Canadian Mineralogist
Vol. 14, pp. 291-298 (1976)

CORONA-BEARING PYROXENE GRANULITE XENOLITHS AND THE LOWER CRUST BENEATH NUNIVAK ISLAND, ALASKA

DONALD M. FRANCIS
Department of Geological Sciences, McGill University, Montreal, Quebec H3C 3G1 Canada

Abstract

Corona-bearing pyroxene granulite xenoliths comprise 9% of the xenolith population of recent alkali basalts on Nunivak Island, Alaska. These xenoliths were originally troctolite cumulates whose olivine and plagioclase have reacted to form coronas of aluminous clinopyroxene-spinel symplectite and aluminous orthopyroxene. They were last in equilibrium at 950°C under at least 9 kbar pressure and are interpreted to be fragments of the base of the crust. The corona structures are a reaction phenomena which developed *in situ* and may reflect isobaric cooling in this environment or the development of the Bering Sea continental shelf.

Sommaire

Des enclaves enallogènes de granulite à pyroxène coronitique représentent 9% de la population d'enclaves enallogènes des basaltes alcalines récents de l'Ile Nunivak, en Alaska. Ces enclaves étaient, à l'origine, des accumulations de troctolite dont l'olivine et la plagioclase ont réagi pour former des couronnes de symplectite à clinopyroxène alumineux + spinelle et d'orthopyroxène alumineux. La dernière fois qu'ils étaient en équilibre, c'était à 950°C, sous une pression minimale de 9 kbar, vraisemblablement des fragments de la base de la croûte. Les structures coronitiques résultent de réactions développées in-situ; elles peuvent réfléter le refroidissement isobarique dans ce milieu ou le développement du plateau continental de la mer Bering.

(Traduit par le journal)

Introduction

An unusual variety of pyroxene granulite xenolith found on Nunivak Island, Alaska, has preserved evidence from the lower crust of the reaction of olivine and plagioclase to an assemblage of two aluminous pyroxenes plus spinel. As the pressure and temperature conditions required for this reaction are known experimentally, constraints may be placed on the evolution of the crust in this region.

Occurrence and Past Work

Nunivak Island is a center of late Tertiary to Recent basaltic vulcanism just off the west coast of Alaska (60°N, 166°W). Two percent of the exposed basalts are alkaline and occur as small spatter cones with associated flows and as maars or explosion craters (Hoare *et al.* 1968). Amphibole lherzolites (Francis 1975), spinel lherzolites, and megacrysts of anorthoclase, kaersutite, and clinopyroxene are abundant in most of the alkali basalts. Hoare (Hoare & Condon 1968; Hoare & Kuno 1968) reported the presence of unusual "eclogite" xenoliths in the maars of the island. He recognized that these xenoliths consist of spinel-clinopyroxene symplectite coexisting with plagioclase and orthopyroxene-mantled olivine. Because of the similarity of the bulk composition of these xenoliths to those of garnet pyroxenites from Salt Lake Crater, Hawaii, Hoare concluded that the symplectite formed by the breakdown of garnet. The present author spent six weeks during the summer of 1972 studying and collecting these "eclogite" xenoliths (hereafter termed pyroxene granulites). They were found to be common in both the maars and spatter cones of the island, comprising approximately 9% of the xenolith population (based on a count of more than 3000 xenoliths).

Petrography

These nodules are metamorphic rocks in which olivine and plagioclase are never juxtaposed, but are always separated by mantles of radially disposed orthopyroxene and spinel-clinopyroxene symplectite. Hoare recognized that there is a complete spectrum of this xenolith type ranging from specimens dominated by plagioclase to those dominated by olivine.

The olivine-rich, pyroxene granulites consist largely of a xenomorphic-granular aggregate of olivine(I) grains (0.5 to 4 mm) with strongly developed kink banding and undulatory extinction. Turbid, 1 to 3 mm clinopyroxene(I)

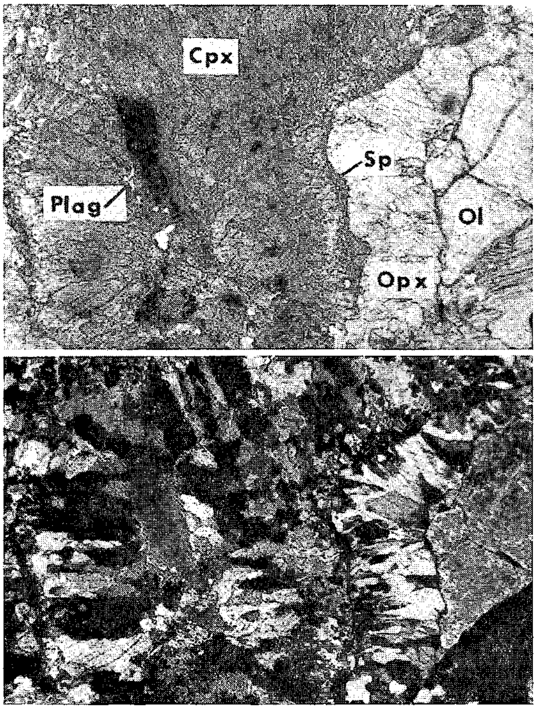


FIG. 1a — (top): Plane polarized light image of corona mineral assemblages developed between olivine (I) and plagioclase(I). Note that ghosts of plagioclase lamellar twinning are visible in the spinel-clinopyroxene symplectite (Cpx). Width of field: 3 mm. (b) Crossed nicols image of Figure 1a.

(with numerous, micron-scale, green spinel inclusions) and 0.4 mm, dark olive-green spinel(I) occur as interstitial accessory phases. In this matrix are oblate, layered corona structures 1 to 10 mm in size (Fig. 1). Their outer layer, adjacent to the olivine matrix, consists of colorless orthopyroxene as elongate, 0.1 to 1 mm crystals, radially disposed to the contact. Lining the inner margin of this layer is a chain of equant, 0.01 to 0.05 mm grains of light green spinel(II). The central portion of the corona structure is spinel-clinopyroxene symplectite. At its outer edge the symplectite consists of anhedral clinopyroxene(II) grains (0.01 to 0.04 mm) intergrown with equant spinel(II) grains ($<$0.01 mm). The interior, however, consists of coarser (0.1 to 0.6 mm), elongate and radially disposed clinopyroxene(II) crystals containing vermicular intergrowths of spinel. Embayed plagioclase(I) is commonly found at the center of the symplectite. This plagioclase(I) is clouded with numerous, 0.004 to 0.02 mm, round spinel(II) inclusions.

Specimens less rich in olivine are dominated by the corona mineral assemblage, which contains isolated pockets of granular olivine(I) or plagioclase(I). Plagioclase-rich pyroxene granulites are essentially the inverse of their olivine-rich counterparts. They consist of a matrix of xenomorphic-granular plagioclase(I), and lesser turbid clinopyroxene(I), containing isolated corona structures. The outer layer is now very fine-grained spinel-clinopyroxene symplectite, whereas the core consists of radially disposed orthopyroxene crystals. In a few cases an embayed olivine(I) grains(s) may be found at the center of these coronas.

The pyroxene-granulite xenoliths exhibit two textural features suggestive of cumulate processes. Most of the xenoliths have a marked layering which is defined by the concentration of spinel(I) in the very olivine-rich examples or by the concentration and oblate shape of the corona bodies (Fig. 2). More convincing is the tendency of clinopyroxene(I), where present in large grains, to enclose subhedral olivine(I) crystals poikilitically (Fig. 3).

Many specimens exhibit textural evidence of partial melting. In such specimens, patches of the spinel-clinopyroxene symplectite are replaced by an assemblage of skeletal olivine(II) in a matrix of plagioclase(II) laths (Fig. 4). Associated with this texture is the development of chains of 0.02 to 0.04 mm, equant olivine(III)

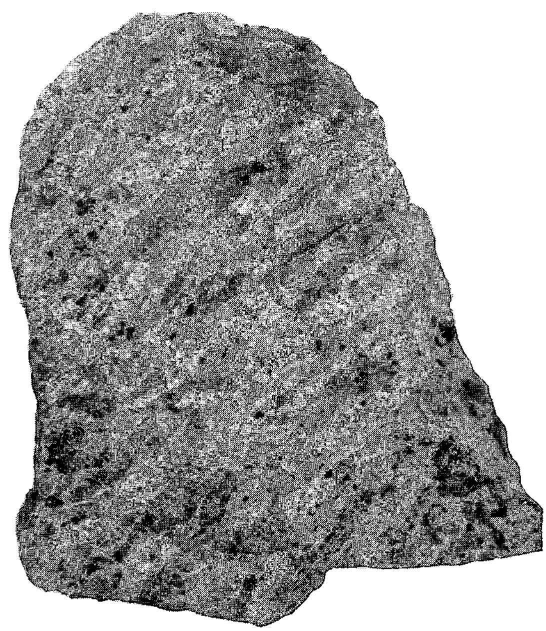


FIG. 2. Layering defined by oblate shape and concentration of corona structures (darker gray areas). Width of object 5 cm.

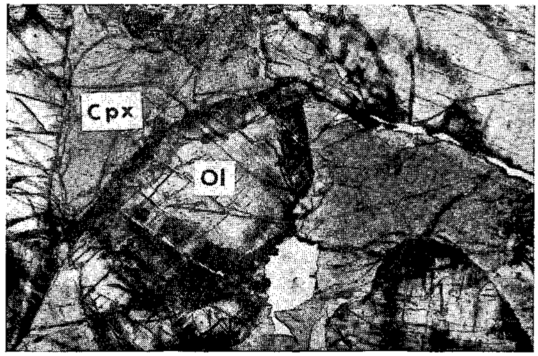
grains between the chains of equant spinel and layers of orthopyroxene in the coronas. This texture appears to have been produced by the reaction suggested by MacGregor (1973) in which orthopyroxene and spinel react to form more aluminous orthopyroxene plus olivine with increasing temperature:

$$\underset{\text{opx.}}{(1 + X)MgSiO_3} + \underset{\text{sp.}}{(X)MgAl_2O_3} \rightarrow \underset{\text{Al-opx.}}{MgSiO_3X(Al_2O_3)} + \underset{\text{ol.}}{(X)\,Mg_2SiO_4} \quad \ldots\ldots (1)$$

Chemistry

Olivine. Olivine(I) ranges from Fo_{72} in feldspar-rich pyroxene granulites to Fo_{87} in the olivine-rich specimens (Table 1). This compositional range is distinctly more Fe-rich than that of olivine in associated spinel lherzolite xenoliths (Fo_{89} to $Fo_{91.5}$). No chemical zoning was detected. The skeletal olivine(II), found with plagioclase(II) laths replacing spinel-clinopyroxene symplectite, is more Mg-rich (Fo_{90}) and contains relatively high Ca contents (0.5 wt.% CaO compared to 0.07 wt.% CaO in olivine(I)). Its habit and high Ca content suggest rapid crystallization (Simkin & Smith 1970).

Feldspar. The matrix feldspar of the plagioclase-rich pyroxene granulites contains 68 to 74% anorthite. Adjacent to spinel-clinopyroxene



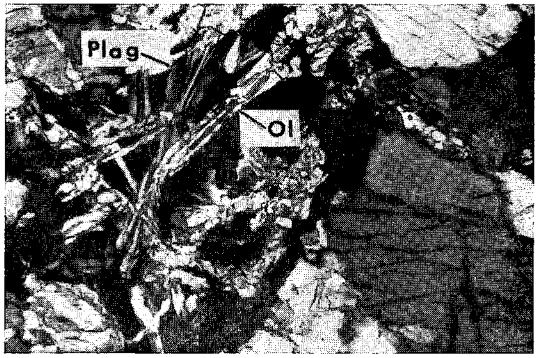


FIG. 3. — (top): Poikilitic clinopyroxene(I) enclosing euhedral olivine(I). Width of field 3 mm.

FIG. 4. — Skeletal olivine(II) and plagioclase(II) formed by quenching of liquid produced by partial melting of spinel-clinopyroxene symplectite. Width of field 0.15 mm.

TABLE 1. ANALYSES OF PRIMARY PHASES OF PYROXENE GRANULITES

	Olivine (I)		Plagioclase (I)		Clinopyroxene (I)		Spinel (I)	
Specimen	12000*	12001†	12000*	12001†	12000*	12024†	12001†	12017†
SiO_2	37.63	40.11	47.91	61.78	51.63	51.69	0.79	0.31
TiO_2	0.15	0.00	---	---	0.56	0.64	0.00	0.00
Al_2O_3	0.11	0.01	33.57	25.67	2.96	3.18	57.36	50.38
Cr_2O_3	0.00	0.05	---	---	0.61	0.76	9.72	15.32
FeO	25.48	12.40	---	---	5.77	3.58	12.56	14.21
MnO	0.53	0.15	---	---	0.16	0.16	0.24	0.33
MgO	36.30	47.34	---	---	14.53	15.53	19.32	18.63
CaO	0.02	0.06	15.41	5.17	22.14	22.81	0.04	0.02
Na_2O	0.20	---	3.05	7.95	0.89	0.53	---	---
K_2O	---	---	0.05	0.39	0.01	0.20	---	---
TOTAL	100.42	100.12	99.99	100.96	99.26	99.08	100.03	99.20
O	4.000	4.000	8.000	8.000	6.000	6.000	4.000	4.000
Si	0.992	0.994	2.194	2.709	1.921	1.912	0.021	0.008
Al^{iv}	---	---	1.812	1.327	0.079	0.088	---	---
Ti	0.003	0.000	---	---	0.016	0.018	0.000	0.000
Al^{vi}	0.003	0.000	---	---	0.051	0.051	1.755	1.607
Cr	0.000	0.001	---	---	0.018	0.022	0.200	0.328
Fe	0.562	0.257	---	---	0.180	0.111	0.273	0.322
Mn	0.012	0.003	---	---	0.005	0.005	0.005	0.008
Mg	1.426	1.749	---	---	0.806	0.856	0.748	0.751
Ca	0.001	0.002	0.756	0.243	0.883	0.904	0.001	0.001
Na	0.010	---	0.271	0.676	0.064	0.038	0.000	0.000
K	---	---	0.003	0.022	0.000	0.009	0.000	0.000
TOTAL	3.009	3.005	5.036	4.976	4.022	4.014	3.002	3.024
	Fo 71.7	Fo 87.2	An 73.4	An 25.8	Mg no. 0.818	Mg no. 0.885		

* Feldspar-rich granulite † Olivine-rich granulite

TABLE 2. ANALYSES OF CORONA PHASES

	Orthopyroxene		Clinopyroxene (II)		Spinel (II)	
Specimen	12001	12004	12001	12004	12001	12004
SiO_2	54.97	55.23	53.82	53.70	1.05	1.05
TiO_2	0.00	0.00	0.02	0.00	0.00	0.00
Al_2O_3	3.45	3.94	5.73	6.56	65.60	64.44
Cr_2O_3	0.08	0.10	0.07	0.08	0.82	0.37
FeO	7.90	7.76	2.69	2.82	10.54	10.35
MnO	0.18	0.17	0.09	0.12	0.06	0.07
MgO	33.11	32.28	14.86	13.91	21.72	23.39
CaO	0.37	0.37	20.78	20.21	0.11	0.12
Na_2O	---	---	1.98	2.43	---	---
K_2O	---	---	0.02	0.01	---	---
TOTAL	100.06	99.85	100.06	99.84	99.90	99.79
O	6.000	6.000	6.000	6.000	4.000	4.000
Si	1.910	1.919	1.939	1.937	0.026	0.026
Al^{iv}	0.090	0.081	0.061	0.063	---	---
Ti	0.000	0.000	0.001	0.000	0.000	0.000
Al^{vi}	0.051	0.080	0.182	0.216	1.928	1.897
Cr	0.002	0.003	0.002	0.002	0.016	0.007
Fe	0.230	0.225	0.081	0.085	0.220	0.216
Mn	0.005	0.005	0.003	0.004	0.001	0.001
Mg	1.715	1.672	0.798	0.748	0.807	0.871
Ca	0.014	0.014	0.802	0.781	0.003	0.003
Na	---	---	0.138	0.170	---	---
K	---	---	0.001	0.000	---	---
TOTAL	4.018	3.999	4.008	4.007	3.002	3.022
Mg no.	0.882	0.881	0.908	0.898		

symplectite, however, these plagioclase(I) grains are depleted in Ca, with anorthite contents as low as 59%. The relict plagioclase(I) grains mantled by corona structures in olivine-rich specimens are strongly depleted in anorthite (An 23 to An 26) but are chemically homogeneous (Table 1). In comparison, the plagioclase(II) laths, with skeletal olivine(II), which replaced spinel-clinopyroxene symplectite are relatively enriched in Ca (An 80).

Orthopyroxene. The Mg numbers (Mg/Mg+ΣFe) of orthopyroxene in the corona assemblage range from 0.77 to 0.88 (Table 2), closely following but always slightly higher than that of the matrix olivine (Mg no. ol./Mg no. opx. = 0.935 to 0.988). The orthopyroxene contains 3 to 4% Al_2O_3. No chemical zoning was observed across the orthopyroxene layers of the coronas.

Clinopyroxene. The interstitial clinopyroxene(I) in the olivine or plagioclase matrix and the clinopyroxene(II) in the spinel-clinopyroxene symplectite are chemically distinct (Tables 1 & 2). The latter has negligible Ti and Cr but is significantly enriched in Na and Al^{vi} (jadeite molecule) and has higher Mg numbers than the matrix clinopyroxene(I). No chemical zoning was detected in either type.

Spinel. The spinels of the pyroxene granulite xenoliths exhibit a wide range of Cr/Cr+Al and Mg/Mg+ΣFe ratios. For an equivalent Cr content they are significantly more Fe-rich, however, than the spinels of associated lherzolite xenoliths. Interstitial spinel(I) in the matrix of olivine-rich granulites has high and variable Cr contents associated with low Mg numbers. Spinel(II) in the spinel-clinopyroxene symplectite is much more aluminous (Cr_2O_3 <1 wt.%) and has higher Mg numbers. The spinel(II) inclusions in relict plagioclase grains have no detectable Cr and have the highest Mg numbers.

Bulk composition. The whole-rock chemistry of a number of pyroxene-granulite xenoliths of varying modes is given in Table 3. The compositions of these nodules can be recalculated largely in terms of olivine(I) and plagioclase(I) neglecting the corona minerals which comprise up to 70% of their mode (Table 3).

Origin of Xenoliths

The xenoliths are termed pyroxene granulites after the nomenclature of Ito & Kennedy (1970) and are transitional between the low- and intermediate-pressure granulites of Green & Ringwood (1967). Rocks similar to these nodules are commonly found in deep-seated anorthosite or gabbro plutons (Gardner & Robbins 1974; Whitney & McLelland 1973; Griffin 1971; Griffin & Heier 1973), but are rare as volcanic xenoliths. The only documented occurrences known to the author are in the Kerguelen Archipelago (McBirney & Aoki 1973) and on Iki Island, Japan (Aoki 1968).

The contrast between the tectonite fabric of the granular aggregates of olivine(I) and/or plagioclase(I) and the corona structure of the orthopyroxene plus spinel-clinopyroxene symplectite assemblage suggests that the latter is a secondary feature produced by the incomplete reaction of the former. The following chemical reaction may be written using analyzed phase compositions for the development of the corona mineral assemblage in a plagioclase-dominated, pyroxene granulite xenolith:

$$\underset{\text{An 72}}{121\text{Plag(I)}} + 100\text{Ol(I)} + \underset{\substack{\text{Cr/Cr+Al}\\ 0.102}}{7\text{Sp(I)}} \rightarrow \underset{\text{An 26}}{16\text{Plag(I)}} + 87\text{Cpx(II)} + 75\text{Opx} + \underset{\substack{\text{Cr/Cr+Al}\\ 0.008}}{49\text{Sp(II)}} \quad \ldots\ldots (2)$$

in weight proportions, calculated after Wright & Doherty (1970).

$$\sum_{\text{10 oxides}} |\text{residuals}| = 1.29\ \text{wt.\%}$$

The following chemical criteria support this proposed model:

(1) The low Cr and Ti contents of the symplectite clinopyroxene(II) compared to clinopyroxene(I) are consistent with the former's origin by the reaction of olivine and plagioclase. In addition, the relatively high Na and Al^{vi} contents of the symplectite clinopyroxene(II) suggest that it formed either at lower temperatures (at constant pressure) or a higher pressures (at constant temperature) than clinopyroxene(I) (Thompson 1974). The reverse would be the case if the coronas were produced by the breakdown of garnet as suggested by Hoare & Kuno (1968).

(2) Similarly, the low Cr and Ti of the symplectite spinel(II) compared to spinel(I) reflects the former's origin by the reaction of olivine(I) and plagioclase(I).

(3) The preferential depletion of anorthite from plagioclase(I) adjacent to coronas reflects the ease with which the secondary clinopyroxene(II) incorporates Ca with respect to Na. (4) The compositions of the reactants of equation 2 can account for the bulk composition of the xenoliths, without considering the corona mineral assemblage.

The pyroxene granulites are therefore concluded to have originally consisted largely of olivine(I) and plagioclase(I) with minor spinel(I) and clinopyroxene(I). The primary rock types ranged from feldspathic dunite to troctolite. The compositions of the olivines, the poikilitic nature of some of the large clinopyroxene(I) grains (Fig. 3) and the pronounced layering (Fig. 2) indicate that these troctolites had a cumulate origin. The development of the corona mineral assemblage clearly post-dates the deformation recorded in the primary olivine(I). However, the development of olivine(III) and partial melting in the symplectite indicate that the coronas predate a later thermal event, probably associated with the entrainment of the xenoliths in their host basanites. These xenoliths are therefore concluded to be accidental fragments of some crustal horizon beneath Nunivak Island, Alaska.

TABLE 3. CHEMICAL ANALYSES AND MODES OF XENOLITHS

	12000	12011	12013	12017
SiO_2	48.40	45.45	44.89	43.25
TiO_2	0.24	0.03	0.04	0.02
Al_2O_3	22.32	16.20	11.68	7.78
Cr_2O_3	0.33	0.86	0.92	0.96
FeO	3.98	6.57	9.01	10.25
MnO	0.08	0.11	0.15	0.16
NiO	0.06	0.29	0.29	0.41
MgO	8.86	22.08	26.45	33.90
CaO	12.44	7.69	5.88	3.17
Na_2O	2.74	0.38	0.46	0.00
K_2O	0.08	0.08	0.02	0.01
P_2O_5	0.47	0.26	0.21	0.09
Total*	100.00	100.00	100.00	100.00
primary phases				
olivine (I)	1.0	0.0	29.0	55.6
plagioclase (I)	69.3	1.3	1.9	0.0
clinopyroxene (I)	13.2	0.0	1.3	0.2
spinel (I)	0.7	0.7	1.4	1.3
corona phases				
orthopyroxene	4.5	26.7	23.8	12.4
clinopyroxene (II)	7.6	63.2	41.3	14.1
spinel (II)**	0.0	4.0	1.3	2.1
quench phases				
olivine (II)	2.5	1.3	0.0	8.7
olivine (III)	0.0	0.1	0.1	0.1
plagioclase (II)	1.2	2.8	0.0	5.5
CALCULATED PRIMARY MODE				
olivine (I)	17.6	48.4	57.4	74.3
	Fo 72.4	*Fo 81.6*	*Fo 78.0*	*Fo 80.3*
plagioclase (I)	70.6	51.6	36.6	25.7
	An 70.0	*An 73.2*	*An 66.0*	*An 65.2*
clinopyroxene (I)	11.9	0.0	5.6	0.0
spinel (I)	0.0	0.0	0.4	0.1
Σ |residuals| oxides	1.29	0.62	2.74	2.91

*XRF analyses by S. Horsky; computer correction to 100%
**includes only grains thicker than section, finer symplectite spinel included with clinopyroxene (II).

Application of the pyroxene geothermometer of Wood & Banno (1974) to the corona mineralogy of 3 pyroxene granulites yields temperatures between 930 and 985°C. With these temperatures, pressures can be estimated from experimental data on the reaction of olivine and plagioclase to form 2 aluminous pyroxenes plus spinel (Fig. 5). Note that the upper stability limit of coexisting olivine and plagioclase shifts to higher pressures with increasing albite content of the plagioclase. This is reflected by the depletion of Ca in plagioclase as the reaction proceeds. The primary composition of the relict plagioclase in the olivine-rich granulites is estimated to be similar to that of the plagioclase in the feldspar-rich granulites (An 68-74). Thus for the Nunivak specimens, a temperature of 950°C indicates a minimum pressure of 9 kilobars. Assuming the foregoing conclusions are correct, then the pyroxene granulite xenoliths were derived from a depth of at least 30 km and were last in equilibrium at approximately 950°C. Shor (1964) has measured a crustal thickness of 27 km for the Alaskan continental shelf near the Pribilof Islands, 400 km to the southwest. The pyroxene granulite xenoliths, therefore, would appear to be fragments of the base of the crust beneath Nunivak Island. There are two possible mechanisms for the origin of the corona structures in such an environment:

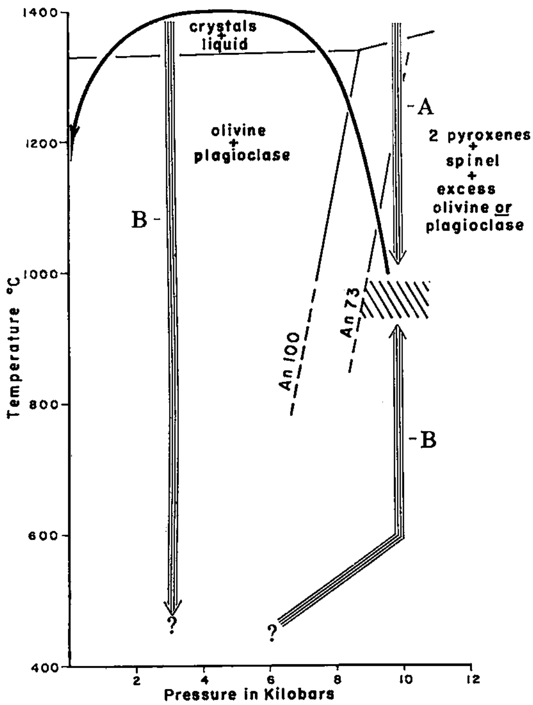


FIG. 5. Possible *P-T* histories of pyroxene granulite xenoliths: ruled pattern—estimated source region of xenoliths; heavy solid line—path of xenoliths entrained in basalts; path A—isobaric cooling at 30 km; path B—isobaric cooling at 10 km, followed by crustal thickening; phase boundaries after Kushiro & Yoder (1966), Emslie (1970), and Green & Hibberson (1970).

(1) *Isobaric cooling.* According to this model, initial magmatic cumulation of olivine(I) and plagioclase(I) crystals at a depth of 30 km is followed by deformation and *in situ*, isobaric cooling (Fig. 5, path A). With a sufficient temperature drop, olivine and plagioclase react to form 2 aluminous pyroxenes plus spinel. This reaction would cease when either all the olivine is consumed or the relict feldspar becomes too Na-rich to react under the prevalent conditions. Following an unspecified interval, fragments of this material are entrained in basanitic magmas. Partial melting of the corona symplectite occurs, and the liquid formed quenches at the surface to a low-pressure assemblage of olivine(II) and plagioclase(II).

Coronas in plutonic bodies are commonly attributed to an isobaric cooling mechanism (Gardner & Robbins 1974; Griffin & Heier 1973). McBirney & Aoki (1973) attribute spinel gabbro xenoliths with similar coronas from the Kerguelen Archipelago to such a process. Support from experimental work, however, is equivocal. Two studies indicate that the olivine-plagioclase reaction curve is considerably steeper than that depicted in Figure 5 (Emslie 1970; Herzberg 1971), possibly almost isobaric. If these studies are correct, it would be impossible to leave the olivine-plagioclase stability field by isobaric cooling. Another problem is the nature of the magma which could have cumulated a troctolite at a depth of 30 km. Few basalts have both olivine and plagioclase near their liquidus above 6 kbar pressure (Green & Ringwood 1967; Ito & Kennedy 1968; Kushiro & Thompson 1972).

(2) *Crustal thickening.* An alternate explanation for the corona structures is illustrated by path B in Figure 5. It requires a thinner (10 km) oceanic crust in the early Mesozoic. A layered dunite to troctolite sequence, resembling the transition zone of ophiolite complexes could accumulate from a magma resembling a mid-ocean ridge tholeiite at the base of such a crust.

On the adjacent mainland of western Alaska, Hoare (1961) has documented heavy sedimentation (Gemuk Group) throughout the early Mesozoic followed by extensive deformation in the lower Cretaceous. Pratt *et al.* (1972) and Scholl

& Hopkins (1969) have shown that the Bering Sea shelf has undergone an analogous history. Moore (1972) would correlate the deformation throughout this region with a proposed Cretaceous to Paleocene subduction zone which followed the present continental margin from Kodiak Island to the Koryak Mountains of Siberia. These geologic observations suggest a thickening of the Bering Sea crust and may record the conversion of the proposed oceanic crust to the Bering Sea shelf. This thickening continued with the deposition of 1500 m of loosely consolidated sediments on the shelf during the Tertiary ("main layered sequence" of Scholl *et al.* 1968). As the proposed troctolite base of this crust approached a depth of 30 km, coexisting olivine and plagioclase would become unstable, and corona assemblages would develop. The coronas would re-equilibrate with rising temperature in the upper mantle at the initiation of the Nunivak vulcanism and finally fragments of the resultant pyroxene granulite rock would be entrained in the basanitic magmas and carried to the surface.

Summary

Corona-bearing, pyroxene granulite xenoliths from Nunivak Island, Alaska, are interpreted to be accidental fragments of the base of the crust. They were initially cumulate rocks consisting of varying proportions of olivine and plagioclase with accessary clinopyroxene and spinel. The primary olivine and plagioclase reacted, *in situ,* to from coronas of aluminous orthopyroxene and clinopyroxene plus spinel. This reaction may have been a response to isobaric cooling of the original troctolite cumulate or to increasing pressure associated with crustal thickening.

Acknowledgements

This study was in part supported by N.S.F. grant G.A.-31728. The author is indebted to Drs. T. R. McGetchin and J. S. Dickey for their guidance and support. The mineral analyses were performed with the M.A.C. electron microprobe at the Department of Earth and Planetary Sciences of M.I.T. S. Horsky analyzed the whole-rock samples and R. Yates drafted Figure 5. Thanks are due S. Marques who prepared a number of versions of this manuscript.

References

Aoki, K. (1968): Petrogenesis of ultrabasic and basic inclusions in alkali basalts, Iki Island, Japan. *Amer. Mineral.* **53**, 241-256.

Emslie, R. F. (1970): Upper P-T stability of a natural olivine-plagioclase assemblage. *Carnegie Inst. Wash. Yearb.* **69**, 154-155.

Francis, D. M. (1975): The origin of amphibole in lherzolite xenoliths from Nunivak Island, Alaska. *J. Petrology,* in press.

Gardner, P. M. & Robins, B. (1974): The olivine-plagioclase reaction: geologic evidence from the Seiland petrographic province, northern Norway. *Contr. Mineral. Petrology* **44**, 149-156.

Green, D. H. & Hibberson, W. (1970): The instability of plagioclase in peridotite at high pressure. *Lithos* **3**, 209-231.

——— & Ringwood, A. E. (1967): An experimental investigation of the gabbro to eclogite transformation and its petrologic applications. *Geochim. Cosmochim. Acta* **31**, 767-833.

Griffin, W. L. (1971): Genesis of coronas in anorthosite of the upper Jatun Nappe, Indre Sogn, Norway. *J. Petrology* **12**, 219-243.

——— & Heier, K. S. (1973): Petrologic implications of some corona structures. *Lithos* **6**, 315-335.

Herzberg, C. T. (1971): Stability fields of plagioclase and spinel lherzolite. *Nat. Envir. Res. Council,* Ser. D., #2, 145-148.

Hoare, J. M. (1961): Geology and tectonic setting of the lower Kuskokwin-Bristol Bay region, Alaska. *Amer. Assoc. Petrol. Geol.* **45**, 594-611.

——— & Condon, W. H. (1968): Occurrence and origin of eclogite and peridotite inclusions in volcanic rocks of Nunivak Island, Alaska. *Geol. Soc. Amer. Spec. Pap.* **101**, 311.

——— & Kuno, H. (1968): Occurrence of olivine eclogite in volcanic ash of Nanwaksjiak Crater, Nunivak Island, Alaska. *Geol. Soc. Amer. Spec. Pap.* **101**, 94.

———, Condon, W. H., Cox, A. & Dalrymple, G. B. (1968): Geology, paleomagnetism, and potassium-argon ages of basalts from Nunivak Island, Alaska. *Geol. Soc. Amer. Mem.* **116**, 377-412.

Ito, K. & Kennedy, G. C. (1970): The fine structure of the basalt-eclogite transition. *Mineral. Soc. Amer. Spec. Pap.* **3**, 77-83.

Kushiro, I. & Yoder, H. S. (1966): Anorthite-forsterite and anorthite-enstatite relations and their bearing on the basalt-eclogite transformation. *J. Petrology* **7**, 337-362.

——— & Thompson, R. N. (1972): Origin of some abyssal tholeiites from the mid-Atlantic ridge. *Ann. Rep. Director Geophys. Lab.*, 1971-1972, 403-406.

McBirney, A. R. & Aoki, K. (1973): Factors governing the stability of plagioclase at high pressures as shown by spinel-gabbro xenoliths from the Kerguelen Archipelago. *Amer. Mineral.* **58**, 271-276.

MacGregor, I. D. (1973): The system MgO-Al_2O_3-SiO_2: solubility of Al_2O_3 in enstatite for spinel and garnet peridotite compositions. *Amer. Mineral.* **59**, 110-119.

MOORE, J. C. (1972): Uplifted trench sediments: southwestern Alaska-Bering shelf edge. *Science* **175**, 1103-1105.

PRATT, R. M., RUTSTEIN, M. S., WALTON, F. W. & BUSCHUR, J. A. (1972): Extension of Alaskan structural trends beneath Bristol Bay, Bering Sea Shelf, Alaska. *J. Geophys. Res.* **77**, 4994-4999.

SCHOLL, D. W. & HOPKINS, D. M. (1969): Newly discovered Cenozoic basins, Bering Sea Shelf. *Amer. Assoc. Petrol. Geol. Bull.* **53**, 2067-2078.

———, BUFFINGTON, E. C. & HOPKINS, D. M. (1968): Geologic history of the continental margin of North America in the Bering Sea. *Marine Geol.* **6**, 297-330.

SHOR, G. G. (1964): Structure of the Bering Sea and the Aleutian Ridge. *Marine Geol.* **1**, 213-219.

SIMKIN, T. & SMITH, J. V. (1970): Minor element distribution in olivine. *J. Geol.* **78**, 304-325.

THOMPSON, R. N. (1974): Some high pressure pyroxenes. *Mineral. Mag.* **39**, 768-787.

WHITNEY, P. R. & MCLELLAND, J. M. (1973): Origin of coronas in meta-gabbros of Adirondack Mountains, New York. *Contr. Mineral. Petrology* **39**, 81-98.

WOOD, J. & BANNO, S. (1973): Garnet-orthopyroxene and orthopyroxene-clinopyroxene relationships in simple and complex systems. *Contr. Mineral. Petrology* **42**, 109-124.

WRIGHT, T. L. & DOHERTY, P. C. (1970): A linear programming and least squares computer method for solving petrographic mixing problems. *Geol. Soc. Amer. Bull.* **81**, 1995-2008.

Manuscript received February 1976, emended March 1976.