

Corona structure from arc mafic-ultramafic cumulates: The role and chemical characteristics of late-magmatic hydrous liquids

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The Genina Gharbia mafic-ultramafic complex consisting of peridotite, pyroxenite, and gabbro-norite represents a remnant of a hydrous magma chamber that was crystallized at the mantle-crust boundary. The hydrous nature of the magma is expressed in the high modal (up to 60%) of amphibole in cumulates and is reflected in variable textural and chemical features of the complex. One of the important manifestations of the hydrous nature is the development of a corona structure between olivine and plagioclase. The corona texture and mineralogy varied according to the activity of the interstitial liquid, temperature, and $P_{\text{H}_2\text{O}}$. The corona in peridotite is limited to thin (<100 microns) orthopyroxene and/or amphibole shells. Thick orthopyroxene-(orthopyroxene-spinel symplectites)-clinopyroxene-amphibole coronas are common in norite. Extensive analysis of different minerals of various textures by electron microprobe and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) revealed distinct chemical difference between the interstitial and cumulus phases of the corona. The corona pyroxenes and amphibole are depleted in V, Ti, Zr, and Nb and enriched in LREE, reflecting the LILE-rich and HFSE-depleted nature of the evolved hydrous liquid. The textural and chemical features of the corona are consistent with the formation of corona minerals at the late-magmatic stage. The orthopyroxene corona in peridotite crystallized directly from the evolved melt, while the amphibole corona developed at the expense of plagioclase. Variable corona minerals in norite are the result of direct crystallization from progressively evolved magma during cooling and continuous increase in $P_{\text{H}_2\text{O}}$.

Keywords: Corona structure, Mineral chemistry, Hydrous liquids, Late-magmatic, Mafic-ultramafic, Egypt

INTRODUCTION

The physical properties and phase relations of a basaltic liquid are considerably modified by the presence of a significant amount of H_2O in it (Andersen, 1980). Early fluid saturation commonly creates exsolved fluids that texturally and chemically modify the immediate cumulates and the fractionation path of the overlying liquids (Meurer and Boudreau, 1998). In addition to the fact that the exsolved hydrous liquids enhance the solid-state reactions between cumulate minerals, they react with the cumulus phases and form new mineral phases. A corona structure is one of the most recognized textures in liquid-bearing cumulates. The coronas of variable minerals were ob-

served between olivine and plagioclase in many gabbroic cumulates worldwide (e.g., Whitney and McLelland, 1983, Gardner and Robins, 1974). Corona mineral assemblages vary from one locality to another and within the same complex. The development of corona minerals was attributed to fluid assisted metamorphic (Lamoen, 1979) or magmatic (Joesten, 1986) processes. The physico-chemical conditions and compositions of reactants control the mineral diversity in coronas; amphibole is more stable than clinopyroxene at high $P_{\text{H}_2\text{O}}$, while orthopyroxene is stable at high temperatures.

Arc mafic magmas are commonly hydrous and undergo fractional crystallization and accumulation at different crustal depths. The increasing water content of such magmas helps to produce a thick sequence of differentiated cumulates with anorthitic plagioclase and interstitial amphibole. The amount of interstitial hydrous liquid increases during crystallization and causes very imperfect

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fractional crystallization processes (Claeson and Meurer, 2004).

In this contribution, we describe the corona mineral assemblage (including enstatite, diopside, and amphibole) from a Genina Gharbia (GG) mafic-ultramafic complex from the Eastern Desert of Egypt that was crystallized at the mantle-crust boundary at the base of a Precambrian island arc (Helmy et al., 2007). The coronas were observed at the olivine-plagioclase and spinel-plagioclase contacts in all plagioclase-bearing rocks. The major (microprobe) and trace-element (laser ablation inductively coupled plasma mass spectrometry, LA-ICP-MS) compositions of the cumulus, intercumulus, and corona minerals are presented. We show that the intercumulus amphibole and corona minerals were crystallized from the evolving hydrous liquid and also that the interstitial hydrous liquids assisted the mineral-mineral reactions during cooling. The corona mineral chemistry reflects both the chemical evolution of hydrous liquids and the chemistry of cumulus phases.

GEOLOGICAL BACKGROUND AND PETROGRAPHY

A complex of igneous and metamorphic rocks of Precambrian age covers about 88000 km² of the Eastern Desert (part of the Arabian-Nubian Shield) of Egypt. This complex comprises widespread exposures of ophiolites, mafic to intermediate metavolcanic rocks, granitoids, immature sedimentary rocks, and abundant intrusive mafic-ultramafic rocks. The intrusive mafic-ultramafic complexes form small elliptical bodies (3.5–11 km long and 0.5–2.5 km wide) and are located along major NE-SW-trending fracture zones. Immediate host rocks of the mafic-ultramafic complexes are calc-alkaline volcanic and granitoid rocks. Recent isotopic studies of one of these complexes revealed a Sm/Nd age of 770 Ma (Helmy et al., 2005). The evidence for island arc setting of these complexes comes from the general geologic context, field relations, mineralogy, and mineral and bulk-rock chemistry (Helmy and El Mahallawi, 2003; Farahat and Helmy, 2006).

The GG mafic-ultramafic intrusion is located about 175 km southeast of Aswan (Fig. 1). It covers an area that is 9.0-km long and 3.5-km wide and comprises peridotites, pyroxenite, and gabbro-norite. This association intruded Precambrian granitoids and island arc volcanoclastic rocks. The latter rocks are frequently garnetiferous within 50 m of the intrusion (Fredriksson, 1974). The GG intrusion is nonmetamorphosed; a complete sequence of cumulates is found.

Peridotites are made of olivine (60%–70%), orthopy-

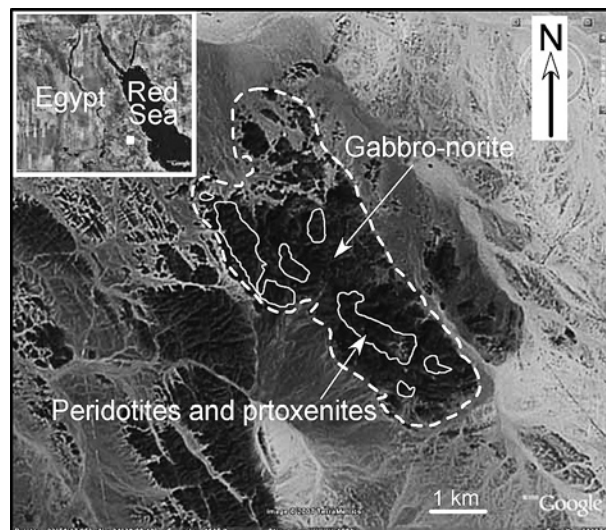


Figure 1. Location map and aerial photograph of the Genina Gharbia complex, Eastern Desert, Egypt.

roxene (30%–40%), amphibole (15%–30%), plagioclase (5%–25%), and clinopyroxene (1%–10%). Pyroxenites are made of orthopyroxene (>70 modal%) and intercumulus amphibole (Fig. 2A) and contain traces (<2% modal) of plagioclase. Abundant biotite and apatite are the characteristics of pyroxenites. Gabbro-norite is classified into norite and two-pyroxene gabbro. Norite is coarse-grained and made up of olivine (5%–8% modal), orthopyroxene (10%–15%), clinopyroxene (5%–15%), amphibole (10%–15%) and plagioclase (45%–60%). Orthopyroxene, clinopyroxene and amphibole form large oikocrysts that enclose plagioclase crystals (Fig. 2B). Biotite and apatite are common accessory minerals in pyroxenites and norite. Helmy (2004) reported high Cl contents in apatite. Two-pyroxene gabbro is made of orthopyroxene (40%–50%), clinopyroxene (20%–30%), plagioclase (20%–30%), and minor amphibole. The various rocks are fresh although some samples show weak alteration manifested by the serpentinization of olivine. Pressure estimates (10 kbar) and other petrological features (high NiO and Al₂O₃ contents in olivine and orthopyroxene, respectively) of GG mafic-ultramafic rocks correspond to a crystallization depth of 30 km at the mantle-crust boundary (Helmy et al., 2007). Similar estimates of the mantle-crust boundary beneath the Eastern Desert of Egypt were made on the basis of other petrological (e.g., Bonatti and Styrer, 1987) and geophysical (Pasyanos and Walter, 2002) data.

Interstitial amphibole is observed in all lithologies. In the peridotites, amphibole content is up to 30 modal% where it forms the groundmass that hosts olivine and pyroxenes. The amphibole is not evenly distributed in single thin sections, being more abundant in olivine-rich parts. In pyroxenites, amphibole is less abundant (up to 20%

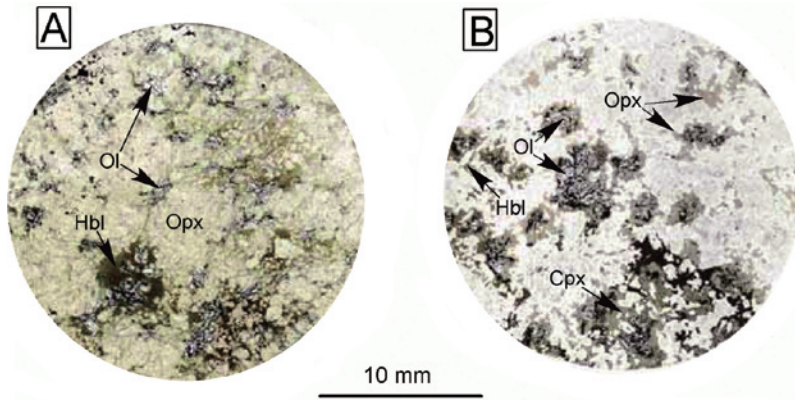


Figure 2. Plane-polarized light photomicrographs of entire thin sections (60-μm thick) of pyroxenite (A) and norite (B).

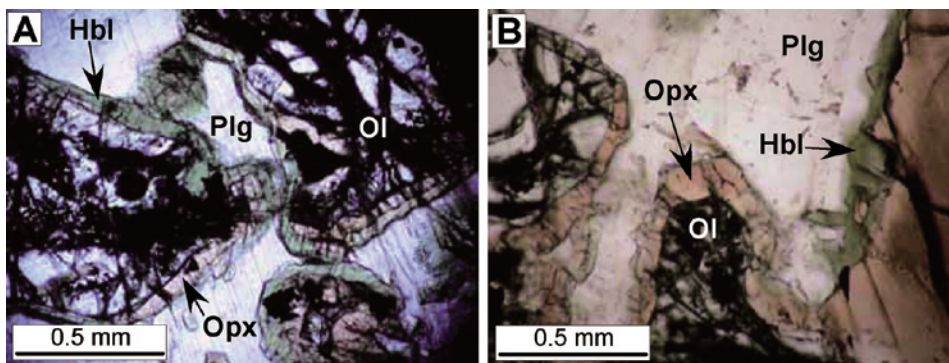


Figure 3. Orthopyroxene (Opx) and hornblende (Hbl) corona between olivine (Ol) and plagioclase (Plg). Note the smooth contact between orthopyroxene and olivine and the irregular contacts between hornblende and Plagioclase (Plg), also the continuity of corona and cumulus orthopyroxene in (B). Samples GG23 and 28 [(A), (B), respectively].

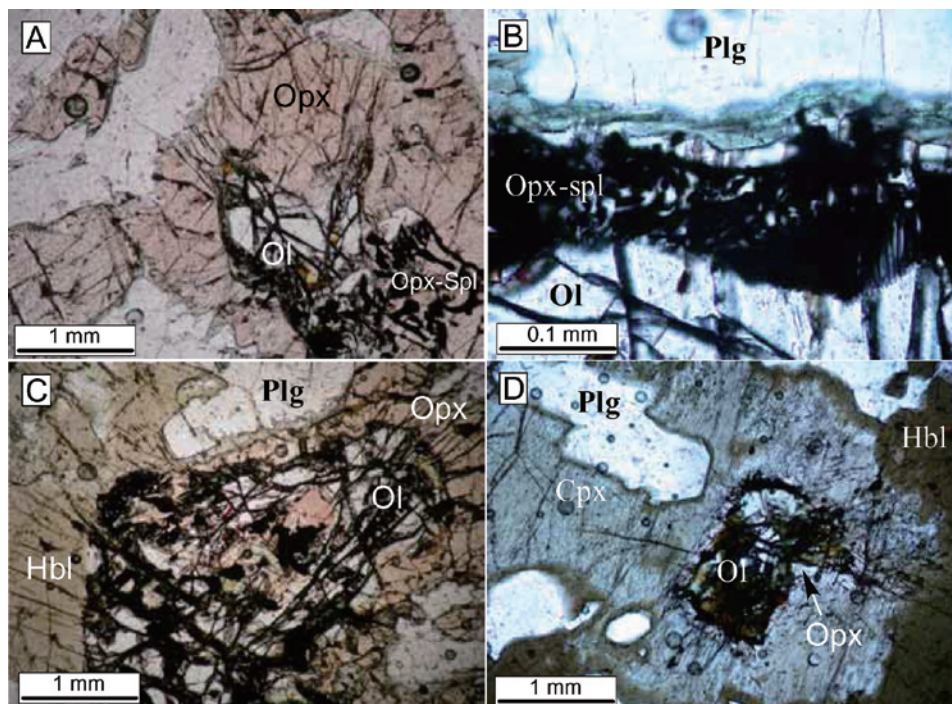


Figure 4. Corona textures in GG norite (sample GG16). (A) Orthopyroxene-spinel symplectites (opx-spl) replacing olivine and surrounded by thick orthopyroxene corona. (B) Thin orthopyroxene-spinel symplectites rimmed by thin clear orthopyroxene and hornblende (green). (C) Orthopyroxene and hornblende (Hbl) shells grow on the same olivine (Ol) crystal. (D) Thick clinopyroxene (cpx) corona enclose anhedral inclusions (adcumulate) of plagioclase (Plg) and overgrown by hornblende.

modal) and forms large continuous masses commonly attached to olivine and host pyroxenes (Fig. 2A). Amphibole and clinopyroxene in norite form large oikocrysts (Fig. 2B) that overgrow corona orthopyroxene on olivine.

CORONA STRUCTURE

Coronas of variable widths have been noted at the contacts of plagioclase with olivine and spinel. In the simple form, the coronas surrounding olivine consist of an inner shell commonly made of orthopyroxene and an outer shell almost entirely composed of amphibole. In pyroxenite and gabbroic rocks, amphibole reaction coronas between orthopyroxene (spinel) and plagioclase are the only type encountered.

Important features of corona structures at GG comprise:

- 1) The coronas in peridotite and pyroxenite are thin (100 μm), while those in olivine norite are commonly thick (>200 μm). There is a relationship between the modal abundance of the intercumulus amphibole and the thickness of the coronas.
- 2) The inner shells of orthopyroxene and amphibole may grow in the same thin section and around the same olivine grain (Figs. 3A and 4C); in particular the peridotite samples are characterized by smooth contacts between orthopyroxene and amphibole with olivine, while orthopyroxene shows a convex contact with olivine in norite.
- 3) Clinopyroxene shells were only observed in norite. When clinopyroxene shells develop, they are commonly thick and always grow on thin orthopyroxene and are overgrown by amphibole shells (Fig. 4D).
- 4) Amphibole inner shells were observed in all rock units containing the olivine-plagioclase and orthopyroxene-plagioclase pairs. Only in gabbroic rocks, amphibole coronas develop between plagioclase and clinopyroxene or spinel.

Corona structure in peridotites

The simple form of coronas between olivine and plagioclase in peridotites consists of an inner shell of enstatite-rich orthopyroxene and an outer shell of amphibole (Fig. 3). Single-shell coronas are also found surrounding olivine and consist of either orthopyroxene or amphibole. Amphibole shells commonly develop on small olivine grains totally included in plagioclase and at the contact between orthopyroxene and plagioclase. In detail, the orthopyroxene inner shell is made of columnar crystals that are radially arranged around olivine; the thickness of this shell never exceeds 50 μm . The thickness of the shell

around a single olivine crystal is almost uniform. A continuous contact between corona and cumulus orthopyroxene is noted (Fig. 3B). In few cases, relatively thick (about 100 μm) orthopyroxene corona was observed with irregular contacts with plagioclase. When present, the amphibole shell is of a variable width ranging from 50 to 100 μm ; sometimes, it contains small isolated grains of orthopyroxene (Fig. 3B) and exhibits irregular extensions inside plagioclase. When an amphibole shell grows directly on olivine, no inclusions of orthopyroxene are observed.

Corona structure in norites

Corona structures in norite are more extensive where the orthopyroxene, clinopyroxene, and amphibole shells are of considerably variable and larger thicknesses (up to 2 mm, Fig. 4A). Orthopyroxene-spinel (Fe-Al spinel) symplectite shells grow directly on olivine; they start as very fine-grained textures (Figs. 4A and 4B) and develop into medium-grained textures. An orthopyroxene-spinel shell is usually surrounded by pure orthopyroxene zone, while the outermost part against plagioclase consists of amphibole. The contact between orthopyroxene-spinel symplectites and olivine is commonly corroded (Fig. 4A). In addition to the orthopyroxene-spinel symplectites, both orthopyroxene and amphibole shells commonly contain small anhedral grains of spinel. Orthopyroxene coronas in norite are of variable widths ranging from 50 μm to 2 mm. Orthopyroxene and amphibole coronas may grow directly on the same olivine grain (Fig. 4C). The corona orthopyroxene, clinopyroxene, and amphibole commonly grow to form large oikocrysts. Textures suggest that the oikocrysts have grown after an initial accumulation of the cumulus (chadacrysts) of olivine. Pyroxene oikocrysts are common in the cumulates formed in gabbro-troctolite rocks (e.g., Mathison, 1987) and are commonly attributed to the reaction of the intercumulus liquid with cumulus phases (Irvine, 1980) to form "adcumulates."

MINERAL CHEMISTRY

Analytical techniques

The chemical compositions of olivine, orthopyroxene, clinopyroxene, amphibole, and plagioclase from different textures have been obtained. The major-element analysis of minerals was carried out with a JEOL JXA-8800 electron probe microanalyser (EPMA) at Department of Earth Sciences, Kanazawa University. The analyses were performed under an acceleration voltage of 20 kV, a specimen current of 20 nA, and a beam diameter of 3 μm . Data were corrected using a ZAF program. The concentrations

of the trace and rare-earth elements contained in amphibole, clinopyroxene, orthopyroxene, olivine, and plagioclase from different rock units were determined by a laser ablation (193-nm ArF excimer: MicroLas GeoLas Q-plus)-inductively coupled plasma mass spectrometry (Agilent 7500S) (LA-ICP-MS) at the Incubation Business Laboratory Center of Kanazawa University (Ishida et al., 2004). For analytical details and quality of data please see Morishita et al. (2004).

Major oxides

The most magnesian olivine ($Mg\# = 100Mg/(Mg + Fe^{2+}) = 86$) is found in peridotite, while the olivine in the gabbro is less magnesian ($Mg\# = 78$). A characteristic feature of the oxides is a positive correlation between the $Mg\#$ of olivine and those of the coexisting orthopyroxene, clinopyroxene, and amphibole (Fig. 5).

The cumulus and corona orthopyroxenes from GG are enstatite. Cumulus orthopyroxene is unzoned and of homogenous composition within the same rock. The Cr contents range from <0.1 to 0.5 wt%. The enstatite $Mg\#$ ranges from 87 in the most Mg-rich peridotite to 72 in the gabbro and correlate positively with the $Mg\#$ of the coexisting olivine (Fig. 5). The orthopyroxene from the orthopyroxene-spinel symplectites in norite has lesser CaO content (<0.3 wt%) than cumulus and oikocryst orthopyroxene (0.6 wt%–0.8 wt%).

Cumulus and corona clinopyroxenes are diopside and are characterized by the Fe enrichment accompanied by the enrichment of their TiO_2 and Al_2O_3 contents (salitic composition). Their Cr contents exhibit a negative trend and range from <0.1 wt% to 0.9 wt%. The $Mg\#$ of diopside varies from 87 (in peridotite) to 77 (in gabbro). The

$Mg\#$ of clinopyroxene correlates positively with the $Mg\#$ of the coexisting olivine and enstatite (Fig. 5). One diopside oikocryst in norite exhibits a high $Mg\#$ (93).

The amphiboles found in peridotite are ferrian tschermakite and pargasite; those in norite and gabbro, magnesiohornblende (Mogessie et al., 2001). Amphibole coronas formed on pyroxenes are edenite. Intercumulus and oikocryst amphiboles exhibit distinct chemical features from corona amphibole. The latter is commonly depleted in CaO, Cr_2O_3 , and TiO_2 . There is a systematic positive correlation of amphibole $Mg\#$ with $Mg\#$ of the coexisting olivine and pyroxenes (Fig. 5). Amphibole has generally high and variable Ti content and low $Mg\#$ than the coexisting olivine and pyroxenes (Fig. 5). Cr_2O_3 contents are constantly high (up to 1.5 wt%) in peridotite and decrease with differentiation (<0.2 wt% in gabbro).

The textural features and calculated K_D value ($K_D = 0.68$) of the cumulus clinopyroxene and orthopyroxene coexisting in gabbros suggest equilibrium ($K_D = [X_{MgSiO_3}/(1 - X_{MgSiO_3})][(1 - X_{MgCaSi_2O_6})/X_{MgCaSi_2O_6}]$, $X_{MgSiO_3} = Mg/(Mg + Fe)$ of orthopyroxene, $X_{MgCaSi_2O_6} = Mg/(Mg + Fe)$ of clinopyroxene; Kretz, 1963). The equilibrium temperatures using geothermometers based on the diopside-enstatite miscibility gap in coexisting pyroxenes (Wells, 1977) yielded temperatures of 950 ± 30 °C. As the chemical compositions of pyroxenes could have been modified during a subsolidus cooling stage, the calculated temperatures are not entirely reliable. The estimated temperatures from corona orthopyroxene and clinopyroxene in the norite are 920 ± 10 °C. The calculated K_D values of corona ortho- and clinopyroxene ($K_D = 0.75$) suggest equilibrium; therefore, we consider the estimated temperatures to be reliable.

Trace and rare earth elements

The amounts of trace and rare-earth elements contained in orthopyroxene, amphibole, and clinopyroxene from all lithologies are listed in Table 1. Important elemental ratios and primitive mantle-normalized rare-earth-element (REE) patterns are shown in Figures 6, 7 and 8.

Within the same sample, the amphibole chemistry varies with texture; in all rock lithologies the corona amphibole is generally depleted in trace elements relative to the intercumulus amphibole (Table 1). The V content of amphiboles generally increases with fractionation; the corona amphibole contains much lesser V than that intercumulus amphibole does (Table 1 and Fig. 6). Amphibole shows a wide range of Ti/V and Zr/Nb ratios (Fig. 6), indicating progressive fractionation; further, a wide range within the same rock unit suggests amphibole crystalliza-

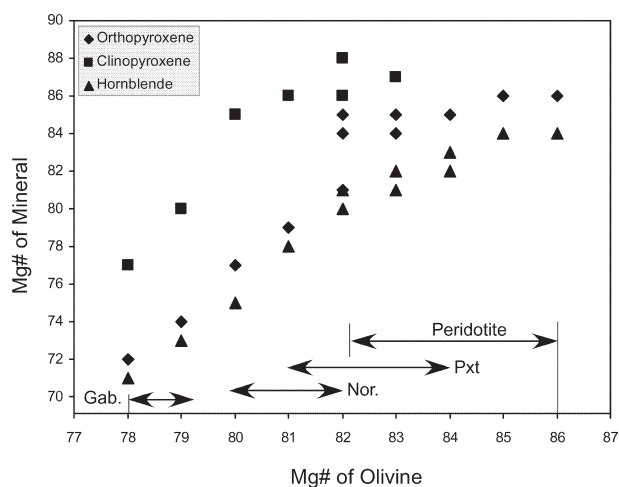


Figure 5. Variation of $Mg\#$ [$100Mg/(Mg + Fe)$] of olivine and coexisting mafic minerals from various rock units at Genina Gharbia.

Table 1. Chemical compositions of mafic minerals from different textures, Genina Gharbia area*

Rock type	Orthopyroxene				Amphibole					
	Gabbro	Norite			Peridotite				Peridotite	
Sample no.	GG22	GG16	GG16	GG16	GG23	GG23	GG16	GG16	GG23	GG23
Texture	C	C	O	Cn	P	Cn	O	Cn	I	Cn
Electron microprobe										
SiO ₂	55.21	55.60	55.66	56.27	55.52	56.02	46.23	44.55	43.46	43.76
TiO ₂	0.23	0.12	0.19	0.06	0.19	0.22	1.75	1.98	3.30	1.38
Al ₂ O ₃	1.26	2.06	1.48	1.80	1.99	2.01	11.35	11.55	12.07	12.15
Cr ₂ O ₃	0.04	b.d.l	b.d.l	b.d.l	0.37	0.39	0.13	b.d.l	1.33	1.38
FeO	16.55	13.67	14.68	12.24	9.56	9.61	9.26	9.11	6.15	6.41
MnO	0.43	0.32	0.38	0.31	0.21	0.18	0.13	0.10	0.06	0.08
MgO	25.34	26.93	27.26	29.19	30.84	29.98	15.72	16.31	15.76	16.21
CaO	0.95	0.76	0.73	0.31	0.63	1.62	11.45	11.25	11.67	11.84
Na ₂ O	0.00	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	2.12	2.53	2.82	2.06
K ₂ O	0.00	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	0.45	0.31	0.49	0.67
Total	100.06	99.51	100.40	100.19	99.39	100.05	98.57	97.69	97.18	96.01
Mg#	0.730	0.77	0.77	0.81	0.85	0.85	0.75	0.76	0.82	0.82
K _D **	0.68			0.75						
La-ICP-MS										
Sc	45	15	14	16	20	25	51	47	69	57
Ti	1878	936	1116	256	952	1249	10433	13179	20257	10867
V	137	69	59	18	84	97	326	355	432	378
Cr	461	3	74	b.d.l	2779	3493	947	38	9338	10271
Co	108	95	89	93	77	72	59	67	53	53
Ni	232	131	94	101	393	374	120	138	500	513
Rb	b.d.l	b.d.l	b.d.l	b.d.l	0.16	b.d.l	3.49	2.23	1.49	2.07
Sr	0.393	0.261	0.217	0.037	0.455	11.7	52.5	101	200	131
Y	4.44	2.86	1.37	1.69	0.74	1.42	26.6	36.4	41.2	29.7
Zr	2.51	7.81	3.46	22.6	2.00	2.47	91.3	72.3	50.3	94.7
Nb	b.d.l	0.005	b.d.l	b.d.l	0.033	0.046	2.81	2.86	4.93	7.39
Ba	0.110	0.088	b.d.l	b.d.l	0.733	3.037	33.0	45.7	98.5	98.1
La	0.033	0.024	0.021	b.d.l	0.039	0.301	3.27	3.11	4.71	7.88
Ce	0.172	0.128	0.065	0.017	0.085	0.769	14.9	14.4	22.1	33.4
Pr	0.04	b.d.l	b.d.l	b.d.l	b.d.l	0.08	2.63	2.69	4.31	5.41
Nd	0.228	0.134	0.064	0.044	0.047	0.323	14.5	16.6	26.3	26.8
Sm	0.124	0.078	0.032	0.044	b.d.l	0.092	4.36	5.68	8.98	6.68
Eu	0.044	0.029	b.d.l	0.014	0.012	0.091	1.36	1.61	2.33	1.79
Gd	0.285	0.162	0.069	0.066	0.041	0.125	4.70	6.72	9.94	6.27
Tb	0.06	0.04	b.d.l	b.d.l	b.d.l	b.d.l	0.752	1.03	1.45	0.939
Dy	0.634	0.372	0.166	0.204	0.096	0.206	4.96	7.03	9.00	5.90
Ho	0.174	0.112	0.051	0.056	0.031	0.056	1.01	1.43	1.69	1.14
Er	0.622	0.390	0.214	0.262	0.123	0.193	2.89	3.94	4.25	3.11
Tm	0.119	0.082	0.051	0.057	0.027	0.038	0.422	0.558	0.547	0.412
Yb	1.02	0.726	0.430	0.555	0.269	0.335	2.91	3.62	3.09	2.77
Lu	0.166	0.136	0.090	0.102	0.050	0.053	0.414	0.513	0.357	0.348
Hf	0.097	0.335	0.096	0.951	0.079	0.063	2.86	2.51	2.20	3.54

C, cumulus; I, intercumulus; P, poikilitic; O, oikocryst; Cn, corona; b.d.l, below detection limit.

* Electron microprobe data in wt%, La-ICP-MS in ppm.

** $K_D = [X_{MgSiO_3} / (1 - X_{MgSiO_3})] [(1 - X_{MgCaSi_2O_6}) / X_{MgCaSi_2O_6}]$, $X_{MgSiO_3} = Mg / (Mg + Fe)$ of orthopyroxene, $X_{CaMgSi_2O_6} = Mg / (Mg + Fe)$ of clinopyroxene (Kretz, 1963)

Table 1. (Continued)

Rock type	Clinopyroxene		Plagioclase	
	Gabbro	Norite	Norite	
Sample no	GG22	GG16	GG16	GG16
Texture	C	O	Cn	
Electron microprobe				
SiO ₂	52.99	53.85	53.64	50.79
TiO ₂	0.65	0.35	0.34	b.d.1
Al ₂ O ₃	2.97	2.57	2.41	31.99
Cr ₂ O ₃	0.27	0.86	0.83	b.d.1
FeO	6.43	4.02	3.93	0.07
MnO	0.17	0.16	0.16	b.d.1
MgO	14.43	15.99	15.71	b.d.1
CaO	22.51	23.04	22.88	14.86
Na ₂ O	0.48	0.37	0.35	3.18
K ₂ O	0.00	0.02	0.02	b.d.1
Total	100.89	101.22	100.26	100.91
Mg#	0.80	0.88	0.85	
K _D **				
La-ICP-MS				
Sc	129	95	93	0.98
Ti	3377	2667	2683	153
V	284	255	251	0.622
Cr	407	3254	6556	0.468
Co	52	39	33	0.075
Ni	152	59	54	0.916
Rb	b.d.1	0.740	0.710	0.085
Sr	22.8	20.6	22.1	483
Y	30.2	11.7	9.81	0.14
Zr	27.6	26.0	11.6	b.d.1
Nb	0.040	0.179	0.096	b.d.1
Ba	1.23	4.42	4.46	33.5
La	1.62	1.18	0.75	0.894
Ce	8.40	5.65	3.15	1.96
Pr	1.77	1.02	0.54	0.210
Nd	11.4	5.48	3.18	0.803
Sm	4.58	1.74	1.30	0.118
Eu	1.15	0.583	0.48	0.292
Gd	5.94	2.11	1.69	0.063
Tb	0.952	0.338	0.29	b.d.1
Dy	6.46	2.31	2.03	0.056
Ho	1.27	0.446	0.40	b.d.1
Er	3.32	1.34	1.07	b.d.1
Tm	0.444	0.189	0.14	b.d.1
Yb	2.90	1.32	0.99	b.d.1
Lu	0.390	0.192	0.13	b.d.1
Hf	1.37	0.621	0.45	b.d.1

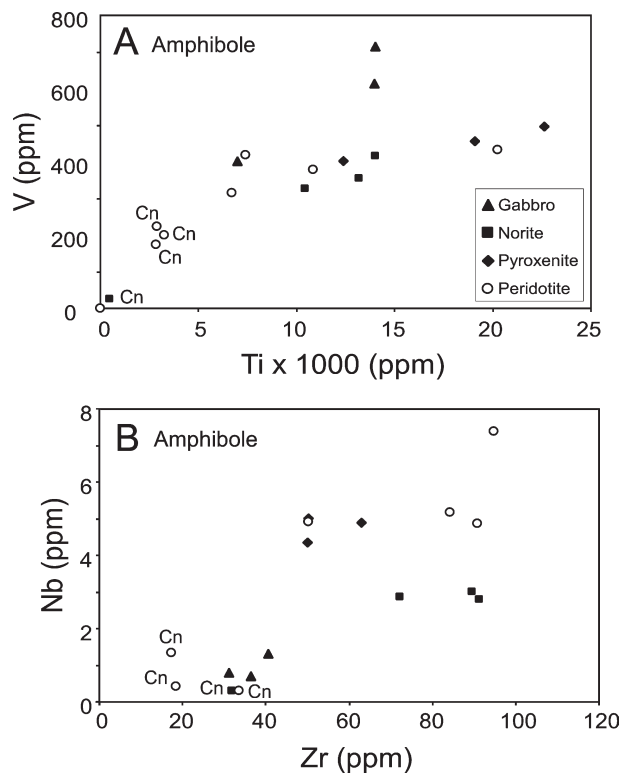


Figure 6. Variation plots of trace-element contents of amphibole. Analyses of coronas are labeled as "Cn."

tion from evolving interstitial hydrous liquid during cooling (e.g., Claeson et al., 2007). The REE patterns of intercumulus and oikocrystic amphiboles (Fig. 7) are parallel, reflecting normal fractionation. The corona amphiboles in norite and peridotite are depleted in REE, particularly the medium REE with strong positive Eu anomaly (Fig. 7A). Similar concentrations and patterns were recognized for late-magmatic amphibole in Eriksberg arc cumulates (Meurer and Claeson, 2002).

Similar to amphibole, clinopyroxene exhibits a positive correlation between its V and Ti (Fig. 8A), however, no difference exists between their corona, which are oikocryst or poikilitic clinopyroxenes. The diopside found in amphibole gabbros contains a higher total REE (46.7 ppm) than those found in norite (20 ppm) and peridotite (17.5 ppm) contain. Despite this difference in the REE content among lithologies, the LREE/HREE ratios (LREE and HREE denote light and heavy REE, respectively) ratios are similar (around 1.3). Clinopyroxene oikocrysts are slightly enriched in REE relative to corona clinopyroxene (Fig. 7B).

Corona orthopyroxene was found in peridotite and norite. Only one relatively thick orthopyroxene corona (developed at the expense of plagioclase) was analyzed by LA-ICP-MS; other coronas in peridotite were too thin to be analyzed. In all types of orthopyroxene (cumulus,

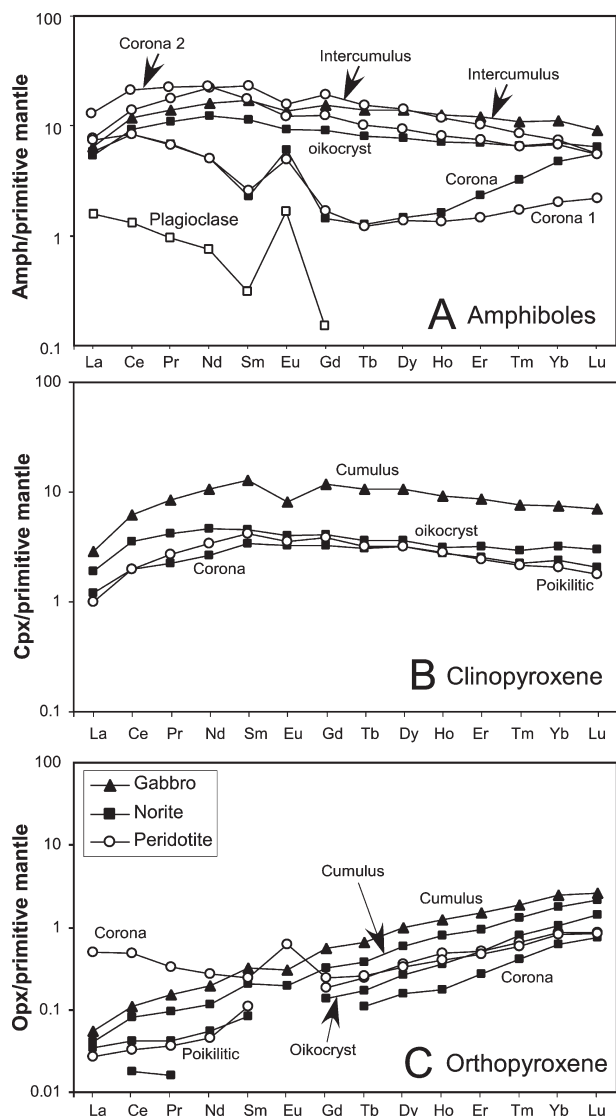


Figure 7. Mantle-normalized REE plots of amphibole and plagioclase (A), clinopyroxene (B), and orthopyroxene (C) from Genina Gharbia. Corona 1 in (A) is thin amphibole replacing plagioclase, while Corona 2 is thick (see text for explanation).

oikocrysts, and corona), the V contents correlate positively with the Ti contents. The corona orthopyroxene from norite contains the lowest V and Ti contents (Fig. 8B). Similar correlation between Sc and Ti contents is also revealed by orthopyroxene. The corona orthopyroxene in peridotite has the same HREE content as that of the cumulus variety, but it is highly enriched in LREE and exhibits a strong positive Eu anomaly (Table 1 and Fig. 7C). Textural evidence suggests that this LREE-enriched orthopyroxene developed at the expense of plagioclase. The corona orthopyroxene in norite has a lower REE content than that which the cumulus orthopyroxene from the same sample has. The REE content of oikocrystic orthopyroxene is higher than that of corona but lower than that of cu-

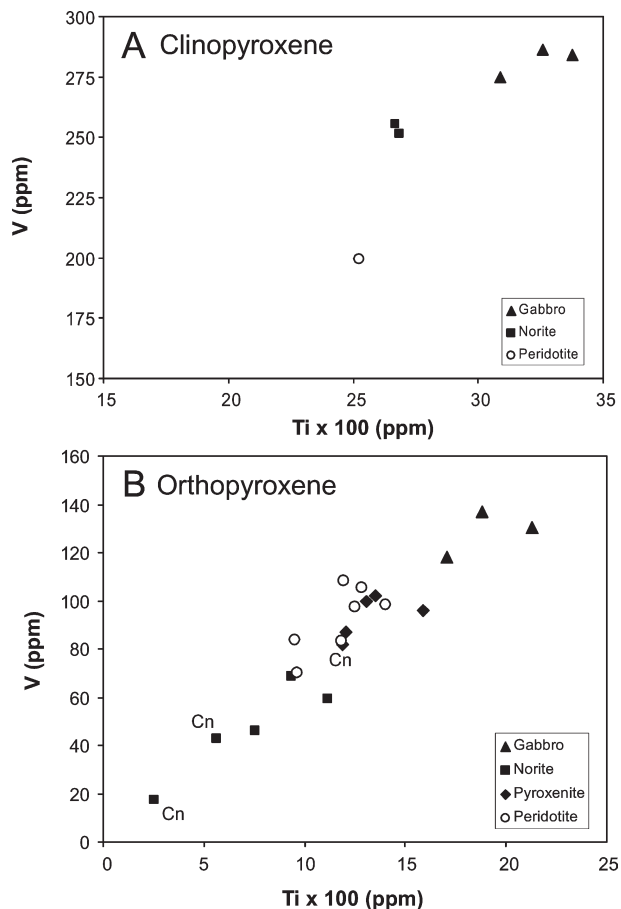


Figure 8. Variation plots of trace-element contents in clinopyroxene (A) and orthopyroxene (B). Analyses of coronas are labeled as "Cn."

mulus orthopyroxene (Fig. 7C).

DISCUSSION

The corona structures between olivine and plagioclase are common in mafic rocks. The development of corona structures is commonly attributed to the chemical disequilibrium between reactants (Claesson, 1998). The reactants are either solids (mineral-mineral reaction) or solids and liquids (solid-liquid reaction). The mineral-mineral reactions are important in metamorphosed rocks and occur through the diffusion of elements, usually catalyzed by the presence of a small amount of late deuteric fluid. Mineral-mineral reactions through diffusion result in thin homogeneous coronas. Solid-liquid reactions are more important during cooling of hydrous magmas and produce thick and more diverse mineral assemblages in the coronas. In all cases, the role of hydrous liquids either as catalysts or reactants is significant.

The GG mafic-ultramafic rocks are considered to be the remnants of a magma chamber that were crystallized

at the deep levels of an island arc (Helmy et al., 2007). Arc magmas are usually hydrous; water contents up to 5% are to be expected in some arc basalts (Grove et al., 2002). The hydrous nature of the GG parent magma is expressed in the dominance of amphibole, biotite, and other accessory minerals in the rock assemblage. The early crystallized olivine in the crystal mush (of peridotite) allowed the early crystallization of amphibole from the interstitial liquid (Holz, 1982). The modal abundance of interstitial amphibole indicates a bulk H_2O content of >1.5% (Beard et al., 2004). Excess liquids (rich in water) will remain even after the crystallization of amphibole from the interstitial hydrous liquid. Trapped hydrous liquid is believed to play a major role in the development of corona structures in cumulate rocks (Irvine, 1980) and has very substantial effects, particularly on the relative concentrations of highly compatible elements (O'Hara, 1993).

Corona microstructures are characteristic of amphibolite-granulite facies terrains (e.g., Whitney and McLelland, 1983; Grant 1988), however, these coronas were also described from nonmetamorphosed gabbros (e.g., Jøesten, 1986). In metamorphic terrains, the coronitic metagabbros are strongly foliated and amphibolitized, and garnet and/or olivine are important constituents of coronas (e.g., Lamoen, 1979; Whitney and McLelland, 1983). The corona development in metagabbros is attributed to solid-state or fluid-assisted metamorphic processes. Although we cannot completely exclude a metamorphic origin of the coronas, we recommend corona development during magmatic cooling, under the influence of changing compositions of interstitial hydrous liquids due to the following reasons:

- 1) The absence of high-grade metamorphic rocks in this region of the Eastern Desert (amphibolite facies metamorphic rocks are only exposed in gneissic domes, namely, the Meatiq-Sibai and Hafafit Domes, Fritz et al., 1996). The basement rocks of the GG area are either non- or weakly- (greenschist facies) metamorphosed.
- 2) The contact thermal metamorphism developed in the volcanosedimentary rocks in contact with the GG intrusion (Fredriksson, 1974) indicates that the intrusion was emplaced at this place and did not suffer from high-grade metamorphism.
- 3) No foliation or amphibolitization is noted in the GG mafic-ultramafic rocks.
- 4) The estimated temperatures in order of 920 °C for a coronitic assemblage suggest cooling-related phenomena (e.g., Dam, 1995).
- 5) The coexistence of both coronitic microstructures and stable plagioclase-olivine contacts on a thin-

section scale. This feature suggests that corona microstructures are limited to parts where hydrous magmatic liquids were available (e.g., de Hass et al., 2002).

The diversity of mineral assemblages and textures within a corona will depend largely on the chemistry of reactants, pressure, temperature, and P_{H_2O} . The relative importance of each of these factors will be reflected in the textures, mineralogy, and chemistry of phases in the coronas. At the GG area, the components of each corona differ from one rock to another and from one corona to another within the same rock. Despite differences in texture, the sequence of mineral growth within coronas in peridotite is orthopyroxene-amphibole. In norite, the sequence is orthopyroxene-(orthopyroxene-spinel)-clinopyroxene-amphibole. Variations in the melt composition can explain the layer sequence olivine-orthopyroxene, orthopyroxene-amphibole, orthopyroxene-clinopyroxene, and clinopyroxene-amphibole. We will discuss the mineral growth within the corona according to their appearance; this will reflect the chemical evolution and pressure, temperature, and P_{H_2O} conditions.

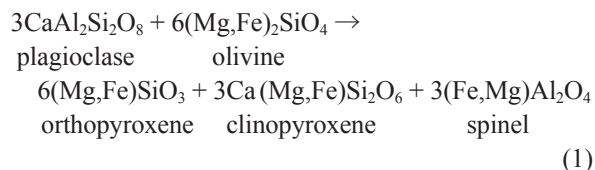
Orthopyroxene and orthopyroxene-spinel symplectites

Orthopyroxene is the first mineral to form in the GG coronas. The olivine-orthopyroxene contacts in peridotite are sharp with no signs of replacement, while those in norite are convex. It is likely that the orthopyroxene corona in peridotite crystallized directly from the magma. The absence of any contacts between corona and cumulus orthopyroxene (e.g., Fig. 3B) supports this suggestion. However, the irregular contacts between some orthopyroxene coronas and plagioclase in peridotite suggest that some orthopyroxene coronas develop at the expense of plagioclase (reaction 1). This may explain the relatively high LREE content of corona orthopyroxene (Fig. 7C). On the other hand, the convex contact between orthopyroxene-spinel symplectites and olivine in norite suggests that they grew at the expense of olivine by partial dissolution. Moreover, spinel could also be produced through the olivine-plagioclase reaction, as shown in reaction 1 below. The corona orthopyroxene in norite is depleted in trace elements and REE relative to the oikocrysts and cumulus orthopyroxene from the same rock (Table 1). However, the trace and REE contents of the corona orthopyroxene are still higher than those of olivine (generally, below the detection limit) from the same rock. Therefore, we suggest a contribution from the interstitial hydrous liquid to account for the relatively higher trace elements and REE content. The parallel REE patterns of corona and orthopyroxene oikocrysts suggest that the latter was formed from

the evolved hydrous liquid.

Clinopyroxene

Although clinopyroxene coronas are not observed in peridotite, we infer that corona clinopyroxene predated amphibole formation, as it was never observed growing on corona amphibole. Positive correlations between V and Ti (Fig. 8A, and Table 1) suggest that clinopyroxene crystallized from the in-situ evolving interstitial liquid (e.g., Claesson et al., 2007). The similar REE patterns of poikilitic, oikocrystic and corona clinopyroxene support this inference. An alternative mechanism to produce clinopyroxene is through the olivine-plagioclase reaction (reaction 1).

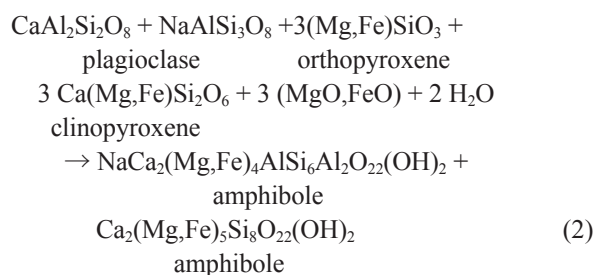


Amphibole

Amphibole coronas were observed in all plagioclase-bearing rocks. In peridotite, the amphibole coronas develop on olivine and orthopyroxene with sharp and smooth contacts with both, but irregular contacts with plagioclase (e.g., Fig. 3). The amphibole coronas grown on olivine are relatively thicker than those developing on orthopyroxene. Textural features suggest that amphibole grew at the expense of plagioclase (reaction 2). The trace-element contents of corona amphibole from peridotite are similar to those of intercumulus amphibole (Table 1). However, the REE are different; La and Ce contents are slightly higher in corona amphibole while HREE are lower than interstitial amphibole (Fig. 7A). The high LREE and low HREE of plagioclase (Fig. 7A) in the same sample can account for the difference between corona and interstitial amphibole. The strong positive Eu anomaly of corona amphibole points toward the evolved hydrous liquid contribution. Therefore, the formation of amphibole at the expense of plagioclase with a contribution from interstitial hydrous liquid is chemically supported.

In norite, the amphibole coronas are much thicker; amphibole oikocrysts develop around olivine. Due to the large thickness, and the trace elements and REE characteristics of amphibole oikocrysts on olivine, we suggest that the amphibole oikocrysts, formed directly from the interstitial hydrous liquid under high $P_{\text{H}_2\text{O}}$. The positive correlations between V/Ti and Nb/Zr (Fig. 6) in amphibole are consistent with the amphibole crystallization

from evolving interstitial hydrous liquid (e.g., Claesson et al., 2007). Thin amphibole shells between plagioclase and other mafics have lower REE contents relative to amphibole oikocrysts. The thin amphibole shells likely formed at the expense of plagioclase (reaction 2) with high input from the interstitial hydrous liquid. This hydrous liquid is likely to be oxidized and will increase the $\text{Eu}^{3+}/\text{Eu}^{2+}$ ratio. Eu^{3+} is highly accommodated in amphibole. This explains the strong Eu anomaly and higher concentration of REE compared with plagioclase in corona amphibole and the different REE patterns of corona amphibole and corona clinopyroxene from the same rock, the latter most having crystallized earlier from the evolved melt.



In addition to H_2O , the late-magmatic liquid contributed to the inputs and outputs of the above reactions and was probably responsible for the trace elements and REE contents of the corona phases, as discussed above.

Pressure, temperature and $P_{\text{H}_2\text{O}}$ evolution during corona formation

According to the above discussion, we believe that the coronas started to grow early at the magmatic stage and continued during cooling, aided by the progressive concentration of hydrous liquid. The sequence of mineral growth in coronas and chemical features indicate a gradual decrease in temperature and increase in $P_{\text{H}_2\text{O}}$ and oxygen fugacity. The first corona mineral to form is orthopyroxene at high temperature, followed by clinopyroxene and amphibole, the last corona mineral to form. The formation of clinopyroxene instead of amphibole in some parts of thin section indicates variable $P_{\text{H}_2\text{O}}$ in a small scale. The development of amphibole as the last stage of corona formation in all rocks and corona types reflects the increase $P_{\text{H}_2\text{O}}$ at the last stages of corona formation. The evolved hydrous liquids were depleted in HFSE but enriched in LILE as indicated by the corona mineral chemistry. Haas et al (2002) raised the question whether the corona shells developed simultaneously (single stage model) or their growth was separated in time. As the hydrous melt fractionation and cooling will lead to a progressive increase in H_2O concentration, we believe that the process

of corona formation at GG was a continuous process at least in norite.

CONCLUSIONS

The petrographic and mineralogical studies of the arc cumulate from GG, which was crystallized from a hydrous magma, reveals that interstitial hydrous liquid played a major role in the development of the corona structure. The high water content of the magma (~ 1.5 wt%) helped to stabilize amphibole early during cooling of the crystal mush at the floor of the intrusion. Further fractionation increased the H₂O content in the liquid and caused extensive textural and mineralogical changes. Corona orthopyroxene started to form at high temperatures directly from the evolved melt and locally by the partial dissolution of olivine. Amphibole was the last corona to form at high P_{H_2O} . Although the amphibole grew at the expense of plagioclase, the mineral assemblage in norite, including corona orthopyroxene, clinopyroxene, and amphibole oikocrysts, is only a stable arrangement due to the changes in the melt composition, drop in temperature, and increase in P_{H_2O} rather than the growth at the expense of another. Despite the mechanism of corona formation, the presence of interstitial hydrous liquid with olivine and plagioclase close to each other is a prerequisite for corona formation. The formation of oikocrysts and corona is a continuous process and occurs at a late-magmatic stage; it is analogous to the metamorphic formation of the corona structures in the cumulates crystallized from anhydrous magmas.

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