

GARNET AND PLAGIOCLASE EXSOLVED FROM ALUMINUM-RICH ORTHOPYROXENE IN THE MARCY ANORTHOSITE, NORTHEASTERN ADIRONDACKS, NEW YORK

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ABSTRACT

Euhedral to subhedral Al-rich orthopyroxene megacrysts, up to $40 \times 13 \times 8$ cm in size, occur in tectonized gabbroic anorthosite and biotite leuconorite near their contacts with andesine anorthosite in the Marcy massif, northeastern Adirondacks, New York. Several of them contain lamellae of garnet ($Al_{4.5}Py_{35.5}Gr_{16}Sp_2Uv_1And_{0.5}$), Mg-, Cr- and Mn-bearing ilmenite, and clinopyroxene in addition to calcic plagioclase, An_{53-97} , all exsolved as rods, spindles, and doubly terminated plates lying parallel to (100) of the bronzite hosts, Mg_{70-76} . Other such megacrysts of the same Mg content, however, lack the garnet. Compositions of these giant crystals of bronzite and of the coexisting plagioclase, Mg_{71} and $An_{54.5}$, are out of chemical equilibrium with their analogues in the enclosing anorthositic host-rocks, in which hypersthene and plagioclase are Mg_{61-65} and An_{48-50} , respectively. Host rocks are garnet-free. Field relationships, along with mineralogical, chemical and isotopic data, are consistent with an interpretation that these megacrysts are derived from primitive, deep-seated material originating at depths on the order of 70 km, where they crystallized in gabbroic to anorthositic liquids at liquidus T above $1200^\circ C$ and P in the range of 20–25 kbar; they exsolved garnet and plagioclase when very slowly cooled to a lower T at a shallower crustal level and were emplaced in fractured anorthositic rocks which subsequently underwent granulite-facies metamorphism.

Keywords: aluminum-rich orthopyroxene, garnet exsolution, plagioclase exsolution, Adirondacks, New York, anorthosite, Marcy massif.

SOMMAIRE

On trouve des mégacristaux d'orthopyroxène, idiomorphes à hypidiomorphes, atteignant jusqu'à $40 \times 13 \times 8$ cm de grandeur et riches en Al, dans l'anorthosite gabbroïque-noritique tectonisée et la leuconorite à biotite, près de leurs contacts avec l'anorthosite à andesine, dans le massif de Marcy de la chaîne des Adirondacks (New York). Plusieurs de ces mégacristaux contiennent des lamelles de grenat ($Al_{4.5}Py_{35.5}Gr_{16}Sp_2Uv_1And_{0.5}$), d'ilmenite à Mg, Cr et Mn, et de clinopyroxène ainsi que de plagioclase calcique (An_{53-97}), toutes exsolvées en bâtonnets, fuseaux, et plaquettes doublement terminées, parallèles à (100) de l'hôte bronzitique (Mg_{70-76}). D'autres mégacristaux de la même teneur en Mg sont sans grenat. Les compositions Mg et An (71 et 54.5) des mégacristaux sont en déséquilibre chimique avec leurs analogues des hôtes anorthositiques

(Mg_{61-65} et An_{48-50}). Les roches encaissantes sont sans grenat. Les relations de terrain ainsi que les données minéralogiques, chimiques, et isotopiques s'accordent bien avec l'interprétation que ces mégacristaux dérivent d'une source primitive, située à une profondeur de l'ordre de 70 km, où ils ont cristallisé dans des liquides allant de gabbroïques à anorthositiques, à une température de liquidus supérieure à $1200^\circ C$ et à une pression entre 20 et 25 kbar. Ils ont exsolvé le grenat et le plagioclase en se refroidissant très lentement aux températures plus basses associées aux niveaux moins profonds de l'écorce terrestre, et ont été mis en place dans des roches anorthositiques fracturées qui ont ensuite subi un métamorphisme au faciès de granulite.

Mots-clés: orthopyroxène riche en Al, lamelles d'exsolution de grenat, lamelles d'exsolution de plagioclase, anorthosite, chaîne des Adirondacks, New York, massif de Marcy.

INTRODUCTION

Aluminum-rich orthopyroxene megacrysts that have exsolved calcic plagioclase occur in anorthosite massifs at many localities, including the Adirondacks. Studies of these were made by Balk (1944) from the Port Kent locality in the Adirondacks (Fig. 1), by Osborne (1949) from the Morin massif and by Hargraves (1962) from the Allard Lake body, both in Quebec, by Wheeler (1973) and Morse (1975) from the Nain massif in Labrador, and more recently by Dymek & Gromet (1984) from the smaller St-Urbain anorthosite massif in Quebec. Both Osborne (1949) and Hargraves (1962) stated that the megacrysts transgress the host anorthosite rock, and Balk (1944) thought that they were emplaced late, in a volatile-rich phase of the anorthosite. Wheeler (1973) ascribed their genesis to higher temperatures of crystallization than those in the enclosing anorthosite magma and to variations in conditions in the magma chamber; he concluded that they were xenocrysts. Emslie (1975, 1980), in more extensive studies of Al-rich orthopyroxene from Harp Lake and numerous additional localities, also concluded that these are exotic xenocrysts, but that they represent relics of early, high-temperature and high-pressure (> 15 kbar) crystallization, ultimately convected and emplaced at shallower crustal levels into incompletely crystallized anorthosite. Morse (1975) offered the interesting idea that the megacrysts from Labrador were formed *in situ* under conditions of aluminum supersaturation at essentially the same temperature and pressure conditions as in the crystallizing anor-

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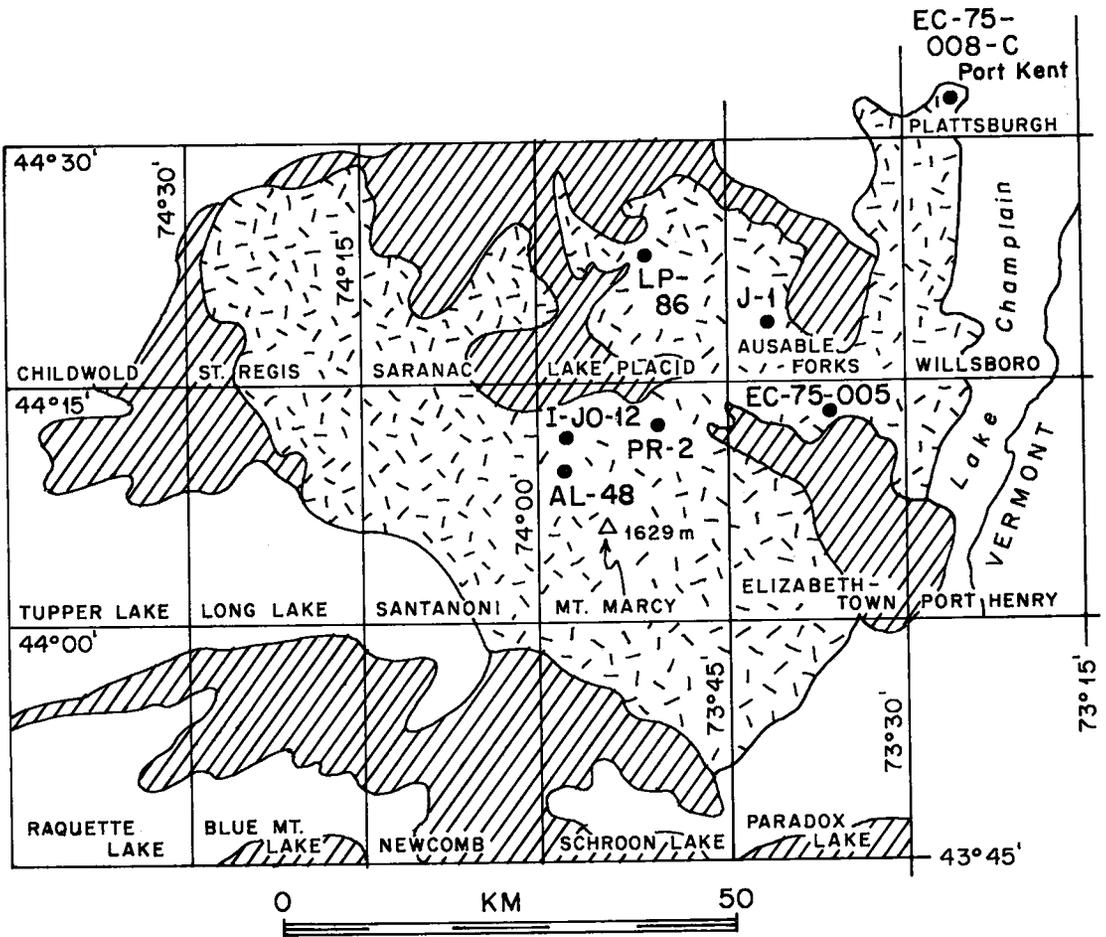


FIG. 1. Geological index map of northeastern Adirondack Mountains, N.Y., showing Marcy anorthositic massif (line stipple), quartz ferromanganese gneiss series (rules), and "Grenville" supracrustal rocks (clear). Points are locations of Al-rich pyroxene megacrysts discussed in text.

thosite host-magma. Dymek & Gromet (1984) concurred, and favored an *in situ* paragenesis for the orthopyroxene megacrysts from St-Urbain. The anorthosites of the world may be considered to represent a very large elephant, and most of us have seen only the trunk, the tusk, or the tail; it thus remains conceivable that Al-rich orthopyroxene megacrysts may have formed by different processes in different massifs.

In a landmark study of pyroxene megacrysts from anorthosites of the world, Emslie (1975) proposed a two-fold classification: Type I consists of orthopyroxene or clinopyroxene rich in Al (about 4–8% Al_2O_3) and contains abundant exsolution lamellae of calcic plagioclase; a megacryst of Type II consists of either orthopyroxene or clinopyroxene, is lower in Al (1.5–2.8% Al_2O_3), and contains blebs and intergrowths of opaque oxides. In this study, we

report on a third category, represented by those pyroxene megacrysts having Al contents of essentially the same magnitude as Emslie's Type I, but that have exsolved garnet in place of, or in addition to, calcic plagioclase.

Emslie's (1975) classification of pyroxene megacrysts in anorthositic rocks may be modified to include the garnet lamellae. Such modification might be as follows: Type I: Al-Opx/ga or Al-Opx/pl and Al-Cpx/ga or Al-Cpx/pl; Type II: Al-Opx/cp or Al-Opx/il and Al-Cpx/il or Al-Cpx/op, where the names of both the megacryst and principal mineral in the exsolution lamellae are apparent.

Microscope observations made of a number of these megacrysts, collected during bedrock mapping of the Mt. Marcy quadrangle in the Adirondacks and on numerous field trips to other localities, are summarized in Table 1, which gives data on the maxi-

imum index of refraction, optically determined Mg content Mg_{γ} , and the nature of the exsolution mineralogy. In general, those crystals of aluminous orthopyroxene having an Mg_{γ} content greater than 66 exsolve either calcic plagioclase or garnet, whereas those with lower Mg content tend to exsolve only clinopyroxene along with smaller amounts of opaque oxides. Rutile, in addition to ilmenite, occurs sporadically in many of the megacrysts.

It will be obvious from Table 1 that values for the optically determined magnesium content, $Mg_{\gamma} = 100Mg/(Mg + Fe^{2+} + Fe^{+3} + Mn)$, from Jaffe *et al.* (1975), show closer agreement with those for atomic percent magnesium, $Mg = 100Mg/(\text{the sum of octahedral cations in } M1 \text{ and } M2 \text{ sites}) = (Mg/2 \text{ for opx, and } Mg/1 \text{ for cpx})$ than those for $x_{Mg} = Mg/(Mg + Fe^{2+})$ from data of Table 2 in this paper. Values for Mg will be minima and those for x_{Mg} , maxima; because these Al-rich pyroxene megacrysts contain relatively large amounts of non-quadrilateral components, the difference will be large. Just as Mg does not equal x_{Mg} , neither can it be equated with %En, because in these examples of Al-rich pyroxene, the presence of a MgTs ($MgAl_2SiO_6$) component in addition to an En component is likely. Using a similar notation, the optically determined anorthite content of plagioclase will be given here as An_{α} , as in Figures 2 and 3, and the value derived from electron-microprobe data simply as An, which will usually be essentially the same as x_{Ca} .

Most anorthosite massifs, including the Marcy, show a normal trend of magmatic fractionation, or a tendency for the proportion of the ferrosilite in orthopyroxene to increase sympathetically with albite in plagioclase (Fig. 2). The Adirondack anorthosites also possess a metamorphic overprint, manifested by the presence of garnet + augite (containing fine

pigeonite exsolution-lamellae) that have grown at the expense of orthopyroxene + oxide minerals + intermediate plagioclase. In the Marcy anorthosite, optical measurements show that these reactions proceed readily when the $Fe/(Fe + Mg)$ content of the matrix orthopyroxene, Fe_{γ} , exceeds 45, and, conversely, are inhibited for more magnesian compositions (Fig. 2). Very similar limitations on garnet-forming reactions were reported by Martignole & Schrijver (1973) for the Morin anorthosites using chemical data. In addition to the Adirondacks and Morin, this chemical control on garnet formation in metamorphosed anorthosites is also dramatically demonstrated along the well-exposed pavement and cliff outcrops of the Egersund-Ogna anorthosite massif of Rogaland, Norway; although metamorphosed, they do not contain a grain of garnet, as the Mg content of the matrix orthopyroxene is consistently greater than 60. It was thus rather surprising to find garnet exsolution lamellae in magnesian orthopyroxene megacrysts such as PR-2, with Mg_{71} , as they are enclosed in garnet-free orthopyroxene-bearing gabbroic anorthosite with a matrix orthopyroxene of Mg_{61-65} (Fig. 2, Table 2). The garnet-bearing orthopyroxene megacryst and the garnet-free matrix orthopyroxene are out of chemical equilibrium by 9 to 12% Mg. The same magnitude of disequilibrium of megacryst and matrix orthopyroxene is also present in sample I-JO-12 and in all other such pairs examined from the Marcy anorthosite massif (Fig. 3). This was first noted by Wheeler (1973) in his studies of anorthosite from Nain, Labrador, in which he found that "giant orthopyroxene megacrysts", normally much richer in Mg than host-rock orthopyroxene, could also, on occasion, be lower in Mg in some high-temperature host-rocks (Fig. 3). Using optical data, Wheeler also found comparable differences of 10-12% Mg in megacryst and matrix orthopyrox-

TABLE 1. Mg CONTENT* AND NATURE OF EXSOLUTION LAMELLAE IN PYROXENE MEGACRYSTS FROM ANORTHOTIC ROCKS FROM THE MARCY MASSIF, ADIRONDACKS, S.W. NORWAY, ONTARIO, AND QUEBEC

ORTHOPYROXENE MEGACRYSTS							
Sample	Locality	Host Rock	n_{γ}	Mg_{γ}^1	Mg^2	x_{Mg}^3	Exsolution Lam.
PR-1L	Porter Mt.	Gab. Anor.	1.7065	66			Pl, Ilm
PR-2 (core)	Porter Mt.	Gab. Anor.	1.6995	71.5	70.9	0.763	Gar, Ilm, Cpx
PR-2 (rim)			1.703	69	64.7	0.668	Pl, Ilm, Cpx, Rt
I-JO-12	Mt. Jo	Leuconorite	1.702	70	69.3	0.746	Pl, Ilm, Cpx, Rt
A1-4600	Algonquin Mt.	Anorthosite	1.709	65			Pl, Ilm
A1-4600	Algonquin Mt.	Anorthosite	1.717	58			Cpx
A1-2	Algonquin Mt.	Pyroxenite	1.717	58			Cpx
NK	Noonmark Mt.	Gab. Anor.	1.716	59			Cpx
HS-3	Haystack Mt.	Anorthosite	1.717	58			Cpx
HL	Heart Lake	Leuconorite	1.7075	65.5			Cpx, Rt
An-5	Allen Mt.	Leuconorite	1.708	65			Cpx, Rt
RB-9	Giant Mt.	Gab. Anor.	1.709	64			Cpx, Ilm
LP-86	Flume, N.Y. 86	Anorthosite	1.7025	69			Pl, Ilm, Cpx, Rt
QG-N	Port Kent	Anorthosite	1.696 ⁴	74			Not indicated
EG-N	Ogna, Norway	Anorthosite	1.702	70			Pl, Ilm
EG-N	Egersund,	Anorthosite	1.696	74			Pl, Ilm
SQ-Q	Lac St. Jean	Anorthosite	1.703	69			Ilm, Pl
CLINOPYROXENE MEGACRYSTS							
J-1	Jay Mt.	Gabbro Peg.	1.715	75			Ilm, Opx
A1-4240	Algonquin Mt.	Anorthosite	1.717	71			Opx, Pig
Gv-82-12	Parry Sound, Ont.	Anor. Gneiss	1.715	75	79.0	0.867	Gar, Opx, Ilm

*determined optically from n_{γ} index of refraction. ¹from optical-composition curves of Jaffe *et al.* (1971), where $Mg_{\gamma} = 100Mg/(Mg + Fe^{2+} + Fe^{+3} + Mn)$. ²from microprobe analysis (Tables 2 and 3, this paper), where $Mg = 100Mg/(\Sigma C.N. VI \text{ cations})$. ³from microprobe analysis (Tables 2 and 3, this paper), where $x_{Mg} = Mg/(Mg + Fe^{2+})$. ⁴from measurements by Balk (1944).

TABLE 2. CHEMICAL COMPOSITION OF MATRIX AND MEGACRYST ORTHOPYROXENE AND EXSOLUTION LAMELLAE

	Sample: PR-2*								Sample: I-JO-12*			
	Matrix		Megacryst		Exsolution lamellae				Matrix		Exsolution lamellae	
	Opx	Opx	core Opx	rim Opx	Gar	Pl	Pl	Ilm	Opx	Opx	Pl	Ilm
SiO ₂	51.34	52.31	52.82	51.78	39.76	54.41	46.29	--	51.58	52.21	43.76	--
TiO ₂	0.08	0.03	0.13	0.41	0.04	--	0.07	50.88	0.06	0.08	0.03	49.55
Al ₂ O ₃	1.32	3.51	1.85	2.80	22.43	29.08	33.77	0.20	1.89	4.38	34.88	--
Cr ₂ O ₃	0.03	0.16	0.01	0.07	0.34	0.03	0.05	0.50	0.03	0.05	--	0.19
Fe ₂ O ₃	--	--	--	--	--	--	--	4.61	--	--	--	7.35
FeO	24.16	17.33	20.81	6.75	21.66	0.61	0.77	39.35	24.54	17.30	0.61	40.51
MnO	0.48	0.26	0.41	0.16	0.91	0.08	0.01	0.52	0.26	0.26	0.01	0.37
MgO	22.05	26.43	23.38	14.64	9.44	0.30	0.25	3.30	21.89	25.91	--	2.04
CaO	0.38	0.30	0.43	22.76	6.54	11.20	17.32	--	0.36	0.30	19.54	0.02
Na ₂ O	--	--	--	0.43	--	5.37	1.98	--	--	--	0.39	--
Total	99.84	100.33	99.84	99.80	101.12	101.08	100.51	99.36	100.63	100.49	99.22	100.03
O	6.000	6.000	6.000	6.000	12.000	8.000	8.000	3.000	6.000	6.000	8.000	3.000
Si	1.921	1.885	1.953	1.913	2.988	2.437	2.128	--	1.916	1.875	2.047	--
Al	.058	.115	.047	.087	.012	1.535	1.830	--	.083	.125	1.924	--
Fe ³⁺	.021	--	--	--	--	--	--	--	.001	--	--	--
Al	--	.034	.034	.035	1.975	--	--	.006	--	.071	--	--
Fe ³⁺	.078	.082	.003	.059	.013	--	--	.086	.074	.047	--	.138
Ti	.002	.001	.004	.011	.002	--	--	.949	.002	.002	--	.929
Cr	.001	.005	--	.002	.020	--	.002	.010	.001	.001	--	.004
Mg	1.230	1.419	1.289	.806	1.058	.002	.017	.122	1.213	1.388	--	.076
Fe ²⁺	.657	.440	.641	.150	1.348	.022	.030	.816	.688	.473	.024	.845
Mn	.015	.008	.008	.005	.058	.002	--	.011	.009	.008	--	.008
Ca	.015	.012	.017	.901	.527	.536	.853	--	.014	.011	.980	.001
Na	--	--	--	.031	--	.465	.177	--	--	--	.035	--
Calculations	4.000	4.001	3.996	4.000	8.001	4.999	5.040	2.000	4.001	4.001	5.010	2.001
%Mg	0.652	0.763	0.668	0.843	0.440	An 53	An 83	--	0.638	0.746	An 97	--
%Mg	61.5	70.9	64.5	80.6	--	--	--	--	60.7	69.9	--	--

*PR-2 Porter Mountain; I-JO-12 Mt. Jo, Mt. Marcy massif, N.Y., composition determined by electron microprobe.

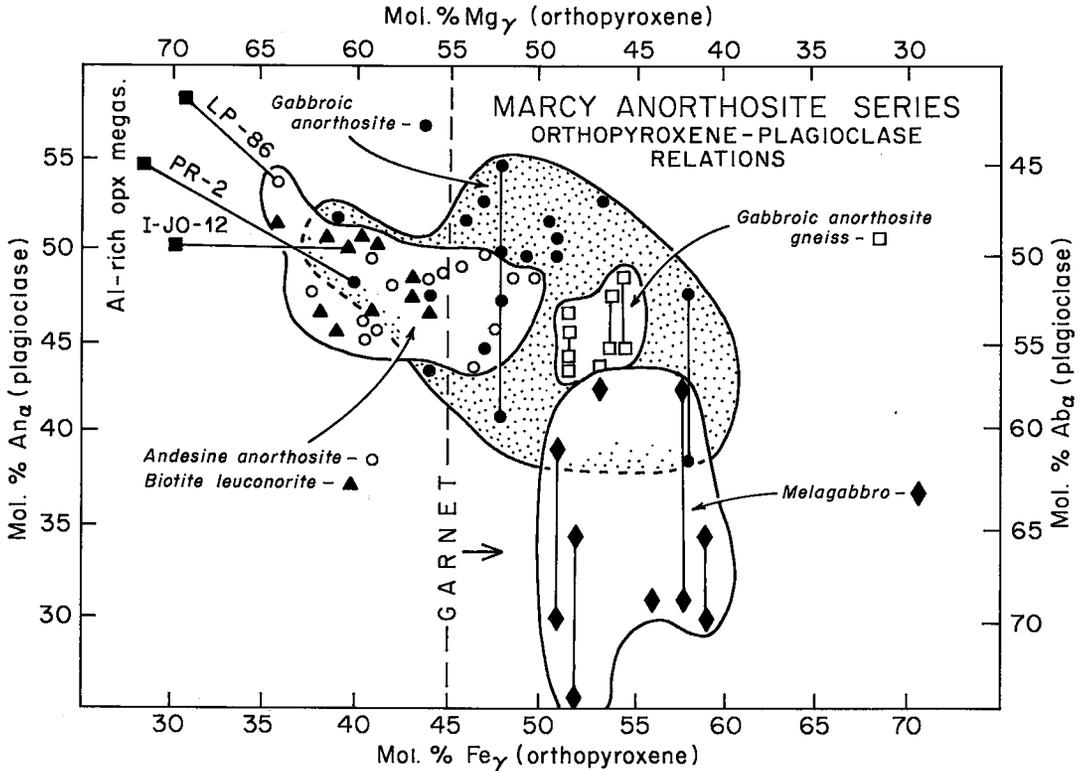


FIG. 2. Plot showing compositional range of orthopyroxene and plagioclase in different facies of the Marcy anorthosite massif. Tie lines connect optically determined compositions of coexisting orthopyroxene and plagioclase megacrysts with those in matrix of host rock; vertical tie-lines connect compositions of megacryst and matrix plagioclase in deformed facies of anorthosite massif.

ene; where large megacrysts of plagioclase accompany (and are in contact with) orthopyroxene megacrysts, these are also richer in An than matrix plagioclase (Fig. 3). Because the Nain anorthosite is unmetamorphosed and the Marcy massif has undergone granulite-facies metamorphism, these differences cannot be ascribed to metamorphic processes.

Although exsolution of garnet in orthopyroxene of anorthositic rocks had not been previously recorded, it has been described by other investigators from various ultramafic rocks, most of which are believed to represent mantle-derived xenoliths. Kuno (1969), Beeson & Jackson (1970) and Wilkinson (1976) reported garnet exsolution-lamellae in both ortho- and clinopyroxene from websterite xenoliths in Hawaiian basalt from Salt Lake Crater, Oahu; Lovering & White (1969) described them from spinel pyroxenite xenoliths in basic pipes from Delegate, Australia; Amthauer *et al.* (1972) described them from ultramafic bodies associated with kyanite-bearing granulites from Ultental, South Tirol, northern Italy; MacGregor (1973) and Boyd (1974) described them from garnet peridotite and garnet pyroxenite xenoliths in the Frank Smith kimberlite pipe of South Africa; Lappin (1974) described them in orthopyroxene eclogite from the Sunndal-Grubse ultramafic mass, and Aoki *et al.* (1980) provided a very detailed report on their occurrence and crystallographic relationships in the Bellsbank and Frank Smith diamond-bearing kimberlite pipes of South Africa. All of these occurrences of ultramafic rock are from more magnesium-rich parageneses ($Mg_{\text{opx}} 79-90$) than those in anorthosites ($Mg_{\text{opx}} 66-76$), so that a direct analogy cannot be made with regard to T and P of initial crystallization and subsolidus exsolution of garnet. Nonetheless, there seems little reason to doubt that the anorthositic orthopyroxene that exsolved garnet had initially crystallized at liquidus temperatures above 1200°C at a deep level of a thickened crust where P was on the order of 20 kbar. The P-T conditions under which exsolution of garnet was initiated and completed are, however, subject to more speculation. Ashwal & Wooden (1983) have called attention to the extremely low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and correspondingly high initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratio that they obtained on an orthopyroxene megacryst, EC-75-005 (Fig. 1), collected by Emslie from within the Adirondack anorthosite massif on which they obtained an age of primary crystallization of 1288 Ma. The "unreasonably" low value of $^{87}\text{Sr}/^{86}\text{Sr}$, expressed as $I_{\text{Sr}} 1290 = 0.698$, is not only the lowest obtained on any anorthositic minerals or whole rocks, but is lower even than that of chondritic meteorites. Ashwal & Wooden suggested that the strontium isotope system in the megacryst was reset, but did not discuss reasons why the same isotopic system in the host anorthosite ($I_{\text{Sr}} 1290 = 0.7038-0.7048$) was appar-

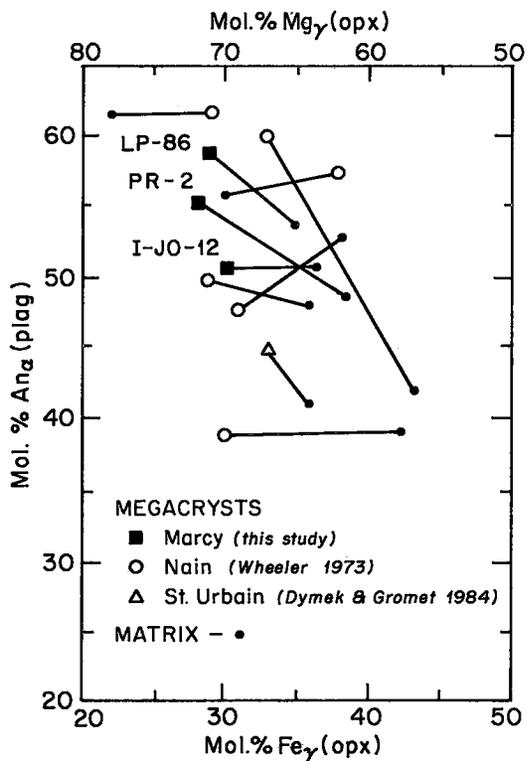


FIG. 3. Composition of Al-rich orthopyroxene megacrysts and associated plagioclase tied to composition of matrix orthopyroxene and associated plagioclase of host rock for different anorthosite massifs.

ently not reset. These investigators also found that the high initial neodymium isotope ratio, $^{143}\text{Nd}/^{144}\text{Nd}$, expressed as: $I_{\text{Nd}} 1290 = 0.5105$ and epsilon neodymium, $\epsilon_{\text{Nd}} 1290 = +5.08$, represents the most primitive material they have analyzed from the Marcy anorthosite massif. These primitive isotopic Nd values are consistent with an interpretation that "the orthopyroxene megacryst represents a fragment of the source materials which gave rise to the anorthositic parental magma" (Ashwal & Wooden 1983).

GEOLOGICAL SETTING

Like all Gaul, *omnia Gallia in tres partes divisa est*, the geology of the Adirondacks is divisible into three parts (Fig. 1): 1) a multiply-deformed supracrustal or "Grenville" series of metamorphosed sedimentary and igneous rocks characterized by wollastonite- and monticellite-bearing marbles (Baillieul 1976, Valley & Essene 1980, Tracy *et al.* 1978), quartzite, amphibolite and felsic gneisses, 2) a Marcy anorthosite series (Fig. 2), after Buddington (1969), which forms a large massif dominated by felsic andesine anorthosite with a Color Index (C.I.) of less than

10, along with attendant biotite leuconorite and gabbroic anorthosite (C.I. 10-35), hornblende-garnet anorthosite augen gneiss (C.I. 20-35), and satellitic bodies of anorthositic gabbro, melagabbro and pyroxenite, some of these oxide-rich, and 3) a quartz ferrosyenite series of highly deformed felsic gneisses dominated by the high-pressure, high-temperature assemblage eulite or orthoferrosilite - ferroaugite - quartz - sodic plagioclase - micropertthite (Jaffe *et al.* 1978, Bohlen *et al.* 1978). Whereas the age of primary crystallization of the anorthosite massif of the core is suggested to be 1288 Ma on the basis of recent Sm-Nd age determinations made by Ashwal & Wooden (1983), the age of the pervasive high-P and high-T metamorphism (or of the Grenville orogeny) is thought to be on the order of 1100 Ma from Pb-U age determinations on zircon made by Silver (1969).

In the Mt. Marcy and adjoining quadrangles, these three major map-units are assigned by Jaffe *et al.* (1983) to a roof and a core facies. The roof facies is highly deformed and consists of Grenville gneisses and granulites, quartz ferrosyenite gneiss and other felsic gneisses of a Pitchoff syenite series, hornblende-garnet-andesine augen gneisses of a Van Hoesenberg anorthosite gneiss series, and brecciated gabbroic anorthosite, anorthosite and leuconorite. The core facies, by contrast, is little deformed and shows primary textures indicative of magmatic flow in predominantly felsic andesine anorthosite, with minor amounts of biotite leuconorite, gabbroic anorthosite and melagabbro. The rocks of the roof facies were deformed and metamorphosed to granulite-facies grade during the peak of the Grenville orogeny. The core facies is an anorthosite nappe thrust over the roof facies late in the Grenville orogeny, perhaps after the peak of the metamorphism. Coincident with the tectonic emplacement of the anorthosite core, gneissic rocks of the roof facies were broken into a series of thrust slices and further deformed. During this event, retrograding of the pyroxenes to hornblende and of plagioclase to scapo-

lite took place, accompanied by minor sericitization of plagioclase.

The Type-I orthopyroxene megacrysts that are the subject of this study tend to be localized in the deformed and brecciated gabbroic anorthosite or leuconorite, either in or marginal to the roof facies. Felsic anorthosite of the core facies, in the interior of the Marcy massif away from its contacts with roof rocks, rarely contains orthopyroxene megacrysts.

FIELD OCCURRENCE

Sample locality PR-2 on Porter Mountain

Orthopyroxene megacrysts that have exsolved both garnet and plagioclase have thus far been found in place only on Porter Mountain at locality PR-2 (Fig. 1). Porter Mountain is made up largely of gabbroic anorthosite of the roof facies of the Marcy anorthosite massif. On and near the summit, the typical block structure of Adirondack anorthosites is prevalent: blocks (to 30 × 15 cm) of coarse-grained (> 10 mm) felsic andesine anorthosite are enclosed in crushed, medium-grained (0.5- 5 mm) gabbroic anorthosite; it is a typical breccia. The gabbroic anorthosite contains 26-27% of mafic minerals (modes PR-2R and PR-1R, Table 3) in which augite greatly exceeds hypersthene and is characteristically marginally retrograded to hornblende. Single crystals of Type-I orthopyroxene megacrysts (2 × 2 to 40 × 13 cm) are in general sporadically distributed. Several of these, however, are well aligned in the gabbroic anorthosite country-rock (Fig. 4A), and some of these are attached to megacrysts of plagioclase, coarser and of higher An content than those found in the enclosing rock. Although this alignment of coarse megacrysts suggests their emplacement in a vein or small dyke, no sharp contacts of a definite dyke are evident. Perhaps they are masked by plagioclase and pyroxene intruding rock containing the same minerals or by subsequent deformation. That the orthopyroxene megacrysts have been deformed is evident from their aberrant shapes (Fig. 4A). Indeed, on the summit of Porter Mountain, a 2- to 5-cm-wide pyroxenite layer made up entirely of smaller (1-3 cm) crystals of Type-I orthopyroxene (sample PR-1L, Table 1) has been folded (Fig. 4B) coincident with the crushing of the more brittle plagioclase-rich gabbroic anorthosite. This layer is believed to have originated from convection and concentration of exotic orthopyroxene crystals into a fracture in gabbroic anorthosite, and subsequently to have been deformed with the other roof rocks during the regional metamorphism.

Sample locality I-JO-12 on Mt. Jo

Locality I-JO-12 (Fig. 1) is in the core of the anorthosite massif, but in a zone marginal to the roof. This mountain is made up of more than ninety percent of felsic andesine anorthosite, with minor

TABLE 3. MODES OF ANORTHOSITIC HOST ROCKS OF THE ORTHOPYROXENE MEGACRYSTS

	PR-2-R	PR-1-R	PR-2-CZ	I-JO-12-R
Orthoclase	0.5	1.0	None	tr.
Plagioclase	72.4	73.4	25.	80.0
Orthopyroxene	3.5	4.1	40.	11.2
Clinopyroxene	15.6	14.1	10.	1.9
Hornblende	5.8	5.5	10.	None
Biotite	None	None	2.	6.8
Scapolite	1.3	1.4	5.	None
Ilmenite	0.9	0.5	3.	0.1
Magnetite	tr.	tr.	None	None
Apatite	tr.	tr.	tr.	tr.
Garnet	None	None	None	None
Sericite	tr.	tr.	5.	tr.

PR-2-R.	Gabbroic anorthosite, near summit Porter Mt., elev. 1210 m (3970').
PR-1-R.	Gabbroic anorthosite, summit, Porter Mt., elev. 1238 m (4059').
PR-2-CZ.	Crush zone, 6 mm wide, at contact of megacryst with host rock.
I-JO-12-R.	Biotite leuconorite, west ledge, Mt. Jo.

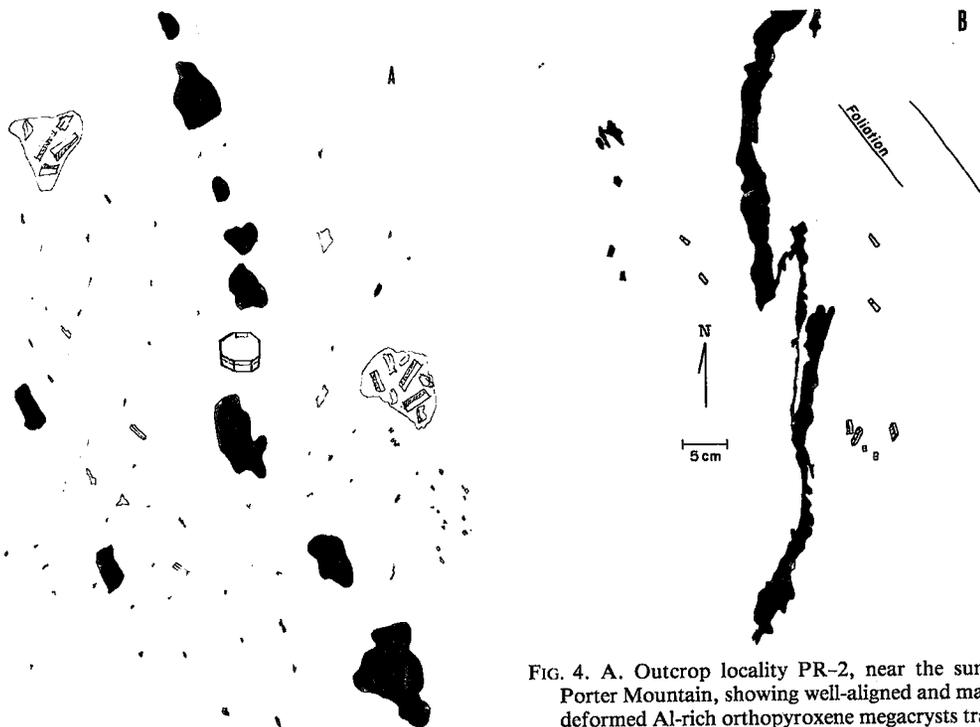


FIG. 4. A. Outcrop locality PR-2, near the summit of Porter Mountain, showing well-aligned and marginally deformed Al-rich orthopyroxene megacrysts traversing gabbroic anorthosite country rock containing fragments of felsic anorthosite (block structure). Brunton compass is for scale. B. Folded layer consisting wholly of orthopyroxene megacrysts in deformed gabbroic anorthosite at the summit of Porter Mountain.

amounts of gabbroic anorthosite and biotite leuconorite. On the west ledge of Mt. Jo ("Orra's Ledge"), where the orthopyroxene megacrysts occur, the felsic andesine anorthosite shows a well-developed primary flow-foliation, with plagioclase megacrysts aligned about N70E and dipping steeply NW. The plagioclase megacrysts average about 4×1.25 cm in size, but a very large megacryst (30×12 cm) attests to convection in the anorthosite melt. The strong foliation of the andesine anorthosite is interrupted by an irregularly defined mass of granulated, nonfoliated biotite leuconorite that outcrops for about 20 m to the west along the ledge. Contacts with the well-foliated andesine anorthosite are concealed, and it is not possible to prove that the leuconorite has intruded the anorthosite, but this appears to be the case. The biotite leuconorite contains about 20% mafic minerals, predominantly hypersthene, with abundant biotite and minor augite along with trace amounts of ilmenite (mode I-JO-12-R, Table 3). Enclosed in the leuconorite are unoriented clusters and dispersed giant single crystals of orthopyroxene: individual megacrysts attain dimensions of $10 \times 10 \times 20$ cm and tend to be more euhedral and less deformed than those described from locality PR-2 on Porter Mountain. The contrast between the quasi-euhedral morphology and great size of the orthopyroxene megacrysts and the comminuted grains of plagioclase and orthopyroxene in the enclosing leuconorite is worthy of note.

MINERALOGY AND PETROGRAPHY

Sample PR-2

The sample selected for detailed study, a $40 \times 13 \times 8$ cm megacryst of bronzite, is mineralogically and chemically zoned, with exsolution lamellae of garnet concentrated in the core of the megacryst, numbered PR-2(core) in Table 2, and exsolution lamellae of calcic plagioclase concentrated in the outer zone, numbered PR-2(rim) in Tables 2 and 4. Under the microscope, the host orthopyroxene, a bronzite, shows the pleochroic scheme: $X = b$ (alizerin red) $> Y = a$ (very pale yellow) $\leq Z = c$ (very pale green), with α 1.684, β 1.695 and γ 1.6995, with $2V_x = 65^\circ$. Exsolution lamellae of garnet, ilmenite, clinopyroxene and calcic plagioclase occur as plates and spindles all oriented parallel to (100) of the host bronzite (Figs. 5, 6A and 6B). The thin sections cut for study are oriented as nearly parallel to (001) as could be determined from the irregular surface morphology of the large megacryst. This orientation was confirmed by the almost centred obtuse bisectrix interference-figure obtained from each section and the pleochroic scheme for the X (red) and Y (pale

TABLE 4. VOLUMETRIC MODES OF ALUMINUM-RICH ORTHOPYROXENE MEGACRYSTS IN ANORTHOSITE

	PR-2 (core)	PR-2 (rim)	I-JO-12	EC-75 -008-C	EC-72 -56-A	RM-69 -345-C	EC-74 -53
Host:							
Opx	89.79	88.38	91.80				
Lamellae							
Cpx	0.04	tr.	0.82				
Ilm	0.91	1.04	0.61	+	+	+	+
Gar	9.26						
P1		10.58	6.77	+	14.7	+	11.8
%An		53-83	97		65-91		75-80
Massif	Marcy ADKS.	Marcy ADKS.	Marcy ADKS.	Marcy ADKS.	Harp L. LAB.	Nain LAB.	Rogaland S. NORWAY

yellow) vibration directions. In the (001) orientation, the elongation of the exsolution lamellae coincides with and serves to readily identify the *b* axis of the bronzite host (Fig. 5).

In PR-2 (core), the bronzite host ($x_{Mg} = 0.763$) contains abundant, narrow, commonly doubly-terminated elongate exsolution-lamellae of almandine-pyrope, $x_{Mg} = 0.440$ (Table 2, Figs. 6A and 6B) showing average dimensions of $7 \times 1700 \mu\text{m}$. A spectrum of sizes measured for the garnet lamellae ranges in width from 2.5 to $10 \mu\text{m}$ and in length from 56 to $1840 \mu\text{m}$. No correlation in length-to-width ratio is evident, as a large proportion of garnet lamellae show a width that varies but little from 7-8 μm , associated with lengths of 600-1840 μm . Intimately associated with the garnet lamellae are much finer elongate lamellae of ilmenite, $0.8-1 \times 32-100 \mu\text{m}$, and yet finer clinopyroxene

lamellae, $0.4-0.5 \times 20 \mu\text{m}$ in size. Sporadic, more-or-less equidimensional crystals of garnet, $24 \times 24 \mu\text{m}$ to $14 \times 60 \mu\text{m}$, occur in line with elongate lamellae and as bulbous nodes perched on the end of an occasional long lamella; all of these show essentially the same chemical composition. Rare microporphroblasts of equant garnet, 200 μm in diameter, occur in zones that have been cleared and scavenged of all other lamellae; these are in part rimmed by olive hornblende (Fig. 7A). Plagioclase lamellae are absent.

In the outer zone of the megacryst, PR-2 (rim), the bronzite, $x_{Mg} = 0.668$, contains abundant exsolution lamellae of calcic plagioclase, An_{53-83} (Table 2), of the same order of size as the garnet lamellae of the core of the crystal. Where the two zones PR-2 (core) and PR-2 (rim) coalesce, exsolution lamellae of garnet and plagioclase occur together along with the ubiquitous much finer lamellae of ilmenite and clinopyroxene. The presence of microfractures that offset an individual garnet lamella and their absence in the adjoining plagioclase lamella (Fig. 7B) imply that garnet exsolved earlier than plagioclase.

The large megacryst of bronzite PR-2 is separated from the enclosing gabbroic anorthosite host-rock by a 6-mm-wide hydrothermally altered fracture-zone that contains rotated fragments of the megacryst in a matrix of augite, hypersthene, plagioclase with reverse chemical zoning, biotite, hornblende, and sericite (Table 3). Water and alkalis

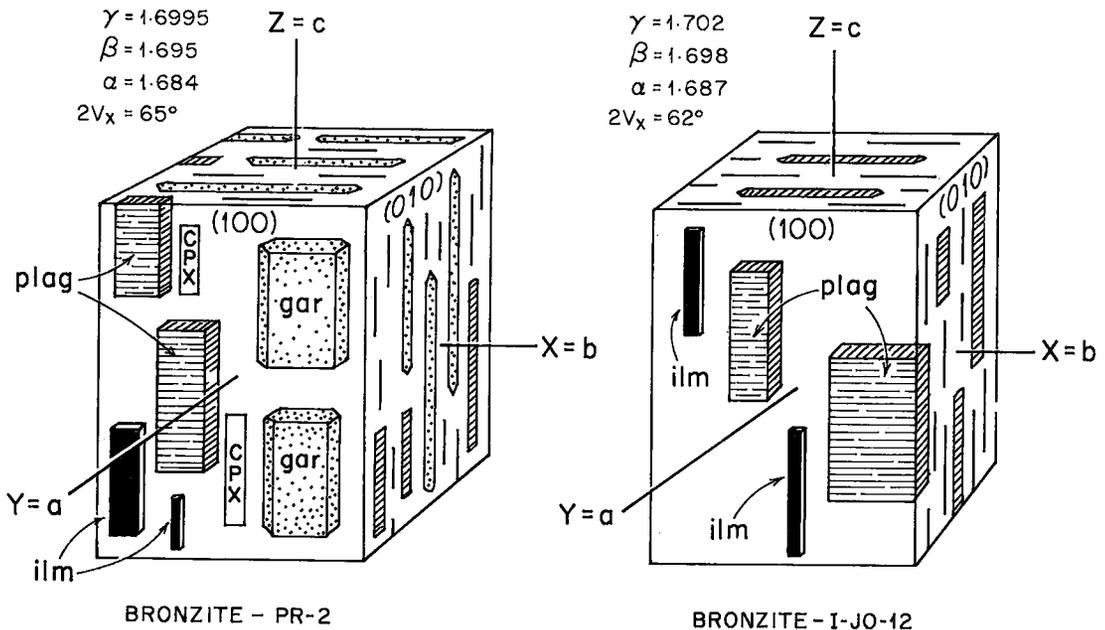


FIG. 5. Schematic illustration showing exsolution lamellae of garnet, calcic plagioclase, ilmenite and clinopyroxene, all oriented parallel to (100) of host Al-rich orthopyroxene megacrysts PR-2 and I-JO-12 from the Mt. Marcy quadrangle. Indices of refraction and optical orientation are shown.

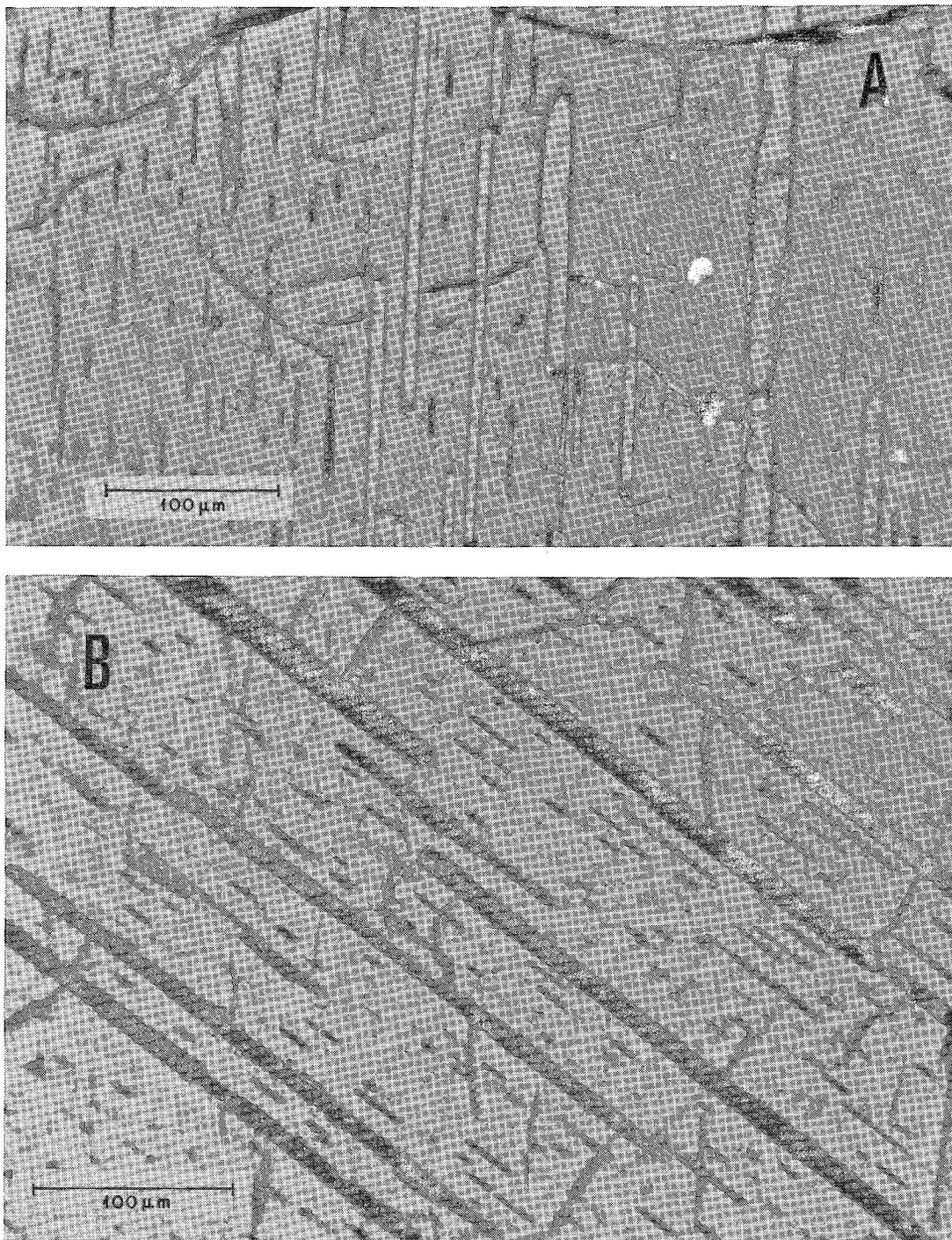


FIG. 6. A. Exsolution lamellae of garnet (white with high relief) and ilmenite (black) in core of Al-rich bronzite megacryst PR-2. Slender, well-terminated lamellae of garnet (centre of photograph) are $7 \times 250 \mu\text{m}$, ilmenite lamellae are $1.5 \mu\text{m}$ thick (plane-polarized light). B. Garnet exsolution-lamellae in Al-rich bronzite, PR-2, under crossed nicols; garnet lamellae are $7\text{--}19 \mu\text{m}$ thick; short, thin lamellae are ilmenite.

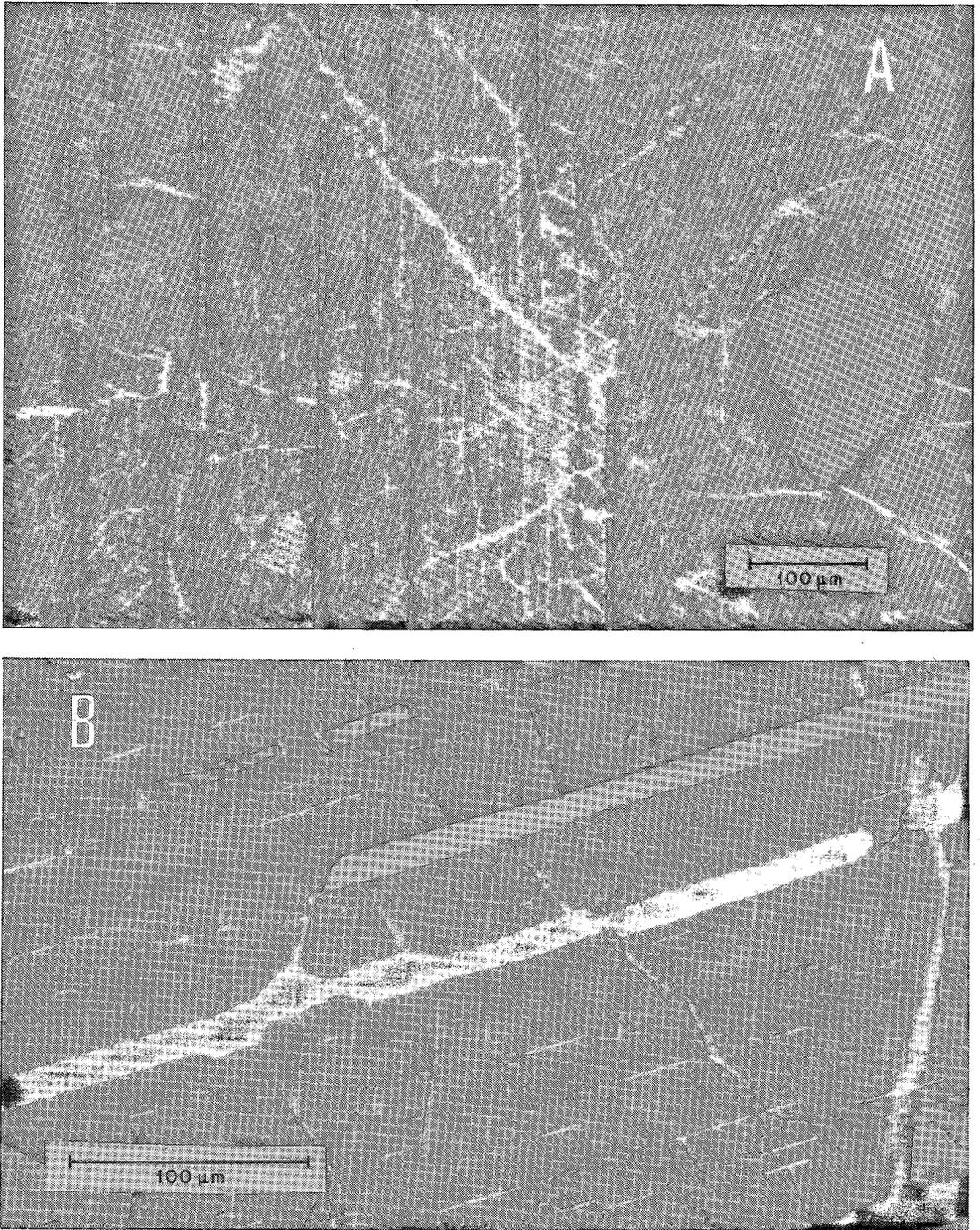


FIG. 7. A. Microporphyroblast of equant garnet with hornblende rim. Large, equant garnet grew from coalescence of thin, earlier-formed lamellae, and area surrounding microporphyroblast is cleared of fine lamellae. Large grain of garnet has a diameter of $200\ \mu\text{m}$ (plane-polarized light). B. Core of orthopyroxene megacryst PR-2 showing broken lamella of garnet (black) and bytownite (white). Fractures that traverse garnet lamella do not transgress plagioclase lamella. Garnet and plagioclase lamellae are $10\ \mu\text{m}$ thick. Note fine opaque ilmenite lamellae and extremely fine clinopyroxene lamellae (white) (crossed nicols).

concentrated in these marginal zones have percolated into fine fractures parallel to (100) of the host bronzite megacryst, altering a large number of plagioclase lamellae to fine, fibrous sericite. Occasional, very fine fractures also transect the interior of the megacryst; these may contain both sericite, hornblende, and patchy blebs of anhedral garnet. Areas marginal to these fine fractures are cleared of elongate exsolution-lamellae. This fracturing and the hydrothermal alteration of megacrysts are ascribed to late stages of granulite-facies metamorphism imposed on the region coincident with the thrust emplacement of the core facies of the felsic anorthosite over the roof facies of more gabbroic anorthosite and associated gneissic rocks (Jaffe *et al.* 1983).

Sample I-JO-12

Several large orthopyroxene megacrysts from this locality were examined in thin section. All of these contain exsolution lamellae of calcic plagioclase, and none contains garnet. The sample selected for detailed study is a $10 \times 10 \times 20$ cm megacryst of bronzite, $x_{Mg} = 0.746$, carrying 6.8% of exsolution lamellae of anorthite, An_{97} , and minor amounts of thin ($< 0.8 \mu\text{m}$) ilmenite and clinopyroxene lamellae (Fig. 8, Tables 2 and 4). The bronzite host shows the same absorption scheme as sample PR-2, with $X = b$ (alizarin red), $Y = a$ (very pale yellow) and $Z = c$ (pale green), with α 1.687, β 1.698, γ 1.702, $2V_x = 62^\circ$. All of the exsolution lamellae are again oriented parallel to (100) of the bronzite host (Figs. 5, 8). Anorthite lamellae range in size from small, spindly plates, $4\text{--}8 \mu\text{m}$ wide \times $1000 \mu\text{m}$ long, to coarser lamellae, $15 \times 1280 \mu\text{m}$ in size. Microfractures have developed along $\{110\}$ cleavages and parallel to $\{100\}$ parting enhanced by the presence of coarse exsolution-lamellae. Sporadic microporphyroblasts of olive hornblende, to $240 \times 520 \mu\text{m}$, are elongate parallel to the anorthite lamellae and, in this case, appear to have grown by scavenging and clearing out lamellae of anorthite, ilmenite and clinopyroxene, accompanied by the introduction of hydrothermal solutions carrying water and alkalis.

Sample Gv-82-12

Although no detailed study was made, a large augite megacryst, $x_{Mg} = 0.77$, collected from a mafic inclusion in allochthonous anorthosite in the Rosseau subdomain, Central Gneiss Belt near Parry Sound, Ontario (Davidson *et al.* 1982), was found to contain warped exsolution-lamellae of almandine-pyroxene garnet (Al_{55}), $8 \times 240 \mu\text{m}$, accompanied by very fine lamellae of ilmenite and orthopyroxene, all oriented parallel to (100) of the host. This is mentioned here because it apparently

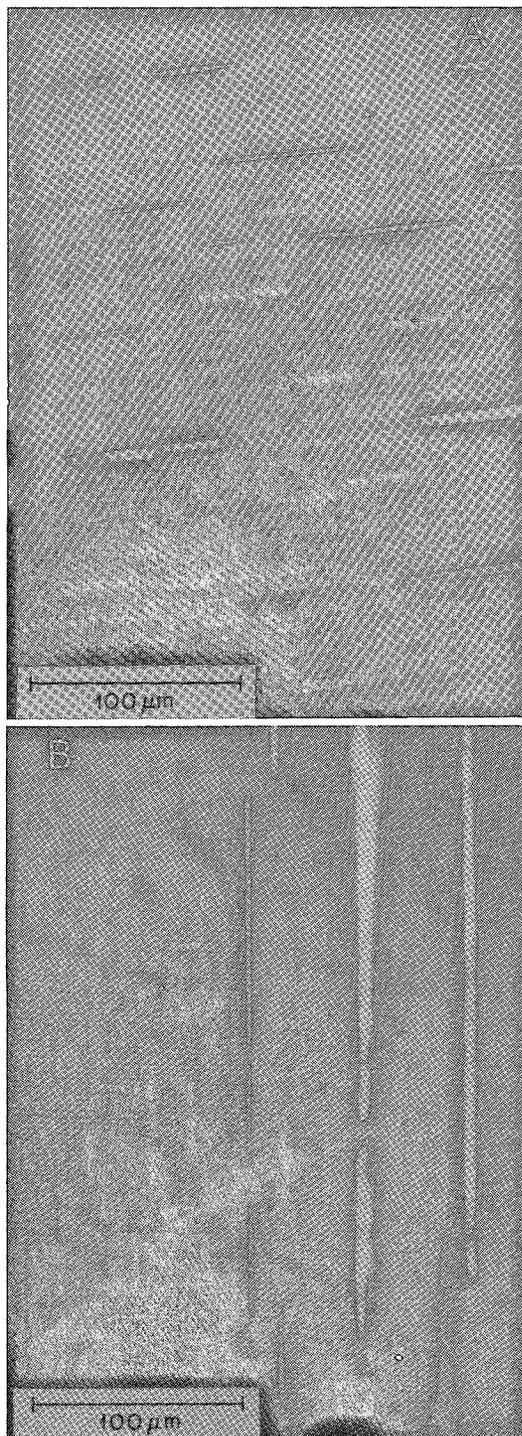


FIG. 8. A, B. Orthopyroxene megacryst I-JO-12, showing 4- to $15\text{-}\mu\text{m}$ -wide exsolution lamellae of anorthite, An_{97} , in orthopyroxene host at extinction. Crossed polars.

represents the first occurrence, in anorthosite, of garnet exsolved in a clinopyroxene host. Although the megacryst was found lying by itself at the base of an anorthosite outcrop, similar large megacrysts are present in the anorthosite, and there is little doubt that the crystal collected came out of the same outcrop. The augite megacryst is traversed by several fracture-zones filled with an equigranular, 0.25 mm mosaic of clear augite and hornblende, the latter derived from the breakdown of the garnet lamellae and host augite in the presence of hydrothermal water associated with the overthrusting that characterizes this region, which consists of a series of piled-up thrust slices or "packages" (Davidson *et al.* 1982). The occurrence of sapphirine, spinel and garnet containing 47% pyrope in the same rock is also suggestive of a high-pressure regimen.

MINERAL CHEMISTRY

Methods

Electron-microprobe analyses of minerals were made on polished thin sections using the ETEC automated electron-probe in the Department of Geology and Geography at the University of Massachusetts. Accelerating potential was 15 kV and beam current, 0.2 μ A. Corrections were done using the procedure of Bence & Albee (1968) and data from Albee & Ray (1970).

Compositions (averaged from 10 or more analyses) of host orthopyroxene and exsolution lamellae of each megacryst are presented in Table 2. Estimates

of ferric iron in the pyroxene are based on an assumption of 4 cations and 6 oxygen atoms; in the ilmenite, they are based on an assumption of 2 cations and 3 oxygen atoms. Modes of all megacrysts reported in Table 4 were made by taking volumetric measurements of all lamellae and host in 30 \times 46 cm enlargements of selected areas of thin sections. The bulk composition of the orthopyroxene crystals (Table 5) was calculated using the volumetric modes (Table 4) corrected to weight percent and the results of microprobe analyses (Table 2) obtained for the exsolved phases and the different parts of the host pyroxene. The clinopyroxene lamellae in both samples are too fine to analyze. As a substitute, the composition of one of the discrete grains of clinopyroxene that coexist with sample PR-2 was used in the calculation of the bulk composition of both crystals of orthopyroxene. The formulae of the analyzed minerals were used to calculate a composition that sums to 100%. The amount of each oxide present in the bulk composition was then found by multiplying the recalculated oxide weight in each mineral by the modal proportion of each mineral, and then summing all the products to give the weight percent oxide in the bulk composition.

Orthopyroxene

In sample PR-2 analyses of the megacryst show that the orthopyroxene is zoned with respect to x_{Mg} and Al_2O_3 . The broad core area with a x_{Mg} of 0.763 and 3.51 wt. % Al_2O_3 changes composition to a x_{Mg} of 0.668 and 1.85 wt. % Al_2O_3 over a few mm at the

TABLE 5. BULK COMPOSITIONS OF ALUMINUM-RICH ORTHOPYROXENE MEGACRYSTS IN ANORTHOSITE

	PR-2 core	PR-2 rim	I-JO-12	EC-75 -008C	EC-72 -56A	RM-69 -345C	EC-74 -53	CHV-80 -33C
S ₁₀ O ₂	49.99	51.57	50.83	51.5	50.36	51.20	49.7	50.68
TiO ₂	0.65	0.85	0.50	0.58	0.18	0.65	0.64	0.76
Al ₂ O ₃	5.41	4.56	6.25	5.65	8.38	4.41	8.00	5.12
Cr ₂ O ₃	0.20	0.02	0.03	0.11	0.23	0.18	0.16	0.15
Fe ₂ O ₃	2.78	0.23	1.68	1.0	1.82	3.4	3.3	--
FeO	15.50	19.23	14.90	16.8	9.99	15.0	13.5	18.44
MnO	0.34	0.38	0.24	0.11	0.21	0.34	0.28	0.25
MgO	24.19	21.12	24.02	20.7	25.56	21.9	22.4	22.90
CaO	.96	1.87	1.51	1.81	1.99	1.59	1.92	1.49
Na ₂ O	.00	0.17	0.02	0.32	0.22	0.40	0.70	0.19
Total	100.02	100.00	99.98	98.58	98.94	99.07	100.60	99.98
Cations on a basis of 6 oxygens								
Si	1.826	1.961	1.843	1.899	1.809	1.887	1.795	1.857
Al	.174	.039	.157	.101	.191	.113	.205	.143
Al	.059	.159	.110	.145	.163	.079	.136	.079
Cr	.006	--	.001	.003	.007	.005	.005	.004
Ti	.018	.023	.014	.016	.004	.018	.017	.021
Fe ³⁺	.076	.006	.046	.028	.049	.094	.090	.031
Fe ²⁺	.074	.593	.452	.518	.300	.462	.408	.534
Mg	1.317	1.160	1.298	1.138	1.368	1.203	1.206	1.251
Mn	.011	.012	.007	.010	.006	.011	.009	.008
Ca	.038	.074	.059	.072	.076	.063	.074	.050
Na	--	.012	.001	.014	.015	.031	.049	.013
Σ cations	3.999	4.039	3.988	3.965	3.988	3.967	3.996	3.991
Mg	65.8	58.0	64.9	56.9	68.4	60.1	60.3	62.6
x_{Mg}	0.735	0.662	0.742	0.687	0.820	0.722	0.747	0.701

PR-2-core, PR-2-rim and I-JO-12 - reconstructed bulk composition, Adirondacks, N.Y., this report.
 EC-75-008C - Bulk composition, Port Kent, Adirondacks, N.Y. (Emslie 1980).
 EC-72-56A - Bulk composition, Harp Lake Complex, Labrador (Emslie 1980).
 RM-69-345C - Bulk composition, Nain, Labrador (Emslie 1980).
 EC-74-53 - Bulk composition, Rogaland Complex, Ana-Sira, S. Norway (Emslie 1980).
 CHV-80-33C - Reconstructed bulk composition, St. Urbain, Quebec (Dymek & Gromet 1984).

edge of the crystal. The megacryst is richer in Mg and more aluminous, even at the rim, than the orthopyroxene (x_{Mg} 0.652, 1.32 wt. % Al_2O_3) in the enclosing gabbroic anorthosite. In sample I-JO-12 a similar compositional relationship is shown between the megacryst (x_{Mg} 0.746, 4.38 wt. % Al_2O_3) and the orthopyroxene (x_{Mg} 0.638, 1.89 wt. % Al_2O_3) in the enclosing leuconorite. Comparisons of the composition of orthopyroxene megacrysts having plagioclase lamellae with that of orthopyroxene in the rocks containing them show this to be a common feature (Fig. 3).

Garnet, clinopyroxene and plagioclase

The exsolved garnet in PR-2 is predominantly a mixture of almandine, pyrope and grossular (Table 2) and has the composition $(Al_{45.1}Py_{35.4}Gr_{15.9}Sp_{1.9}Uv_{1.0}And_{0.7})$. The exsolved garnet has a x_{Mg} of 0.440. The discrete clinopyroxene from PR-2 is Mg-rich, with a x_{Mg} of 0.843, and aluminous, containing 2.80 wt. % Al_2O_3 (Table 2). Plagioclase exsolved from the rim of PR-2 ranges in composition from An_{53} to An_{87} (Table 2). Plagioclase associated with the clinopyroxene at the edge of the megacryst is more calcic (An_{70-75}) than the plagioclase of the enclosing anorthosite (An_{54}). Plagioclase lamellae from I-JO-12 are uniform in composition and very calcic (An_{97} , Table 2).

Possible chemical effects of late hydration

Analyses of the orthopyroxene rim in PR-2 and of the plagioclase lamellae (Table 2), which were used to calculate the bulk composition of the rim, should be viewed with some caution. It is in this part of the sample that features of late-stage hydration are most common. The calcic plagioclase at the edge of the megacryst shows strong retrograde and reverse zoning to Na-rich compositions, particularly where it is in contact with hornblende. These textures suggest that the Mg component of orthopyroxene and the An component of plagioclase have reacted to form hornblende. If this is the case, then the rim of the megacryst may be enriched in Fe and the plagioclase lamellae located at the rim may be enriched in Na. From the textures the clinopyroxene appears not to have participated in the hornblende-forming reactions.

Bulk composition of the megacrysts from various localities

The calculated bulk-composition of orthopyroxene megacrysts PR-2 and I-JO-12 are compared with those from other anorthosite localities (Table 5). These include samples from Harp Lake and Nain (Labrador), Rogaland (Norway) and Port Kent (Adirondacks), all of which have been described by

Emslie in his classic studies of these megacrysts (1975, 1980), and an additional reconstructed bulk-composition of a megacryst from St-Urbain (Quebec) described by Dymek & Gromet (1984). The bulk compositions of these megacrysts are seen to differ little in both major and minor elements, showing: a Mg/(Mg + Fe) ratio in the range 0.66 to 0.76, CaO content of 0.96–1.99%, Al_2O_3 content of 4.4–8.4%, and negligible variation in the SiO_2 content. Almost all contain minor Cr, and there is no bias in Mn, Ti, or other minor elements with the exception of Ca. Sample PR-2(core) shows the lowest CaO content, 0.96%, and has exsolved garnet; all the others show CaO contents of 1.49–1.99%, and have exsolved plagioclase.

In view of the very limited range of bulk compositions of these megacrysts, it is important to note that they occur in anorthosite massifs in which the average plagioclase compositions show a more significant range, varying from An_{40} at St-Urbain (Dymek & Gromet 1984), An_{47} in the Marcy Massif (Jaffe *et al.* 1983) and An_{53} in the Nain Massif (Morse 1973) to An_{55} in the Harp Lake Complex (Emslie 1980). It is difficult to reconcile these data with a theory of *in situ* or synmagmatic crystallization of megacrysts in country rock; they accord better with suggestions by Wheeler (1973) and Emslie (1975, 1980) that the megacrysts are xenocrysts con-

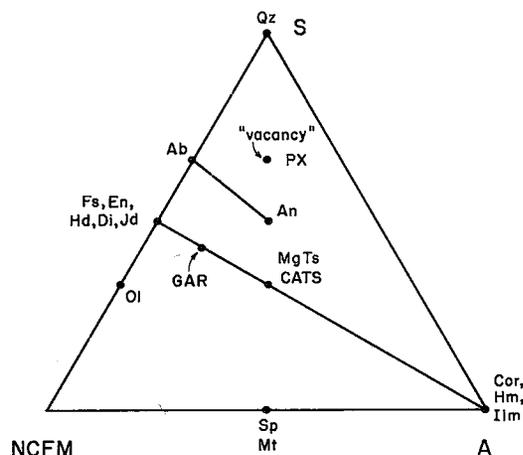


FIG. 9. Triangular composition-diagram showing pyroxene components and selected other phases. Co-ordinates: S Si, NCFM $2Na + Ca + Mg + Fe^{2+} + Mn - Ti$, A $(Al + Fe^{3+} + Cr + 2Ti - Na)/2$. Abbreviations: Fs ferrosilite, En enstatite, Hd hedenbergite, Di diopside, Jd jadeite, MgTs Mg-Tschermak component, CaTs Ca-Tschermak component, Cor corundum, Hm hematite, Ilm ilmenite, Ab albite, An anorthite, Ol olivine, Sp spinel, Mt magnetite, Qz quartz, Gar garnet. Line shows the fixed ratio of Si to divalent cations for all pyroxene components except the "vacancy component". After Robinson (1980).

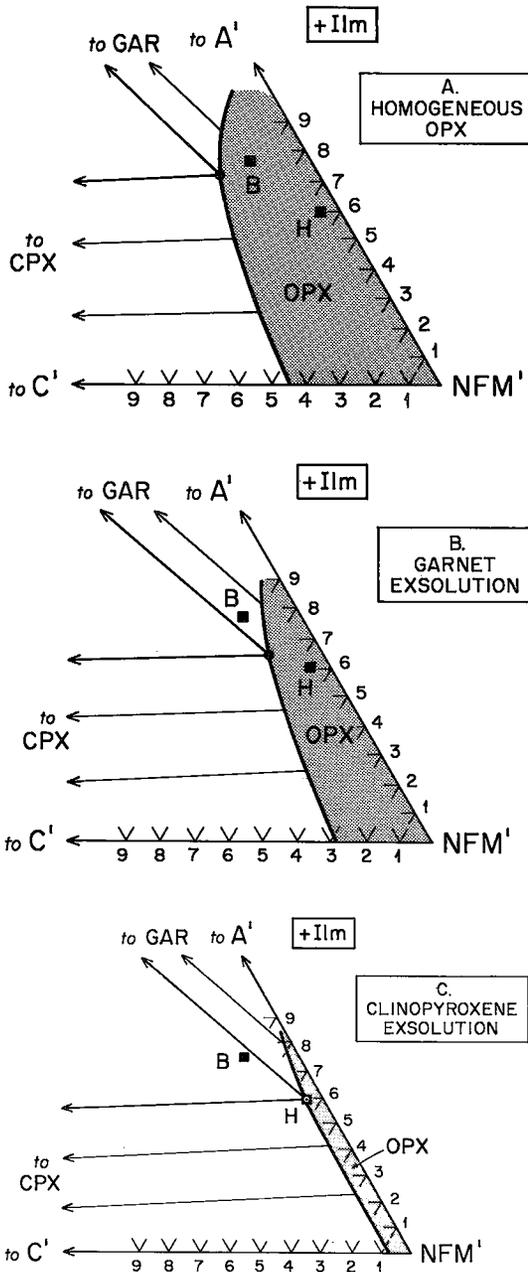


FIG. 10. Projection from ilmenite (Ilm) of the bulk (B) and host (H) compositions of orthopyroxene (Opx), sample PR-2, onto a composition diagram that contains all pyroxene components except the "vacancy component". Co-ordinates: A' (Al + Fe³⁺ + Cr - Na - 0.107 Ti)/2, NFM' 2Na + Mg + Fe²⁺ + Mn - Ti, C' = Ca. Shape of the composition field of orthopyroxene is schematic. A through C show the possible phase-relations leading to garnet (Gar) and clinopyroxene (Cpx) exsolution in orthopyroxene.

ected or transported from a deeper and hotter P-T regimen to a site of emplacement at a shallower level.

EXSOLUTION

The two orthopyroxene megacrysts discussed here, PR-2 and I-JO-12, are very similar in bulk composition, except for their Ca and Al contents, which are both higher in the orthopyroxene that exsolved plagioclase (Table 2). The composition of the pyroxene hosts after exsolution is even more similar. The Al content of the orthopyroxene that exsolved plagioclase remains higher, but the Ca contents of both orthopyroxene hosts are essentially the same (Table 2) and extremely low. These observations suggest that the instability of Ca in the orthopyroxene structure under conditions of slow cooling initiated exsolution of Ca-bearing garnet in one orthopyroxene and of calcic plagioclase in the other. If this explanation is valid, then other aspects of the phase relations must explain why one exsolved garnet and the other exsolved calcic plagioclase.

The compositions of the pyroxene end-members and associated phases are shown in a triangular plot with SiO₂ as one apex(S), divalent oxides as another apex(NCFM), and trivalent oxides as the third apex(A) (Fig. 9; see Robinson 1980). All pyroxene components except the "vacancy pyroxene" of Gasparik & Lindsley (1980) lie on the line that originates at the midpoint between the SiO₂ and divalent oxides apices and ends at the trivalent oxide apex (Fig. 9). In addition, garnet, ilmenite and hematite lie on the same line and can be easily expressed as pyroxene components.

From the chemical relations shown in Figure 9, it is seen that exsolution of garnet, ilmenite, and clinopyroxene can be accomplished by removing these components from solution in the pyroxene. No material needs to be added or removed to form these phases.

It is more difficult to obtain anorthite (plagioclase) from pyroxene components. As seen in Figure 9, anorthite is richer in SiO₂ than all pyroxene components except the "vacancy pyroxene" component, which has a half-filled M2 site ($\square_{0.5}\text{Ca}_{0.5}\text{AlSi}_2\text{O}_6$; Gasparik & Lindsley 1980). Because of the excess SiO₂, plagioclase can only be obtained from "normal" pyroxene components if 1) a low-SiO₂ phase, for example olivine or spinel (Fig. 9), forms with the plagioclase, or 2) the pyroxene reacts with another phase to form the plagioclase. A third way to form plagioclase requires the presence of a "vacancy component", which would combine with the Ca-Tschermak (CaTs) component to form anorthite alone. Examples of these mechanisms have been used to explain plagioclase exsolution in pyroxene at other localities. Emslie (1975) has suggested that the CaTs component (CaAlAlSiO₆) and En-Fs components

($Mg_2Si_2O_6$ - $Fe_2Si_2O_6$) could combine to form anorthite + olivine. He based this suggestion on the presence of minute grains of olivine in one of the megacrysts. This mechanism requires that the volume of olivine present should be roughly half that of the exsolved plagioclase. In the Adirondack samples, no olivine is associated with the pyroxene megacrysts, making this an unlikely mechanism for plagioclase exsolution here. The possibility that oxidation reactions, or a magnetite component, may have played a role in the exsolution of calcic plagioclase from orthopyroxene megacrysts has been suggested by several investigators, including Buddington (pers. comm. 1972, cited in Wheeler 1973), Morse (1975), Bohlen & Essene (1978), and most recently by Dymek & Gromet (1984). Morse (1975) has suggested that plagioclase exsolution in orthopyroxene from Nain accompanied oxidation. The Fs component, the CaTs component and O_2 would combine to form anorthite + magnetite. The presence of magnetite associated with the plagioclase lamellae described by Morse (1975) strongly supports this mechanism of plagioclase exsolution for the Nain orthopyroxene; however, magnetite has not been identified in the Adirondack examples, making this a less attractive mechanism here. Dymek & Gromet (1984) have appealed to reduced solubility of the "vacancy pyroxene" component to explain plagioclase exsolution in orthopyroxene from the St-Urbain anorthosite. With this mechanism, the "vacancy component" and the CaTs component combine to form plagioclase + orthopyroxene poorer in Ca, Al and Si. This mechanism is appealing for the Adirondack samples, because it involves only pyroxene components, which makes it unnecessary to involve any other phase in the process. This explanation is tentatively adopted here.

Exsolution in PR-2

From the measured modes (Table 4), it is evident that most of the Ca from the bulk orthopyroxene was taken up by the larger and more abundant garnet lamellae. The finer clinopyroxene lamellae contain only a small part of the Ca from the bulk composition. The relative sizes of these two types of lamellae suggest that garnet exsolved first and clinopyroxene exsolved later. Figure 10 shows the possible phase-relations of exsolution in sample PR-2. A Ca-bearing and Al-rich orthopyroxene (Fig. 10A, symbol B) would first encounter the two-phase field of orthopyroxene-garnet (Fig. 10B) as Ca solubility in orthopyroxene decreases. This would be the region where garnet exsolves. The bulk composition could then enter the three-phase field of garnet-orthopyroxene-clinopyroxene (Fig. 10C) with further decrease in the Ca solubility. At this point clinopyroxene would exsolve.

The generalized shape of the orthopyroxene field in Figure 10A can be justified from the studies of Perkins & Newton (1980), Perkins *et al.* (1981) and Lindsley (1983). At fixed P and T in the pure Mg system, the Ca content is greater in Al-free orthopyroxene than in aluminous orthopyroxene coexisting with clinopyroxene and Ca-bearing garnet. Their most aluminous orthopyroxene contains no Ca. Factors that can influence the size of the composition field include P, T and x_{Fe} . The diagrams of Lindsley (1983) show that Ca solubility increases slightly with higher Fe^{2+} content at fixed T and P. Perkins & Newton (1980) indicated that increasing P will slightly lower the Ca content at constant T in the pure Mg system. Temperature appears to be the most important parameter controlling Ca content. In Al-free orthopyroxene the Ca content increases markedly with increasing T (Lindsley 1983). Similar changes, but of smaller magnitude, are seen in Mg-orthopyroxene richer in Al (Perkins & Newton 1980). Thus the exsolution of garnet and clinopyroxene portrayed in Figure 10 is likely to reflect decreasing T.

Exsolution in I-JO-12

In sample I-JO-12, Ca was removed from the original orthopyroxene by exsolution of anorthite, An_{97} , and clinopyroxene. Most of the Ca is now contained in the coarse anorthite lamellae, and the finer clinopyroxene lamellae only account for a small part of the Ca from the original pyroxene. The relative sizes of the two kinds of lamellae suggest that the anorthite exsolved first and the clinopyroxene exsolved either during the late stages or after anorthite exsolution. Figure 11 shows the possible phase-relations of exsolution in I-JO-12 and is based on the assumption that the "vacancy pyroxene" component is soluble in orthopyroxene. A homogeneous orthopyroxene (Fig. 11A) would enter the two-phase field orthopyroxene-anorthite (Fig. 11B) as solubility of the "vacancy pyroxene" component decreases. Following complete removal of the "vacancy pyroxene" component (Fig. 11C), the bulk composition would enter the three-phase field anorthite-orthopyroxene-clinopyroxene (Fig. 11D) with the reduction of Ca solubility in orthopyroxene. Tie lines to clinopyroxene in Figures 11A and 11B assume that the "vacancy pyroxene" component would be higher in the coexisting Ca-pyroxene.

As with sample PR-2, discussed earlier, the relatively high Ca content of the bulk orthopyroxene (sample I-JO-12) probably reflects formation at high T. If the assumed "vacancy component" substitution is correct and analogies with this substitution in the synthetic Ca-pyroxenes are reasonable, then the data of Gasparik & Lindsley (1980) would suggest that the original orthopyroxene held 0.015 of

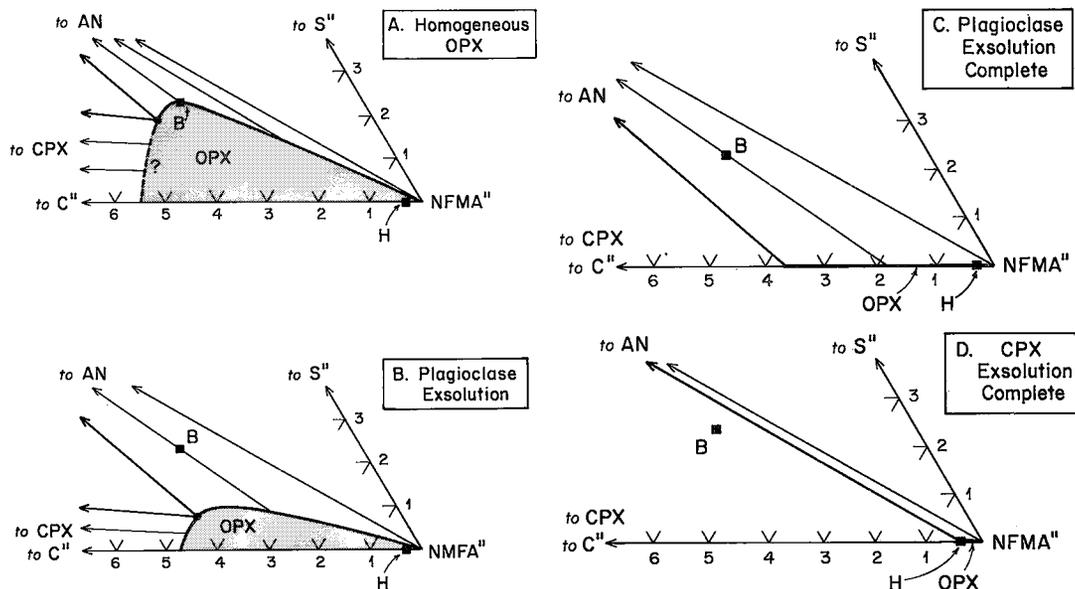


FIG. 11. Composition diagram showing bulk (B) and host (H) compositions of orthopyroxene (Opx) in sample I-JO-12. Co-ordinates: S'' Si-Mg-Fe²⁺-Mn-Ca-2Na, $NFMA''$ 2Na + Mg + Fe²⁺ + Mn + [(Al + Fe³⁺ + Cr-Na)/2], C'' Ca. A through D portray the possible phase-relations that lead to anorthite (An) and clinopyroxene (Cpx) exsolution. The composition field of orthopyroxene is schematic.

the $M2$ vacancy component (Table 5) formed at a P in excess of 10 kbar. Gasparik & Lindsley (1980) showed that "vacancy" substitution increases with P, and that T has very little effect on the extent of substitution within the stability field of this component. This suggests that plagioclase exsolution would accompany a pressure decrease at a relatively high T (Figs. 11A, B) and that subsequent exsolution of clinopyroxene would accompany a T decrease (Figs. 11C, D).

Exsolution of garnet versus plagioclase

Exsolution of garnet versus plagioclase in the orthopyroxene can best be explained by small differences in bulk composition. This is most clearly demonstrated in sample PR-2, which has a core rich in garnet exsolution-lamellae and a rim rich in plagioclase exsolution-lamellae. Since this crystal would have been subjected to the same P-T conditions throughout, differences in bulk composition represent the best explanation for the two dominant types of exsolution in this sample. In addition, variation in bulk composition can also explain why only plagioclase is exsolved in sample I-JO-12. Following the previously discussed assumptions, exsolution of plagioclase in orthopyroxene would require compositional solution toward the "vacancy pyroxene" component. The chemical effect of this substitution is to increase the ratio of Si to divalent cations

(Si/R^{2+}) in the pyroxene. The same compositional variation (increasing Si/R^{2+}) would be seen in gabbroic liquids (pyroxenes + plagioclase) progressively enriched in plagioclase (*i.e.*, approaching anorthite composition). Since the pyroxene composition should reflect the composition of the liquid from which it crystallized, pyroxenes crystallized from plagioclase-rich liquids would potentially have the highest extent of substitution by the "vacancy pyroxene" component, providing that crystallization occurred within the stability field of this component. This postulated compositional dependency can explain the zonation in PR-2. The early crystallized orthopyroxene, if formed in a gabbroic liquid, would be low in the "vacancy component" and, in PR-2, would be represented by the core, which contains exsolved garnet and, only exceedingly rarely, exsolved plagioclase. However, crystallization of pyroxene would drive the liquid to higher plagioclase content (higher Si/R^{2+}). If this change in the liquid is reflected in later growth of pyroxene, then it would result in higher solubility of the "vacancy component" in the later pyroxene. This explanation can account for the rim of PR-2, which contains abundant plagioclase lamellae (Table 4). A pyroxene such as I-JO-12 that contains chiefly plagioclase lamellae can be explained by postulating that it crystallized from a liquid much richer in plagioclase than the one that produced PR-2.

LIMITS ON P-T CONDITIONS

The conditions of formation for the orthopyroxene megacrysts and the exsolution features cannot be determined with certainty, but some deductions can be made. One possible constraint on the conditions of formation can be deduced from the mode of occurrence. Field relations discussed earlier suggest that the orthopyroxene is a phenocryst in dykes emplaced in the anorthosite. In PR-2 this interpretation is further supported by the presence of finer-grained clinopyroxene and plagioclase found in contact with the orthopyroxene megacryst; these may represent minerals crystallized after emplacement of the dykes. The conclusion drawn from these observations is that orthopyroxene was probably the first phase to crystallize (and was most likely the only phase to crystallize) before emplacement. Thus, experimental work by Boyd (1970), Akella & Boyd (1973, 1974), Akella (1974) and Hensen (1973) on calcium-saturated systems in which two pyroxenes

coexist with garnet are not directly applicable. Similarly, the data of MacGregor (1971) involve the coexistence of olivine with Al-rich orthopyroxene, and these data too are not directly relevant. Experimental studies on gabbroic anorthosite (Green 1969, 1970) indicate that pyroxene replaces plagioclase as the first phase to crystallize at pressures above 18–20 kbar (Fig. 12). The mineral compositions (Table 5) indicate that PR-2 was richer in Mg, $x_{Mg} = 0.735$, than the composition used by Green, $x_{Mg} = 0.44$ (Fig. 12), but a crude analogy would at least suggest that the initial growth of the Adirondack orthopyroxene phenocrysts would have been restricted to relatively high pressures.

It is possible to apply the calibration of the garnet–orthopyroxene geobarometer by Harley & Green (1982) to PR-2. The first calibration of this barometer in the system CaO–FeO–MgO–Al₂O₃–SiO₂ (FMAS) by Wood (1974) was based on unreversed data, whereas Harley & Green (1982) based their new calibration on reversed runs. The

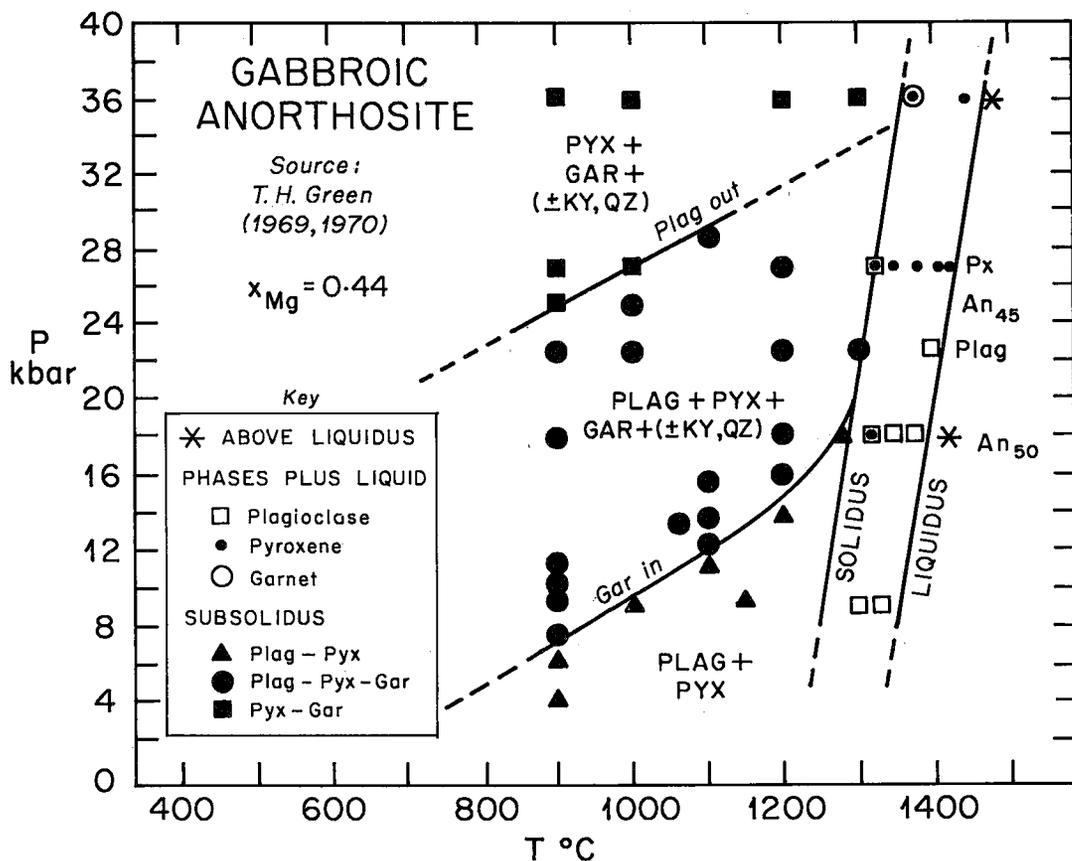


FIG. 12. Phase diagram for gabbroic anorthosite composition, showing pressure dependence of the liquidus phases (plagioclase, aluminous pyroxene and garnet) and the subsolidus assemblages, for a composition $x_{Mg} = 0.44$. Modified by Ashwal (1978) from data of Green (1969, 1970).

calibration of Harley & Green (1982) gives pressure estimates about 2 kbar higher than those of Wood (1974) at a given T and composition.

The garnet and orthopyroxene from PR-2 are suited for this geobarometer because the compositions lie almost entirely within the CFMAS system. The only significant departure from CFMAS is shown by orthopyroxene PR-2, which contains 2.78 wt. % Fe_2O_3 , calculated. However, this calculated value of ferric iron is lower than that in some of the natural samples of orthopyroxene to which Harley & Green (1982) applied their calibration. With this possible limitation in mind, the garnet-orthopyroxene geobarometer was applied to PR-2, and the following two assumptions apply: 1) the garnet composition remained constant, which seems justified by the absence of detectable zoning, and 2) the calculated bulk-composition (Table 5) represents the first orthopyroxene coexisting with garnet, and the host orthopyroxene (Table 2) represents the final one. These assumptions make it possible to calcu-

late two sets of pressures and temperatures, one representing the range of conditions at which exsolution might have commenced, and the other representing the range of conditions at which exsolution might have ceased. These are shown as solid lines, OPX(B.C.)-GAR and OPX(H)-GAR, respectively, on Figure 13. The range of temperature over which exsolution would have occurred depends on the depth (P) at which the orthopyroxene was slowly cooled. Garnet exsolution probably occurred before emplacement in anorthositic country-rocks, although the calculated field of garnet exsolution (Fig. 13) suggests that if the temperature remained high enough in the parts of the massif containing the megacrysts, then garnet exsolution may have nearly coincided with the cooling that followed the granulite-facies metamorphism. The presence of fractured exsolution-lamellae of garnet next to unbroken lamellae of plagioclase (Fig. 7B) would tend to confirm a premetamorphic origin for the garnet lamellae. Further, the recrystallization and clearing out of fine garnet + ilmenite + clinopyroxene lamellae into occasional microporphyroblasts of garnet rimmed by hornblende (Fig. 7A) would appear to coincide with a postexsolution metamorphic episode. At specific temperatures the orthopyroxene from PR-2 would have formed at pressures less than those at which exsolution would occur (Fig. 13), but at temperatures and pressures great enough to crystallize orthopyroxene from the liquid. From the previous discussion and Figure 13, this suggests pressures between roughly 20 and 25 kbar at temperatures above 1200°C for crystallization of the pyroxene with $x_{\text{Mg}} = 0.735$. These high temperatures are consistent with high Ca content of the pre-exsolution orthopyroxene.

The proposed incorporation of the "vacancy pyroxene" component into orthopyroxene exsolving plagioclase alone (I-JO-12) would be consistent with a high-temperature and a relatively high-pressure origin for such orthopyroxene. A high temperature is suggested by the Ca content and a high pressure (> 10 kbar) is suggested by analogy with synthetic clinopyroxene containing the "vacancy pyroxene" component.

The data of Table 6 show that even after copious exsolution of coarse lamellae of garnet (2.5–10 μm) and plagioclase (4–15 μm), the orthopyroxene host in samples PR-2 (core) and I-JO-12 still retains Al_2O_3 contents two to three times greater than that of representative orthopyroxene from the core of the Adirondack anorthosite massif, e.g., sample I-JO-8 (Table 6) collected from within one km of I-JO-12. Orthopyroxene I-JO-8 contains only thin (0.2–0.8 μm) lamellae of augite exsolved at temperatures estimated to be about 600°C (Jaffe *et al.* 1975, Robinson *et al.* 1977), well below the peak temperature of granulite-facies metamorphism.

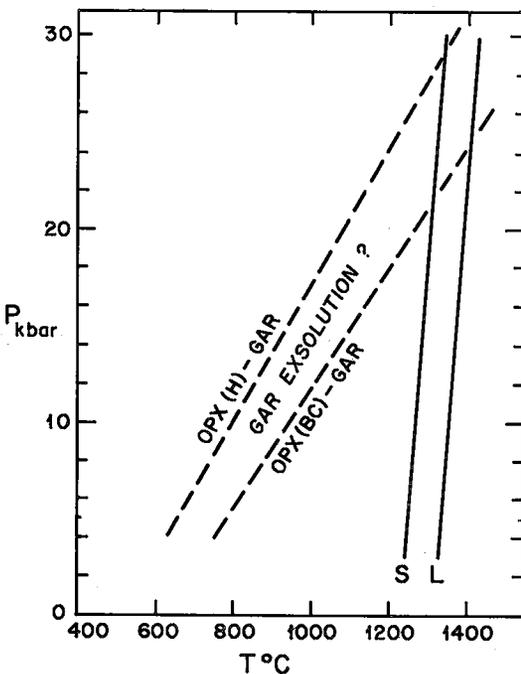


FIG. 13. Al isopleths, after Harley & Green (1982), limiting P-T conditions for commencement and completion of exsolution of garnet in orthopyroxene megacryst (sample PR-2). OPX(BC) refers to bulk composition of orthopyroxene at onset of exsolution, GAR refers to garnet lamellae, and OPX(H) refers to orthopyroxene host at completion of exsolution. S and L are solidus and liquidus lines from data of Green shown in Figure 12.

TABLE 6. VARIATION OF LAMELLAR THICKNESS AND CHEMICAL PARAMETERS IN SAMPLES OF ORTHOPYROXENE FROM THE ADIRONDACKS AND CORTLANDT COMPLEX (NEW YORK) AND BELLSBANK, SOUTH AFRICA

	PR-2(Core)		I-JO-12		I-JO-8	T-52	T-65	BB-54
	Bulk*	Host**	Bulk*	Host**				
x _{Mg}	0.735 → 0.763		0.742 → 0.746		0.557	0.776	0.744	0.922
%Al ₂ O ₃	5.41 → 3.51		6.25 → 4.38		1.50	4.72	4.25	1.86
%CaO	0.96 → 0.30		1.51 → 0.30		0.53	1.21	1.11	1.14
Lamellae:								
Gar(μm)		3-10	-	-	-	-	-	10
Pl(μm)		-		4-15	-	-	-	-
Ilm(μm)		0.8-1		<0.8	-	-	-	-
Cpx(μm)		0.4		<0.5	<0.4	<1	<1	10

PR-2(core) Opx megacryst, near summit, Porter Mt. (Fig. 1, Table 2).

I-JO-12 Opx megacryst, W. ledge, Mt. Jo (Fig. 1, Table 2).

I-JO-8 Opx from biotite leuconorite, W. ledge Mt. Jo, Jaffe *et al.* (1975).

T-52 Opx from Ol pyroxenite (Opx-Cpx-01), Cortlandt Complex, N.Y.

T-65 Do., both from Tracy (1970), Jaffe *et al.* (1975).

BB-54 Opx megacryst, kimberlite pipe, Bellsbank, South Africa, Aoki *et al.* (1980)

*Bulk compositional data are from Table 5.

**Composition of Opx megacryst after exsolution of Gar, Ilm and Cpx
Arrows show change in composition with exsolution in PR-2 and I-JO-12.

Although orthopyroxene samples T-52 and T-65 (Table 6) from the Cortlandt Complex, New York (Tracy 1970, Jaffe *et al.* 1975), contain x_{Mg}, %Al₂O₃ and %CaO comparable to bulk compositions of PR-2 and I-JO-12, they have exsolved only very thin (< 1 μm) lamellae of augite, emphasizing the importance of cooling rate to exsolution. The combination of high x_{Mg}, %Al₂O₃ and %CaO, with only thin, low-temperature (600°C-type) exsolution lamellae of augite in host orthopyroxene, and the well-developed contact metamorphic aureole around the ultramafic Cortlandt Complex add up to relatively shallow emplacement and rapid cooling. It is well known that coarse exsolution-lamellae require a history of high temperature followed by very slow cooling. Robinson *et al.* (1977) have correlated lamella thickness with temperature for multiply-exsolved lamellae of pigeonite in host augite of the Main Zone Gabbro (x_{Mg} = 0.58) at Bushveld as follows: the coarsest lamellae, 5–12 μm, exsolved at a T near 1000°C; the finer lamellae 1 μm, exsolved at a T near 800°C, and the finest lamellae 0.8 μm, exsolved at a T near 560°C. Pigeonite or hypersthene hosts inverted from pigeonite commonly coexist with or occur in place of the multiply-exsolved augite hosts and commonly carry very coarse lamellae of augite. Their occurrence in large layered intrusive bodies crystallized at a high temperature has been described from the Stillwater Complex by Hess (1960), the Skaergaard Complex by Wager & Brown (1967), the Nain Complex by Ranson (1978), the Rogaland Complex by Rietmeijer (1979), the Marcy Massif by Jaffe *et al.* (1983) and Ollila (1984). At high values of x_{Mg}, in the range 0.70–0.80, pigeonite crystallized near 1200°C should exsolve its coarse lamellae of augite near 1000°C, as indicated by Robinson *et al.* (1977) for host augite from the Main Zone Gabbro at Bushveld.

According to Aoki *et al.* (1980), 10-μm-thick lamellae of pyrope, comparable to garnet lamellae in PR-2, exsolved from orthopyroxene megacrysts

crystallized at 1100–1400°C at 50–70 kbar in the Bellsbank (South Africa) kimberlite pipe (Table 6). Aoki *et al.* (1980) could not determine the temperature at which the garnet exsolved in the Bellsbank megacryst, nor can we do so for the Adirondack megacrysts. If an analogy can be made between lamella thickness and temperature for exsolution of pigeonite in magnesian augite, augite in hypersthene inverted from magnesian pigeonite, and garnet in magnesian orthopyroxene, then data of Robinson *et al.* (1977) may be applicable to PR-2. Thus, the intersection of the 1000°C isotherm with line OPX(B.C.)–GAR in Figure 13 suggests that exsolution of garnet in a dry environment would have commenced at 40 km depth (P 11 kbar) and have been completed where the line OPX(H)–GAR is intersected for this depth at 850°C.

These P–T conditions exceed estimates of 7–9 kbar at 750°C for the peak of granulite-facies metamorphism in the Adirondack massif by Jaffe *et al.* (1978) and Bohlen *et al.* (1978), and serve to underscore an exotic, premetamorphic origin for both crystallization and exsolution of garnet in orthopyroxene megacryst PR-2.

SUMMARY AND CONCLUSIONS

Evidence pointing to a high-temperature and high-pressure, deep crustal or mantle crystallization of Al-rich orthopyroxene megacrysts is varied and formidable.

1. The high bulk Al₂O₃ content (4.5–6.25%), the high Mg content (x_{Mg} 0.67–0.76), and the 10–12% higher Mg content of the Al-rich orthopyroxene megacrysts than that of the enclosing anorthositic host-rocks (x_{Mg} 0.75 versus 0.64, respectively) all suggest a high-temperature, exotic origin rather than *in situ* crystallization in anorthosite.

2. The Al-rich orthopyroxene megacrysts from

a wide spectrum of the world's anorthosites all show a very limited range of Mg content (x_{Mg} 0.66–0.76); yet they are enclosed in anorthosites of different average plagioclase compositions, An₄₀, An₄₈, An₅₃ and An₅₅, which would appear to cast doubt on their origin by a process of *in situ* magmatic crystallization.

3. The average thickness of the exsolution lamellae of garnet in sample PR-2 (7–8 μ m) is of the same order of magnitude as that shown by high-temperature lamellae of augite exsolved in inverted pigeonite and comparable lamellae of pigeonite exsolved in host augite at a temperature in the range 800–1000°C (Robinson *et al.* 1977, Rietmeijer 1979), and is consistent with a high-temperature origin. By contrast, “low-temperature” pigeonite lamellae in host augite and augite lamellae in host orthopyroxene, both exsolved at about 600°C, are much finer in width (0.5–1 μ m) and shorter in length (Jaffe *et al.* 1975).

4. The exsolution of garnet and plagioclase in orthopyroxene results from Ca instability in orthopyroxene slowly cooled to a lower temperature.

5. The exsolution of garnet in PR-2 is a consequence of its high Al and Ca (CaTs component) that allowed the bulk composition to enter a garnet–orthopyroxene two-phase field as Ca solubility decreased.

6. It is suggested that the exsolution of plagioclase is also the result of high Al and Ca as well as very minor solubility toward a “vacancy pyroxene” component. This allowed the bulk composition of sample I-JO-12 to enter a plagioclase–orthopyroxene two-phase field as Ca solubility decreased.

7. The exsolution of garnet *versus* plagioclase in zoned megacrysts such as PR-2(core) and PR-2(rim) and in other megacrysts, *e.g.*, I-JO-12, can be explained by minute variations in the bulk composition of the pyroxene. The important variable is solid solution toward pressure-dependent crystallization of “vacancy pyroxene”, which, in terms of chemical behavior, could be linked to the plagioclase content of the liquid that produces the orthopyroxene.

8. Exsolution of garnet may also be favored by decreasing temperature at a high pressure, and exsolution of plagioclase, by decompression at a high temperature. Paragenetic relations (Fig. 7B) suggest that fractured lamellae of garnet exsolved earlier than adjoining nonfractured lamellae of plagioclase in sample PR-2.

9. Experimental data of Green (1969, 1970), Harley & Green (1982), Wood (1974), Gasparik & Lindsley (1980) and Wood & Henderson (1978) all support a deep crustal or mantle source for these megacrysts.

10. Additional evidence of a high pressure is

found in an example of garnet exsolution in a clinopyroxene megacryst collected from a mafic inclusion in allochthonous anorthositic gneiss of the Rosseau subdomain, Central Gneiss Belt, Parry Sound, Ontario (Davidson *et al.* 1982). This outcrop also contains sapphirine, spinel and garnet with a 47% pyrope molecule (Davidson *et al.* 1982).

11. Further evidence of the very primitive nature of these megacrysts is given by isotopic values of $I_{Nd}^{1290} = 0.5105$ and epsilon Nd, $\epsilon_{Nd}^{1290} = +5.08$, that are higher than those of any other material from the Marcy anorthosite massif (Ashwal & Wooden 1983).

12. Field, mineralogical and chemical criteria suggest that the Al-rich orthopyroxene megacrysts in the Marcy anorthosite massif grew in gabbroic to anorthositic liquids at high temperatures (> 1200°C) and relatively high pressures (20–25 kbar). They were subsequently transported from a depth of 70–85 km to their level of emplacement in anorthositic country-rocks and underwent exsolution before the regional granulite-facies metamorphism at 25–30 km depth (Jaffe *et al.* 1978, 1983). Their vehicle of transport and mode of emplacement may be debated, but field relations favor their introduction into solidified anorthosite as leuconoritic dykes and veins. Alternatively, after Emslie (1975), the megacrysts may represent exotic xenocrysts convected from depth into an incompletely crystallized anorthosite.

13. Paragenetic relationships observed in thin section are consistent with the origin postulated above. These show a sequence of: 1) exsolution of garnet from a homogeneous orthopyroxene solid-solution, 2) fracturing of host and garnet lamellae, 3) exsolution of calcic plagioclase lamellae, 4) fracturing of megacrysts, particularly at their contacts with the enclosing country-rock, 5) hydrothermal introduction of water and alkalis primarily at megacryst boundaries, and 6) sericitization of lamellae of calcic plagioclase accompanied by minor recrystallization of garnet to form bulbous nodes perched on elongate exsolution-lamellae, and occasional microporphyroblasts of hornblende-rimmed garnet.

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