

PYROXENE MEGACRYSTS FROM ANORTHOSITIC ROCKS: NEW CLUES TO THE SOURCES AND EVOLUTION OF THE PARENT MAGMAS

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ABSTRACT

Two types of pyroxene megacrysts in anorthositic rocks each has distinct modes of occurrence and chemical compositions. *Type 1* pyroxenes, containing regularly-distributed plagioclase lamellae and blebs of exsolution origin, are interpreted to have crystallized within the mantle and at deep crustal levels. *Type 2* pyroxenes are free of included plagioclase, have low Al_2O_3 contents, higher Fe:Mg ratios, and are interpreted to have crystallized within the anorthositic complexes in which they occur.

From the mineral chemistry of these pyroxene megacrysts it is inferred that the parent magmas of many anorthositic complexes were derived from sources in the mantle which were undergoing fractional crystallization and periodically injecting magma to upper levels of the crust to complete crystallization. Magmas that crystallized anorthositic rocks within upper-crustal magma chambers existed at high temperatures and had very low water contents.

Widespread preservation of Precambrian high-pressure megacrysts in subalkaline igneous and meta-igneous rocks suggests that these and other megacrysts and xenoliths may eventually provide direct evidence to test models of Precambrian crustal and mantle evolution.

INTRODUCTION

Pyroxene megacrysts in anorthositic rocks, although relatively rare, have been reported by field geologists from localities in many parts of the world. Little detailed descriptive or chemical information, however, has been available for these pyroxenes. Preliminary results of studies of two distinct types of megacrysts are reported. *Type 1* pyroxene megacrysts containing regularly distributed and oriented lamellae of plagioclase are the principal subjects for discussion. *Type 2* pyroxene megacrysts occur in pegmatoidal masses and do not have included plagioclase. Initial assessment of these pyroxenes indicates that they contain much useful information applicable to interpretation of the petrogenesis of anorthositic complexes.

In a study of a large hypersthene crystal from the Lac St. Jean anorthosite, Quebec, Bertrand (1963) reported that the material contained more than 7 weight per cent Al_2O_3 . He also reported

that the crystal contained 14.2 volume per cent quartz as blebs and lamellae which he considered to have formed by exsolution. Material from a nearby locality examined during the present study suggests that plagioclase was misidentified as quartz. Philpotts (1966) reported plagioclase lamellae in clinopyroxene from a small anorthositic complex in southwestern Quebec. He considered origins of the plagioclase by exsolution and by simultaneous intergrowth but rejected the former because the plagioclase lamellae had compositional similarities similar to plagioclase in the host rock.

Hargraves (1962) described large pyroxenes in the Allard Lake anorthosite and referred to other examples reported in the literature. Recently, Wheeler (1973) and Morse & Wheeler (1974) described occurrences of apparently similar pyroxenes from the Nain complex in Labrador.

This paper is concerned primarily with *Type 1* pyroxenes from the Harp Lake Complex, Labrador, the Lac St. Jean anorthosite and the Morin Complex in the Grenville Province, Quebec, and the Egersund-Ogna, Ana-Sira, and Haaland-Helleren massifs of the Rogaland complex, southwestern Norway (Michot & Michot 1969). Six examples of *Type 2* pyroxenes from Michikamau (Labrador), Harp Lake, and Morin are also described and discussed.

Microprobe analyses reported here were done on an MAC instrument equipped with an energy dispersive system automated to produce simultaneous multi-element analysis and data reduction. Ten elements (Si, Al, Ti, Cr, Fe, Mn, Mg, Ca, Na and K) were analyzed in the pyroxenes and six elements (Si, Al, Fe, Ca, Na and K) in the plagioclases. Analyses reported are averages of 3 to 6 closely-agreeing spot analyses from different parts of a sample. Broad-beam microprobe analyses were performed using a beam 80-100 μm in diameter and are averages of three or more results in good agreement.

NATURE OF OCCURRENCES

Two distinct types of occurrence of very coarse grained or "giant" pyroxenes in anortho-

sitic rocks are described in this paper: *Type 1*—crystals range in size from 2 to 3 cm up to 0.5 m. They are most commonly orthopyroxenes but clinopyroxenes also occur. Sub-rounded to irregular masses occur singly or in groups in anorthositic host rocks. Larger masses may be single crystals or comprise two or more intergrown individuals. Only one sample (EC65-50) has been found so far that contains separate orthopyroxene and clinopyroxene crystals. Plagioclase megacrysts may or may not accompany the large pyroxenes but they are never intergrown with them. Orthopyroxenes are typically a deep, lustrous, bronze color and have a lamellar structure caused by regular parallel lamellae of plagioclase commonly visible by eye or with a hand lens. The lamellar structure is frequently warped and sometimes is crossed by kink bands (Fig. 1,E). *Type 2*—very coarse orthopyroxene or clinopyroxene occurs in pod-like or irregular pegmatoidal masses within anorthositic rocks. The pyroxenes are intergrown, commonly subophitically, with coarse plagioclase accompanied often by large opaque oxide mineral grains. The maximum size of these pyroxenes may reach 20 to 30 cm but on the whole they are smaller than Type 1, although there is considerable overlap in size ranges. Orthopyroxenes tend to be dull brown or khaki-colored and clinopyroxenes are dull dark green. Cleavage surfaces are commonly warped.

CHARACTERISTICS OF TYPE I PYROXENE MEGACRYSTS

Plagioclase within these pyroxenes has forms ranging from well-developed lamellae (in some samples these can be seen with a hand lens to be plates that extend throughout large cleavage fragment:) to long lenses, spindles, and fat

elongate blebs (Fig. 1). The long dimensions of these forms lie parallel to (100) of the host orthopyroxene or clinopyroxene. One sample, EC74-54 (Fig. 1,F) has a small proportion of elongate blebs oriented perpendicular to the dominant (100) direction and the resulting texture is reminiscent of inverted pigeonite. In the two clinopyroxenes, narrow orthopyroxene lamellae are present parallel to the plagioclase lamellae. In all pyroxenes, plagioclase within a single lamella is usually not optically continuous for more than a few millimeters and commonly much less. Adjacent plagioclase lamellae may be optically continuous, but only locally. In some specimens from meta-anorthosite (e.g. EC65-50, Fig. 1,D) the lamellar form is retained, but within thicker lamellae plagioclase has recrystallized into a granular habit.

Plagioclase compositions in most anorthositic complexes fall dominantly within a range of about 50 ± 10 mol per cent anorthite. Plagioclase within pyroxene megacrysts in all of the samples is more calcic and commonly much more calcic (Table 1) than typical anorthositic host rock plagioclase. Margins of larger lamellae and blebs are almost always slightly to markedly more anorthitic than central parts and microprobe scans indicate that the variation is continuous (Fig. 3). A range of lamella sizes exists in most specimens and narrower lamellae clearly tend to be more calcic than broader ones (in Table 1, thick lamellae are 25 to 200 μm wide, thin lamellae are 10 to 15 μm wide). Within most specimens there is a well-defined inverse correlation between anorthite content and lamella thickness. Strong optical zoning can commonly be seen within plagioclase lamellae and blebs. Because plagioclase within a lamella commonly changes optical orientation abruptly along its length and because plagioclase twinning with-

TABLE 1. SUMMARIZED MICROPROBE AND MODAL DATA FOR TYPE I PYROXENES

		Host Px. Away From Plag. Lam.		Host Px. Adjacent To Plag. Lam.		Mol % An In Middle Portions	Vol. % Plag. Within Host Plag.	Est. Wt. % Al ₂ O ₃ In Orig. Px.
		Ca:Mg:Fe at. %	Al ₂ O ₃ wt. %	Ca:Mg:Fe at. %	Al ₂ O ₃ wt. %			
Morin								
EC64-206		Cpx	47.1 40.1 12.8	5.96	46.9 41.9 11.1	3.15		
EC64-206	lamellar	OPX	1.0 69.2 29.9	2.93	0.9 69.7 29.4	2.26	82.8	90.5
EC64-318		OPX	0.8 69.0 30.2	2.59	0.8 69.0 30.2	2.59	57.2	74.9
EC65-50		Cpx	46.4 41.7 11.9	3.59	40.2 45.7 14.1	3.59	91.6	89.9
EC65-50		OPX	0.5 69.3 30.1	3.16	0.5 69.3 30.1	2.57	87.7	87.0
EC65-65		OPX	0.7 69.3 30.0	4.05	0.4 69.5 30.1	2.95	81.3	82.2
Harp Lake								
EC72-56A		OPX	1.0 76.9 22.2	3.24	0.6 76.7 22.7	2.74	64.6	91.3
EC72-149B		OPX	0.4 72.0 27.6	3.93	0.5 72.0 27.5	3.68	86.2	87.4
Lac St. Jean								
BT-07-06A-74(1)		OPX	0.4 73.5 26.1	3.57	0.6 73.7 25.7	3.57	55.8	74.6
BT-07-06A-74(2)		OPX	0.6 75.0 24.3	3.26	0.4 75.6 23.9	2.65	57.2	84.4
Egersund-Ogna								
EC74-2		OPX	0.6 76.8 22.6	5.56	0.5 77.1 22.4	5.37	82.2	85.6
EC74-33A		OPX	0.8 69.5 29.7	2.26	0.9 70.0 29.1	1.85	77.1	81.4
EC74-56A		OPX	0.9 72.4 26.8	2.00	0.8 72.7 26.5	1.83	65.2	78.8
EC74-72		OPX	1.1 66.0 31.0	1.81	0.7 68.6 30.8	1.60	75.9	77.1
Ana-Sira								
EC74-53		OPX	0.5 73.2 26.4	5.18	0.5 74.0 25.6	4.62	75.2	79.6
Haaland-Helleraen								
EC74-54		OPX	0.8 69.9 29.3	4.06	0.6 70.4 29.0	3.40	58.2	73.0

Total iron calculated as Fe

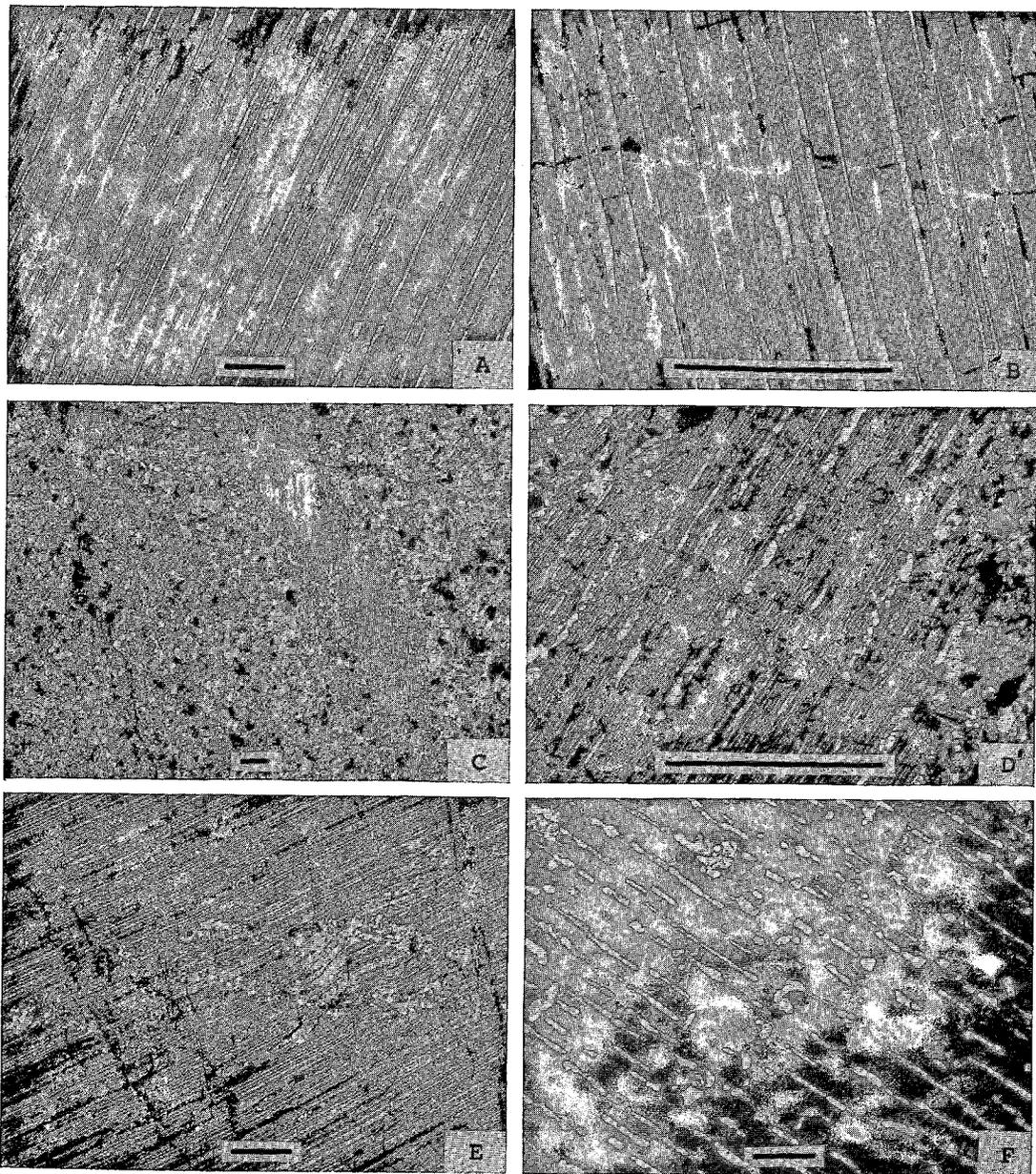


FIG. 1. Photomicrographs of Type 1 pyroxenes. A—BT-07-06A-74(1): Note regular distribution of plagioclase lamellae (light) in orthopyroxene; black lamellae and grains are opaque oxide. B—BT-07-06A-74(1): Note optical zoning in bleb, middle of photo; opaque oxides occur as lamellae and as grains within plagioclase lamellae. C—EC65-50: Relict deformed clinopyroxene augen in recrystallized matrix of low-Al pyroxenes and anorthitic plagioclase. D—EC65-50: At higher magnification clinopyroxene augen show granular plagioclase within thick lamellae; thin lamellae consist of plagioclase and orthopyroxene. E—EC65-65: Orthopyroxene with abundant fine plagioclase lamellae shows deformation and recrystallization; light area enclosed by the two granular zones is a kink band. F—EC74-54: Blebby exsolution in orthopyroxene; note suggestion of crystallographic control perpendicular to the dominant (100) direction; much of the plagioclase has well-developed twinning (not visible). All photomicrographs taken in cross-polarized light. Bars are 1 mm long.

in lamellae occurs at all angles to the walls, there cannot be a strong preferred structural orientation of plagioclase relative to the host pyroxene.

All of the pyroxene hosts contain variable proportions of opaque oxides as platelets, lamellae, rods and granules (Fig. 1,A,B). These lie parallel to (100) of the host and are interpreted to be dominantly or entirely of exsolution origin. There appears to be no correlation between amounts of opaque oxides and plagioclase contained within pyroxenes. Qualitative probe analysis of the opaque oxide minerals in several samples showed that they are Fe-rich with minor contents of Ti and Mn.

Most of the pyroxene hosts are significantly depleted in Al_2O_3 adjacent to plagioclase lamellae (Table 1, Fig. 3). Mg and Fe concentrations in host pyroxenes, however, remain remarkably constant throughout individual specimens. This is clearly shown in multi-element scans that show progressive Al depletion approaching plagioclase lamellae. Where zoning of Al and Si (depletion in Al and complementary increase in Si) occurs toward plagioclase lamellae it is the reverse of zoning in these elements in plagioclase toward the pyroxene host.

One sample (EC72-56A) from Harp Lake contains a very small amount (<<1%) of tiny, rounded olivine (FO_{81}) grains. Where two or more of these grains are closely associated they are distributed parallel to (100) of the host pyroxene. They appear to have been incorporated on growing pyroxene crystal faces.

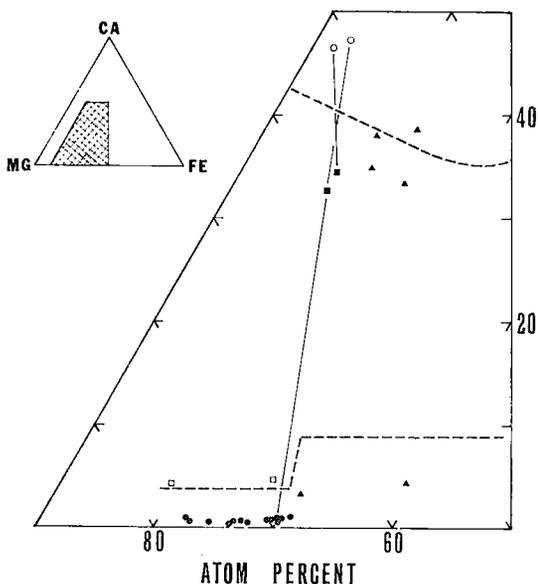


FIG. 2. Compositions projected on the pyroxene quadrilateral. Heavy dashed lines are Skaergaard pyroxene trends. Analyses from Tables 1, 2 and 3. *Type 1 pyroxenes*: solid dots are orthopyroxene hosts away from plagioclase lamellae; open squares are bulk orthopyroxenes (including plagioclase lamellae, Table 2, cols. 1 and 3); solid squares are bulk clinopyroxenes (including plagioclase lamellae, Table 2, cols. 5 and 6); open circles are clinopyroxene hosts away from plagioclase lamellae (Table 1). *Type 2 pyroxenes*: solid triangles are broad-beam probe analyses (Table 3). The long tie-line is for EC64-206 and joins the bulk composition to the compositions of the exsolved pyroxene components. The short tie-line joins the bulk clinopyroxene EC65-50 and its exsolved clinopyroxene component (the orthopyroxene component is too fine for analysis). The unusual orientation of the short tie-line is due to uniformly distributed, abundant, exsolved Fe-rich opaque oxides that were incorporated into the broad-beam analyses but not into the spot analyses of the exsolved clinopyroxenes.

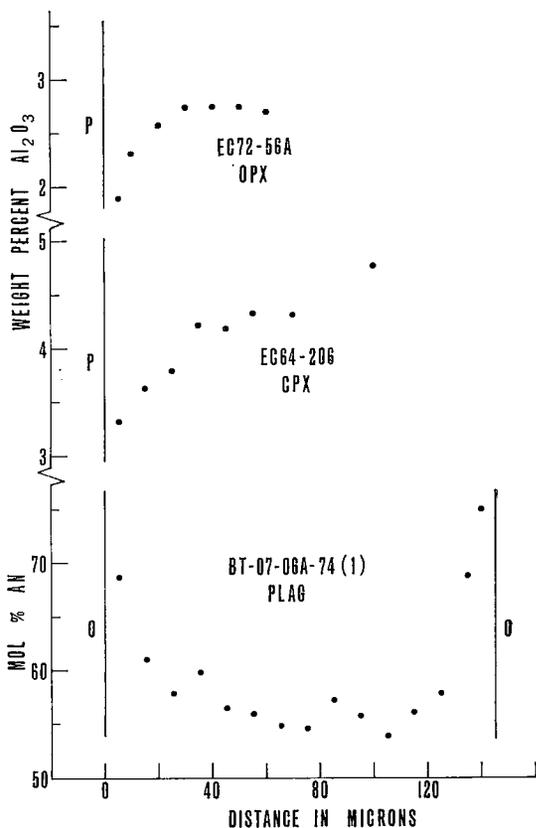


FIG. 3. Electron microprobe scans. Top — Al_2O_3 variation in orthopyroxene adjacent to a 40 micron plagioclase lamellae. Middle — Al_2O_3 variation in clinopyroxene adjacent to a 20 micron plagioclase lamella. Bottom — variation in anorthite content across a thick plagioclase lamella in orthopyroxene. P — plagioclase, O — orthopyroxene. Vertical lines are crystal margins.

CHARACTERISTICS OF TYPE 2 PYROXENE MEGACRYSTS

Macroscopically, Type 2 pyroxenes are not always readily distinguished from Type 1 pyroxenes. In thin sections, however, it is apparent that Type 2 pyroxenes do not contain lamellae or regularly disposed blebs of plagioclase. Fine rods and plates of opaque minerals and hematite are visible in most specimens. The clinopyroxenes contain fine, regular orthopyroxene lamellae parallel to (100) of the host. Commonly these lamellae are 5 μm or less in thickness and cannot be analyzed confidently with the probe. Clinopyroxene lamellae occur in orthopyroxenes EC73-161 and EC73-232A but are extremely rare and only a few microns thick.

All of the Type 2 pyroxenes have relatively low Al_2O_3 contents (Tables 2 and 3). Broad-beam microprobe analyses show that two of the clinopyroxenes are markedly subcalcic and two others have Ca contents comparable to Skaergaard pyroxenes (Fig. 2). The two orthopyroxenes are relatively calcic. Type 2 pyroxenes all have higher Fe:Mg ratios than Type 1 pyroxenes.

TABLE 2. CHEMICAL ANALYSES OF REPRESENTATIVE PYROXENES

Wt %	Type 1				Type 2			
	1	2	3	4	5	6	7	8
	EC72-56A	BT-07-0	6A-74(1)	EC64-206	EC65-50	EC64-133	EC73-161	
	OPX	OPX	OPX	CPX	CPX	CPX	OPX	
SiO ₂	50.36	52.45	49.19	51.95	50.35	50.70	49.96	52.36
Al ₂ O ₃	8.38	2.74	7.28	3.57	4.21	3.87	2.68	1.74
TiO ₂	0.18	0.23	0.62	0.18	0.62	0.40	0.76	0.47
Cr ₂ O ₃	0.23	0.26	0.08	0.06	0.11	0.16	0.12	0.08
Fe ₂ O ₃	1.82		3.62					
FeO	9.99	15.07*	13.19	16.87*	11.25*	11.33*	13.06*	19.95*
MgO	25.56	28.61	22.48	27.13	17.22	16.50	15.37	24.02
CaO	1.99	0.53	2.15	0.28	15.86	16.71	16.88	1.67
MnO	0.21	0.25	0.28	0.29	0.21	0.22	0.25	0.37
Na ₂ O	0.22	0.02	0.29	0.01	0.27	0.31	0.46	0.00
K ₂ O	0.00	0.00	0.02	0.00	0.03	0.03	0.02	0.00
P ₂ O ₅	0.01		0.01					
CO ₂	0.00		0.02					
H ₂ O*	0.66		0.26					
H ₂ O ⁺	0.24		0.18					
Total	99.85	99.96	99.67	100.47	100.13	100.23	99.56	100.68
	Cations per 6 oxygens X1000							
Si	1809	1893	1803	1882	1868	1884	1891	1926
Al	191	107	197	118	132	116	109	74
Al	163	10	117	34	52	54	11	1
Ti	4	6	17	5	17	11	22	13
Cr	7	8	2	2	3	5	3	2
Fe ³⁺	49		100					
Fe ²⁺	300	455	404	511	349	352	413	613
Mg	1368	1539	1227	1464	952	913	867	1316
Ca	76	13	84	11	630	665	694	66
Mn	6	7	9	9	6	7	8	12
Na	15	1	21	1	19	22	34	10
K	0	0	1	0	1	1	1	0
Total	3988	4039	3982	4037	4029	4030	4043	4023
	Atomic per cent							
Ca	4.2	0.6	4.6	0.6	32.6	34.4	34.8	3.3
Mg	76.3	76.7	67.6	73.7	49.3	47.3	44.1	66.0
Fe	19.5	22.7	27.8	25.7	18.1	18.2	21.0	30.7

Columns 1 and 3 are bulk analyses of large cleavage fragments by rapid methods. Analyst G. Bender.

Columns 2 and 4 are averaged microprobe analyses adjacent to plagioclase lamellae.

Columns 5 and 6 are averaged broad-beam microprobe analyses away from plagioclase lamellae.

Columns 7 and 8 are averaged broad-beam microprobe analyses.

* Total iron calculated as FeO

TABLE 3. SUMMARY OF BROAD-BEAM PROBE ANALYSES OF TYPE 2 PYROXENES

		Per Cent			Wt. % Al ₂ O ₃	
		Ca	Mg	Fe		
EC62-83	CPX	38.5	38.6	22.9	2.18	Mitchikamau, Labrador
EC62-351A	CPX	33.4	42.2	24.4	2.43	Mitchikamau, Labrador
EC64-133	CPX	34.8	44.1	21.0	2.68	Morin, Quebec
EC73-117	CPX	38.0	42.2	19.8	2.78	Harp Lake, Labrador
EC73-161	OPX	3.3	66.0	30.7	1.74	Harp Lake, Labrador
EC73-232A	OPX	4.2	56.8	39.1	1.48	Harp Lake, Labrador

Total iron calculated as Fe

DISCUSSION

From the data presented in Tables 1 and 2 and the foregoing description it is apparent that the conclusion that plagioclase exsolved from Type 1 pyroxenes is difficult to escape. In particular, the following features are consistent with exsolution of plagioclase but difficult to reconcile with epitaxial intergrowth: regular distribution and arrangement of plagioclase lamellae parallel to (100) of the pyroxene hosts; correlation of plagioclase lamellae sizes with their compositions; depletion of Al in pyroxene adjacent to plagioclase lamellae; characteristic strong reverse zoning to plagioclase lamellae adjacent to pyroxene; constancy of Fe and Mg in pyroxene hosts despite marked changes in Al and Si adjacent to plagioclase lamellae; lack of preferred lattice orientation of plagioclase within lamellae.

Experimental data on synthetic systems and natural rock compositions demonstrate that pyroxenes with high Al_2O_3 contents are stable at high pressures and temperatures (e.g. Green & Ringwood 1967; Green 1969). There is widespread recognition that aluminous pyroxenes in subalkaline rocks and in some alkaline rocks have crystallized at moderate to high pressures. Anorthositic rock suites have subalkaline characteristics (Emslie 1973) and are believed to have crystallized from magmas at or near silica saturation. It is therefore not possible to appeal to strongly silica-deficient magmas to account for the aluminous nature of Type 1 pyroxenes (see Table 1 for calculated original Al_2O_3 contents of the megacrysts). The fact that the pyroxenes have exsolved Al in the form of a silica-saturated phase (plagioclase) rather than spinel or corundum is supporting evidence that the original pyroxenes did not crystallize from silica-deficient magmas.

Kushiro & Yoder (1966), have demonstrated that reaction between anorthite and enstatite to produce aluminous pyroxenes plus quartz is promoted by pressure increase and by temperature decrease in the range of magmatic temperatures. The reaction is relatively more sensitive to pressure than temperature. If a similar reaction is inferred to apply to Type 1 pyroxenes, it follows that high temperature is very unlikely

to account for significant solid solution of plagioclase components in the pyroxenes, nor is cooling alone likely to have caused plagioclase exsolution.

By comparing analysis 1 with 2 and analysis 3 with 4 in Table 2 it can be seen that the original bulk pyroxenes contained a significant proportion of octahedral Al, whereas the pyroxene hosts after exsolution of plagioclase have drastically reduced octahedral Al contents. For most samples in Table 1 it can be seen that Al_2O_3 in pyroxene adjacent to plagioclase lamellae is significantly lower than in pyroxene distant from plagioclase (see also Fig. 3). This behavior of Al (accompanied by complementary changes in Si) is not associated with corresponding variations in Fe and Mg which remain essentially constant in most samples. This constitutes evidence that the exsolution process involved principally the components of plagioclase (ignoring the much smaller and variable amounts of Fe-rich opaque oxides also believed to be of exsolution origin).

The fact that plagioclase exsolved from the pyroxenes, although Ca-rich, is not pure anorthite is of particular interest. It indicates that the original pyroxenes contained the plagioclase components in solid solution as jadeite ($NaAlSi_2O_6$) as well as Ca Tschermak's molecule ($CaAl_2SiO_6$). Kushiro (1969) has shown that in clinopyroxenes an increase in pressure at constant temperature initially favors increasing solid solution of $CaAl_2SiO_6$ with respect to $NaAlSi_2O_6$. With further increase in pressure larger amounts of the $NaAlSi_2O_6$ component enter the clinopyroxene solid solution. If similar relationships hold for orthopyroxenes, an explanation is readily provided for the characteristic reversed zoning observed within exsolved plagioclase lamellae. Decompression of an initially homogeneous Type 1 orthopyroxene solid solution would be expected to result in initial exsolution of a $NaAlSi_2O_6$ -rich component followed by increasingly $CaAl_2SiO_6$ -rich components. As previously pointed out, in most specimens narrower lamellae are more calcic plagioclase as are margins of thicker lamellae.

Estimated Al_2O_3 contents of the original pyroxene solid solutions listed in Table 1 range from 3.9 to 9.4 weight per cent. The estimates take into consideration the proportions of various-sized lamellae, their compositions, and zoning, and are believed to be subject to errors not exceeding 10 per cent. By analogy with the results of existing experimental data, the more aluminous compositions are consistent with crystallization at pressures of 15 ± 5 kilobars. This suggests an origin within the mantle or perhaps near the base of an orogenically thickened

crust. The occurrence of small, rounded (residual ?) olivine grains in specimen EC72-56A provides a shred of support for a mantle environment.

It may be seen from Table 1 that estimated higher original Al_2O_3 contents of Type 1 pyroxenes are not clearly correlated with more calcic plagioclase lamellae compositions. If higher jadeite components are indicative of higher pressures of crystallization in orthopyroxenes, Type 1 pyroxenes with more sodic exsolved plagioclase may have crystallized at greater depths than suggested by consideration of their original Al_2O_3 contents alone.

Type 1 pyroxenes probably reflect crystallization conditions over a range of pressures. Those suggestive of higher pressures (higher Al, higher Na) and temperatures may provide an indication of the depths of magma segregation, or fractional crystallization, of the parental magmas of anorthosite complexes. Other specimens suggesting lower pressures of crystallization may have formed during the rise of the magmas to shallower levels. The megacrysts have a fairly limited range of Fe:Mg ratios (Fig. 2) — nevertheless there is a range (the Rogaland samples span nearly the entire range). This suggests that they may be products of fractionation processes that took place in magmas at depth, prior to final emplacement.

Type 1 pyroxenes were clearly unstable in the environment of the complexes into which they were carried. The pyroxenes responded by attempting to re-equilibrate to lower Al_2O_3 contents by exsolving plagioclase, a process that was arrested at various stages. Subophitic groundmass orthopyroxenes, without plagioclase lamellae, that have clearly crystallized in place, contain 1.3 to 2.1 weight per cent Al_2O_3 in anorthositic rocks of the Morin Complex and 0.1 to 2.0 weight per cent Al_2O_3 in anorthositic rocks of the Harp Lake Complex (unpublished data of the author).

The large sizes of Type 1 pyroxene megacrysts suggest that they originated as liquidus or near-liquidus phases of magmas at depth. Early crystallization of such pyroxenes would enrich the remaining liquids in components of intermediate plagioclase. Such fractionated liquids, when intruded to higher levels, would be expected to have plagioclase on the liquidus (e.g. Emslie 1970), a necessary condition for the parent magmas of anorthositic complexes.

The fact that Type 1 pyroxene megacrysts have survived without being resorbed after being brought into the large chambers that characterize anorthositic plutons is surprising. It suggests that they may have been brought up pe-

riodically and were preserved because of relatively rapid crystal accumulation and removal from contact with magmatic liquids.

Type 2 pyroxenes, although occurring in pegmatoidal masses, have compositions that are not consistent with precipitation from low-temperature, residual pegmatitic fluids. Two of the clinopyroxenes have Ca contents (Fig. 2, Table 3) suggesting that they crystallized at temperatures at least as high as similar Skaergaard pyroxenes and two others are substantially subcalcic, suggesting even higher temperatures of crystallization. The relatively calcic orthopyroxenes are also in accord with a high-temperature origin. All Type 2 pyroxenes have low Al_2O_3 contents (Table 3) and, considering their mode of occurrence, are interpreted as having crystallized within the intrusions. The pegmatoidal masses within which these pyroxenes occur may have formed in place from a trapped liquid pocket or they may have formed elsewhere in the intrusions where conditions favorable to large crystal growth existed and were subsequently disrupted and dispersed. The higher Fe:Mg ratios of Type 2 pyroxenes (Fig. 2) are consistent with their having crystallized later than Type 1 pyroxenes. The nature of these Type 2 pyroxenes provides good evidence that the magmas that crystallized anorthositic rocks were not rich in H_2O or other volatiles that depressed liquidus and solidus temperatures. On the contrary, the subcalcic clinopyroxenes suggest crystallization from unusually water-deficient magmas.

SUMMARY AND CONCLUSIONS

Evidence has been presented to support the interpretation that megacrysts of Type 1 pyroxenes from anorthositic rocks were once homogeneous aluminous pyroxene solid solutions. These pyroxenes are believed to have crystallized under moderate to high pressures at depth (some probably within the mantle) by analogy with pyroxenes produced under experimentally-controlled conditions. It is clear that Type 1 megacrysts crystallized under ambient conditions strongly contrasting with those under which they finally came to rest, suggesting that anorthositic complexes complete most of their crystallization at relatively shallow levels in the crust. The range of Fe:Mg ratios in Type 1 pyroxenes (e.g. Rogaland) suggests that they were produced by fractionating magmas at depth. This is in accord with other evidence supporting formation of anorthositic complexes by periodic intrusion of magma from fractionating sources at depth as opposed to solely *in situ* fractional

crystallization of large magma reservoirs within the crust (Emslie 1975, in press).

Type 2 pyroxene megacrysts occurring in pegmatoidal masses in anorthositic rocks have low Al_2O_3 contents and higher Fe:Mg ratios than Type 1 pyroxenes. Their compositions suggest that they crystallized under high- (perhaps unusually high-) temperature conditions within anorthositic complexes. Magmas that crystallized such pyroxenes must have had very low water contents.

High-pressure megacrysts have previously been reported mainly from alkalic basalt and basanite associations of relatively young geological ages. The data presented in this paper demonstrate that high-pressure megacrysts also occur in definitely subalkaline associations and are preserved in Precambrian (Proterozoic) rocks, some of which have been subjected to later intense deformation and metamorphism. One is encouraged to speculate that high-pressure megacrysts and perhaps deep crustal and mantle xenoliths may be preserved in other Precambrian igneous rocks. The nature of such relicts could provide important direct evidence on geotherms, crustal thicknesses, and evolution of the crust and mantle during the Precambrian.

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