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Calcium-rich melt inclusions in Cr-spinels from Borgarhraun, northern Iceland

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Abstract

Two groups of primitive melts are observed as inclusions in Cr-spinels in a picrite (Fo_{88–92.4}) from northern Iceland. Group I inclusions have 12.2–13.8 wt% MgO, high CaO (14.6–15.8 wt%), low Al₂O₃ (10.1–11.8 wt%) and very high CaO/Al₂O₃ (1.3–1.5); they occur in spinels with a cr# between 0.63 and 0.70. Group II inclusions occur in spinels with slightly lower cr# (0.55–0.60) and they have 13.3–15.8 wt% MgO, 12.0–13.8 wt% CaO, 11.2–13.4 wt% Al₂O₃ and CaO/Al₂O₃ 0.9–1.1. Both groups have low concentrations of the incompatible minor elements (TiO₂, K₂O and P₂O₅) and relatively high SiO₂. The two groups converge at MgO approximately 10 wt%. A single inclusion in a low cr# spinel could represent a more evolved member (9.00 wt% MgO) of either group. Group I inclusions are on a clinopyroxene control line while Group II inclusions are close to being on an olivine control line. Groups I and II cannot be derived one from the other. They require high degree of melting from a refractory mantle source which probably is pyroxenitic to account for the high CaO. Melts with such high CaO/Al₂O₃ cannot be generated by melting commonly assumed lherzolites, so that pyroxenite or wehrlite mantle component is the suggested source. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: picrite; chrome spinel; inclusions; heterogeneity; pyroxenite

1. Introduction

When mantle melts are generated by polybaric fractional melting, it is inevitable that liquids with a large range of chemical composition will form. Another complexity is a possible heterogeneity in

the source mantle. Before these primary melts appear at the surface they will mix and evolve, making it difficult to identify the various contributing melt fractions.

Melt inclusions in minerals offer a unique way of catching melt samples during or before mixing. Such early-formed minerals have a better chance of surviving the final mixing processes than possible discrete liquid batches. However, with falling temperature, the included melts react with the host mineral and undergo some crystallization. Therefore they must be remelted and chilled to recover, as far as possible, the original melt com-

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position for analysis with microbeam instruments. This type of work has revealed that inclusions in olivine in Icelandic basalts and mid-ocean ridge basalts (MORBs) show a range of incompatible element concentrations exceeding those in the host lavas and that cannot result from liquid–olivine interaction [1,2]. This demonstrates that crystals do indeed pick up and preserve variable liquid compositions.

Another set of unusual inclusion compositions has been observed in MORB olivines [2] and plagioclases [3] with $\text{CaO}/\text{Al}_2\text{O}_3$ as high as 1.16 and in island arc samples up to 1.38 [4]. Such high ratios have not been recorded in aphyric natural rocks in either of these environments, and experimental evidence suggests that partial melting of a clinopyroxenitic mantle component would be needed [2,5].

Borgarhraun in North Iceland is an early Holocene lava that contains abundant crystals of olivine, chrome diopside and plagioclase, in addition to chrome-spinel found both as discrete microphenocrysts and as inclusions in olivine. The lava is a picrite and hence primitive olivine tholeiite, and should have suffered a minimum of crustal modification when compared with other Icelandic olivine tholeiites. Work has already been performed on inclusions in olivine, plagioclase and diopside in the lava [6,7] but in the present account work on inclusions in the chrome-spinels is reported. There are three distinct compositional groups of spinel found in a single sample from Borgarhraun, in addition to a fourth group which has been observed in other samples from the lava. Two of the spinel groups are of an unusual composition not previously recorded in Iceland, and inclusions in these spinels, when reheated and instantly chilled, have exceptionally high $\text{CaO}/\text{Al}_2\text{O}_3$. Before heating, the inclusions consist largely of crystallized clinopyroxene, and temperatures of 1320–1340°C were needed to melt all the daughter minerals in the inclusions.

Analyses of glass inclusions in the two types of unusual spinel likewise fall into two distinct groups, indicating that they were isolated inside the crystals before the two types of magma had an opportunity to mix. Therefore, the inclusions are probably close to being true samples of primary

melts. One of the groups of inclusions described here is ultracalcic, with up to 15.9 wt% CaO and $\text{CaO}/\text{Al}_2\text{O}_3 = 1.27\text{--}1.5$. Such compositions have for MORBs been ascribed to derivation from a clinopyroxene-rich component [2,3]. Various authors have suggested that the Earth's mantle, and mantle plumes in particular, are made of lherzolite streaked with pyroxenite, the latter being recycled oceanic crust [2,3,8,9]. The melting behavior of pyroxenite is not well known [9], but preliminary experiments on synthetic clinopyroxenite and wehrlite do suggest that after about 50% melting at 1 GPa pressure, a composition not unlike the present ultracalcic glasses is obtained. The temperature ($\sim 1375^\circ\text{C}$) required for generating the ultracalcic melt is high for being a likely explanation for ultracalcic inclusions in MORB [5,10].

2. Technical

Cr-spinel in the Borgarhraun picrite occurs both as discrete microphenocrysts and inclusions in olivine. To obtain enough suitable spinel grains, the sample was crushed and then boiled in a mixture of hydrofluoric and perchloric acids. When all the silicate phases had dissolved, the Cr-spinels were washed in boric acid. The heating was done in a heating stage (designed and built at the Vernadsky Institute in Moscow [11]) in helium atmosphere. In each experiment, from one up to 10 Cr-spinels were heated to a fixed temperature (1240, 1300, 1320, 1340 or 1360°C) and kept there for 10 min before they were quenched. Shorter and longer heating periods, from 5 to 30 min, had previously been found not to affect the results. Heated and unheated Cr-spinels were mounted in epoxy and ground and polished on a diamond compound to expose the inclusions. This technique is similar to that described by Kamenetsky [12]. The mineral and glass analyses were done with a recently updated ARL-SEM-Q microprobe with seven WDS spectrometers (four fixed on Si, Al, Fe and Ca and three scanners) using a fully focused beam at 15 kV and 15 nA sample current, with natural minerals and glasses as standards.

3. Sample description and whole-rock geochemistry

3.1. General

Sample NO 42, from which the crystals of chrome-spinel were separated, comes from Borgarhraun, a 35-km² picrite lava in N Iceland. It belongs to the Theistareykir volcanic system which is the northernmost of five such fissure swarms straddling the northern part of the plate boundary crossing Iceland from SW to NE (Fig. 1). Dominating the central part of the volcanic system is a large olivine tholeiite lava shield associated with the crater Stora-Viti. Like many such shields in Iceland, it formed in the early Holocene, which circumstance has been associated with decompression in the upper mantle due to isostatic rebound [13]. Broadly coeval with the shields are picrite lavas like Borgarhraun, which postdates the shield, and others nearby which are earlier than the shield, e.g. Höfudreidarmúli (TH29 in [14]).

Sample NO 42 contains approximately 5 vol% phenocrysts and 12.2 wt% MgO (Table 1), but other samples from the same lava flow extend up to 19 wt% MgO, mainly due to variable phenocryst content [7,14,15]. A chilled scoria sample from the crater area contains sideromelane glass

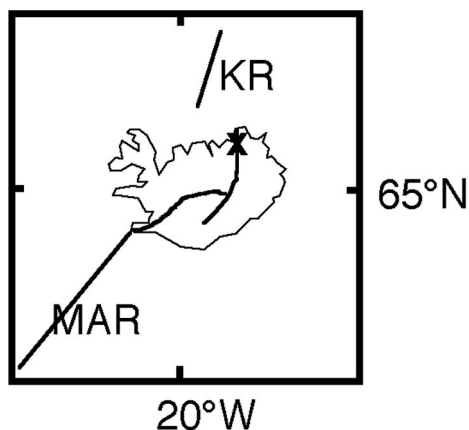


Fig. 1. Location map showing Iceland in relation to the North-Atlantic rift system. The location of Borgarhraun, at the north end of the Northern Rift Zone, is shown with a star. MAR and KR are the Mid-Atlantic and Kolbeinsey Ridges, respectively.

Table 1

Whole-rock and glass analyses from Borgarhraun, TH15 is from [14]

Sample #	NO 42	Glass	TH15
SiO ₂	48.33	48.00	46.34
TiO ₂	0.63	0.77	0.52
Al ₂ O ₃	14.78	15.70	11.75
FeO		9.30	
Fe ₂ O ₃	10.07		10.40
MnO	0.16	0.18	0.16
MgO	12.21	9.73	19.00
CaO	13.01	13.70	10.60
Na ₂ O	1.63	1.62	1.20
K ₂ O	0.06	0.04	0.12
P ₂ O ₅	0.07	0.09	0.14
LOI	−0.60		
Total	100.35	99.13	100.23
<i>Trace elements</i>			
Rb	1		0.87
Ba	15.5		
Sr	87.5		90
La	1.2		1.61
Ce	3.52		4.47
Pr			0.72
Nd	3.11		3.86
Sm	1.24		1.31
Eu	0.54		0.55
Gd			2
Tb	0.36		0.379
Ho	0.55		0.574
Er			1.74
Tm			0.252
Yb	1.37		1.65
Lu	0.21		0.246
Y	15.2		16
Th			0.076
U			0.027
Zr	26		33
Hf	0.86		
Nb	1.3		1.5
Sc	42.9		
V	231.7		245
Cr	645.4		820
Ni	274		

as groundmass, representing the liquid part of the magma, with 9.6 wt% MgO, which is but a little less than the most primitive liquid/glass composition found so far in Iceland. The incompatible-element concentration ratios are broadly similar to N-MORB (Fig. 2) but at lower absolute values. Although close in space and time, Borgarhraun and other lavas in the Theistareykir volcanic sys-

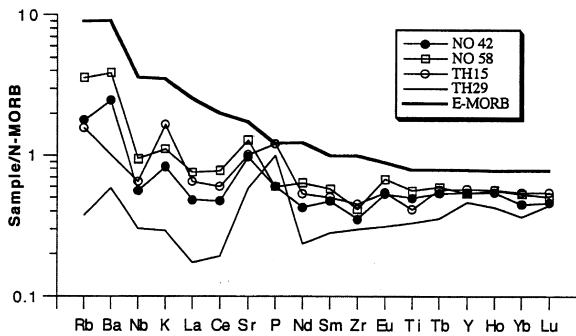


Fig. 2. N-MORB normalized trace element diagram. NO 42 and NO 58 are from [18] and TH15 and TH29 are from [14]. N-MORB and E-MORB values are taken from [24].

tem have significantly variable Sr, Nd, and Pb isotopic ratios [14–16].

Borgarhraun contains the most forsteritic olivines reported from Iceland [6,17,18]. The olivine population is bimodal: most common are compositions between $Fo_{92.4}$ and Fo_{90} but a smaller group has composition Fo_{88} to Fo_{90} . In addition to olivine and Cr-spinel, sample NO 42 (like other Borgarhraun samples) contains chromian endiopside and plagioclase (An_{83-90}). All phenocryst phases contain magmatic inclusions and all are notably unzoned except for normal zoning at the very outermost rim.

Minerals in a small xenolith from Borgarhraun, composed of olivine, clinopyroxene and plagioclase were analyzed. The olivines have compositions between Fo_{87} and Fo_{90} , coinciding with the smaller peak of the olivine population in the lava. The plagioclases in the xenolith are indistinguishable from the plagioclases in the lava but a small difference exists between the clinopyroxenes, with those in the xenoliths containing higher FeO and TiO_2 and lower Cr_2O_3 and mg#. No Cr-spinels were observed in the xenolith.

3.2. Cr-spinel

Thin sections of samples from Borgarhraun reveal that Cr-spinel occurs both as discrete euhedral microphenocrysts and as smaller inclusions in olivine. The single crystals analyzed from sample NO 42, however, were almost exclusively from the larger microphenocryst population, hand-picked

from the residue of oxides after dissolving the silicates in acid. The separated Cr-spinel divides clearly into three distinct groups (Fig. 3A). Group I has $cr\#$ ($Cr/Cr+Al$) above 0.6, Group II has $cr\#$ between 0.5 and 0.6, and Group III has $cr\#$ below 0.5. Many of the Cr-spinels have a thin rim with much lower mg# ($Mg/Mg+Fe$) but the same or slightly higher $cr\#$ (Fig. 3A). The NiO content is below 0.2 wt% in Group I but generally above

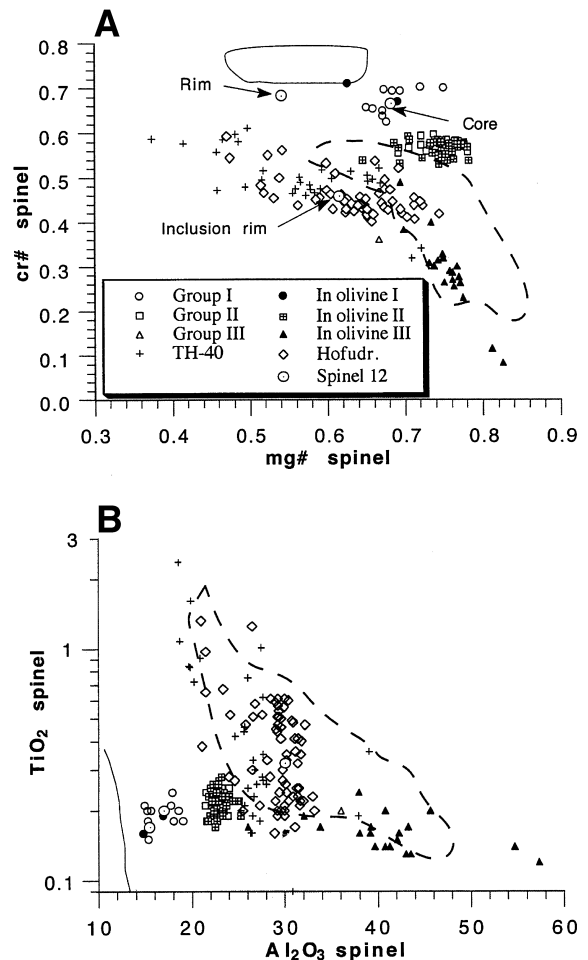


Fig. 3. Compositional variation of Cr-spinels from Borgarhraun. We have divided the Cr-spinels into three groups (I, II and III) based on their $cr\#$. Cr-spinel inclusions in olivine are grouped using the same criteria. Also shown are spinels from Höfudreidarmúli (Höfudr.) and the three compositions (Spinel 12) from Table 2. Continuous-drawn envelope is spinels in boninites from the Hunter Ridge–Hunter Fracture Zone [25]; dashed envelope is MORB-spinels [26,27].

0.2 wt% in Groups II and III (Table 3). Groups I and II both contain abundant melt inclusions but only one inclusion was found in Cr-spinel from Group III; that inclusion has a composition similar to the chilled glassy groundmass at the crater.

Cr-spinels analyzed in polished sections from other Borgarhraun samples (TH40), both as microphenocrysts and olivine inclusions, plot between Groups II and III but at lower mg# (Fig. 3A,B). This is either because smaller crystals, clearly visible under the microscope, were ignored and discharged after the acid digestion, or that sample NO 42 is not representative.

The presence of four groups of Cr-spinel in Borgarhraun, and three in a single sample, is clearly significant and either reflects xenocrystic origin for some of the spinels or, less likely, the preservation of stepwise earlier evolution of the Borgarhraun magma.

4. Melt inclusions

4.1. Unheated inclusions

All unheated inclusions contain a mixture of glass and crystals, mostly clinopyroxene which occupies up to 70% of the polished inclusion surface (Fig. 4B). Minor sulfide droplets were observed in several inclusions. Compositional profiles taken across unheated inclusions show that the clinopyroxenes have variable compositions, as expected from closed-system crystallization, with high TiO_2 , Cr_2O_3 and Na_2O content and low CaO content compared to the clinopyroxene phenocrysts in the lava. This is a strong indication that the pyroxenes are true daughter crystals but were not trapped together with the melt. The accompanying glass is highly variable and generally high in SiO_2 , Al_2O_3 and Na_2O and low in FeO , MgO and CaO (Table 2). A significant change in the Cr-spinel compositions is observed at the spinel/melt inclusion interface where Al_2O_3 increases markedly while Cr_2O_3 decreases (Table 2). This shows that crystallization of Cr-spinel continued on the inclusion walls after the inclusion was sealed off from the surrounding melt.

Mass balance calculations, using the observed

phases and interstitial glass in an unheated inclusion on one hand and heated glass inclusions on the other, gave a good fit for 76 wt% clinopyroxene, 19 wt% interstitial glass and 5 wt% spinel making up the composition of the heated inclusions.

4.2. Heated and quenched inclusions

At 1240°C, all the inclusions contain clinopyroxene together with the melt, and the largest in-

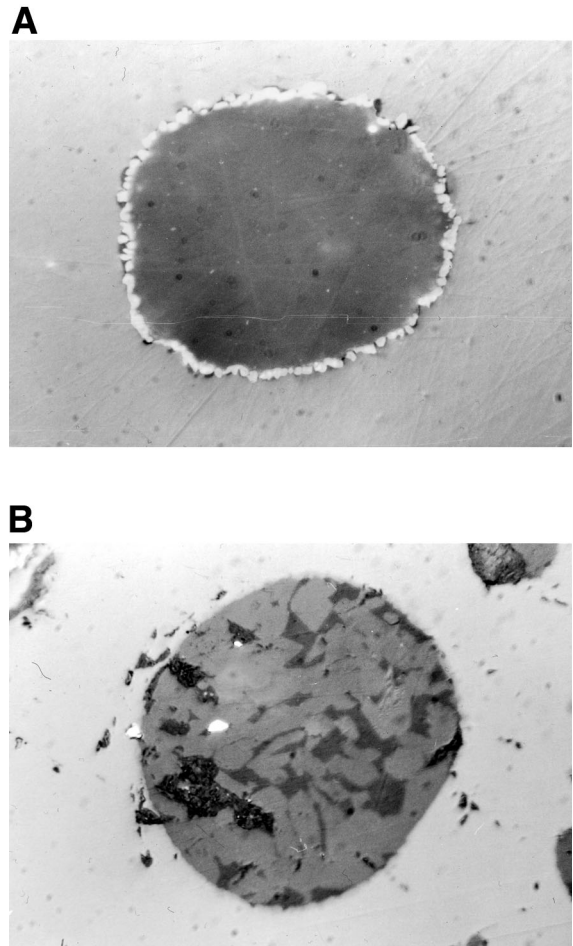


Fig. 4. (A) Melt inclusion in Cr-spinel (diameter 0.04 mm) quenched from 1360°C. Microprobe analyses across the thin light rim on the inclusion walls did not reveal any compositional difference. (B) Naturally quenched melt inclusion in Cr-spinel (diameter 0.06 mm). Pyroxene crystals (light gray) occupy over 70% of the surface. Also present in the inclusion are sulfides (bright) and glass (dark gray).

Table 2

Composition of unheated spinel (1), its outermost rim (2) and melt inclusion rim (3) that are shown in Fig. 3; Fe₂O₃ calculated assuming stoichiometry; (4) interstitial glass in unheated inclusion; (5) plagioclase in inclusion heated and quenched from 1240°C

Element	1	2	3	4	5
SiO ₂				59.87	52.51
TiO ₂	0.20	0.17	0.32	0.54	
Al ₂ O ₃	17.00	15.49	30.07	24.56	27.92
Fe ₂ O ₃	4.67	5.12	2.24		
FeO	12.04	16.74	15.54	3.05	
MnO	0.37	0.43	0.28	0.07	
Cr ₂ O ₃	50.60	49.76	37.91	0.47	0.67
MgO	14.48	11.08	13.95	0.94	
CaO				6.11	14.21
Na ₂ O				3.72	3.61
K ₂ O				0.1	0.02
NiO	0.14	0.12			
Total	99.50	98.91	100.30	99.43	98.94
mg#	0.682	0.541	0.615		
cr#	0.666	0.683	0.458		
X _{mt}	0.055	0.063	0.025		
Fe ²⁺ /Fe ³⁺	2.863	3.635	7.731		

clusion (125 × 30 μm) contains both clinopyroxene and plagioclase. At 1300°C, clinopyroxene is still present in the inclusions, and in two inclusions we observed additional low-Ca pyroxenes. A chemical profile taken across a pyroxene crystal shows a very complex zoning pattern indicating exsolution or incongruent melting. At 1320°C, some of the inclusions had a few small clinopyroxenes, and olivine (Fo₉₂) was seen in one inclusion, the only olivine we observed in a melt inclusion in spinel. Eight inclusions that were quenched from 1320°C contain glass with no silicate crystals observed. At 1340 and 1360°C, the inclusions consist of glass with no silicate crystals present. In some of the inclusions, the interface between the host and the inclusion is jagged, unlike what we have observed in olivine. Due to the stereometric effect of this jaggedness, a thin rim of spinel sometimes appears to have come loose from the spinel host (Fig. 4A). We could not obtain a clean analysis of this rim but it could be the remnants of the Al₂O₃-rich spinel rim that were observed in the unheated inclusions. However, a number of profiles analyzed across the interface did not reveal an increase in Al₂O₃ content. Shrinkage or gas

bubbles are always present in the quenched glasses at all temperatures. These temperatures (1320–1340°C) are significantly higher than what would be expected for the matrix glass and the less fosteritic olivines but more in line with what would be expected from the most fosteritic olivines [6].

With total melting at 1320, 1340 and 1360°C, individual glass inclusions are chemically homogeneous. The only exception is chromium that significantly increases towards the host spinel in all cases. Roeder and Reynolds [19] noticed that large Cr-spinel crystals interfered with their microprobe analyses of low-Cr₂O₃ glass because of secondary fluorescence from the spinel, leading to artificially higher concentrations. We repeated some glass analyses using lower sample current and/or defocused beam but got exactly the same results. This does not exclude analytical artifact but, if this high concentration was real, it would require exceptionally low oxygen fugacity for the basaltic inclusion to dissolve this much chromium, according to the Roeder and Reynolds' [19] experiments.

The major-element composition of representative melt inclusions is shown in Table 3. The two main notable features are (a) that there is no correlation between quench temperature and inclusion composition, and (b) that inclusions in Cr-spinel of Groups I and II have distinct compositional trends (Fig. 5). The difference between Group I and II inclusions is most striking in Al₂O₃ (10.3–12 wt% and 11.3–14.4 wt%, respectively) and CaO (14.8–15.9 wt% and 12.1–13.8 wt%) but it is also seen in SiO₂, TiO₂ and Na₂O. There is, however, complete overlap in FeO between the two groups and it is quite variable at a given MgO. Cr₂O₃ is problematic due to the analytical uncertainties. All the inclusions have very low concentrations of the minor and the most incompatible elements, TiO₂, P₂O₅ and K₂O, and the latter two are in effect below the detection limit. Group I has exceptionally high CaO/Al₂O₃ (1.27–1.5) and this ratio is also high in Group II (0.87–1.13) compared to Group III (0.82), the natural host glass (0.85–0.88), and melt inclusions in Cr-spinels from the Reykjanes Peninsula (0.77–0.98, our unpublished data). Group I

glasses appear to be on a clinopyroxene control line whereas Group II is closer to being on an olivine control line. The single inclusion belonging to Group III Cr-spinel is similar to the host glass.

5. Discussion and conclusions

5.1. *Glass inclusions as primary melts*

Fundamental to this type of study is the question how truly the reconstructed melt inclusions represent original melt composition. This is especially important in view of the fact that the reconstructed melt inclusions in Cr-spinel have a significantly different composition from whole-rock and glass compositions observed in the present-day Icelandic rift zones. Therefore they represent liquids far removed from any known lavas, but a similar trend has also been observed in MORB olivine inclusions [2] (e.g. Fig. 5g).

The composition of spinels is highly sensitive to the environment in which they form, particularly the composition of their parent magma [20]. The three groups of Cr-spinel in sample NO 42 (Fig. 3), and the fourth group found elsewhere in Borgarhraun, must represent different liquid compositions. That three of the groups are observed in a single fist-sized sample suggests that the crystals are unrelated xenocrysts or derive from small magma batches picked up by the host magma shortly before or during ascent. The unusual spinel compositions of Groups I and II call for unusual magma compositions. Group III, and the spinel analyzed in thin sections from Borgarhraun, represents compositions commonly found in Icelandic primitive lavas.

5.2. *Post-entrapment modification and reconstruction*

Post-entrapment modification of melt inclusions in minerals can be in situ crystallization, and diffusion of chemical species into or out of the liquid inclusion. The most likely effect is host crystallization at the crystal–liquid interface. One rationale for working on inclusions in Cr-spinel is

that the very low Cr content of the trapped melt would prevent significant Cr-spinel crystallization [12]. Analytical profiles on the Cr-spinel/glass contact in unheated inclusions did, however, show a fractionated Cr-spinel composition (Table 2). At the maximum temperature of reheating, a thin lining is still occasionally observed optically (Fig. 4A), but microprobe profiles across the interface only revealed homogeneous Cr-spinel and glass. A 5 wt% spinel lining remaining after heating would be too thin to be detected, and would result in an insignificant increase in CaO/Al₂O₃ despite slightly higher SiO₂ and CaO and lower FeO and Al₂O₃ relative to the originally trapped melt. MgO would not be affected (Table 2). The reverse would be the case for host-mineral melting. The observed lack of variation in glass composition with heating temperature shows that this is not a major problem.

The case of diffusion is more difficult to evaluate as much depends on the temperature history of the host mineral subsequent to entrapment. If the crystal is kept at high temperatures for an extended time, and possibly in liquids with different composition from the original one, then diffusion of elements common to the mineral and magma will take place. Studies of inclusions in olivine show that diffusion of this type will cause changes in Mg, and especially a decrease in Fe, that are not reconstituted by heating (e.g. [6]). We note that reheated incompatible-element enriched melt inclusions in spinel from Thjórsárdalur in South Iceland (our unpublished analyses) do not show this low FeO content, indicating that low FeO is a primary characteristic associated with depletion in incompatible elements, as in NO 42.

Group I and II spinels were found both as small phenocrysts (left after acid digestion) and as inclusions in unheated olivine crystals. Being sealed within an olivine envelope prevents diffusion of elements incompatible to olivine due to changing the composition of the host magma, even at high temperatures. It also shows that olivine was crystallizing together with spinel in the host magma. This, and the absence of zoning in both spinel and olivine, suggests that no significant modification of the inclusions has occurred. Only one inclusion was found in the Group III

spinel. The composition of this inclusion is broadly similar to the matrix glass (Fig. 5 and Table 3). This supports the view of successful reconstruction although we note slightly lower FeO in the reconstructed inclusion compared to the matrix glass.

5.3. Reconstructed melt inclusions

The composition of the reconstructed melt inclusions is different from any whole-rock or glass composition (hyaloclastite or pillow rim) observed in the Icelandic rift system. Furthermore, the MgO content of the heated inclusions (12–16 wt%) is higher than that found in any matrix glass and whole-rock analyses of aphyric samples; only in the case of very olivine-phyric rocks like Borgarhraun does MgO exceed 12 wt%. Work on other Icelandic picrites, using a similar extraction method, has not revealed spinels similar to Group I and II spinels, which remain unique in Iceland. The concentration of incompatible elements like Ti and Na in the Borgarhraun inclusions is lower than observed in any lavas, and K and P are below or at the microprobe detection limit. If these are actual melt compositions – and it is difficult to see how any post-entrapment process could decrease the incompatible-element concentration in the inclusions – they reflect a highly refractory source.

For comparison, we plot in Fig. 5 two whole-rock analyses from Borgarhraun – mainly reflecting different olivine content – matrix glass and clinopyroxene phenocrysts from Borgarhraun, and matrix glasses from the neighboring Höfudreidarmúli. Fig. 5 also includes some experimentally generated melt compositions and glass inclusions in MORB olivine from the literature [2,5,23]. The Group I and II inclusions are clearly different from the matrix glasses and whole-rock analyses although both seem to converge with decreasing MgO towards the glasses and whole-rock for the major elements. Group I is the more exotic, having exceptionally high CaO/Al₂O₃ ratios and extending towards the clinopyroxene compositions. Group II on the other hand plots largely between the two Borgarhraun whole-rock analyses, indicating mainly olivine control. Prim-

itive magma represented by the melt inclusions could fractionate towards the Höfudreidarmúli composition (and hence the commonly observed whole-rock characteristics) except that the incompatible elements would still be far too low for such a fractionation to work. The unusual composition of the spinels containing the two inclusion groups supports the interpretation that whereas the melts from which they crystallized are real, they do not make it to the surface in significant quantities, mixing instead in small amounts into more evolved and incompatible-element-rich melts.

The trend of Group I inclusions towards clinopyroxene could be explained by chrome diopside assimilation, as has been suggested for primitive (MgO = 8–10 wt%) high-CaO/Al₂O₃ melts from the Hengill area in Southwest Iceland [21], which would also help to explain the formation of high *cr#* spinel similar to Group I [22]. The clear separation between the two inclusion groups at higher MgO would, however, not be expected if assimilation of clinopyroxene was responsible. If the two well separated groups (I and II) are indeed genuine, they converge toward 9–10 wt% MgO, either after extensive fractionation of clinopyroxene and olivine, or by mixing with the more common Theistareykir magma as represented by the Höfudreidarmúli matrix glass.

5.4. Heterogeneous mantle

Very depleted magmas like Groups I and II must be generated by very extensive melting, or from a refractory source from which melts had already been extracted. However, refractory lherzolite or harzburgite cannot yield melt composition like Group I inclusions at any pressure or temperature [23]. This circumstance has, for inclusions with unusually high CaO/Al₂O₃, led to suggestions of pyroxenite melting to account for the high CaO content [2]. Hirschmann and Stolper [9] made a case for the melting of garnet pyroxenite to explain garnet signature in MORB but, as this would start melting before the peridotite, it would not account for the refractory and depleted characteristics of the melt inclusions. Kamenetsky et al. [2] reported CaO-rich melt inclusions (CaO/

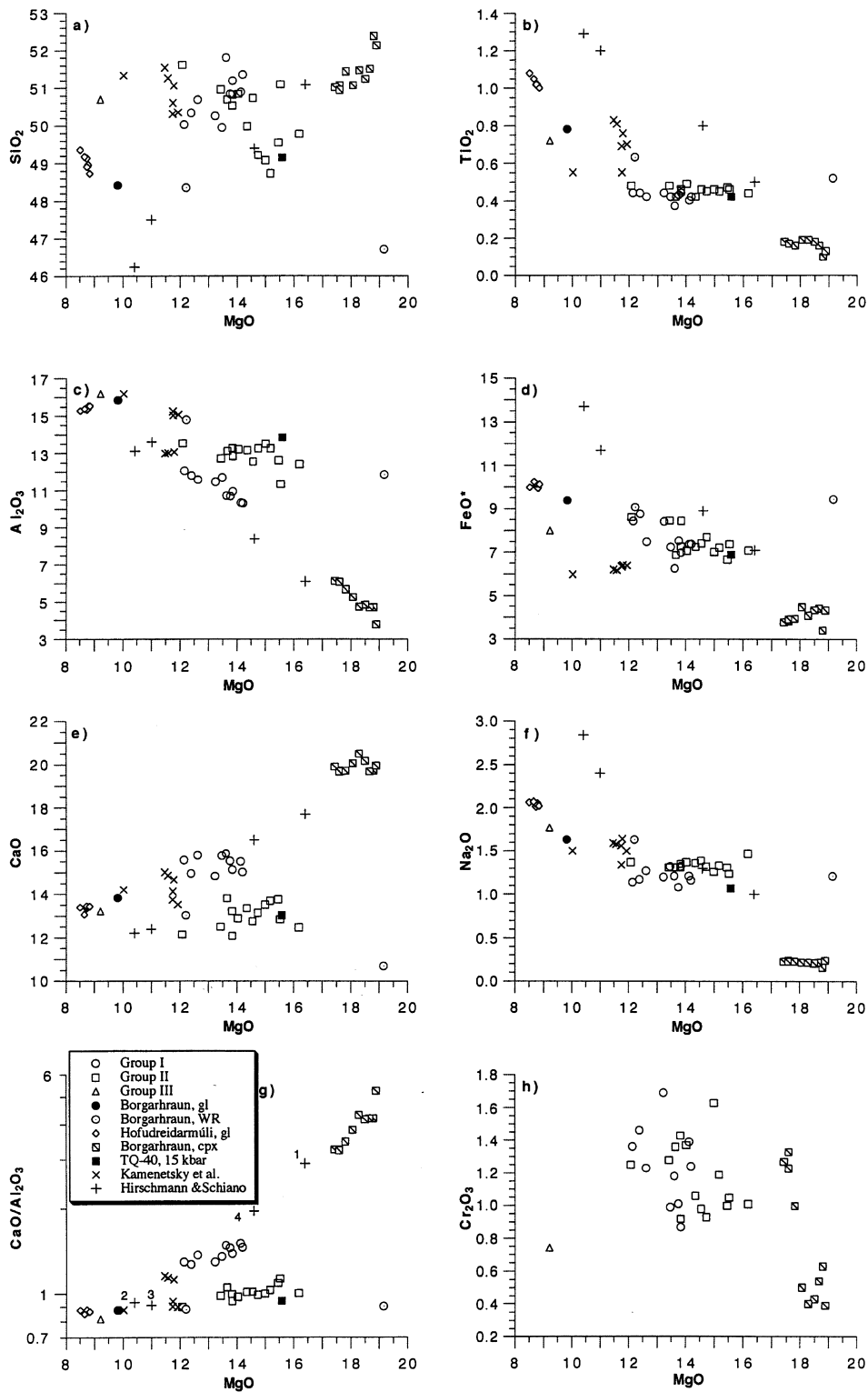


Fig. 5. Major-element compositions of inclusions from the three spinel groups. Also shown are a calculated primary melt composition and a single inclusion in spinel from Borgarhraun [6], glass analyses from Borgarhraun and Höfudreidarmúli, the two whole-rock analyses from Table 1, clinopyroxenes from Borgarhraun, melt inclusions in olivine from the Mid-Atlantic Ridge [2], and experimental melt compositions from Tinaquillo lherzolite – 40% olivine [23] and synthetic pyroxenite [5]. The numbers in (g) refer to analyses in [5]: 1 is original composition, 2 is 21% melt, 3 is 30% melt, and 4 is 69% melt.

$\text{Al}_2\text{O}_3 = 0.8\text{--}1.2$) in primitive olivine in MORB, with compositions that appear to fall in the gap between the Borgarhraun melt inclusions and the matrix glasses (Fig. 5). Primitive CaO-rich melts are also present in some island arcs, both as inclusions and whole-rock compositions, but these melts are silica-undersaturated unlike the MORB and Borgarhraun inclusions [4]. To explain the high CaO content and often high $\text{CaO}/\text{Al}_2\text{O}_3$ in these melts, the above authors have proposed pyroxenite melting. Melting of magnesian clinopyroxenite or wehrlite veins in peridotite would explain the major-element characteristics, and the melting could be delayed until even after the clinopyroxene had been exhausted from the main peridotite source. Only preliminary experiments on clinopyroxenite and wehrlite (75% cpx+25% olivine) at 1 Gpa are available (Fig. 5). The pyroxenite did produce high-CaO liquids at temperatures over 1350°C and more than 30% melting [5]. The wehrlite produced melts that are reported to be similar to the inclusions in MORB and Borgarhraun in major elements at 1375°C and at high melt fractions [10]. A primary melt composition in equilibrium with the most fosteritic Borgarhraun olivine ($\text{Fo}_{92.2}$) has the calculated liquidus temperature of 1325°C [6].

An isotopically heterogeneous mantle has been proposed to explain variations observed among Icelandic basalts [14]. Nearly contemporaneous lavas erupted in the vicinity of Borgarhraun show significant isotopic variation in Sr, Nd and Pb. The picrites of Höfudreidarmúli (TH29) have MORB-like radiogenic isotopic ratios whereas Borgarhraun (TH15) is more enriched, and other lavas are even higher and closer to what is commonly found in Northern Rift Zone tholeiites [14]. There is a general relationship between the radiogenic isotopic ratios and the incompatible content of the lavas, indicating that at least some of the compositional characteristics are

source-related and do not only reflect processes of melting and fractionation.

5.5. Conclusions

Sample NO 42 from the Borgarhraun picrite contains two groups of chrome-spinel with very unusual composition, both as microphenocrysts and inclusions in olivine. The microphenocrysts contain abundant melt inclusions that on reheating have a melt composition unlike any basalts in Iceland or MORBs. They are characterized by a high $\text{CaO}/\text{Al}_2\text{O}_3$ ratio.

This composition is unlikely to result from melting of commonly assumed garnet lherzolite mantle compositions, either by extensive melting or melting of residual harzburgite. The high CaO suggests that these melts result from melting of pyroxenite or wehrlitic mantle. Mantle heterogeneity in the Borgarhraun area is already demonstrated from radiogenic isotopes.

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References

- [1] A.A. Gurenko, M. Chaussidon, Enriched and depleted primitive melts included in olivine from Icelandic tholei-

- ites: Origin by continuous melting of a single mantle column, *Geochim. Cosmochim. Acta* 59 (1994) 2905–2917.
- [2] V.S. Kamenetsky, S.E. Eggins, A.J. Crawford, D.H. Green, M. Gasparon, T.J. Falloon, Calcic melt inclusions in primitive olivine at 43°N MAR: evidence for melt-rock reaction/melting involving clinopyroxene-rich lithologies during MORB generation, *Earth Planet. Sci. Lett.* 160 (1998) 115–132.
- [3] R. Sours-Page, K.T.M. Johnson, R.L. Nielsen, J.L. Karsten, Local and regional variation of MORB parent magmas: evidence from melt inclusions from the Endeavour Segment of the Juan de Fuca Ridge, *Contrib. Mineral. Petrol.* 134 (1999) 342–363.
- [4] P. Schiano, J.M. Eiler, I.D. Hutcheon, E.M. Stolper, Primitive CaO-rich, silica-undersaturated melts in island arcs: Evidence for the involvement of clinopyroxene-rich lithologies in the petrogenesis of arc magmas, *Geochim. Geophys. Geosyst.* 1 (2000) Paper number 1999GC000032.
- [5] M. Hirschmann, P. Schiano, Experimental study of partial melts of clinopyroxenite and the origin of ultra-calcic melt inclusions (abstract), Ninth Annual International Goldschmidt Conference, Cambridge, MA, 1999.
- [6] A.A. Gurenko, A.V. Sobolev, A.I. Polyakov, N.N. Kononkova, Primary melt of rift tholeiites of Iceland: composition and conditions of crystallization, *Trans. (Doklady) USSR Acad. Sci.* 301 (1988) 109–113.
- [7] L. Slater, Melt generation beneath Iceland, Ph.D. thesis, University of Cambridge, 1996.
- [8] A.W. Hofmann, W.M. White, Mantle plumes from ancient oceanic crust, *Earth Planet. Sci. Lett.* 57 (1982) 421–436.
- [9] M.M. Hirschmann, E.M. Stolper, A possible role for garnet pyroxenite in the origin of the ‘garnet signature’ in MORB, *Contrib. Mineral. Petrol.* 124 (1996) 185–208.
- [10] T. Kogiso, M.M. Hirschmann, Partial melting experiments of wehrlite and the origin of CaO-rich melt inclusions (abstract), *Am. Geophys. Union, Spring Meeting*, 2000.
- [11] A.V. Sobolev, L.V. Dmitriev, V.L. Barsukov, V.N. Nesorov, A.V. Slutsky, The formation conditions of the high-magnesium olivines from the monomineralic fraction of Luna 24 regolith, *Proc. 11th Lunar Planet. Sci. Conf.* 1 (1980) 105–116.
- [12] V.S. Kamenetsky, Methodology for the study of melt inclusions in Cr-spinel, and implications for parental melts of MORB from FAMOUS area, *Earth Planet. Sci. Lett.* 142 (1996) 479–486.
- [13] M. Jull, D. McKenzie, The effect of deglaciation on mantle melting beneath Iceland, *J. Geophys. Res.* 101 (1996) 21815–21828.
- [14] C. Hemond, N.T. Arndt, U. Lichtenstein, A.W. Hofmann, N. Oskarsson, S. Steinthorsson, The heterogeneous Iceland plume: Nd–Sr–O isotopes and trace element constraints, *J. Geophys. Res.* 98 (1993) 15833–15850.
- [15] T. Elliott, C.J. Hawkesworth, K. Grönvold, Dynamic melting of the Iceland plume, *Nature* 351 (1991) 201–206.
- [16] R.K. O’Nions, R.J. Pankhurst, K. Grönvold, Nature and development of basalt magma sources beneath Iceland and the Reykjanes Ridge, *J. Petrol.* 17 (1976) 315–338.
- [17] A.A. Gurenko, A.V. Sobolev, N.N. Kononkova, New petrological data on Icelandic rift alkali basalts, *Geochim. Int.* 29 (1992) 41–53.
- [18] I.A. Sigurdsson, Primitive magmas in convergent margins and at oceanic spreading ridges: evidence from early formed phenocryst phases and their melt inclusions, Ph.D. thesis, University of Tasmania, 1994.
- [19] P.L. Roeder, I. Reynolds, Crystallization of chromite and chromium solubility in basaltic melts, *J. Petrol.* 32 (1991) 909–934.
- [20] T.N. Irvine, Chromian spinel as a petrogenetic indicator. Part 2. Petrologic applications, *Can. J. Earth Sci.* 4 (1967) 71–103.
- [21] R.G. Trønnes, Basaltic melt evolution of the Hengill volcanic system, SW Iceland, and evidence for clinopyroxene assimilation in primitive tholeiitic magmas, *J. Geophys. Res.* 95 (1990) 15893–15910.
- [22] J.H. Bédard, R. Hébert, Formation of chromitites by assimilation of crustal pyroxenite and gabbros into peridotitic intrusions: North Arm Mountain massif, Bay of Islands ophiolite, Newfoundland, Canada, *J. Geophys. Res.* 103 (1998) 5165–5184.
- [23] T.J. Falloon, D.H. Green, Anhydrous partial melting of peridotite from 8 to 35 kb and the petrogenesis of MORB, *J. Petrol. Spec. Lithosphere Issue* (1988) 379–414.
- [24] S.S. Sun, W.F. McDonough, Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes, in: *Magmatism in the Ocean Basins*, *Geol. Soc. London Spec. Publ.* 42, 1989, pp. 313–345.
- [25] I.A. Sigurdsson, V.S. Kamenetsky, A.J. Crawford, S.M. Eggins, S.K. Zlobin, Primitive island arc and oceanic lavas from the Hunter Ridge–Hunter Fracture Zone. Evidence from glass, olivine and spinel compositions, *Mineral. Petrol.* 47 (1993) 149–169.
- [26] H. Sigurdsson, J.-G. Schilling, Spinels in Mid-Atlantic Ridge basalts: chemistry and occurrence, *Earth Planet. Sci. Lett.* 29 (1976) 7–20.
- [27] J.F. Allan, R.O. Sack, R. Batiza, Cr-rich spinels as petrogenetic indicators: MORB-type lavas from the Lamont seamount chain, eastern Pacific, *Am. Mineral.* 73 (1988) 741–753.