Origin of macrocrysts and gabbro-nodules in Hengill, SW Iceland

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90 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Geology

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Abstract

A number of lava flows in Iceland contain large plagioclase phenocrysts and some contain abundant olivines (picrites). The origin of these macrocrysts and their relationship to their host magmas are of fundamental petrologic importance.

Two separate pillow/hyaloclastite formations, Maelifell and Midfell, in the Hengill Central Volcano in SW Iceland contain macrocrysts (large phenocrysts) of olivine, plagioclase and clinopyroxene and gabbro nodules with the same mineralogy. The composition of the macrophenocrysts and the gabbro minerals are similar and within a relatively narrow range. These are embedded in a primitive basalt matrix, best represented in pillow-rim glasses. Closely adjacent is the highly plagioclase porphyritic formation of Sandfell also included in the present study.

Strontium isotope ratios, $^{87}Sr/^{86}Sr$, are easily measurable in the glasses and there is also enough Sr in the plagioclase macrophenocrysts so that $^{87}Sr/^{86}Sr$ can be measured with the same precision in individual crystals. Sr isotopic ratios were measured in two sample sets, macrocrysts and plagioclase from the gabbros. The results were compared with $^{87}Sr/^{86}Sr$ ratios from the pillow rim glasses, previously published by Magna et al. (2011). For Sandfell only plagioclase was included as it has no nodules.

The long half-life of ^{87}Rb, parental to ^{87}Sr, and the low abundance of Rb in Icelandic basalts means that any differences in $^{87}Sr/^{86}Sr$ detected should be a long term one and not related to or caused by any recent petrologic processes but reflecting different mantle differences.

The resulting data show that the glasses are significantly different from both the macrocrysts and gabbro plagioclases. The plagioclase macrocysts and the gabbro show no significant difference. The main conclusion is therefore that the macrocrysts and host magma are genetically unrelated.

The $^{87}Sr/^{86}Sr$ ratios of the xenoliths and megacrysts resemble the average crustal ratios of the Reykjanes Peninsula ($^{87}Sr/^{86}Sr$ = 0.703099-0.703164). Their origins are most likely from deep intrusions of olivine-tholeiite at the base of the crust.

Their carrying magmas have a more primitive isotopic signature ($^{87}Sr/^{86}Sr$ = 0.703007-0.703089). They are a collection of melt aggregates from a dynamic melting column in the upwelling mantle beneath Iceland.

Útdráttur

Á Íslandi eru hraun sem innihalda stóra plagíóklasdíla algeng. Sum þeirra eru einnig auðug af ólivíndílum og flokkast sem pikrít. Uppruni þessara díla og samband þeirra við burðarkvikuna er grundvallar-atriði til að skilja bergfræðileg ferli í möttli og skorpu.

Tveir aðskildir móbergshryggir í Hengils-kerfinu, Mælifell og Miðfell innihalda stóra ólivín-, plagíóklas- og klínópýroxendíla. Í þeim finnast einnig gabbró-hnyðlingar með sömu steindir og finnast sem stórdílar. Efnafræðileg samsetning stórdílanna og steindanna úr hnyðlingunum er einnig mjög svipuð. Frumstæð basalt-burðarkvika flutti steindirnar upp á yfirborð. Glerjaðir bólstrabergsrimar endurspegla best samsetningu burðarkvikunnar á þeim tíma sem hún gaus. Sandfell, sem liggur upp við Mælifell, inniheldur mikið magn af plagíóklas-stórdílum. Þessir þrír hryggir, Miðfell, Mælifell og Sandfell, eru til rannsóknar í þessu verkefni.

Strontínhlutföll $^{87}Sr/^{86}Sr$ eru auðmæld í gleri og það er einnig er nægilegt Sr í plagíóklasi til að hægt sé að mæla $^{87}Sr/^{86}Sr$ hlutföll í einstökum stórdílum. $^{87}Sr/^{86}Sr$ hlutföll voru mæld í plagíóklas-stórdílum og plagíóklasi úr gabbró-hnyðlingum. Niðurstöðurnar voru bornar saman við mælingar úr bólstrabergs-rimum sem hafa áður verið birtar af Magna et al. (2011). Þar sem engir hnyðlingar finnast í Sandfelli voru einungis mæld $^{87}Sr/^{86}Sr$ hlutföll í plagíóklas-dílum.

Langur helmingunartími ^{87}Rb, móðurefnis ^{87}Sr, og lágur styrkur þess í íslensku basalti leiðir til þess að allur munur á $^{87}Sr/^{86}Sr$ hlutföllum sé ævaforn og verði ekki skýrður með neinum bergfræðilegum ferlum, heldur skýrist hann af mismunandi $^{87}Sr/^{86}Sr$ hlutföllum í möttlinum.

Niðurstöðurnar sýna að $^{87}Sr/^{86}Sr$ hlutfall glersins er talsvert frábrugðið hlutfalli bæði plagíóklas-stórdílanna og gabbró-hnyðlinganna. Hins vegar er ekki marktækur munur á stórdílunum og hnyðlingunum. Aðal niðurstaðan er því sú að stórdílarnir og hnyðlingar eiga annan uppruna en burðarkvikan.

$^{87}Sr/^{86}Sr$ hlutföll hnyðlinganna og stórdílanna endurspegla meðalsamsetningu skorpunnar á Reykjanesi ($^{87}Sr/^{86}Sr$ = 0.703099-0.703164). Uppruni þeirra er líklegast úr ólivín-þóleiít innskotum, djúpt í skorpunni.

Burðarkvikurnar hafa frumstæðari $^{87}Sr/^{86}Sr$ hlutföll ($^{87}Sr/^{86}Sr$ = 0.703007-0.703089). Þær eru samansafn bráðarhluta úr síbráðnandi (dynamic melting) súlu í rísandi möttli.

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Abbreviations

MORB = Mid Ocean Ridge Basalt

RVZ = Reykjanes Volcanic Zone

WVZ = Western Volcanic Zone

NIVZ = North Iceland Volcanic Zone

SISZ = South Iceland Seismic Zone

Fo = Forsterite

Di = Diopside

An = Anorthite

M = Midfell

S = Sandfell

H = Maelifell

Cpx = Clinopyroxene

Plag = Plagioclase

Ol = Olivine

Sp = Spinel

Wt% = Weight percentage

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I am eternally thankful for my wonderful family and I wish to extend my admiration to them for their incredible patience and helpfulness.

1 Introduction

Basaltic rocks on the oceanic ridges (MORB) have a range of chemical composition. One end of the compositional spectrum is referred to as being primitive, based on high MgO and Mg/Fe which reflects the high liquidus temperature of the melts. The other end of the compositional spectrum is said to be evolved. In terms of fractional crystallization the high-MgO rocks can potentially be considered parental to more evolved liquids. One possible explanation for the primitive nature of these rocks involves the original melting process i.e. the formation from an originally different mantle, or a mantle that had previously suffered melt extraction. This model for such high-MgO-rocks is supported by their low concentration of K_2O and other incompatible trace-elements, as originally observed by Engel and Engel (1964) who referred to these rocks on the oceanic ridges as magnesian low-K tholeiites. These rocks are often olivine-phyric and the term "picrite" was used to describe them (originally defined as rocks with >25% olivine). The use of the term was later extended to include high-MgO (>12%) aphyric rocks and glasses with less than 3% total alkalis (LeBas 2000). The original use of primitive is for the high-MgO end of the compositional range but in more recent times it is also used to refer to the isotopic and trace-element characteristics. The term depleted is as well often used, in contrast to enriched.

Within the Icelandic volcanic systems there are a few occurrences of high-MgO rocks, often picrites, according to the old definition. There are a number of such small lava flows along the southern part of the Reykjanes peninsula and a few within the Northern Rift Zone, most notably at Theistareykir that have been extensively studied (Maclennan et al., 2003a; Maclennan et al., 2003b; Slater et al., 2001; Stracke et al., 2003b). Many of these rocks also carry, in addition to olivine, less abundant large phenocrysts of plagioclase and chromian diopside and microphenocrysts of chromian spinel, also often seen as inclusions in olivine.

One of the main questions posed in the present work is whether these large phenocrysts originate from the host magma or whether they are xenocrysts - accidentally picked up by the ascending host/carrier magma. The focus is on three hyaloclastite ridges in the Hengill volcanic system (Figure 1). Pillow lava outcrops are found in all of the ridges, two of them are picritic (Midfell and Maelifell) and one is plagioclase ultraphyric (Sandfell).

Both Midfell and Maelifell contain gabbroic nodules and macrocrysts of plagioclase, olivine and clinopyroxene. The mineralogy and petrology of these ridges have been previously studied (Gurenko and Chaussidon, 1995; Gurenko and Sobolev, 2006; Hansteen, 1991; Hardardóttir, 1986; Risku-Norja, 1985; Tronnes, 1990) without addressing the in-depth relationship between the nodules, megacrysts and the carrier magma.

Throughout the up to 16 million year old accessible lava-pile in Iceland, plagioclase ultraphyric basalts are common (Halldorsson et al., 2008; Hansen and Gronvold, 2000; Jakobsson, 1979; Walker, 1963). In Iceland, primitive (gabbroic) nodules are only found in primitive basalts, mantle-derived (peridotitic) nodules have never been found. The relationship between these phases and their host magmas has been discussed in the literature. The nodules and megacrysts have been interpreted either as crustal fragments or as crystals cognate with their carrying magmas (Gurenko and Chaussidon, 2003; Sigurdsson, 1989). Recent studies have suggested and confirmed cases of disequilibrium between plagioclase megacrysts and their carrying magmas (Halldorsson et al., 2008; Hansen and Gronvold, 2000).

The question whether the plagioclase in Midfell, Maelifell and Sandfell is cognate, or representing true xenoliths and xenocrysts is addressed in this contribution, i.e. if the plagioclase represents cognate equilibrium-phenocrysts, cognate disequilibrium-antecrysts or accidental xenocrysts. The method selected is to examine the strontium-isotopic ratios of plagioclase and its host magma. $^{87}Sr/^{86}Sr$-ratios were measured in single handpicked plagioclase megacrysts and gabbroic nodules and compared with $^{87}Sr/^{86}Sr$-ratios in pillow-rim glasses (Magna et al., 2011) to determine the genetic relationship between these phases. Sr has a high plagioclase/liquid distribution coefficient (Irving, 1978) making it possible to use small sample sizes; hence it is possible to measure $^{87}Sr/^{86}Sr$-ratios in single plagioclase crystals.

The low concentrations of Rb in Icelandic basalts along with the long half-life of ^{87}Rb (4.9×10^{10} years) means that timescales are too short to produce measurable differences in $^{87}Sr/^{86}Sr$-ratios within the Icelandic rift-zone. McKenzie et al. (2004) showed that model ages (ages according to chondrite-Earth) for Theistareykir lavas, obtained by fitting lines to isotopes (Sr, Nd, Hf and Pb) and parent-daughter ratios showed a range between 0.05 and 2.0 Ga, far greater than the age of the Icelandic crust. This shows that all radiogenic-isotope heterogeneity in the Icelandic rift-zones has developed in the mantle over a long time. Radiogenic isotopes are therefore the best tracers available to establish relationships within magmatic systems (Davidson et al., 2007).

1.1 Geological setting

Iceland rises above sea-level due to unusually high mantle temperatures, and possibly because of different mantle composition, which leads to an increase in magma production. The cause of this increased activity is a mantle plume with a center under NW Vatnajokull (Wolfe et al., 1997). The extensive magma production in Iceland leads to an increase in crustal thickness. The Icelandic crust is ∼15 km thick directly offshore of the Reykjanes Peninsula and its thickness increases towards the Iceland mantle plume where it reaches a maximum of ∼40 km (Darbyshire et al., 2000). Normal oceanic crust is ∼7 km (Foulger et al., 2003).

Volcanic activity in Iceland can be separated into volcanic systems by geology, tectonics and petrology. Each volcanic system in the rift zones has a central volcano and a fissure swarm (Jakobsson, 1980; Johannesson and Saemundsson, 2009a; Johannesson and Saemundsson, 2009b; Saemundsson, 1974). One of these volcanic systems is Hengill, located at the triple junction between the Reykjanes Volcanic Zone (RVZ) the Western Volcanic Zone (WVZ) and the South Iceland Seismic Zone (SISZ).

The Hengill volcanic system can be divided into two subsystems. The first is associated with the Hengill central volcano. Arnason et al. (1987) defined a separate subsystem in the eastern part of Hengill, as suggested by geothermal activity, the occurrence of silicic and intermediate rocks and a separate fissure system. The slightly older, currently inactive, Hromundartindur subsystem, produced the three hyaloclastite ridges under observation in this study; Midfell, Maelifell and Sandfell. The very late Pleistocene origin of these ridges is manifested by their limited glacial erosion. Slopes of loose hyaloclastite screes might indicate their formation shortly before the onset of the Holocene deglaciation in the area, some 13-14 kyr ago.

Midfell is a ~3 km long hyaloclastite ridge that lies on the eastern shore of lake Thingvallavatn (Figure 1). It is separated into two subunits. The outcrop of interest is the south-western part of the formation, rightfully named Dagmalafell, which is slightly younger than the north-eastern part. Although all samples in this study derive from Dagmalafell it is referred to as Midfell as Risku-Norja (1985) originally did. South of lake Thingvallavatn lie Maelifell and Sandfell. They form a ~3.5 km long hyaloclastite ridge separated by a gorge. Sandfell forms the north-eastern part and Maelifell the south-western. Midfell and Maelifell are highly olivine-porphyritic picritic pillow basalts and hyaloclastite tuffs, with lesser amounts of plagioclase and pyroxene macrocrysts as well as gabbroic nodules. Sandfell is a highly plagioclase-porphyritic pillow lava formation, containing no gabbroic nodules.

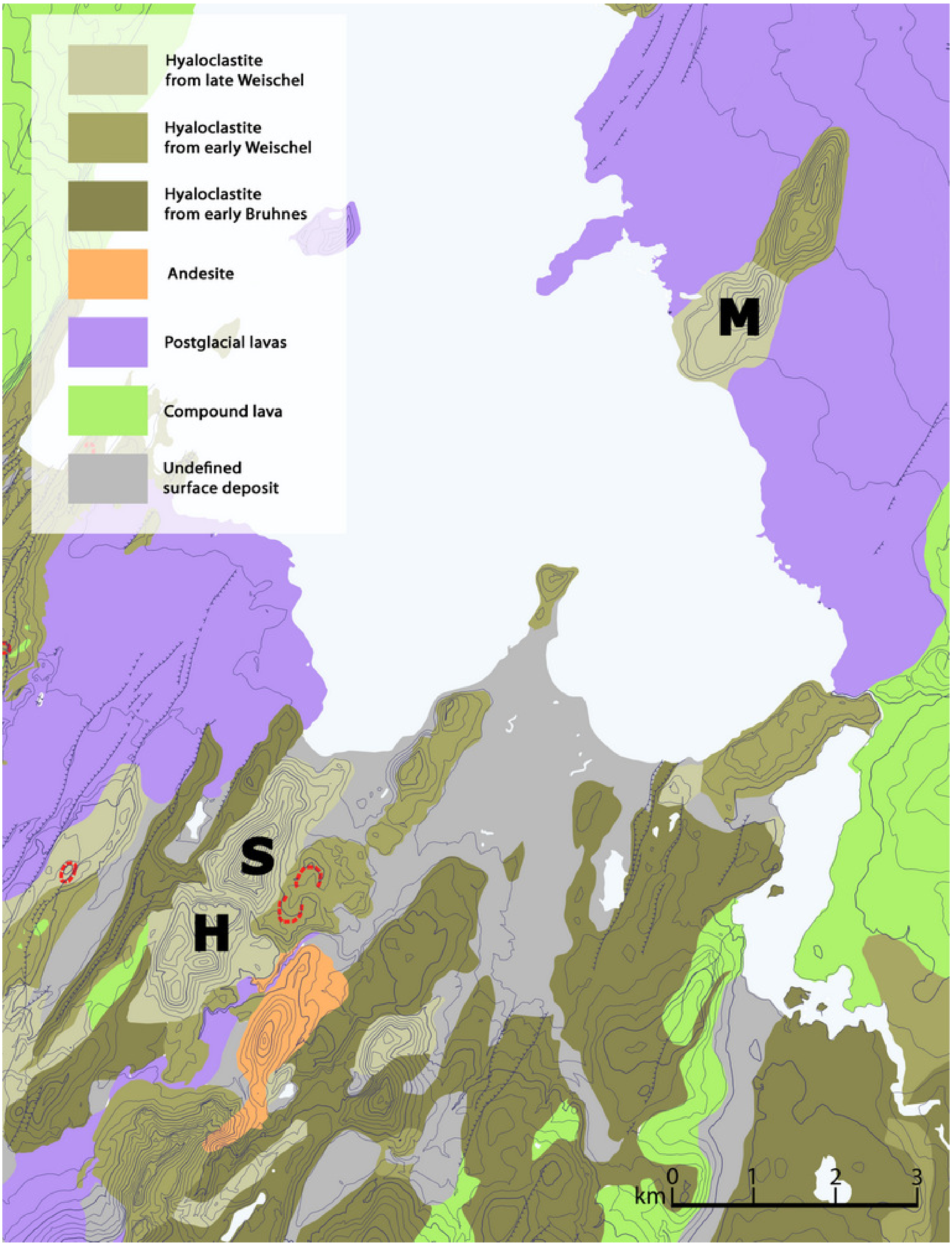

Figure 1: Geological map of the Hromundartindur sub-system in Hengill volcanic-system. M = Midfell, S = Sandfell, H = Maelifell. (Adapted from Saemundsson et al. (2010)).

2 Sampling and analytical methods

Rock samples from Midfell were collected from a quarry on the south side of Dagmalafell (64° 10,476'N, 21° 2,863'W). Rock samples from Sandfell and Maelifell were collected from either side of Langagrof, the gorge separating the formations (64° 6,414'N, 21° 10,675'W and 64° 6,333'N, 21° 10,884'W).

Thin-sections were prepared for petrographic examination of the contact between macrocrysts/nodules with the groundmass. Rock samples were crushed in a jaw crusher and sieved. Single mineral grains (cpx, plag, ol) were handpicked for microprobe analysis. The mineral-grains were mounted into epoxy, then polished and coated with carbon. Running conditions for microprobe analyses were 15kV accelerating voltage at 15 nA beam current. The mineral analyses were done on the ARL-SEMQ30 microprobe at the Institute of Earth Sciences.

For isotopic analyses, single nodules were crushed and plagioclase minerals handpicked. Single plagioclase megacrysts were carefully etched out of rock samples. 0.1 g of each sample was weighed in and thoroughly washed in ultrasonic bath with grade I water (<18 ohm) as well as with HCl.

Strontium for isotopic analysis was separated after sample dissolution in HF and HNO_3. The solution was then saturated with HF and the precipitated fluorides were collected by centrifugation. After washing and repeated separation the solid fluorides were dissolved in 12M HNO_3 and run through Empore® Sr-Rad-Disk® (® 3M Company). After washing with 12M HNO_3 the moist disk was neutralized with ammonia and the adsorbed Sr was then eluted with dilute basic EDTA solution. After evaporation to dryness the Sr samples were taken up in 1% HNO_3 for isotopic analysis. Isotopic analyses were made on Nu-Instruments ICP multicollector mass spectrometer at the Institute of Earth Sciences.

3 Analytical results and comparison with previous studies

The petrography and the mineral and glass chemistry of Midfell and Maelifell has been intensively studied and described before (Gurenko and Chaussidon, 1995; Gurenko and Chaussidon, 2003; Gurenko and Sobolev, 2006; Hansteen, 1991; Hardardóttir, 1986; Risku-Norja, 1985). The present petrographic observations and microprobe analyses conform well with previous results.

3.1 Petrographic observations

The petrographic relations of the picritic rocks of Midfell and Maelifell are similar; both have macrocrysts of clinopyroxene (Cr-Al endiopside), olivine, plagioclase and microphenocrysts of Cr-spinel. Melt inclusions are found in all types of macrocrysts and Cr-spinel inclusions are found in olivine. Gabbroic nodules (1-10 cm), with the same mineral assemblages (ol-cpx-pl-sp) are found in both Midfell and Maelifell.

The amounts of macrocrysts and nodules vary both between eruption units and within them. Plagioclase macrocrysts are more common in Midfell while Cr-Al-endiopside is more common at Maelifell. Both outcrops contain substantial amounts of olivine up to 1 cm in diameter. The amount of olivine varies due to crystal settling, best observed within individual lava pillows. Olivine crystals, being heavier than the liquid, sink to the bottom of the pillows. The Cr-Al-endiopside macrocrysts are up to 2 cm in diameter and plagioclase macrocrysts are up to 3 cm.

As noted in by Tronnes (1990) the clinopyroxene macrocrysts found, were being resorbed. In addition, the gabbroic nodules seem to be disintegrating as they contain minor amounts of interstitial microcrystalline melt. Other macrocryst phases seem to be unstable as well, though they do not show it as clearly as the clinopyroxene (Figure 2).

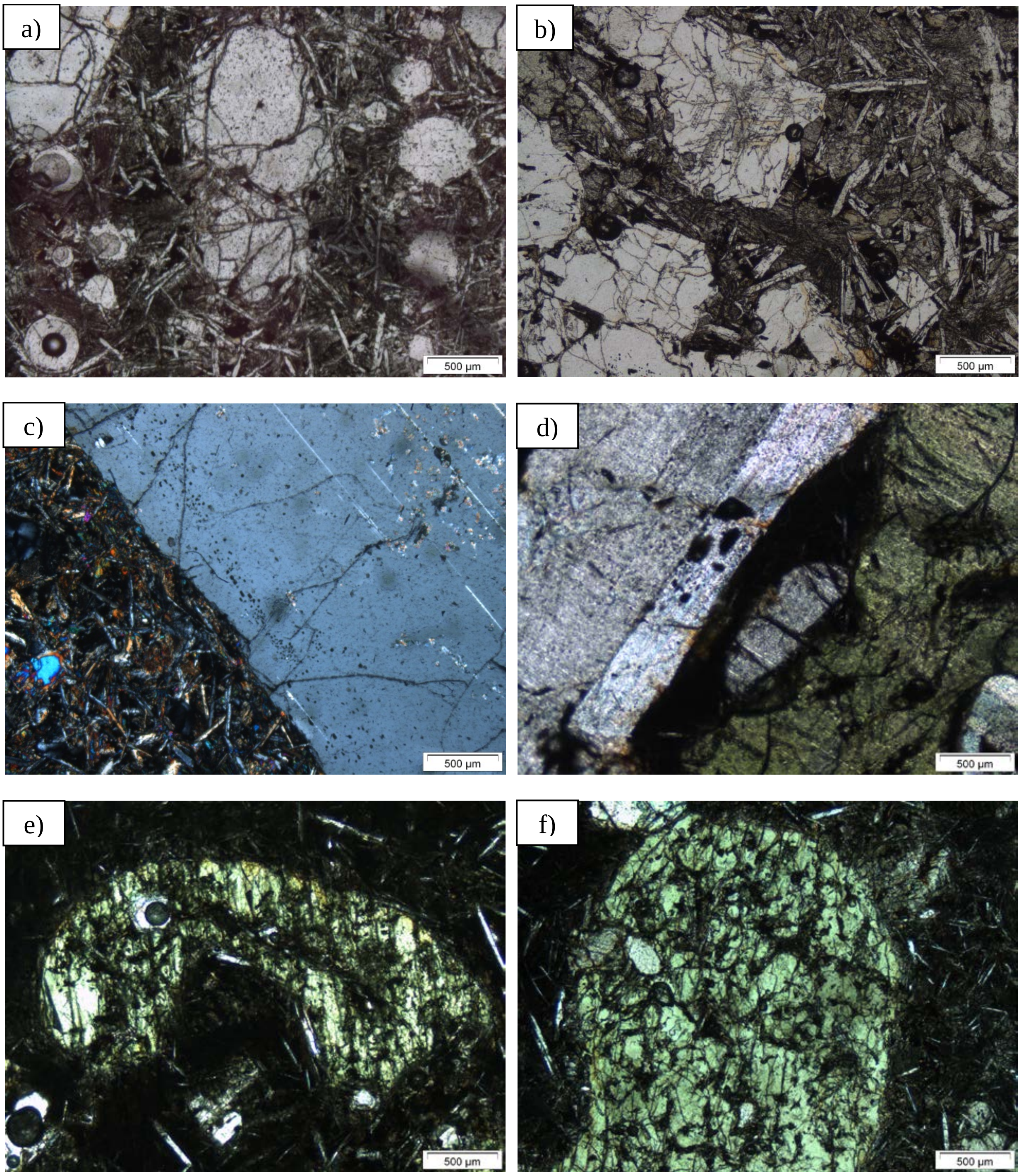

Figure 2: a) Olivine macrocryst in a state of dissolution. b) A contact between a xenocryst and its carrying magma. Seemingly the clinopyroxene is dissolving faster than the other mineral phases. c) Edges of plagioclase-megacrysts indicate dissolution. d) Melt pocket inside a nodule. e) and f) Clinopyroxene in the state of dissolution.

3.2 Glass chemistry

Quenched volcanic glass is the best indicator of the liquid composition at the time of quenching. Shards of quenched glass from pillow rims in Midfell and Maelifell were analyzed for major elements in the microprobe.

Representative analyses from Midfell are shown in Table 1. The Midfell glass shows a range in MgO from 8.79 wt% to 9.29wt%. Previous studies show MgO range in the Midfell pillow rim glass from 9.18 wt% to 9.74wt% (Gurenko and Sobolev, 2006; Risku-Norja, 1985). The total analyzed MgO range is therefore 8.79 wt% to 9.74 wt%.

Representative analyses from Maelifell are shown in Table 1. The Midfell glass shows a range in MgO from 8.18 wt% to 9.22 wt%. Previous studies show a MgO range from 8.60 wt% to 9.83wt% (Gurenko and Chaussidon, 1995; Hansteen, 1991; Hardardóttir, 1986). The total analyzed range is therefore 8.18 wt% to 9.83 wt%.

The relatively high MgO content of the samples along with low FeO (8.58 – 9.13 wt%), K_2O (0.01 - 0.05 wt%), TiO_2 (0.68 – 0.91) and P_2O_5 (0 – 0.45 wt%) indicates the true primitive nature of this nodule- and macrocryst-bearing magma (Figure 3).

Both locations show high CaO, and low CaO/Al_2O_3 ratios compared to other Icelandic glasses. This is indicated in Figure 4 where the samples are plotted along with other glass samples from Hengill.

The Sandfell glass (unpublished data from Thor Hansteen) is significantly more evolved than Midfell and Maelifell (lower MgO, higher K_2O). As can be seen in Figure 3, the Sandfell carrying magma is an outlier in the general Hengill trend. It has lower K_2O than expected for a given MgO value. It also has unusually high Al_2O_3 (Table 1). This suggests resorption of plagioclase by the carrying magma.

Table 1: Representative glass analyses from Midfell (M) and Maelifell (H). The Sandfell data is unpublished data from from Thor Hansteen

Sample	SiO_2	TiO_2	Al_2O	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SUM
M-133	48.90	0.90	14.58	9.07	0.15	9.29	15.07	1.79	0.05	0.04	99.83
M-131	48.73	0.90	14.70	9.10	0.17	9.29	15.37	1.71	0.05	0.04	100.0
M-65	47.74	0.71	14.91	9.02	0.16	9.19	15.69	1.69	0.04	0.00	99.15
M-134	48.37	0.86	14.88	9.13	0.16	9.10	15.18	1.75	0.03	0.03	99.49
M-72	48.14	0.74	15.05	8.83	0.18	9.00	15.63	1.62	0.02	0.06	99.29
M-127	47.96	0.86	14.23	9.09	0.17	9.00	15.02	1.79	0.04	0.07	98.23
M-78	47.47	0.75	15.02	8.79	0.17	8.99	15.47	1.74	0.04	0.04	98.48
M-75	48.34	0.70	15.41	8.84	0.14	8.95	15.63	1.64	0.04	0.03	99.73
M-70	47.22	0.68	14.91	8.91	0.21	8.92	15.46	1.68	0.02	0.05	98.06
M-71	47.76	0.74	15.16	8.90	0.17	8.79	15.44	1.69	0.04	0.05	98.74
H-59	47.15	0.78	14.57	8.98	0.17	9.22	15.68	1.79	0.05	0.17	98.57
H-105	48.29	0.91	13.97	9.10	0.15	9.21	15.00	1.87	0.04	0.04	98.58
H-110	48.51	0.86	14.27	9.04	0.26	9.16	14.70	1.82	0.05	0.05	98.73
H-88	48.44	0.86	14.55	8.82	0.17	8.87	15.01	1.71	0.05	0.04	98.51
H-104	49.38	0.87	15.01	8.87	0.25	8.85	15.30	1.78	0.02	0.07	100.4
H-95	48.78	0.88	14.94	8.80	0.22	8.79	15.21	1.83	0.05	0.03	99.52
H-89	48.31	0.83	14.91	8.76	0.15	8.61	15.13	1.84	0.04	0.04	98.62
H-58	48.23	0.79	15.98	8.65	0.24	8.58	15.56	1.71	0.01	0.28	100.0
H-94	48.60	0.87	15.22	8.75	0.19	8.49	15.12	1.73	0.05	0.06	99.09
H-53	50.00	0.84	16.12	8.58	0.17	8.18	15.22	1.87	0.03	0.45	101.4
S	48.75	0.95	19.07	8.10	0.14	6.10	14.58	1.95	0.16	0.09	99.90

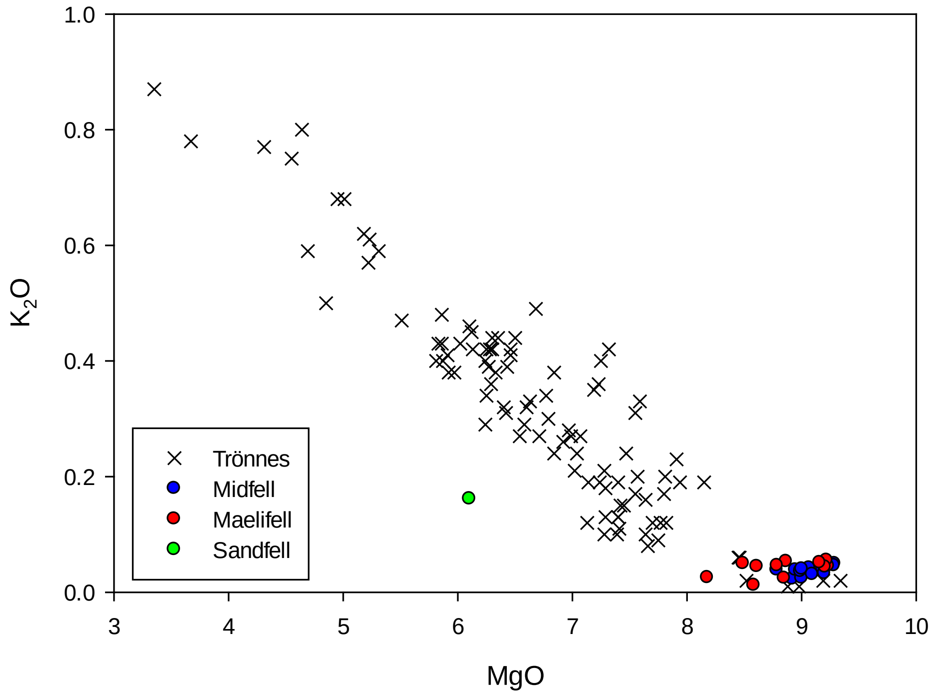

Figure 3: K_2O vs. MgO in glass from Midfell, Maelifell and Sandfell compared with other glass analyses from Hengill (Tronnes, 1990). The data from Tronnes include samples from Midfell and Maelifell

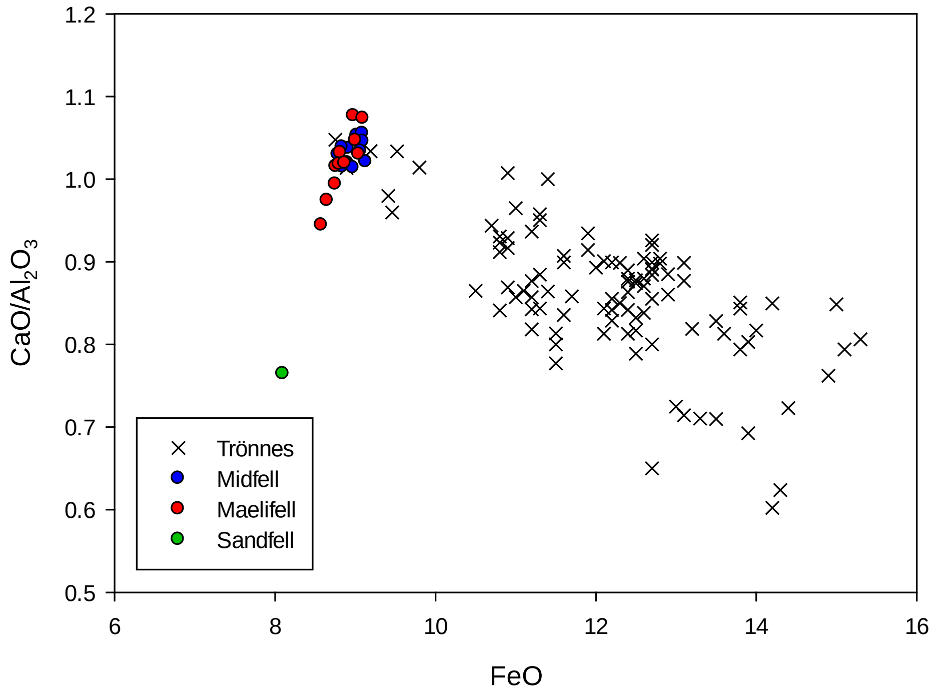

Figure 4: CaO/Al_2O_3 vs. FeO in glass from Midfell, Maelifell and Sandell compared with other glass analyses from Hengill (Tronnes, 1990). The data from Tronnes include samples from Midfell and Maelifell.

3.3 Mineral chemistry

3.3.1 Olivine

The Midfell and Maelifell outcrops are rich in olivine macrocrysts, their composition being summarized in Table 2 and Figure 5. The analyzed forsterite content of olivine in Midfell ranges from 84.8 – 90.6 and in Maelifell 82.2-87.6%. CaO ranges from 0.20-0.33% in Maelifell and 0.22-0.41% in Maelifell. MnO ranges are 0.20 – 0.37% in Maelifell and 0.15-0.30% in Midfell. NiO ranges are 0.18 – 0.29% in Maelifell and 0.19-0.35% in Midfell. Olivine macrocrysts from Maelifell are either chemically unzoned or weakly normally zoned (Table 2). I did not notice any reverse zoning as Hansteen (1991) and Hardardóttir (1986) did in their studies.

Table 2: Representative olivine analyses from Midfell (M) and Maelifell (H).

Sample	SiO_2	FeO	MnO	MgO	CaO	NiO	SUM	Fo%
H1-c	41.82	12.48	0.25	45.47	0.26	0.25	100.5	86.7
H1-r	40.42	12.90	0.22	46.36	0.28	0.25	100.4	86.5
H2-c	40.13	12.44	0.24	46.59	0.30	0.23	99.9	87.0
H2-r	41.27	12.30	0.24	45.96	0.30	0.25	100.3	87.0
H7-c	39.15	14.47	0.31	45.13	0.25	0.22	99.5	84.8
H7-c	38.79	15.25	0.30	44.32	0.26	0.24	99.2	83.8
H7-r	41.04	16.14	0.31	42.91	0.28	0.20	100.9	82.6
H4-c	40.24	12.58	0.24	46.32	0.23	0.24	99.8	86.8
H4-r	40.75	12.74	0.24	46.09	0.30	0.24	100.4	86.6
H2-c	40.76	12.43	0.26	46.87	0.31	0.25	100.9	87.0
H2-r	41.27	12.30	0.24	45.96	0.30	0.25	100.3	87.0
M3-c	40.64	9.88	0.19	48.46	0.27	0.29	99.7	89.7
M3-r	40.35	9.82	0.18	48.69	0.27	0.27	99.6	89.8
M19-c	42.38	11.86	0.21	46.59	0.29	0.24	101.6	87.5
M19-r	43.22	11.09	0.22	46.43	0.31	0.24	101.5	88.2
M25-c	40.40	11.49	0.23	47.24	0.32	0.24	99.9	88.0
M25-r	40.19	11.41	0.23	47.50	0.31	0.25	99.9	88.1
M28-c	41.54	13.21	0.28	43.69	0.28	0.21	99.2	85.5
M28-r	40.72	14.03	0.30	44.06	0.32	0.19	99.6	84.8
M20-c	41.03	11.84	0.23	46.18	0.30	0.23	99.8	87.4
M20-r	41.07	11.80	0.24	46.37	0.32	0.24	100.0	87.5

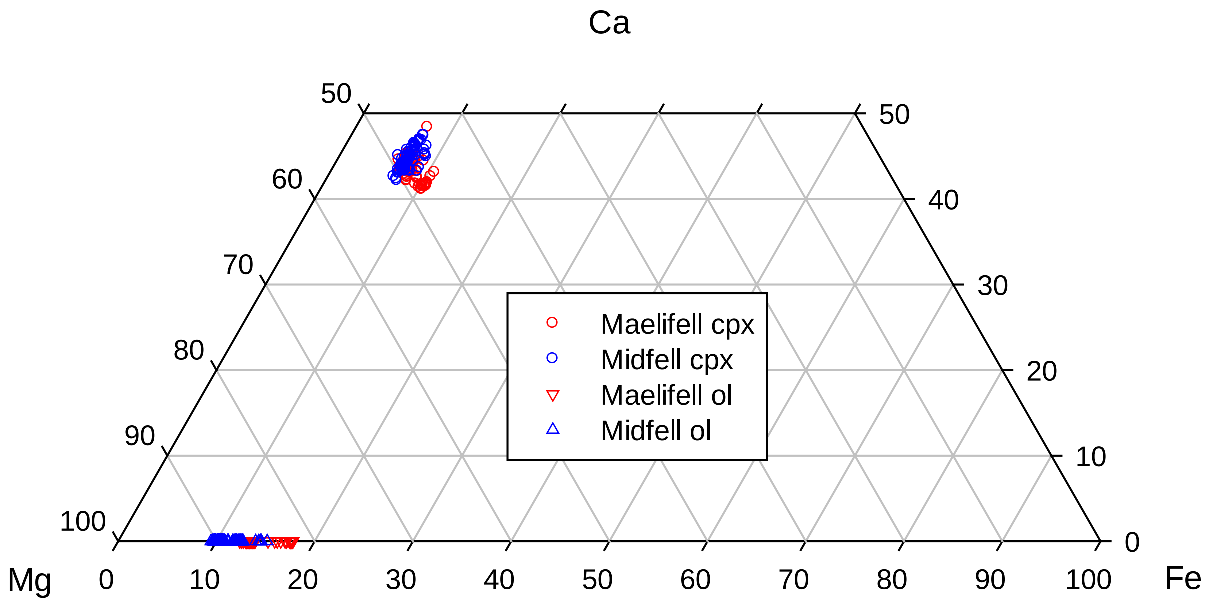

Figure 5: Composition of clinopyroxenes and olivines from Midfell and Maelifell.

3.3.2 Pyroxene

The pyroxenes from Midfell and Maelifell are compositionally similar. They are of Cr and Al rich endiopside composition. Representative analyses are listed in Table 3 and Figure 5. The Mg# ((Mg/Mg+Fe)*100) range in Midfell is 83.9 – 89.1, and 81.3 – 88.7 in Maelifell. Al_2O_3 and Cr_2O_3 positively correlate with Mg#. Al_2O_3 content is usually higher in Maelifell (Figure 6) while Cr_2O_3 content is higher in Midfell (Figure 7). No compositional zoning was observed.

Table 3: Representative clinopyroxene analyses from Midfell (M) and Maelifell (H)

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Cr_2O_3	SUM	Mg#
H1-c	51.39	0.56	3.15	6.52	0.19	16.55	20.28	0.26	0.23	99.13	81.91
H1-r	52.04	0.52	3.23	6.44	0.12	16.44	19.92	0.25	0.20	99.16	81.99
H3-c	51.34	0.34	4.85	4.17	0.07	16.55	21.07	0.20	1.11	99.70	87.61
H3-r	52.12	0.28	4.75	4.23	0.14	16.58	21.01	0.18	0.93	100.22	87.48
H5-c	52.03	0.43	2.79	6.13	0.19	16.88	19.95	0.18	0.34	98.93	83.08
H5-r	52.27	0.43	2.46	5.78	0.17	16.94	20.13	0.23	0.30	98.71	83.94
M1-c	53.00	0.23	4.49	4.18	0.09	15.41	20.76	0.18	1.20	99.55	86.78
M1-r	53.27	0.32	4.14	4.11	0.05	15.11	20.83	0.19	1.52	99.54	86.77
M9-c	53.97	0.26	3.51	4.24	0.08	15.57	20.88	0.21	1.58	100.30	86.74
M9-r	53.39	0.29	4.54	4.41	0.11	15.03	20.02	0.20	1.33	99.32	85.87
M11-c	55.00	0.42	2.56	5.14	0.14	15.37	20.85	0.19	0.74	100.42	84.21
M11-r	55.07	0.33	2.57	5.18	0.11	15.13	20.48	0.21	0.76	99.85	83.88

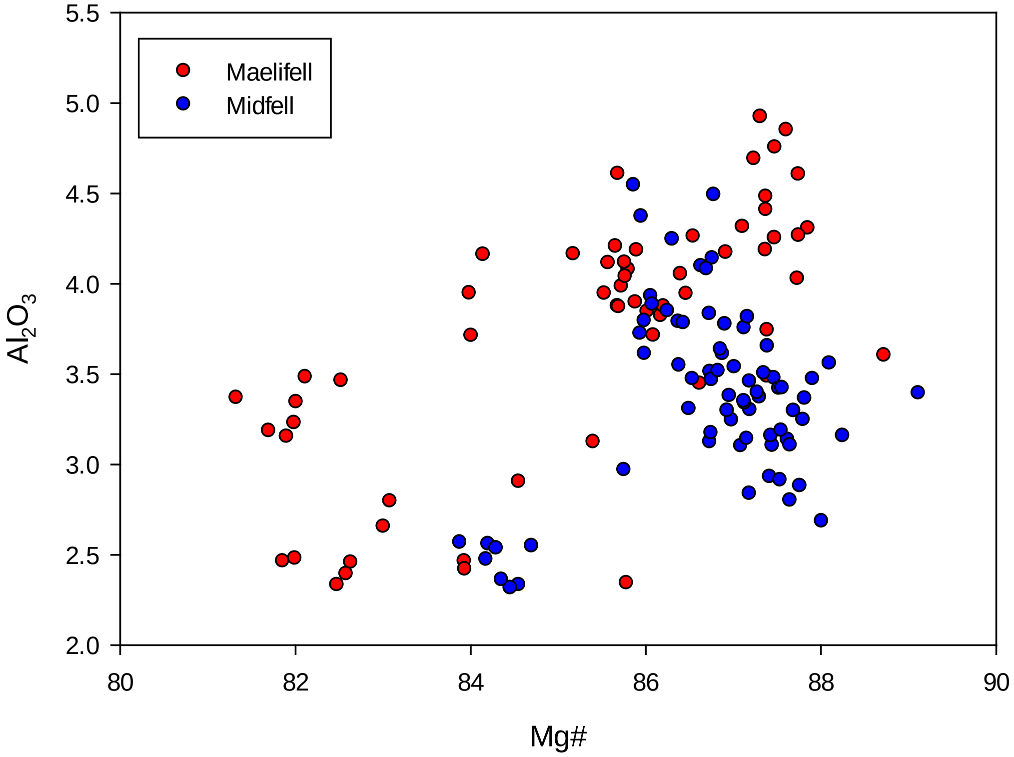

Figure 6: Al_2O_3 content in clinopyroxenes from Midfell and Maelifell.

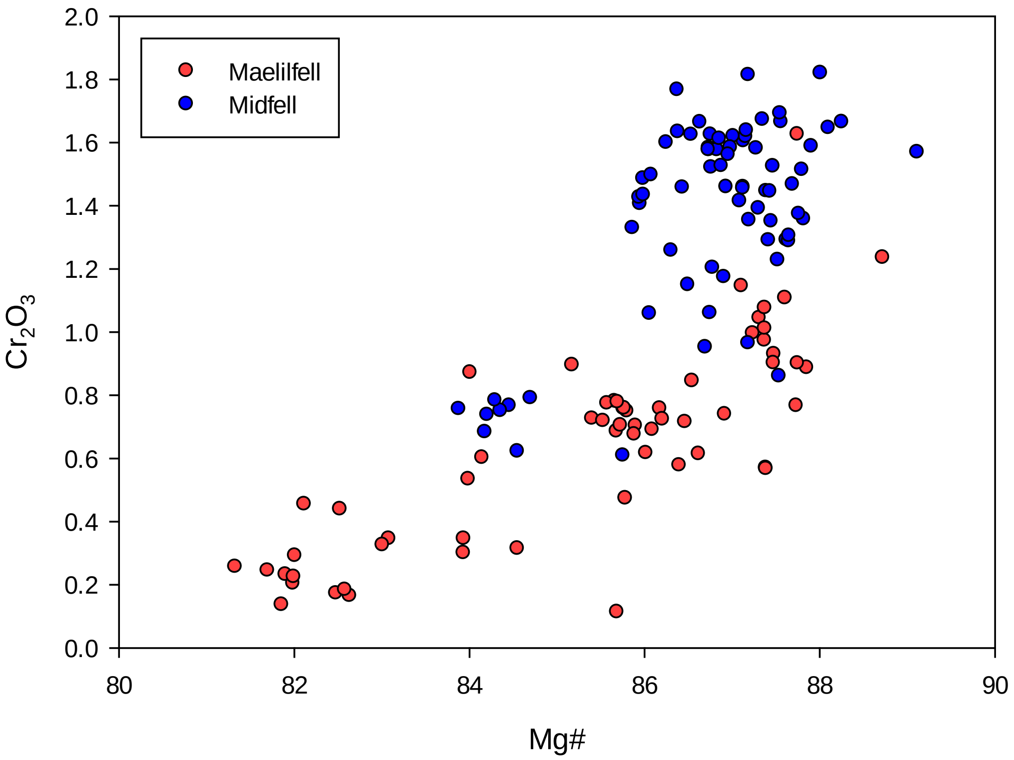

Figure 7: Cr_2O_3 content in clinopyroxenes from Midfell and Maelifell.

3.3.3 Plagioclase

Plagioclase macrocrysts are more common in Midfell than in Maelifell. The analyzed An content of plagioclase in Maelifell is 82.7 – 89.8 and 83.2 – 87.6 in Midfell. The combined An content, including other studies is the same as above for Maelifell and 80.5 – 89.7 in Midfell. The macrocrysts are either chemically unzoned or weakly reversely zoned.

Sandfell is extremely rich in plagioclase macrocrysts. The analyzed An range is 86.1-87.5 in Sandfell, no zonation was observed.

Table 4: Representative plagioclase analyses from Midfell (M), Maelifell (H) and Sandfell (S).

Sample	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	SUM	An%
H8-c	47.50	34.59	0.73	17.80	1.33	0.02	101.90	88.00
H8-r	47.37	33.71	0.69	17.34	1.46	0.03	100.53	86.67
H8-c	47.54	33.43	0.71	16.85	1.65	0.03	100.13	84.83
H8-r	47.30	33.04	0.74	16.77	1.58	0.02	99.39	85.34
H1-c	46.42	34.63	0.62	16.55	1.51	0.01	99.67	85.76
H1-r	45.93	34.44	0.64	16.63	1.49	0.01	99.07	86.00
M1-c	47.43	34.11	0.75	17.06	1.75	0.02	100.64	84.27
M1-r	46.92	34.19	0.74	17.64	1.52	0.01	100.56	86.48
M3-c	46.84	33.79	0.72	17.61	1.62	0.02	100.14	85.64
M3-r	47.38	34.25	0.66	17.72	1.42	0.01	101.03	87.27
M5-c	46.94	33.32	0.69	17.26	1.71	0.00	99.49	84.75
M5-r	46.66	33.46	0.64	17.58	1.47	0.00	99.41	86.81
S1-c	47.19	34.87	0.57	17.43	1.54	0.01	101.55	86.13
S1-r	47.49	34.33	0.57	17.25	1.48	0.02	101.09	86.46

3.4 Strontium isotope analysis

In Midfell, Maelifell and Sandfell the glass values from Magna et al. (2011) show lower $^{87}Sr/^{86}Sr$ ratios than the measured values from single plagioclase megacrysts and plagioclase from single nodules, measured in this study. The carrier magmas (glass) from Maelifell (0.703007) and Sandfell (0.703015) show an especially depleted isotopic signature while Midfell (0,703089 – 0,703095) has ratios closer to those of incorporated plagioclases and nodules (Table 5). The plagioclase megacrysts and nodules from all outcrops have $^{87}Sr/^{86}Sr$ ratios (0.703100 – 0.703164) close to the WVZ average (0.70314) (Bragason, 2012).

Table 5: Strontium isotopic analyses.

Sample	$^{87}Sr/^{86}Sr$	2σ
MIDFELL-MEGACR.1	0.703100	±27
MIDFELL-MEGACR.2	0.703121	±22
MIDFELL-MEGACR.3	0.703152	±33
MIDFELL-MEGACR.4	0.703133	±30
MIDFELL-XENOLITH*	0.703164	±39
MIDFELL-GLASS**	0.703089	±14
MIDFELL-GLASS**	0.703095	±14
SANDFELL-MEGACR***	0.703164	±31
SANDFELL-GLASS**	0.703015	±12
MAELIFELL-MEGACR.1	0.703149	±49
MAELIFELL-MEGACR.2	0.703162	±47
MAELIFELL-XENOLITH*	0.703099	±68
MAELIFELL-GLASS**	0.703007	±14

**Plagioclase assemblage from single xenolith.*
***Data from Magna (2011).*
****Plagioclase assemblage.*
Error refers to the last two digits.

4 Discussion

The three subglacially-erupted ridges under investigation in this study all contain groundmass/glass in which are embedded isotopically different and possibly unrelated macrocrysts and nodules. This raises the question of the origin of the different phases. In the following chapter we will speculate on and make an attempt to answer this problem. The question is broken up into three parts; the origin of xenocrysts and xenoliths, the origin of the carrier liquids, and the interaction between the different phases.

4.1 Origin of xenocrysts and xenoliths

In Midfell, Maelifell and Sandfell, $^{87}Sr/^{86}Sr$ ratios in plagioclase megacrysts (0.703100 – 0.703162), plagioclase from xenoliths (0.703099-0.703164) and glass samples (0.703007-0.703089) clearly show that the minerals are in all cases isotopically unrelated to their carrier magmas (Figure 8).

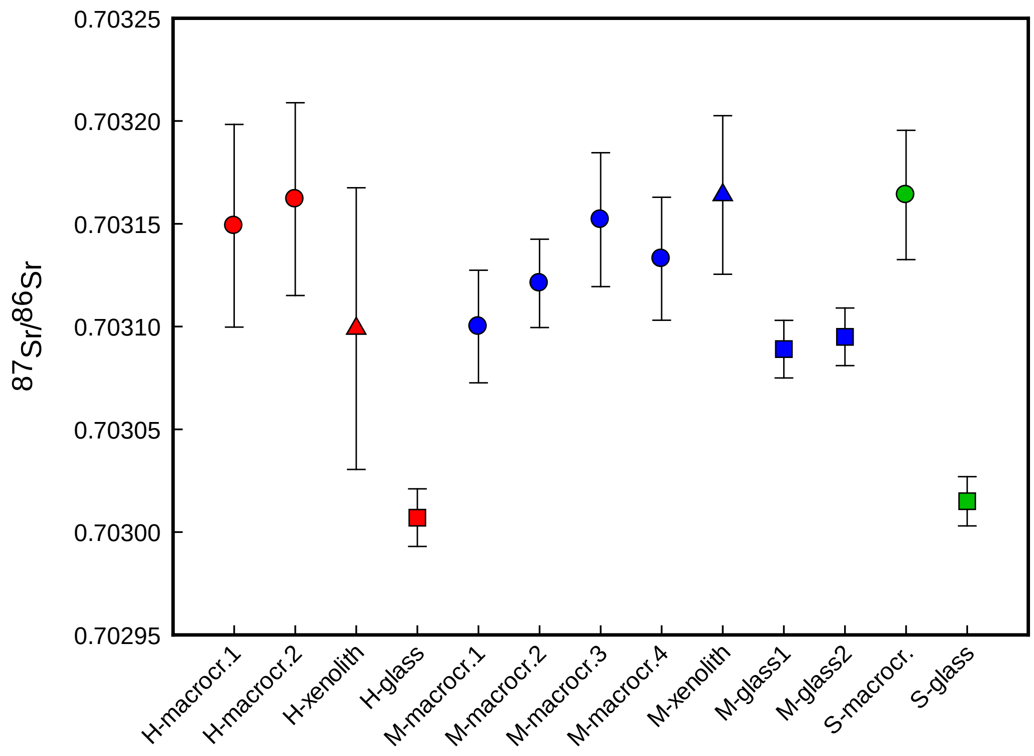

Figure 8: Strontium isotopic analyses. H=Maelifell, M=Midfell, S=Sandfell. Circles represent macrocrysts, triangles represent xenoliths and boxes represent glass. The glass samples from Magna et al. (2011) show significantly lower $^{87}Sr/^{86}Sr$ ratios from the plagioclase megacrysts and the nodules.

The plagioclase megacrysts and gabbroic nodules show $^{87}Sr/^{86}Sr$ ratios close to the WVZ average (0,70314) (Bragason, 2012), while the glass samples are among the most primitive (low $^{87}Sr/^{86}Sr$ ratios) found in Iceland (Kokfelt et al., 2006; Stracke et al., 2003a; Thirlwall et al., 2004).

Seismic studies indicate that the Icelandic crust is significantly thicker than normal oceanic crust and that the layering is for the most part similar to ophiolites. In ophiolites, extrusive rocks are underlain by sheeted dykes which in turn are underlain by gabbroic complexes, isotropic gabbros at shallower depths and layered gabbros at greater depths. The gabbros reside on peridotite that defines the MOHO discontinuity. The lithosphere beneath Iceland on the other hand, has no or ill-defined seismic MOHO discontinuity that may indicate that intrusive rocks reach to greater depth above the Icelandic mantle plume. (Foulger et al., 2003; Gudmundsson, 2003; Maclennan et al., 2001a). The gabbroic complexes are formed by multiple sill intrusions that crystallize, at various depths, subside and form layered gabbros (Boudier et al., 1996; Kelemen et al., 1997b). These sill intrusions were noted seismically, in Askja, in the NIVZ (Key et al., 2011). Pure plagioclase layers (anorthosite) have been observed in the layered gabbro of the ophiolites. Their formation may be favored during rapid decompression events analogous to those that took place in Iceland in early Holocene (Kelemen and Aharonov, 1998).

The secondary mineralogy in the Icelandic crust is controlled by kinematic processes first suggested by Palmason (1973), where magmas that reach the surface get buried and subside. The magmas that erupt closest to the spreading axis sink furthest and form the deeper parts of the Icelandic crust. The sinking material undergoes progressive metamorphism, from zeolite to amphibolite and then granulite facies. Below 7 km. depth, the crust is characterized by amphibolite to granulite facies (Oskarsson et al., 1982).

The minerals in the nodules found in Midfell and Maelifell overlap compositionally with the macrocrysts. There is some chemical variance between crystals but single crystals are remarkably homogenous. The mineral composition of the nodules and macrocrysts are similar to minerals found in the layered gabbro complexes in ophiolites (Kelemen et al., 1997b). Some nodules found in Iceland contain interstitial glass or microcrystalline melts. This suggests that the nodules could be disintegrating. In Fontur, a possible eruption site for the porphyritic Thjorsa lava, anorthosite nodules with interstitial glass are found. The composition of the interstitial glass does however not resemble an estimated final melt from an anorthositic magma source, but has the same composition as the carrying magma (Hansen and Gronvold, 2000). The carrying liquid could be intruding the nodules and disintegrating them. Disintegrated nodules are therefore a possible source for xenocrysts.

The gabbroic nodules found in Midfell and Maelifell are compositionally similar though they show some differences, most notably in the pyroxenes. The pyroxenes from Maelifell are consistently Al_2O_3 richer and Cr_2O_3 poorer than pyroxenes from Midfell (Figure 6 and Figure 7). These observations indicate that the nodules from Midfell and Maelifell are not from the same source units. As Al_2O_3 is more easily incorporated into pyroxene at higher pressures, the Maelifell xenoliths probably originate from greater depth. Previous studies indicate that the xenoliths originate from the crust-mantle boundary, and that the olivine xenocrysts originate from the upper mantle (Gurenko and Chaussidon, 2003; Gurenko and Sobolev, 2006; Hansteen, 1991). Maclennan et al. (2001b) estimated depths of crystallization of clinopyroxene macrocrysts in MgO rich basalts from Theistareykir at ~30km.

Melt inclusions in olivines from single picritic eruptions show significant chemical variation (Gurenko and Chaussidon, 1995; Maclennan, 2008; Maclennan et al., 2003b). This suggests that they form at various depths and sample the different melts that they grow from, in the ascending mantle. The olivines in Midfell and Maelifell could origin from the magma, or at least melt batches that later formed a part of the magma. Another possibility is that they originate from dunite-surrounded melt-conduits in the mantle (Kelemen et al., 1997a).

4.2 Origin of the carrier liquids

The quenched glass in the pillow rims at Midfell and Maelifell formations are ideal to recognize the composition and the origin of the carrier magma that conveyed the incorporated xenocrysts and xenoliths to the surface. The carrier magmas in Maelifell and Midfell are both of olivine-tholeiitic composition (Fig. 3 and 4). They do not fall into the strict definition of picrites by Le Bas (2000) that requires 12% MgO, but they are among the most primitive glasses found in Iceland (Figures 3 and 4) (Breddam, 2002; Tronnes, 1990). High MgO and low K_2O values reveal their true primitive nature. Whole rock samples previously analyzed have MgO values around 25%, reflecting olivine addition (Gurenko and Sobolev, 2006; Hardardóttir, 1986). Such melts would require large degree of melting of mantle peridotite to form (Kushiro, 2001). Picrites in Iceland are all of small volumes. Their small volumes along with their primitive composition indicate that they form from a mantle that had previously undergone partial melting.

The Sandfell glass is significantly more evolved than the glass from Midfell and Maelifell. It is rich in Al_2O_3 and poorer in K_2O than similarly evolved rocks in the Hengill system (Figure 3). This chemical signature could indicate reworking of plagioclase. It nonetheless has a very primitive isotopic composition; -contradicting reworking of isotopically more evolved plagioclase (Figure 8).

Maximum values of incompatible elements, and radiogenic-isotope signature (Pb, Hf, Nd, Sr, Os) increase systematically along the mid-ocean Reykjanes Ridge towards Iceland and peak in central Iceland, where the center of the Iceland mantle plume is located (Sigmarsson et al., 2008, and references therein). It is therefore likely that the Iceland mantle plume is tapping a source more isotopically enriched than the depleted Normal-MORB source. An early model suggested a depleted upper mantle and an enriched lower mantle and that different isotopic ratios reflected different melt ratios from either source.

The origins of different mantle sources have been debated. A large part of the oceanic mantle has undergone one or more episodes of partial melting. The partial melting leaves the mantle with a depleted chemical signature, with incompatible elements concentrated in the extracted melt. It is however clear that the mantle contains patches with a range of more enriched material. The sources of these enriched patches are most often thought to come from recycled crustal material i.e. oceanic crust that has been brought back to the mantle at convergent margins and into the mantle convection cycle (Chauvel and Hemond, 2000; Stracke, 2012). The recycled oceanic crust is of pyroxenite composition which is more fusible than the depleted source.

A recent study (Mukhopadhyay, 2012) on noble gases (He Ne Ar and Xe) in the Midfell pillow-rim glass -suggests a third mantle source. The Midfell glass contains an undegassed primitive component from a less disturbed part of the mantle. He shows that this part of the mantle has been isolated from the mantle-convection dynamics for 4.45 Gyr while other parts of the mantle have undergone extensive degassing due to previous, extensive partial melting episodes.

The picrites (low-K_2O. high-MgO tholeiites) in the neovolcanic zone in Iceland have a depleted isotope signature (Sr Nd Hf and Pb). This suggests that a significant part of the picrite melt comes from the depleted mantle source. Olivines from Midfell and Maelifell have depleted and enriched glass inclusions (Gurenko and Chaussidon, 1995). This is also seen in a picrite from the Theistareykir area (Maclennan et al., 2003b). Therefore it can be assumed that Icelandic picrites do not only sample the depleted part of the melting column. Mukhophadhyay´s (2012) study confirms this. The picritic melts that reach the surface are therefore formed by aggregates from the entire dynamic melting column, though the largest part comes from the depleted part of the mantle. The cumulative melts that reach the surface are formed by aggregates of multiple partial melts from various parts of the melting column. We have three established sources; a previously depleted peridotite source, a more enriched recycled oceanic crust source (pyroxenite) and a more pristine mantle source that probably originates from the deeper and isolated parts of the mantle.

Partial melts begin to flow in isolated conduits that are often surrounded by dunite. The dunites form when ascending basaltic melts react with surrounding wall-rocks, most dominantly harzburgite, i.e. peridotite that has undergone previous partial melting. The ascending melts crystallize olivine, and form the dunite conduits (Kelemen et al., 1997a). The melts formed in the column are then combined and homogenized on their transit up to the surface.

Recent studies show that the mantle beneath Iceland is heterogeneous on a small scale, within individual volcanic systems and even within single eruptions (Gronvold et al., 2008; Halldorsson et al., 2008; Kokfelt et al., 2006). The $^{208}Pb/^{206}Pb$ ratios in melt-inclusions in olivines from a single eruption from in the Reykjanes Peninsula span 50-90% of the total range found in Atlantic MORB (Maclennan, 2008). The isotopic range in the melt-inclusions indicate that the mantle beneath Iceland is heterogeneous at a very small scale (<1 km). The olivine that reached the surface must therefore have sampled various melts from different depths in a dynamic melting column. Geochemical studies indicate that MORB basalts are formed this way i.e. by dynamic melting and that they are an accumulation of melts from a range of depths in an ascending mantle (Kushiro, 2001).

Geochemical variation within single flows in Iceland suggests that the mixing of melts is not always perfect. The mixing of primitive lavas tends to be less extensive than in more evolved lavas. Fissure eruptions, often more evolved, show less geochemical variation than long-lived primitive shield volcano eruptions (Eason and Sinton, 2009; Sigmarsson et al., 1991; Sinton et al., 2005). The composition of a melt that reaches the surface, largely depends on the ratios and the melting behavior of the mantle phases and the extent of melt homogenization that takes place (Stracke, 2012, and references therein). The largest part of the homogenization probably takes place in magma chambers within the crust or in the uppermost part of the mantle. The melting and homogenization process is explained in Figure 9. (Maclennan, 2008; Rubin et al., 2009).

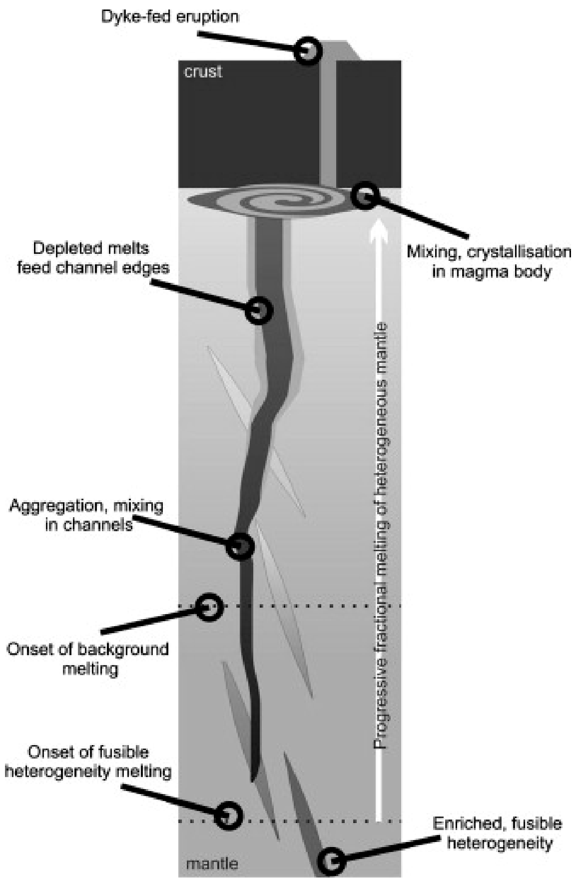

Figure 9: The melting and homogenization process benath Mid Ocean Ridges (from Maclennan (2008)). The melting takes place in a dynamic melting plume in a heterogenous mantle. Melt aggregates from different parts of the column combine and homogenize on their way to the surface.

Picrites in the neovolcanic zones in Iceland are all of similar age, from late Pleistocene or early Holocene. Studies indicate that magma production was 8-50 times higher during the first 2-5 kyr following deglaciation than during the glaciation and the recent 3-4 kyr. (Jakobsson et al., 1978; Sigmarsson et al., 2008; Sigvaldason et al., 1992; Sinton et al., 2005). In addition to the increase in magma production the early postglacial lavas in Reykjanes tend to be more MgO rich (Gee et al., 1998; Jakobsson et al., 1978). This is probably because of an increase in melting due to glacial unloading. During the Ice Age, the glacier reached a thickness of up to 2000 m in most parts of Iceland, although the maximum thickness in central Iceland is not well constrained (Norðdahl et al., 2008). The weight of the glacier caused a crustal depression of 500 m (Sigmundsson, 1991). The glacier started to retreat very fast 13-14 kyr ago leading to a rebound of the crust, causing a substantial pressure drop in the crust and mantle. Jull and McKenzie´s (1996) modelling of mantle melting due to glacial unload, suggested that mantle melting could increase significantly, especially in the upper mantle region, if a glacier this big retreated fast enough.

The quenched pillow-rim glasses in Midfell and Maelifell have low FeO and high Al_2O_3 and CaO compared to MORB and other basalts in Hengill (Figure 4). High-MgO basalts from early Holocene usually show similar trends (Jakobsson et al., 1978; Maclennan et al., 2003b). Falloon et al. (1988) argued that melts originating from deeper parts of the mantle column should have higher FeO values while melts originating from shallower parts should have lower FeO values and higher MgO. This agrees well with the idea that a large part of the melt-batches forming the carrying liquids comes from the shallower part of the mantle. Gurenko and Sobolev (2006) suggested that the CaO/Al_2O_3 ratio in the Midfell glass could not be from original mantle melting and had to come from percolation through a gabbroic matrix at the base of the crust.

4.3 Magma-crust interaction

Substantial crustal interaction has been suggested to play a large role in the geochemistry of Icelandic lavas (Oskarsson et al., 1982; Oskarsson et al., 1985). A recent study on boron in melt inclusions from the relatively evolved Lakagigar eruption (MgO ~5.7%), confirms crustal assimilation (Brounce et al., 2012). Brounce et al. (2012) suggest that the magma that reached the surface assimilated up to 30% of altered crustal material.

The prominent dissolution of Cr-Al endiopside (cpx) in Midfell and Maelifell brings up the question of the origin of plagioclase macrocrysts commonly seen in Icelandic basalts. The dissolution rate of minerals in nodules depends on their stability at different pressures. At low pressures in the Fo-Di-An system the primary phase field of cpx expands with increasing pressure (Brearley and Scarfe, 1986; Presnall et al., 1978). The dissolution rate of clinopyroxene at crustal pressures, where the clinopyroxene is not on the liquidus, is therefore high. If rising magmas should reside in magma reservoirs it would lead to substantial dissolution of clinopyroxene and break-up of cpx-bearing nodules, leaving plagioclase- and/or olivine-phyric magmas. The dissolution of the clinopyroxene can leave a fingerprint in the carrier liquids as shown by Halldorsson et al. (2008). Clinopyroxene dissolution seems to be a common process in magma-crust interaction in Iceland. Eason and Sinton (2009) suggested that clinopyroxene dissolution along with olivine and/or plagioclase crystallization could explain the compositional heterogeneity observed in the primitive Lambahraun shield lava.

Plagioclase ultraphyric basalts as found in Sandfell are common in Iceland (Halldorsson et al., 2008; Hansen and Gronvold, 2000; Jakobsson, 1979). The voluminous (25 km^3) Thjorsa lava in South Iceland is a good example. The megacrysts in the Thjorsa, have been shown to be true xenocrysts as they show significantly different $^{87}Sr/^{86}Sr$ ratios from the groundmass. Plagioclase megacrysts in the Thjorsa lava have been interpreted to originate from disintegrated nodules (Halldorsson et al., 2008). Rests of Cr-Al endiopside in a state of dissolution, are often found in association with the megacrysts and the groundmass carries a chemical fingerprint that can be traced to the dissolution of primitive clinopyroxene i.e. elevated Sc/Y ratios with lower $^{87}Sr/^{86}Sr$ ratios. Compared to the Thjorsa lava, all three formations studied here are formed under a glacier that cools the extruded lavas and hinders their flow. They are also much less voluminous. All three formations nevertheless contain isotopically unrelated xenocrysts and/or xenoliths in a state of dissolution The rapid cooling of the pillow lava compared with more voluminous lava flows, reduces xenocryst dissolution, and therefore the chemical fingerprint from the crust is more limited i.e. the xenocrysts had less time to dissolve and therefore have less impact on the chemical composition of their carrying liquids.

The sudden glacial unloading could have caused a shift in the phase boundaries in the Fo-Di-An system towards pyroxene (Presnall et al., 1978) causing the pyroxene in the crustal gabbros to become unstable. This would create interstitial melt (as noted in the nodules in Midfell and Maelifell) in the gabbro formation, making it easier for the mantle melts to disintegrate the gabbros. Another scenario of increased magma-crust interaction is the opening of a new fracture. The Hromundartindur sub-system has several eruption units that carry nodules and/or xenocrysts (Midfell, Maelifell, Sandfell, Tjarnarhnukur, Hromundartindur and Selholl) indicating crustal interaction. It seems as if the rifting in the Hengill-system shifted temporarily to the east, causing the magmatism in the sub-system. The seemingly temporary shift gave opportunity to unusually extensive crustal interaction.

The disequilibrium between the xenocrysts, xenoliths and their carrier magmas show that researchers must be careful when using radiogenic isotopes as mantle tracers. Mantle heterogeneity has been used as an explanation for isotopic variations between and within volcanic systems in Iceland (e.g. O'Nions et al., 1976; Stracke et al., 2003b; Zindler et al., 1979). Carrier magmas (excluding xenocrysts) even show isotopic variation (Halldorsson et al., 2008). This could either be because of uneven mixing of the aggregates of melts formed in the dynamic melting column or because of crustal interaction, i.e. assimilation of crustal material with isotopic signature different from the carrier magma.

5 Conclusions

The relationship between large phenocrysts and their host magma is fundamental for petrology. The hyaloclastites used in the present study, from Midfell and Maelifell, are unusually porphyritic with macrocrysts of olivine, plagioclase and clinopyroxene. They also contain gabbroic nodules with the same mineralogy and mineral composition with similar range as the macrocrysts. These are embedded in pillow lavas where the composition of the host magma is frozen as glass at the time of eruption.

The plagioclase crystals contain enough Sr for precision $^{87}Sr/^{86}Sr$ analyses to be made on single crystals and since all crystal species are found in the nodules it can be assumed that the three crystal species are cogenetic. So measurements were made on macrocrysts and gabbros and compared with previously analyzed host-pillow glasses (Magna et al., 2011). Also included were plagioclase megacrysts from Sandfell, a highly plagioclase rich hyaloclastite-ridge continuation of Maelifell.

The main result is clear; there is a significant $^{87}Sr/^{86}Sr$ difference between the plagioclase megacrysts and the gabbro from that of the host magma, represented by the pillow rims. The host magma has $^{87}Sr/^{86}Sr$ ratios that are similar to the lowest values reported from the Icelandic rift zones. The macrocrysts and gabbro-plagioclases have ratios that are similar to the average or common ratios found in the WVZ.

The similar ratios for macrocrysts and gabbros supports the suggestion that the macrocrysts are disintegrated nodules as also indicated by the similar limited compositional range of the minerals. The compositional range of the macrocrysts is also more primitive than expected from the host magma composition, as previously observed in other porphyritic occurrences.

The ridges under investigation in this study are all of late-glacial age. The rapid decompression due to the deglaciation that started 13-14 kyr ago caused increased magma production in the mantle below Iceland. This increased magma production along with the opening of a new fracture in the Hengill volcanic system could have led to a scenario ideal for comprehensive interaction between the mantle melts and the crust.

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