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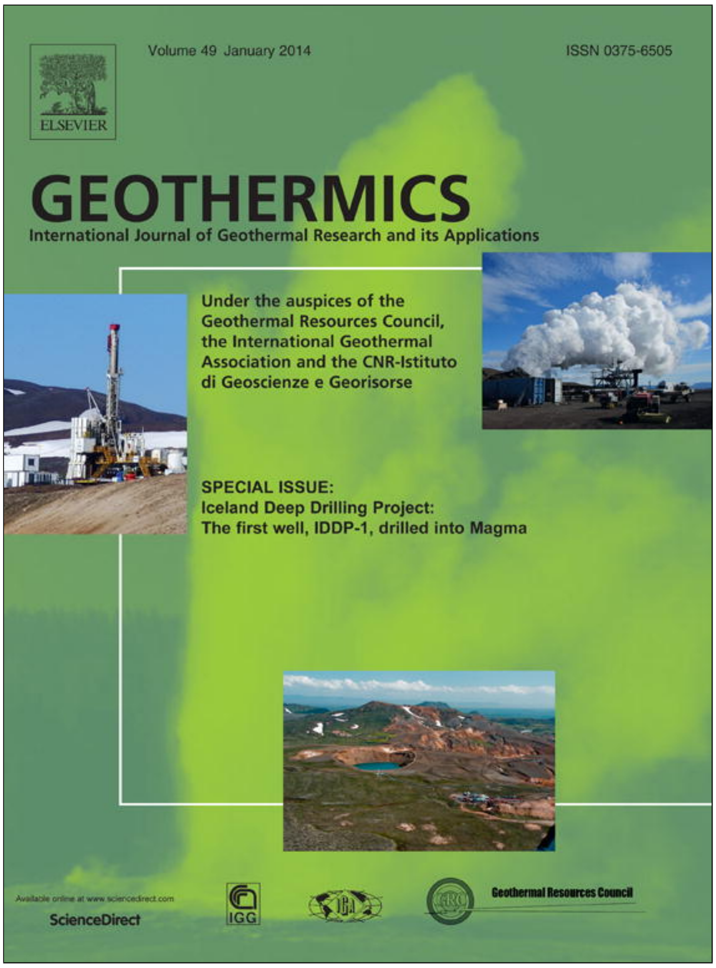

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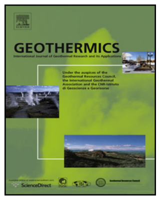

High temperature metamorphism in the conductive boundary layer adjacent to a rhyolite intrusion in the Krafla geothermal system, Iceland

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A B S T R A C T

A rhyolite magma body within the Krafla geothermal system that was encountered at a depth of 2.1 km during drilling of the IDDP-1 borehole is producing high temperature metamorphism within a conductive boundary layer (CBL) in adjacent host rocks. Cuttings recovered during drilling within a few meters of the intrusive contact in IDDP-1 are mainly comprised of granoblastic hornfelses, the rock type which confirms the presence of the CBL at the base of the IDDP-1 bore hole. The two pyroxenes in these hornfelses record temperatures that are in the range of 800–950 °C. The minimum heat flow across the CBL is 23 W m^{-2}. Country rocks at distances beyond 30 m of the intrusive contact are essentially unaltered, implying that they have been emplaced very recently and/or as yet unaffected by hydrothermal fluid flow.

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1. Introduction

The study of active geothermal systems has long offered unique perspectives into metamorphic processes, including fluid–mineral equilibria (e.g., Bird et al., 1984), mineral growth rates (e.g., Browne et al., 1989), and the transitions amongst low-pressure metamorphic facies (e.g., Kristmannsdóttir and Tómasson, 1978; Schiffman et al., 1984; Marks et al., 2010). These studies have only been possible through petrologic investigation of drill cuttings, and more rarely, core samples recovered from boreholes. To date, drilling has been almost entirely focused on the convective portions of geothermal systems, from which fluids are extracted for power generation and/or space heating. One of the goals of the Icelandic Deep Drilling Project (IDDP; Friðleifsson and Elders, 2005) is to penetrate the deeper, higher-temperature portion of a magmatically-heated geothermal system, and specifically to investigate fluid-rock interactions under supercritical conditions. In this thermal regime, a conductive boundary layer (CBL) should separate the magmatic source from the convective portion of the overlying hydrothermal system (Lowell and Germanovich, 1994). High temperature metamorphic rocks recrystallized in CBL's have now been identified in outcrops from ophiolites (Gillis, 2008) and in drill core from mid-oceanic ridges (Koepke et al., 2008).

In the spring of 2009, drilling of the IDDP-1 borehole in the Krafla geothermal area (Fig. 1) was terminated at a depth of 2.1 km when the drill string penetrated a silicic magma body (Elders et al., 2011). In addition to quenched rhyolitic glass, cuttings returned included those of crystalline felsic and mafic lithologies. Petrologic study of the cuttings directly above this rhyolitic intrusion in IDDP-1, as well as cuttings recovered from similar depths in well K-25 located ca. 100 m south (Gudmundsson et al., 2008), provides the basis for evaluating the nature of fluid-rock interactions in the CBL, constraining models of heat transfer in active geothermal systems, and better evaluating the potential for most efficiently harvesting magma energy.

2. Materials and methods

Drill cuttings from the bottom portions of IDDP-1 (depths between 2000 and 2070 m, as well as from 2100 m) and K-25 (depths between 2054 and 2104 m) were mounted on glass slides and doubly polished for electron microprobe analysis. Backscattered electron imaging (BSE) and mineral compositional analyses were performed at UC Davis using a Cameca SX-100 electron microprobe equipped with 5 spectrometers. Quantitative wavelength-dispersive analyses of pyroxenes, feldspars, oxides, and glasses were performed at 15 keV and 10 nA beam current using beam diameters of a 1–10 μm.

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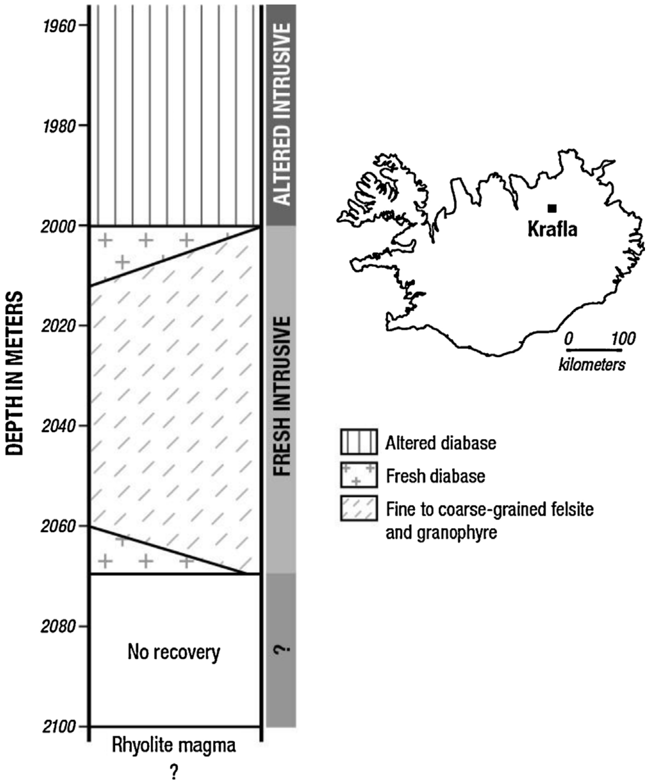

Fig. 1. Location map of the Krafla geothermal area and schematic lithologic column of the IDDP-1 borehole below 1960 m. The relationship between mafic and felsic intrusive lithologies between 2000 and 2070 m is not well constrained.

3. Results

3.1. The rhyolite magma

Quenched fragments of rhyolite magma were returned to the drill rig after penetration to a depth of ~2104 m following approximately 30 m of total circulation loss and no cutting returns. The initial samples included white pumice and some stretched vesicle pumice, but later the dominant fragments were mm size fragments of angular quenched brown, sparsely-phyric, poorly vesiculated rhyolite glass (Fig. 2). The rhyolite has high silica content (~75 wt%, Table 1), low TiO_2, is relatively dry with ~1.77 wt% H_2O, and has $\delta^{18}O$ and δD values of 3.1‰ and −121‰, respectively (Zierenberg et al., 2012; Elders et al., 2011). The rhyolite is compositionally and isotopically similar to rhyolites previously described from the Krafla caldera area (Jónasson, 1994; Swantesson and Kristmannsdóttir, 1978), and is interpreted to have formed by partial melting of hydrothermally altered basaltic rocks at depth within the Krafla rift zone (Jónasson, 1994; Elders et al., 2011; Zierenberg et al., 2012). Phenocrysts are typically present as less than 5 vol.% of the rock and include andesine plagioclase, augite, pigeonite, and titanomagnetite. Temperatures calculated from the compositions of co-existing augite–pigeonite range from 990 °C for phenocrysts cores to 890 °C for rim compositions (Zierenberg et al., 2012). Geochemical modeling of the crystallization of the melt suggest that the minimum in situ temperature is <850 °C (Zierenberg et al., 2012).

Table 1
Average composition of the rhyolite melt and the interstitial melt in the felsite determined by electron microprobe analysis of glass quenched by drilling fluids.

	Rhyolite glass	Felsite partial melt
SiO_2	74.99	76.29
Al_2O_3	11.79	11.57
TiO_2	0.32	0.21
Na_2O	3.72	3.52
K_2O	2.99	4.98
MgO	0.19	0.07
CaO	1.32	0.48
FeO	2.70	1.82
MnO	0.07	0.09
Total	98.07	99.03

3.2. Petrology of cuttings recovered above the rhyolite magma

Cuttings recovered ca. 80 m above the contact with the rhyolitic magma are mainly of fine to medium grained mafic, and fine to coarse-grained silicic, hypabyssal intrusive rocks (Fig. 3). The mafic rocks are exceedingly fresh and comprised of plagioclase, clinopyroxene, orthopyroxene, magnetite, and ilmenite. Some of the medium-grained mafic rocks contain small (<1 mm) pockets

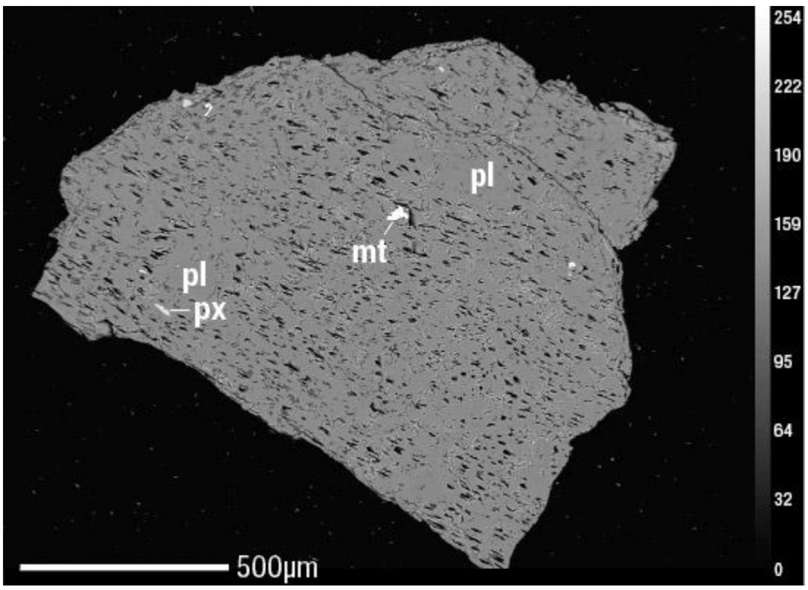

Fig. 2. BSE image of sparsely phyric rhyolite melt encountered at approximately 2100 m depth in IDDP-1 well and quenched to glass by drilling fluid. The high silica rhyolite (Table 1) is poorly vesiculated with phenocrysts of plagioclase (pl), pigeonite and augite (px), and titanomagnetite (mt).

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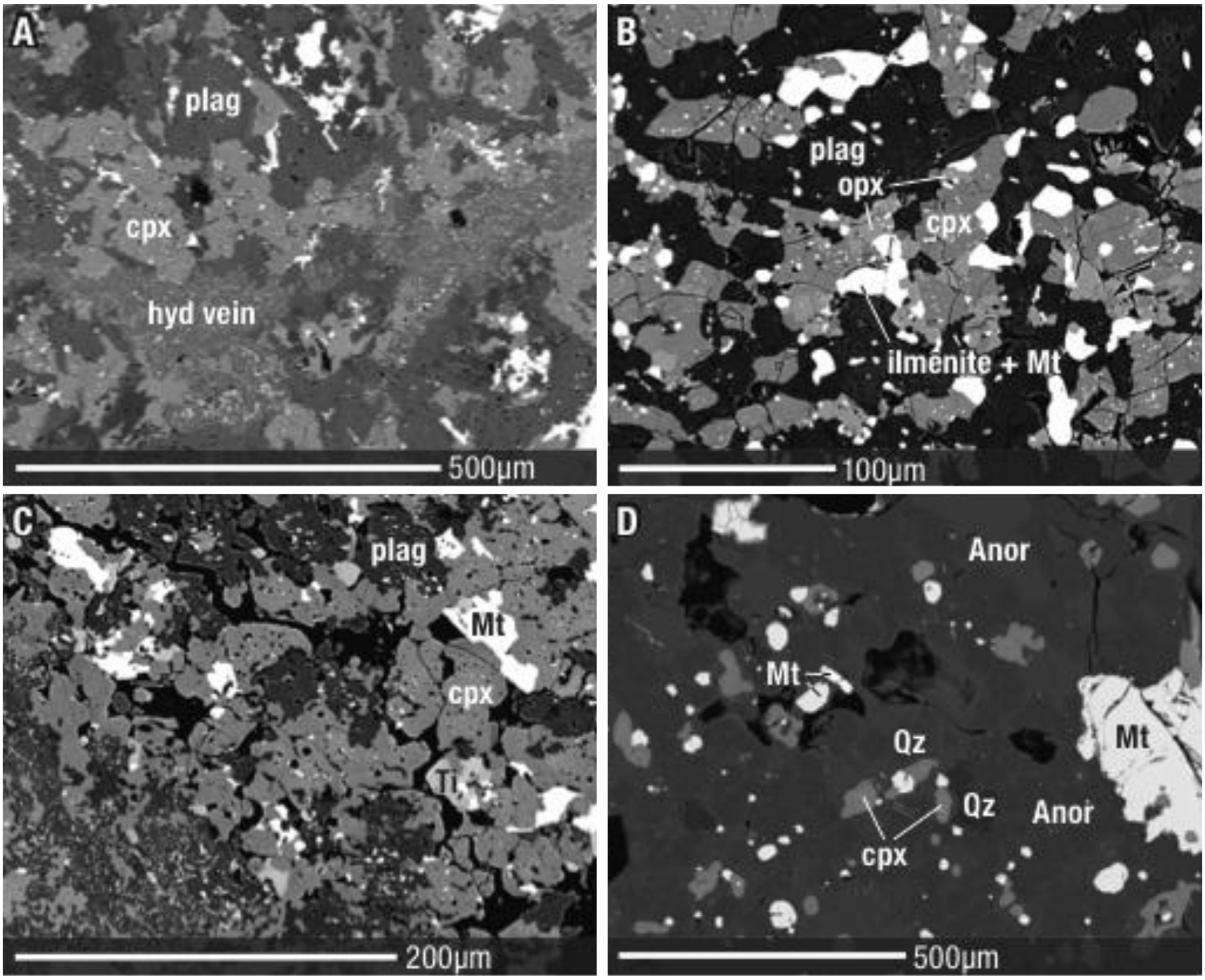

Fig. 3. Back-scattered electron micrographs of metamorphosed cuttings from IDDP-1 (a) diabase with clinopyroxene and plagioclase cut by a hydrothermal vein ("hyd vein") containing fine-grained clinopyroxene and anorthite (2044 m), (b) mafic granoblastic hornfels (2100 m), (c) partially recrystallized diabase with relict igneous texture on the right and finer hydrothermal texture on the lower left (2100 m); (d) felsic granoblastite (2100). Abbreviations: Plag, plagioclase; Cpx, clinopyroxene; Mt, magnetite; Anor, anorthoclase.

of late-stage potassium feldspar and quartz as well as veins of fine-grained, intergrown clinopyroxene, anorthite, and magnetite, presumably of hydrothermal origin (Fig. 3a). The silicic rocks – including unaltered granophyres and felsites – contain quartz, alkali feldspar, plagioclase, clinopyroxene, ilmenite, and magnetite. From inspection of cuttings alone, it is not possible to determine the temporal relationships between the mafic and silicic intrusions. Based upon the wide variation in grain size and textures, but general absence of hydrothermal alteration (relative to the greenschist grade alteration of diabasic rocks at depths above 2000 m), it seems likely that these cuttings represent an unknown number of recently emplaced small dikes and/or sills. The last cuttings of these "fresh" intrusive rocks were recovered from 2070 m, and no cuttings of any kind were recovered in the final 30 m before encountering the rhyolite magma.

Cuttings of very fresh-appearing, but generally very fine-grained mafic and silicic lithologies were recovered along with quenched rhyolitic magma at 2100 m. Based on the abundance of cuttings and the degree of interaction with the rhyolite melt, we infer that the melt was intruded into crystalline felsic rocks of approximately similar composition. High potassium values detected in geophysical logging of the hole support the interpretation that the melt was emplaced into felsic wall rocks (Gautason et al., 2010). Some fragments of felsite wall rock cuttings show textures and glass compositions indicating localize assimilation of the felsite wall rock into the rhyolite melt (Zierenberg et al., 2012).

Many of the felsite wall rock cuttings recovered from the bottom of the IDDP-1 well show signs of incipient melting, with the melt quenched to interstitial glass by the drilling fluid (Fig. 4a). A felsite cutting from 2104 m in KG-25 contains a vein of silicic melt, presumably derived from incipient, in situ melting of ultra-metamorphosed felsite, that was quenched to glass during drilling (Fig. 4b). Rounded and partially embayed xenocrysts of Fe-rich augite, quartz, anorthoclase, magnetite, and ilmenite (all generally <0.1 mm in diameter) occur within patches of glass and partially resorbed low Ca-alkali feldspar (Fig. 3d). Other fragments contain larger xenocrysts of anorthoclase coexisting with plagioclase (An 40–44; Fig. 5). These plagioclase crystals consistently contain higher K_2O contents than those of comparable An-contents in mafic rocks (Fig. 5). Interstitial pockets of quenched rhyolitic glass make up 5–10% of the mode in these felsites. This glass, which is compositionally distinct from the intrusive rhyolite magma (Fig. 6, Table 1),

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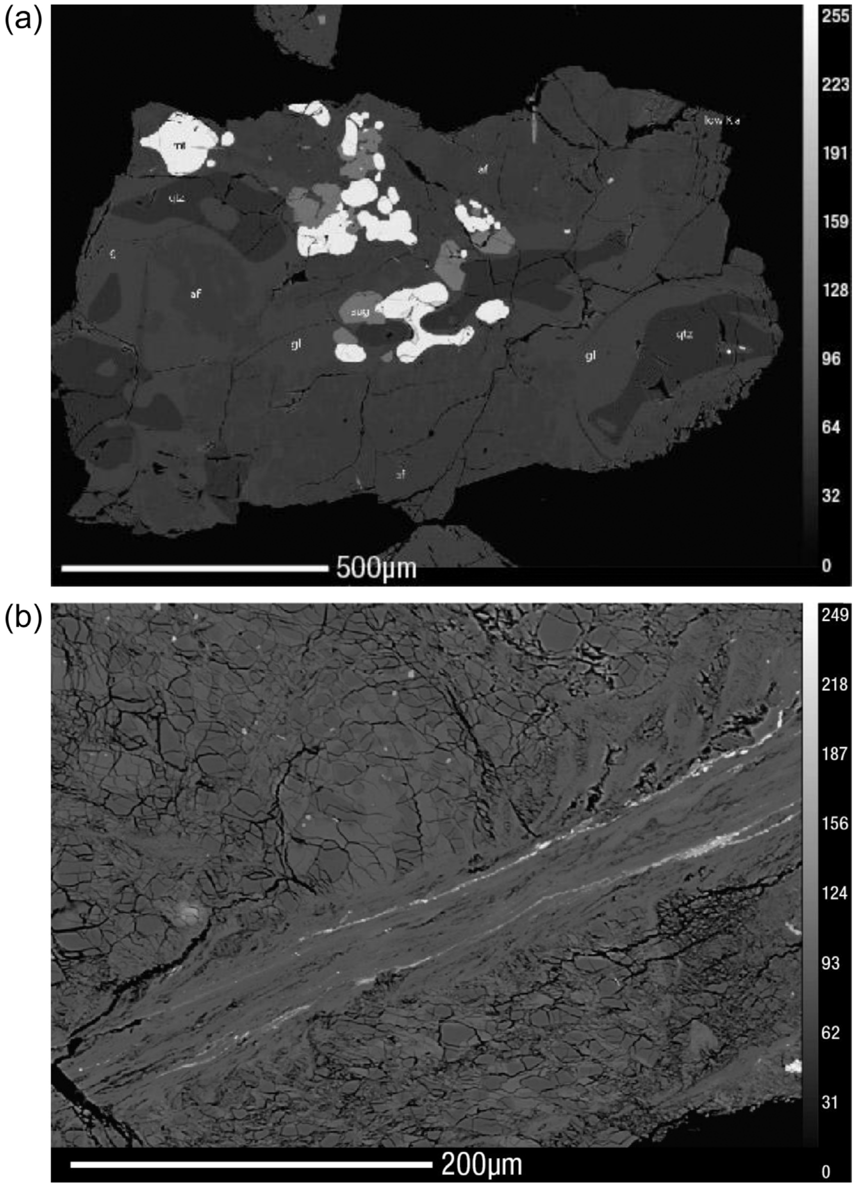

Fig. 4. BSE images of partially melted felsites. (a) Crystalline felsite from IDDP-1 with anorthoclase or a low K alkali feldspar (low K af), alkali feldspar (af), quartz (qtz), augite (aug) and titanomagnetite (mt). This is the host rock for the rhyolite melt which has undergone partial melting. Interstitial patches of glass (gl) have a composition similar to minimum melt in the granite system. (b) incipiently melted felsite from KG-25 (2104 m) contains a veinlet of rhyolitic melt apparently produced in situ and quenched during drilling (see text). The host rock to the melt vein is predominantly quartz (darker) and alkali feldspar (brighter).

is also close to a minimum melt in the granite system at 200 bars. This glass is also distinct from quenched silicic glasses recently described from Krafla well KJ39 (Mortensen et al., 2010) that are believed to be derived from partial melting of hydrothermally-altered mafic rocks.

Backscattered electron imaging (BSE) of the less abundant diabasic cuttings recovered with the rhyolite melt reveals that most mafic protoliths have recrystallized into distinctive granoblastic textures that have partially (Fig. 3b) to completely (Fig. 3c) overprinted the original igneous textures. Xenoblastic plagioclase (An 44–61; Fig. 5) and augite, both <0.1 mm in maximum dimension, are riddled with fine (<0.005 mm) inclusions of magnetite (Fig. 3b and c). Magnetite and ilmentite also occur as coarser idioblasts, some of which retain relict igneous compositional domains. Grains of xenoblastic hypersthene (<0.05 mm) occur within or immediately adjacent to the augite. Partially recrystallized samples exhibit wider ranges of grain sizes, including very fine-grained intergrowths of plagioclase and clinopyroxene that appear to be the remnants of much larger primary igneous grains (e.g., Fig. 3c, lower left).

3.3. Mineral thermometry

The thermal structure within the CBL was assessed using QUILF, the pyroxene and oxide geothermometer (Anderson et al., 1993), assuming an equilibration pressure of 200 bars. Temperatures (Fig. 7, Table 2) obtained from pairs of adjacent clinopyroxene and orthopyroxene grains in granoblastically-textured, mafic hornfels range from 810 (±17)°C to 954 (±43)°C. Attempts at pyroxene thermometry were not possible for the felsites since they do not contain co-existing orthopyroxene. Results of two oxide thermometry and oxybarometry indicate partly overlapping, but generally lower equilibration temperatures −615 (±14)°C to 778 (±33)°C – which presumably reflect the less texturally- and compositionally- equilibrated nature of magnetite and ilmenite in the cuttings from the CBL. Alternatively, the closure temperature of

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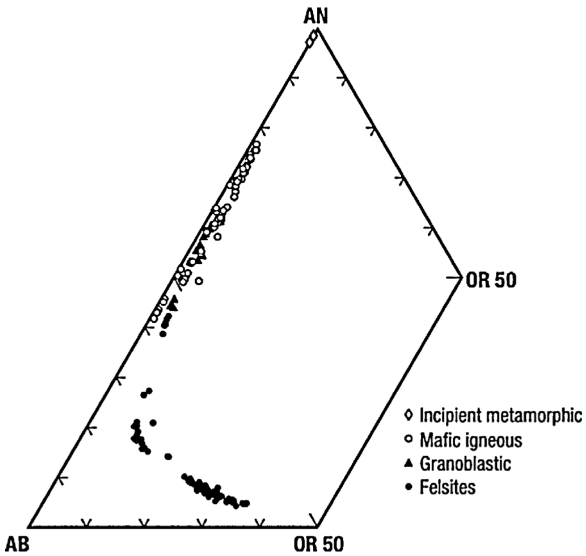

Fig. 5. Composition of feldspars from mafic and felsic rock cuttings recovered from IDDP-1.

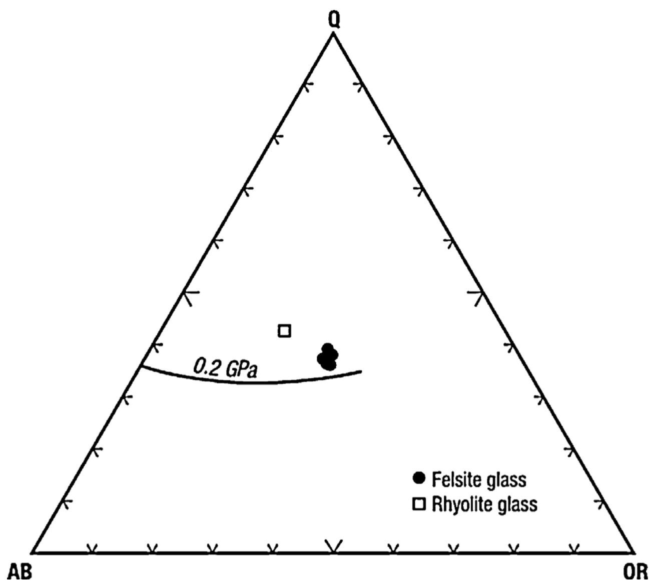

Fig. 6. Composition of glass in partially melted felsites as well as the average composition of rhyolite glass from IDDP-1 (Zierenberg et al., 2012). The former plots close to the 0.2 GPa cotectic curve for minimum melting in the system AB-AN-OR (after Winter, 2001).

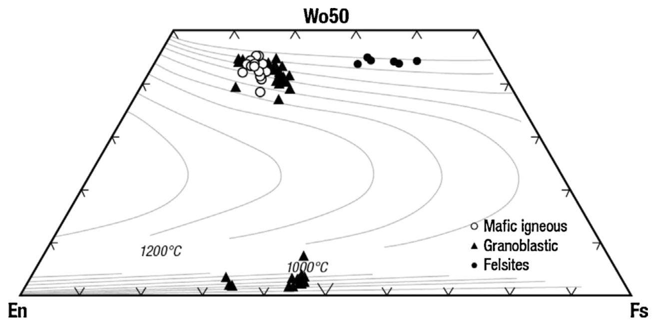

Fig. 7. Composition of pyroxenes from IDDP-1. Isotherms (Anderson et al., 1993) shown pertain to the mafic rocks only. The felsites do not contain coexisting orthopyroxenes.

Table 2
Mineral geothermometry of mafic hornfels in IDDP-1.

	2100–2003	2100–2005	2100–2006	2100–2013
Pyroxenes				
$X_{EN, cpx}$	0.36	0.37	0.37	0.37
$X_{WO, cpx}$	0.44	0.42	0.42	0.40
$X_{FS, cpx}$	0.20	0.21	0.21	0.14
$X_{EN, opx}$	0.55	0.52	0.53	0.54
$X_{WO, opx}$	0.02	0.03	0.03	0.03
$X_{FS, opx}$	0.43	0.45	0.45	0.43
T, °C	810	869	903	954
Uncertainty (°C)	17	13	38	43
Oxides				
$X_{NTi, Spinel}$	0.367	0.121	0.125	0.154
$X_{NMg, Spinel}$	0.037	0.024	0.027	0.023
$X_{NMn, Spinel}$	0.009	0.005	0.005	0.006
$X_{Hem, Ilmenite}$	0.080	0.094	0.059	0.044
$X_{Gk, Ilmenite}$	0.060	0.055	0.061	0.054
$X_{py, Ilmenite}$	0.013	0.010	0.011	0.015
T, °C	778	678	633	615
Uncertainty (°C)	33	28	32	14
log fO_2 (Δ to QFM)	0.38	1.79	0.80	−0.15

the magnetite–ilemenite thermometer may be lower than the two-pyroxene thermometer. This would imply some degree of cooling following peak metamorphism. The oxygen fugacities attending recrystallization of the mafic granoblastic hornfels ranged from near those of the quartz–fayalite–magnetite buffer to two log units more oxidizing (Table 2).

Surprisingly, no amphibole- or epidote-bearing mineral assemblages have been observed in cuttings of this mafic hornfels. However, since no cuttings at all were returned from depths between 2070 and 2100 m, it is not possible to determine if lower temperature (i.e., in the range 400–800 °C) mineral assemblages exist in that 30 m interval. Cuttings of mafic intrusive rocks recovered from 2070 m exhibit no significant reconstitution of their igneous textural or mineralogical properties. Rare hydrothermal veins (Fig. 4a) containing very fine-grained intergrowths of hydrothermal clinopyroxene and anorthite – the latter are the "incipient metamorphic" compositions plotted on Fig. 5 – imply that fluids of temperatures exceeding 400 °C (Marks et al., 2011) have flowed through small fractures in the mafic intrusive rocks at depths below 2070 m.

4. Discussion

4.1. Origin of the granoblastic conductive boundary layer above the IDDP-1 rhyolite intrusion

The high-temperature, granoblastic assemblages described above have clearly recrystallized in response to emplacement of the rhyolitic magma, but we can only speculate on the nature of these country rocks prior to the intrusion. Had these rocks been extensively altered prior to their high temperature metamorphism? A few lines of evidence argue that they were most likely unaltered, or at least not ubiquitously altered. Inspection of cuttings reveals no indication of extensive alteration of any of the lithologies at depths below 1900 m. Moreover, the metamorphic mineral assemblages identified in cuttings of the mafic granoblastic rocks all reflect essentially normal basaltic protoliths, and none indicate recrystallization of pre-existing hydrothermal veins which would for example recrystallize into Mg-rich and Si-poor mineral assemblages. Such cordierite-bearing assemblages observed in similar granoblastic assemblages from the Reykjanes geothermal system in SW Iceland, apparently represent recrystallization of earlier-formed chlorite–actinolite veins (Marks et al., 2011). Earlier reports on rock alteration at depth in the Krafla field (e.g., in well 4, Kristmannsdóttir, 1978; Kristmannsdóttir et al., 1976)

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have documented the occurrences of alteration minerals, specifically wollastonite, pyroxene, and garnet, presumed to be of contact metamorphic origin. In Krafla well 4, these mineral assemblages which occur adjacent to dike margins and over a large depth range (from ca. 700 to 2000 m), presumably reflect lower temperature metamorphism than the 2-pyroxene, granoblastic assemblages described here.

The redox conditions recorded by two oxide oxybarometers (Table 2) indicate that at least some of the mafic hornfels were metamorphosed under significantly more oxidizing conditions up to 2 log units above those of the quartz–fayalite–magnetite buffer typical for mafic igneous rocks (Bézos and Humler, 2005). The higher fO_2 recorded by the oxybarometry may reflect the recrystallization of some previously hydrated, epidote- (i.e., Fe^{3+}) bearing rocks. Nonetheless, in total, the available data imply that the CBL developed within presumably young and mostly unaltered, intrusive igneous rocks.

Have these country rocks that apparently constitute the CBL been heated to temperatures in excess of their solidus and thus produced some partial melt in situ?

Experimental studies indicate that at a pressure of 1 Kb, the first melt from a greenschist facies, hydrated basaltic starting material occurs at approximately 900 °C (Beard and Lofgren, 1991), and that this first melt is dioritic, not rhyolitic in composition. However, for an unaltered, "dry" basaltic protolith – such as the fresh intrusive rocks identified below 1900 m in IDDP-1 – solidus temperatures would generally exceed 1000 °C (Grapes, 2011). The granoblastic, mafic dikes described from the (relatively deeper) root zones of ophiolites and midoceanic ridges – in which pressures exceed 1 Kb – may have undergone small degrees of partial melting (France et al., 2010). However, unlike those from Krafla, the protoliths for these granoblastic dikes are hydrous metabasites. We see no textural evidence for partial melting of the mafic country rocks in IDDP-1, a finding consistent with the two pyroxene geothermometry indicating that temperatures did not exceed 950 °C. Conversely, the textural evidence (e.g., Fig. 4a and b) indicates that felsitic country rocks at Krafla have undergone partial melting at these same temperatures.

4.2. Constraints on the temperature regime and thickness of the conductive boundary layer

Unfortunately a constriction developed in the casing at a depth of 620 m while discharging the well 223 days after completion of drilling. This prevented temperature and pressure logging of the well below this constriction after it was allowed to come to thermal equilibrium after drilling. Therefore the following analysis uses temperature estimates derived from mineral geothermometers.

The identification of high temperature granoblastic hornfelsic rocks in cuttings recovered adjacent to the rhyolite magma confirms the presence of a CBL above this intrusion. The volatile content of the rhyolite glass implies that it quenched at temperatures between 760 °C and 990 °C, and mineral geothermometry suggests that pyroxene rims in the rhyolite equilibrated in the range of 890–910 °C (Elders et al., 2011). These temperature estimates overlap and exceed those (615–954 °C) recorded by pyroxenes and oxides in the granoblastic hornfels. These temperatures generally exceed that of the brittle–ductile transition for mafic rocks in the oceanic crust at a depth of 2.1 km (Hirth et al., 1998). Therefore the hornfelsic rocks would be incapable of sustaining a fracture network capable of allowing advective cooling, and thus heat transfer from the rhyolite magma through its roof would be mainly conductive.

Assuming a standard thermal conductivity (k) for the (mainly mafic) metamorphic rocks within the CBL (2.2 W/m K; Glassley, 2010), heat transfer (q) out of the rhyolite magma is mainly controlled by the (1) temperature gradient (ΔT) across, and (2) thickness (l) of, the CBL.

$$q = \frac{k\Delta T}{1}$$

We can estimate both a maximum and minimum thermal gradient across the CBL assuming a lower-most temperature of 400 °C based on hydrothermal veins of fine-grained anorthite and clinopyroxene found in cuttings from 2070 m. The temperature at the magmatic interface ranges from a maximum of 1000 °C to a minimum of 760 °C based on two pyroxene geothermometry as described above. Thus the thermal gradient across the CBL ranges from a maximum of 600° to a minimum of 340 °C. There are no data that delimit the minimum thickness of the CBL; the maximum thickness is on the order of 30 m, inasmuch as the cuttings recovered from 2070 m are unmetamorphosed. With these temperature constraints, and assuming a maximum thickness of 30 m, the heat flux across the CBL ranges from 25 to 44 W m^{-2}. These estimates are comparable to those – on the order of 20–30 W m^{-2} – for heat flow from mid-oceanic ridges at spreading rates > 30 mm/year (Chen and Phipps-Morgan, 1996).

4.3. Potential for geothermal energy production from high enthalpy fluids

Since the IDDP-1 borehole was drilled in spring, 2009, downhole temperatures have gradually recovered and in the fall of 2011, flow tests have produced super-heated steam at temperatures > 440 °C and a wellhead pressure of 137 bars, with yields of 12 kg/s yield (Friðleifsson et al., 2014). Preliminary modeling suggests that superheated steam discharged from IDDP-1 can be produced through heating of the fluid by the hot rocks within the permeable zone and that no direct contact to the magma is required (Axelsson, 2010). This single well is now believed to have the potential to produce up to 40 MW electrical power generation on its own. However, further testing and modeling will be necessary to determine whether recharge to this well is sufficient to maintain such output in the long term.

4.4. Conclusions

Petrologic study of drill cuttings from borehole IDDP-1 has provided the data necessary to constrain the temperature conditions at the interface between rhyolite magma and its host rocks. Coexisting clinopyroxene and orthopyroxene mineral pairs in mafic granoblastic rocks recovered at depths immediately above the rhyolite intrusion record equilibrium temperatures of 800–950 °C. These very high temperature metamorphic rocks constitute a conductive boundary layer for heat transport between the magma body and the overlying hydrothermal system. The heat flow across the boundary layer is calculated to be a minimum of 23 W m^{-2}. The size of the intrusive body and the extent of the conductive boundary layer above it are still unknown. Nonetheless, identification of the conductive boundary layer encountered at the bottom of the IDDP-1 borehole establishes the thermal "link" between rhyolite magma and the overlying hydrothermal system.

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