was minor due to near total loss of circulation and below 2654 m depth there was no recovery of cuttings, but with reference to borehole loggings the stratigraphy may be resolved. Stratigraphy down to 1400 m depth comprises successions of altered hyaloclastite and lava intersected by basaltic dykes of variable thickness. The successions are almost all basaltic in composition. Below 1400 m depth the well enters an intrusive complex, which may be roughly divided into three sequences, a basaltic dyke sequence at 1400-1500 m depth, felsic and intermediate intrusives at 1500-2000 m depth, and a dolerite/gabbro complex below 2000 m depth (figure 2).

The alteration mineral assemblage comprises quartz, epidote, wollastonite, actinolite representative of the epidote-actinolite alteration zone, but below 2000 m depth the basaltic intrusive complex is dense, relatively little altered and accordingly is the amount of alteration minerals sparse.

Borehole logging also verify that the intrusive rocks are dense with high neutron-neutron counts. The neutron count increases further below 2250 m depth attaining unusual high counts of up 750 cps on the far detector, an indication that the formation is even denser and that H_2O-bearing alteration minerals are sparse (figure 2).

During drilling the rocks were observed to be softer below 2800 m depth in particular at 2827-2847 m depth. Target depth was reached at 2865 m depth, but few hours after drilling was completed the drill string got stuck with the drill bit at 2848 m depth. After a week of unsuccessful attempts to get the drill string free, was it retrieved from 2808 m by detachment with the aid of explosives. The three lowermost retrieved units in the bottom hole assembly contained cuttings, which comprised up to 30% fresh, quenched glass, indicating that the well had penetrated magma.

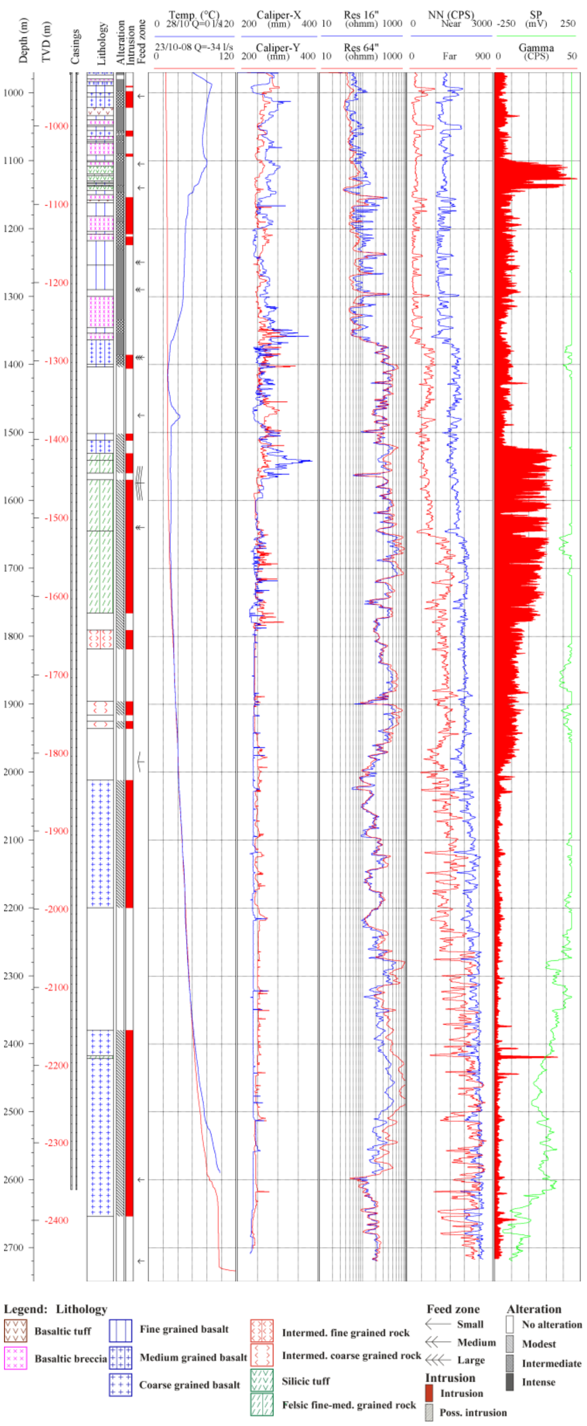

Figure 2: Lithology of well KJ-39 plotted with temperature, caliper and geophysical logs

4. FEED ZONES, TEMPERATURE CONDITIONS AND FLUID COMPOSITION OF KJ-39

The major feed zones are situated between 1100-1650 m depth within KJ-39, partly within the sequence of felsic intrusives. Below 1650 m depth three feed zones have been identified with temperature logs at 2000 m, 2600-20 m and 2720 m depth (figure 3). The feed zone at 2000 m depth appears at the transition between intermediate intrusives and dolerite sequence, but it may also be tied to the fracture beneath an explosion crater. The feed zones at 2600-20 m and 2720 m are located within a dense sequence of dolerite or gabbro. There did not appear to be any leakage below 2720 m depth, where temperature increased rapidly and a maximum temperature of 385.6°C was recorded at 2822 m depth (2533 m TVD), revealing that the well had indeed entered a very hot environment in vicinity of the Hólseldar volcanic fissure. Although temperature was above the supercritical point of water, the corresponding reservoir pressure remains undefined as logging was carried out within the stuck drill string.

Eventually the well was plugged with cement up to 2620 m depth as high temperatures and vicinity to magma raised the concern that fluid from the lowermost feed zone would be acidic and cause damage to the well and render it unsuitable for steam generation. Furthermore the wellhead and the casing programme were not constructed to withstand pressures and temperatures under the conditions that might be anticipated in the well. Based on these considerations and the priority of steam generation the bottom of the well was plugged.

Subsequent discharging, testing and logging of KJ-39 revealed that the well has a high enthalpy ~2600 kJ/kg. The

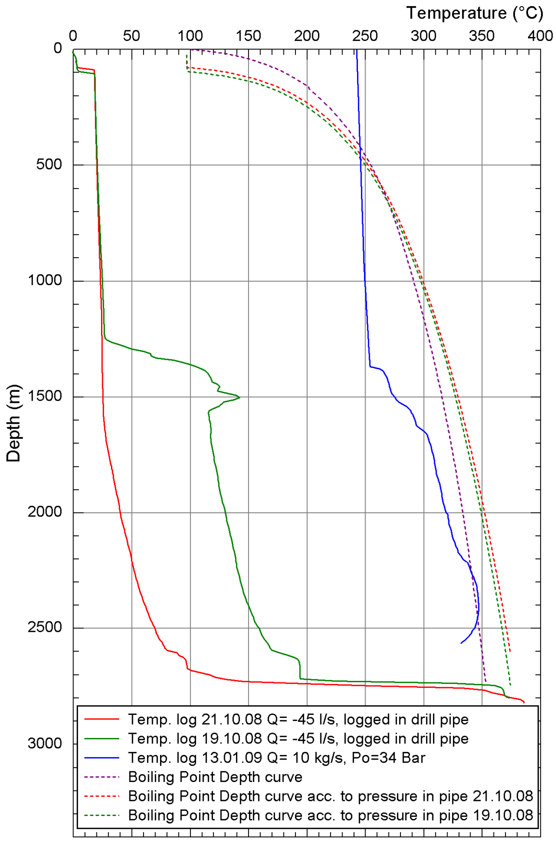

Figure 3: Temperature logs from KJ-39 while drill pipe was stuck in hole and while the well was discharging

feed zones between 1100-1650 m depth are water saturated while superheated steam is released from the feed zones in the boiling reservoir in the lowermost part of the well and up to 65-90°C of superheating and temperatures of up to 350°C was recorded below 2400 m depth (figure 3). However, boiling in the lower reservoir appears to lead to the volatilisation of HCl. This subsequently causes severe corrosion of the liner, where the superheated steam mixes with water-saturated steam from the feed zones above 1650 m depth (Einarsson *et al.*, 2010).

Corrosion due to HCl in superheated steam has previously been a problem that seemed to pertain to wells located within the Leirbotnar-Vitismó field (Ármannsson *et al.*, 1989; Truesdell *et al.*, 1989). However, recent years of drilling within Krafla geothermal system have revealed that superheated conditions occur widely when producing from feed zones below 2000-2200 m depth (Einarsson *et al.*, 2010).

5. PETROGRAPHY AND GEOCHEMISTRY OF QUENCHED, SILICIC GLASS

The cuttings that were retrieved from the BHA units of the drill string consist of rather fresh and unaltered holocrystalline basalt and up to 30% quenched, silicic glass. The holocrystalline basalt consist of plagioclase (bytownite-anorthite; $An_{74\text{-}90}$), clinopyroxene (augite with 13-27 mol% Fs), opaque oxides (homogeneous titanomagnetite) and minor olivine (Fo_{60}). The composition of the mineral phases in the basalt reveals minor compositional variation, suggesting that the glass appears in association with unaltered dolerite or micro-gabbro with olivine tholeiite composition.

The glass is fresh and dark- to light-brown in colour with tubular vesicles (figure 4). Glass fragments with conchoidal fractures are common, while some surfaces are coated with a thin grey-greenish film, which is possibly a film of amorphous silica or clay (figure 4) that has formed while the glass suffered minor dissolution/alteration during exposure to fluid in the hole. Contrary to the dolerite, which comprises minerals with euhedral habit, then the glass fragments do contain minerals of plagioclase, clino-pyroxene and opaque oxides with anhedral habit and hence they appear to have been partially resorbed.

Fresh silicic glass is very rare, if not unknown, in hydrothermally altered outcrops within eroded volcanic centres. Devitrified rhyolitic glass is, however, commonly observed. Due to the high reactivity of silicic glass at hydrothermal conditions it may be inferred that it is the most short-lived phase of a volcanic pile. It is, therefore, surprising to find fresh fragments of silicic glass among the cuttings from a geothermal well.

Microprobe analyses of fresh glass fragments from sample KJ-39 are listed in table 1. The table shows compositions calculated on a dry basis. The actual analyses show sums of 92 to 95 wt% indicating water content of 5-8 wt%. The glass is dacitic-rhyolitic in composition and with minor compositional variation.

A striking feature of the glasses is the strongly subalkaline, peraluminious composition. Although the subalkaline fingerprint, in general, conforms to the tholeiitic series of evolved rocks, these glasses are strikingly different from any rift-zone rock type in being strongly potassic. In fact they do not resemble any magmatic erupted rhyolite in Iceland (Kristmannsdóttir *et al.*, 1976; Jónasson, 1994, 2007).

The composition is, however, known worldwide as minor silicic rocks that appear in hornfels-facies close to intrusions. Patches of silicic magmas that form by local anatexis of hydrated rocks during the initial stages of contact metamorphism (hornfels facies) are most commonly found in sedimentary rocks, e. g. in metapelites surrounding intrusive igneous rocks. A common feature of these peraluminous silicic rocks, rarely seen in other rock types, is 4-6% of normative corundum. This is indeed the case for glasses retrieved from well KJ-39, which contain 4-5% corundum in the norm. The only (known to the authors) similar rocks reported in Iceland are found among the xenoliths from the 1875 Askja eruption (G. E. Sigvaldason, pers comm.), where fragments of typical hornfels facies occur, containing cordierite, corundum and quartz as well as fine-grained subalkaline silicic rock, assumed to derive from anatectic melts.

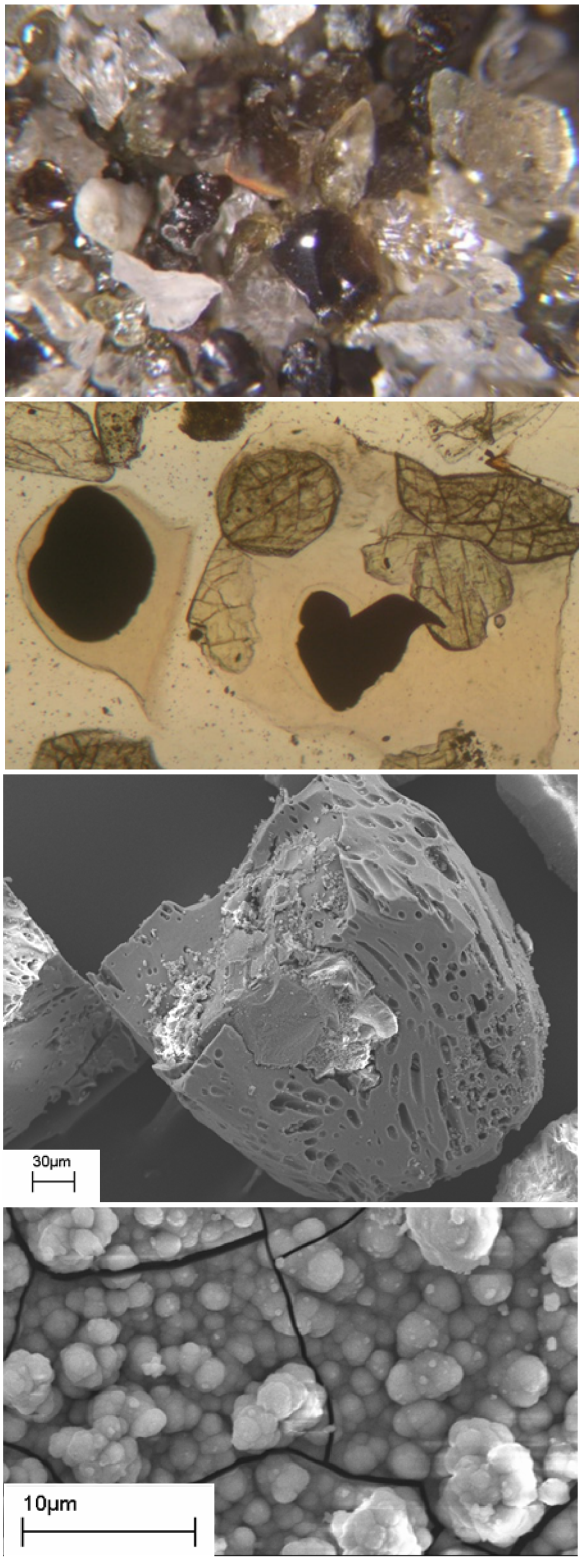

Figure 4: A) Cuttings (~0.5 mm in grain size) containing dark- to light-brown glass retrieved from bottom hole assembly in KJ-39 (top), B) Thin section with silicic glass containing clinopyroxene and opaque oxides with anhedral habit, C) SEM image of glass fragment with vesicles, D) Close-up of film of amorphous silica or clay formed on glass fragment (bottom)

The conditions for the formation of silicic anatectic melts in contact metamorphism have been simulated by melting experiments. The last two lines in table 1 show an experimentally produced melt (EXP) and anatectic hornfels in biotite schist from the Huntley gabbro complex, NE Scotland (Droop et al, 2003). Similarities among the KJ-39 glasses and the Scottish hornfels, as well as the experimental melt, are fairly convincing. Experimental conditions for anatexis producing the EXP glass were 10 kb and 4% total water in biotite schist at 600-800°C. These conditions were selected based on the assumed intrusion depth of the Huntley gabbro. However, the anatectic melting of hydrated sheet-silicates proceeds readily at pressures down to some 0.5 kb (1.5 km) or as long as the released water stays within the system.

Table 1. Microprobe Analyses of Glass – Normalized to 100% Sum. Analyzed Sums are Between 92-95 wt%.

	SiO_2	TiO_2	Al_2O_3	FeOt	MnO	MgO	CaO	Na_2O	K_2O
KJ-39	68.99	1.04	14.50	5.04	0.13	1.03	4.20	2.17	2.90
KJ-39	70.52	1.02	14.55	5.59	0.16	0.93	3.59	1.32	2.31
KJ-39	70.83	0.94	14.67	5.73	0.10	0.96	3.07	1.38	2.30
KJ-39	71.07	1.02	14.53	5.54	0.00	0.97	3.34	1.25	2.28
KJ-39	72.02	0.96	13.64	5.23	0.04	1.01	3.48	1.35	2.27
KJ-39	75.78	0.68	13.22	3.19	0.14	0.60	2.44	1.46	2.48
KJ-39	75.92	0.62	13.21	3.20	0.03	0.64	2.55	1.44	2.39
KJ-39	76.14	0.51	13.91	2.00	0.00	0.38	1.52	2.18	3.44
KJ-39	77.42	0.47	13.38	2.09	0.07	0.32	1.33	1.77	3.15
KJ-39	77.66	0.52	12.81	2.16	0.17	0.33	1.31	1.97	3.07
KJ-39	77.67	0.56	13.09	2.11	0.00	0.33	1.38	1.74	3.12
KJ-39	77.70	0.56	12.68	2.22	0.14	0.37	1.34	1.84	3.16
KJ-39	77.77	0.44	13.26	2.07	0.36	0.35	1.39	1.49	2.87
KJ-39	77.80	0.41	12.71	2.20	0.06	0.34	1.32	1.98	3.18
KJ-39	78.10	0.35	12.23	2.17	0.18	0.35	2.05	1.66	2.91
KJ-39	78.18	0.44	12.53	2.05	0.00	0.32	1.42	1.80	3.26
KJ-39	78.36	0.51	12.26	2.01	0.13	0.33	2.04	1.66	2.70
KJ-39	78.37	0.44	12.79	2.07	0.00	0.30	1.37	1.80	2.94
KJ-39	78.40	0.57	12.64	2.07	0.07	0.31	1.41	1.60	2.92
KJ-39	78.44	0.55	12.09	2.14	0.16	0.29	1.33	1.79	3.21
KJ-39	78.63	0.52	12.42	1.91	0.11	0.35	1.40	1.71	2.95
KJ-39	78.77	0.37	12.75	1.86	0.10	0.31	1.25	1.68	2.91
EXP	74.08	0.36	16.28	1.59	0.04	0.44	2.25	2.04	3.53
Gr-Bt	69.34	0.84	14.60	4.97	0.00	3.93	0.74	2.38	3.11

Regardless of the actual mineralogical composition of hydrated silicates in host rock suffering anatexis the system has to be closed to the surroundings. This implies that a fluid phase (steam) released by heat from the intruded magma has to be confined within the contact zone.

The best known anatectic system is muscovite: K:fsp:Ab:Qz at 600-700°C. The incipient melting following breakdown of muscovite is evidently strongly potassic. Following breakdown of the hydrated K-silicate the inevitable equilibration with albite and quartz sets in and the wet peraluminious melt segregates into liquid patches within the hornfels.

It may be argued that silicic anatectic melts would hardly form within a basaltic environment. This may be correct as long as the basaltic assemblage is dry but in hydrothermally altered and hydrated basalt the anatectic melt forms from the ever-present K-fsp, albite, quartz and mica or its common low pressure equivalent, illite.

6. CONCLUDING REMARKS

From major element analysis of the silicic glass retrieved from well KJ-39 it is presumed that the melt formed from anatexis (i.e. partial melting) of hydrated, hydrothermally altered basalt. However, further analyses are in progress to substantiate this hypothesis. The conditions needed for the formation of anatectic melt within hornfels facies involve impermeable strata confining the released volatiles and the secondary mineral assemblage. Indeed the strata below 2000 m depth in KJ-39 are characterised by a thick and dense sequence of dolerites/micro-gabbros that are almost impermeable; the lowermost feed zone being located at 2720 m depth, more than 100 m from where the silicic melt was intersected.

Persistence of fresh anatectic glass in the hornfels facies is likely to be short. This time span is set by its formation by a basaltic intrusion and the inevitable subsequent ingress of supercritical fluid. The low alteration state of the coarse euhedral minerals in the samples indicates the presence of young intrusions. A plausible heat source for generation of the silicic melt encountered in KJ-39 is the 2200-2500 year old Hólseldar Fires, as it was anticipated that the well would penetrate the Hólseldar volcanic fissure at this depth. However it cannot be excluded that the heat source originates from intrusions associated with the more recent volcanic eruptions in Krafla.

Melts have been encountered not only in KJ-39 but even shallower at 2104 m depth in IDDP-1, and presents further insights to the reservoir conditions in Krafla. Above 1400 m depth there is considerable variation in temperature between the fields, but below 1400 m the variation in temperature diminishes considerably as a boiling reservoir becomes prevalent. Within the Krafla caldera there is a shallow magma chamber at approximately 3 km depth (Einarsson, 1978). Furthermore, the strata are characterised by high frequency of basaltic intrusions below 1000-1500 m depth. These basaltic intrusions appear, probably in conjunction with the shallow magma chamber, not only to release enough heat to cause minor partial melting of hydrated basaltic rocks at shallow depths but also to cause superheated conditions within the reservoir.

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REFERENCES

Ármannsson, H., Gudmundsson, Á., Steingrímsson, B.S.: Exploration and development of the Krafla geothermal area. *Jökull*, **37**, (1987), 13-30.

Ármannsson, H., Benjamínsson, J., Jeffrey, A.W.A.: Gas changes in the Krafla geothermal system, Iceland. *Chemical Geology*, **76 (3-4),** (1989), 175-196.

Böðvarsson, G.S., Pruess, K., Stefánsson, V. and Elíasson, E.T.: The Krafla geothermal field, Iceland. 2. The natural state of the system. *Water Res. Res.*, **20**, (1984), 1545-1559.

Carmichael, I.S.E.: The petrology of Thingmúli, a Tertiary volcano in eastern Iceland. *J. Petrology*, **5**, (1964), 435-46.

Condomines, M.P., Grönvold, K., Hooker, P.J., Muehlenbachs, R.K., O´Nions, N., Oskarsson, N., Oxburgh, E.R.: Helium, oxygen, strontium and neodymium isotopic relations in Icelandic volcanics. *Earth Planet. Sci. Letters*, **66**, (1983), 125-136.

Droop, G.T.R., Clemens, J.D., Dalrymple, D.J.: Processes and Conditions during Contact Anatexis, Melt Escape and Restite Formation: the Huntly Gabbro Complex, NE Scotland. *J. Petrology*, **44 (6)**, (2003), 995-1029.

Einarsson, K., Pálsson, B., Gudmundsson, Á., Hólmgeirsson, S., Ingason, K., Matthíasson, J., Hauksson, T., Ármannsson, H.: Acid Well in the Krafla Geothermal Field. *Proceedings World Geothermal Congress 2010,* Bali, Indonesia, 25-29 April (2010).

Einarsson, P.: S-wave shadows in the Krafla caldera in NE-Iceland, evidence for a magma chamber in the crust. *Bull. Volcanol.* **41**, (1978), 1-9.

Gudmundsson, Á.: The geology of the Krafla Suðurhlíðar field (In Icelandic). In *"Ravens´ Congregations"* on the status of the Krafla geothermal power station, March 2nd-3rd, Krafla Power Station, Akureyri, Iceland, (1983), 77-85.

Jónasson, K.: Rhyolite volcanism in the Krafla central volcano, north-east Iceland. *Bull. Volcanol.*, **56**, (1994), 516–528.

Jónasson, K.: Silicic volcanism in Iceland: Composition and distribution within the active volcanic zones. *Journal of Geodynamics*, **43**, (2007), 101-117.

Kristmannsdóttir, H., Fridleifsson G. Ó., Gunnlaugsson E.: Well 3, 4 and 5 in Krafla – Drilling, feed zones and results of whole rock analyses (In Icelandic). *Orkustofnun JHD-7641*, (1976), 70 pp.

Macdonald R., McGarvie, D.W., Pinkerton, H., Smith, R.L., Palacz, C.A.: Petrogenetic evolution of the Torfajökull volcanic complex, Iceland. I. Relationship between the magma types. *J. Petrol.*, **31**, (1990), 429-459.

O'Nions, R.K. and Grönvold, K.: Petrogenetic relationships of acid and basic rocks in Iceland: Sr isotopes and rare-earth elements in late and post-glacial volcanic. *Earth Planet. Sci. Letters*, **19**, (1973), 397-409.

Oskarsson, N., Sigvaldason, G.E., Steinthórsson, S.: A dynamic model of rift zone petrogenesis and the regional petrology of Iceland. *J. Petrol.*, **23**, (1982), 28-74.

Sigmarsson, O., Hémond, C., Condomines, M., Fourcade, S., Oskarsson, N.: Origin of silicic magma in Iceland revealed by Th isotopes. *Geology*, **19**, (1991), 621-624

Sigvaldason, G.E.: The petrology of Hekla and origin of silicic rocks in Iceland. *Soc. Sci. Islandica V*, (1974), 1-44.

Sæmundsson, K.: The eruption history of the Krafla volcano during the last 3000 years (In Icelandic). In *"Ravens´ Congregations"* on the status of the Krafla geothermal power station, November 1-2, Krafla Power Station, Akureyri, Iceland, (1984), 9-25.

Sæmundsson, K.: Geology of Krafla Volcanic System (In Icelandic) In: Arnþór Garðarsson og Árni Einarsson (ritstjórar): Náttúra Mývatns. Hið íslenska náttúrufræðifélag, Reykjavík, (1991), 25-95.

Sæmundsson, K.: Krafla. Geological Map, 1:25.000. *Landsvirkjun (The National Power Company) and Iceland GeoSurvey*, (2008).

Stefánsson, V.: The Krafla geothermal field, Northeast Iceland. Chapter 10 in Rybach, L. and Muffler, L.J.P. (eds.) Geothermal systems: Principles and case histories. John Wiley and Sons Ltd., New York, (1981), 273-294.

Truesdell, AH., Haizlip, JR., Armannsson, H. and D'Amore, F.: Origin and transport of chloride in superheated geothermal steam. *Geothermics,* **18 (1/2)**, (1989), 295-304.