

Osumilite of deep-seated origin in the contact aureole of the anorthositic Nain complex, Labrador

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Abstract

Pink osumilite occurs with quartz, hypersthene, orthoclase, cordierite, plagioclase, graphite, and pyrrhotite in a granulite in the contact aureole of the Precambrian Nain complex. It occurs as a discrete phase as well as with quartz and hypersthene in symplectites. The osumilite is uniaxial positive (locally anomalously biaxial), $\epsilon = 1.5473 \pm 0.0002$, $\omega = 1.5406 \pm 0.0002$, $a = 10.117(2)$ Å, $c = 14.255(6)$ Å, and density is 2.62–2.64 g/cm³. Its composition, determined by electron probe analyses, is $\square^{IX}(K_{0.88}Na_{0.07}Ba_{0.02}Ca_{0.01})^{XII}(Mg_{1.46}Fe_{0.55}Mn_{0.01})^{VI}(Al_{2.59}Mg_{0.39}Ti_{0.02})^{IV}(Si_{10.35}Al_{1.65})^{IV}O_{30}$. When its composition is compared with other osumilites and related minerals, the following prominent substitutions are apparent: $Al^{3+} \rightleftharpoons Fe^{3+}$; $Mg^{2+} \rightleftharpoons Fe^{2+}$; $Na^{+} \rightleftharpoons K^{+}$; $Si^{4+} + (Mg,Fe)^{2+} \rightleftharpoons 2(Al,Fe)^{3+}$; and $(Na,K)^{+} + (Al,Fe)^{3+} \rightleftharpoons \square + Si^{4+}$.

Prior experimental and natural evidence has indicated that osumilite is formed only at very low pressures and probably metastably. However, in the Nain specimen textural and chemical data suggest osumilite was a stable phase and, based on P - T data for the metamorphic aureole of the Nain complex, the osumilite formed at $P_{Total} \sim 5$ kbar and $T = 700^{\circ}$ – 900° C, but $P_{H_2O} \ll P_{Total}$. We conclude that osumilite is stable at moderate pressure under anhydrous conditions.

Introduction

Natural osumilite, $\square^{IX}(K,Na,Ba,Ca)^{XII}(Mg,Fe^{2+},Mn)^{VI}(Al,Fe^{3+},Ti,Mg,Fe^{2+})^{IV}(Si,Al)^{IV}_2O_{30}$, has been reported previously from four localities in each of which a low pressure origin is certain: Sakkabira, Japan (Miyashiro, 1956); Monte Arci, Sardinia (Rossi, 1963); Obsidian Cliffs, Lane County, Oregon (Olsen and Bunch, 1970); and Tieveragh, Co. Antrim, Ireland (Chinner and Dixon, 1973). In the first three localities it occurs as euhedral crystals lining cavities or as anhedral crystals in the groundmass of rhyolite or rhyodacite. In the fourth locality it occurs in fused hornfels within the contact aureole of an olivine dolerite. A low pressure origin for this rare mineral has been supported by experimental work (Schreyer and Seifert, 1967) which indicated that osumilite of composition $KMg_2Al_3Si_{10}Al_2O_{30}$ could not

be synthesized above 1 kbar P_{H_2O} , and osumilite of unknown composition could not be synthesized above 4 kbar P_{H_2O} . In fact, Schreyer and Seifert found that with longer experimental runs, both synthetic and natural osumilite (Sakkabira) broke down even under the conditions of synthesis. This led them to suggest that natural osumilite may form only metastably under conditions of rapid and non-equilibrium crystallization.

We report a new and radically different natural occurrence of osumilite from near Nain, Labrador, Canada, in a granulite within the contact aureole of the anorthositic Nain complex (Wheeler, 1960). Associated minerals are quartz, hypersthene, orthoclase, cordierite, plagioclase, graphite, and pyrrhotite. Phase relations in surrounding rocks (Berg, 1974, and in preparation) suggest that the osumilite formed at P_{Total} near 5 kbar ($P_{H_2O} \ll P_{Total}$), temperatures between 700° C and 900° C, and low f_{O_2} .

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Occurrence and Paragenesis

The osumilite-bearing granulite occurs at the margin of a tongue of Archaean country rock which extends southward into buff-weathering anorthosite (Wheeler, 1960) of the Nain complex. The sample is from the north branch of Ikkinikulluit Brook (56° 28.8'N, 62° 21.1'W), and a general description of the geology of that area is given by Wheeler (1974). Associated rock types in this contact aureole include plagioclase-hypersthene-quartz granulites and cordierite-garnet-hypersthene-quartz-feldspar granulites. Representative modes of the osumilite-bearing granulite and of two associated granulites are listed in Table 1.

The osumilite occurs in an optically continuous, meandering, and vein-like habit throughout the rock. It is commonly separated from polycrystalline cordierite knots by a zone of plagioclase. There are places, however, where the cordierite and osumilite are in direct contact. The polycrystalline cordierite knots enclose minor amounts of a brown hercynitic spinel. Quartz, orthoclase, and graphite may form large (2-4 mm) porphyroblasts throughout the granulite, whereas hypersthene and pyrrhotite are typically fine-grained and equigranular. An unusual barian biotite occurs only as rare, very fine sheafs adjacent to pyrrhotite and may be related to alteration of the osumilite.

Locally, the osumilite occurs in spectacular symplectic intergrowths with quartz and hypersthene (Fig. 1). Roughly estimated, the symplectites consist of about 50 percent osumilite, 35 percent quartz, and 15 percent hypersthene. All of the osumilite in the

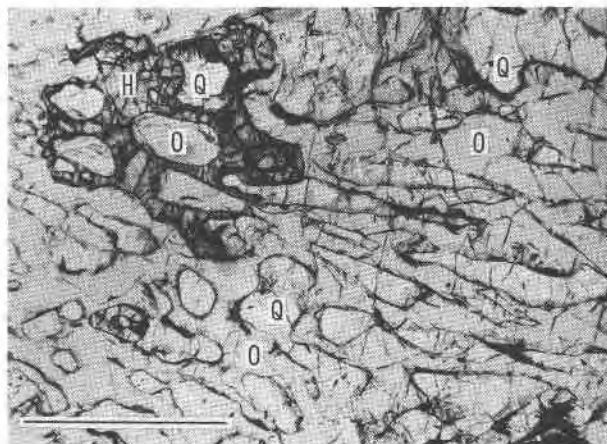


FIG. 1. Photomicrograph of osumilite-hypersthene-quartz symplectite (plain transmitted light). Hypersthene (H) is dark gray and cleaved, osumilite (O) is medium gray, and quartz (Q) is light gray and mottled. Bar is 1 mm.

symplectite is optically continuous, as are all of the quartz and all of the hypersthene. In addition, the osumilite in the symplectite is optically continuous with the vein-like osumilite.

The osumilite is locally altered to fans of extremely fine-grained, low-birefringent material which show radial extinction. Electron microprobe analyses of this material, all of which have oxide summations between 99.19 and 99.84 wt percent, give a compositional range of $\text{SiO}_2 = 65.90 - 70.30$, $\text{Al}_2\text{O}_3 = 19.04 - 22.56$, $\text{MgO} = 6.23 - 6.98$, and $\text{FeO} = 3.53 - 4.15$. From these data the conclusion is drawn that the material is multi-mineralic and represents a partial retrograde breakdown of osumilite. However, it should be pointed out that potassium was not detected in this material, so the alteration cannot be isochemical.

Optical and Physical Properties

The osumilite appears black in hand specimen, but in thin section it has a marked pink color, in contrast to the blue color of the type specimen from Sakkabira (Miyashiro, 1956). The osumilite is optically positive and nominally uniaxial; however, much of it is anomalously biaxial with $2V$ of 5°-15°. No cleavage is apparent and the birefringence is low (0.0067). The mineral is dichroic with E = colorless and O = pink.

The refractive indices are $\epsilon = 1.5473 \pm 0.0002$ and $\omega = 1.5406 \pm 0.0002$, as determined by the dispersion method. These values are lower than those listed by Miyashiro (1956) for Sakkabira osumilite, but similar to those given by Chinner and Dixon (1973) for

TABLE 1. Point-Counted Modes of Granulites in the Contact Aureole of the Nain Complex

| Sample No. | 2-1817 ^(a) | 2-1816 ^(b) | 2-1833 ^(c) |
|----------------------------|-----------------------|-----------------------|-----------------------|
| Plagioclase | 33.5 | 41.5 | 29.6 |
| Orthoclase | 2.6 | -- | 7.7 |
| Quartz | 5.4 | 20.8 | 0.5 |
| Orthopyroxene | 15.4 | 26.5 | 1.2 |
| Biotite | trace | 0.2 | 0.7 |
| Fe-Ti oxides + sulfides | trace | 1.3 | 1.6 |
| Graphite | 3.9 | -- | -- |
| Cordierite | 19.1 | -- | 49.9 |
| Osumilite | 13.3 | -- | -- |
| Garnet | -- | -- | 0.2 |
| Spinel | 0.1 | -- | 3.4 |
| Alteration | 6.8 ^(d) | 9.7 | 5.1 |

(a) Osumilite granulite.

(b) Enderbitic granulite.

(c) Cordierite (+ garnet) granulite.

(d) Extremely fine-grained, low-birefringent material.

Tieveragh osumilite (Table 2). The differences can be easily explained by differences of composition. The Sakkabira osumilite has $Mg/(Mg+Fe) = 0.49$ and $K/(K+Na+Ca) = 0.66$ (Olsen and Bunch, 1970). In contrast, the Nain osumilite has $Mg/(Mg+Fe) = 0.77$ and $K/(K+Na+Ca) = 0.92$ (Table 2). The higher Mg-ratio and the higher K-ratio result in lower refractive indices for the Nain osumilite as well as for the Tieveragh osumilite.

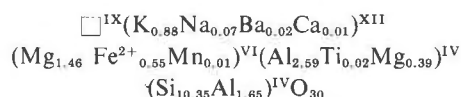
Replicate determinations with the Berman balance produced a range in density from 2.62 – 2.64 g/cm³, as compared to the density determined according to the rule of Gladstone and Dale (Jaffe, 1956), which is 2.69 g/cm³. The Sakkabira osumilite has a measured density of 2.64 g/cm³ (Miyashiro, 1956) and a calculated density of 2.71 g/cm³. It is important to note that density, refractive indices, and other optical properties of osumilite are quite similar to those of quartz, and thus a colorless osumilite would very likely be misidentified.

X-ray powder data for the Nain osumilite yield a unit cell with $a = 10.117(2) \text{ \AA}$ and $c = 14.255(6) \text{ \AA}$ by least squares refinement. In Table 3 the unit cell dimensions of several osumilite-type phases are compared.

Composition and Crystal Chemistry

The osumilite and associated minerals from Nain were analyzed using a MAC 400 electron microprobe. Analyses were run at 15 kV and 0.03 μ amp beam current. An on-line computer reduced the data using the quantitative analysis program of Finger and Hadjidiacos (1972).

Fourteen separate analyses of the osumilite showed it to be extremely homogeneous. The average and range of these 14 analyses are listed in Table 4, and the resulting structural formula is:



The oxide total ranges from 99.05 to 101.51 wt percent, suggesting that no structural water need be assumed. This agrees with the conclusions of Olsen and Bunch (1970) and Chinner and Dixon (1973), also based on electron probe summations. The cation sum assuming 30 oxygens is not in excess of 18, indicating that ferric iron is essentially absent. This conclusion is supported by the presence of graphite and pyrrhotite in the rock, indicating low $f\text{O}_2$ conditions of formation.

The structure of osumilite was first determined by

TABLE 2. Comparison of Nain, Sakkabira, and Tieveragh Osumilites

| | Osumilite (Nain, Labrador) | Osumilite (Sakkabira, Japan) | Osumilite ^(a) (Tieveragh, Ireland) |
|------------|-------------------------------|---------------------------------|--|
| ϵ | 1.5473(± 0.0002) | 1.549–1.551 ^(a) | 1.546(± 0.002) |
| ω | 1.5406(± 0.0002) | 1.545–1.547 ^(a) | 1.540(± 0.002) |
| B | 0.0067(± 0.0003) | 0.004 ^(a) | 0.006 |
| Color | Pink | Blue ^(a) | Blue |
| ρ | 2.62–2.64 | 2.64 ^(a) | 2.58–2.68 |
| Mg/Mg+Fe | 0.77 | 0.49 ^(b) | 0.89 |
| K/K+Na+Ca | 0.92 | 0.66 ^(b) | 0.88 |

(a) Miyashiro (1956).

(b) Olsen and Bunch (1970).

(c) Chinner and Dixon (1973).

Miyashiro (1956) and later refined by Brown and Gibbs (1969). With a structure somewhat analogous to cordierite and beryl, it is a member of the milarite-type structural group (Forbes, Baur, and Khan, 1972) and is classified as a framework silicate (Brown and Gibbs, 1969; Zoltai, 1960). It is hexagonal and crystallizes in space group $P6/mcc$. Basically, $T1$ tetrahedra (Si,Al) form double hexagonal rings which are linked laterally and vertically by $T2$ tetrahedra (Al,Fe³⁺,Mg,Fe²⁺,Ti) to form a tetrahedral framework. Flattened M octahedra (Mg,Fe²⁺,Mn,Ti) each share three edges with the $T2$ tetrahedra and further link the double hexagonal rings. The cavities which lie vertically between the double hexagonal rings are hexagonal antiprisms and form 12-coordinated C sites (K,Na,Ba,Ca, \square). Cavities which lie laterally between the double hexagonal rings resemble truncated trigonal dipyramids and form 9-coordinated B sites (K,Na,Ba,Ca, \square). The B sites, delineated by Khan *et al* (1972), remain vacant in osumilite. Cavities within the double hexagonal rings form 18-coordinated sites, and they may or may not contain water molecules.

In Table 4 the Nain osumilite analysis is compared with analyses of osumilite from the other localities as well as analyses of closely related yagiite, roedderite,

TABLE 3. Unit Cell Dimensions of Several Osumilite-Type Phases

| Name | a (Å) | c (Å) | Reference |
|------------------------|---------|---------|------------------------------|
| Osumilite | | | |
| Nain, Labrador | 10.12 | 14.26 | (This paper) |
| Sakkabira, Japan | 10.16 | 14.28 | (Brown and Gibbs, 1969) |
| Monte Arci, Sardinia | 10.10 | 14.35 | (Rossi, 1963) |
| Tieveragh, Ireland | 10.08 | 14.35 | (Chinner and Dixon, 1973) |
| Synthetic | 10.08 | 14.32 | (Schreyer and Seifert, 1967) |
| Yagiite | 10.09 | 14.29 | (Bunch and Fuchs, 1969) |
| Merrillueite | 10.16 | 14.32 | (Dodd <i>et al</i> , 1965) |
| Synthetic merrillueite | 10.22 | 14.15 | (Seifert and Schreyer, 1969) |
| Roedderite | 10.14 | 14.28 | (Fuchs <i>et al</i> , 1966) |

TABLE 4. Chemical Analyses and Structural Formulae of Osumilite-Type Minerals

| | OSUMILITE | OSUMILITE | OSUMILITE | OSUMILITE | OSUMILITE | YAGIITE | MERRIHUEITE | ROEDDERITE | ROEDDERITE |
|--------------------------------|-----------------------|---------------------------|-------------------------|--------------------------------|-----------------------------------|---------------------------|-------------------------------|--------------------------|------------------------------------|
| | Nain, Labrador (a) | Tieveragh, Ireland (b) | Sakkabira, Japan (c) | Monte Arci, Sardinia (c) | Obsidian Cliffs, Oregon (e) | Colomera Meteorite (d) | Mezö-Madaras Meteorite (e) | Indarch Meteorite (f) | Wichita County Meteorite (g) |
| SiO ₂ | 62.18 (61.77-62.97) | 64.35 | 61.6 | 61.2 | 61.8 | 61.7 | 61.8 | 71.0 | 68.0 |
| Al ₂ O ₃ | 21.58 (20.72-22.69) | 19.38 | 21.4 | 22.0 | 21.8 | 19.1 | 0.2 | 0.4 | 2.5 |
| TiO ₂ | 0.12 (0.07-0.15) | 0.06 | 0.11 | 0.12 | 0.11 | 0.8 | n.s. | n.s. | n.s. |
| Cr ₂ O ₃ | 0.03 (0.00-0.09) | n.s. | n.s. | n.s. | n.s. | 0.1 | n.s. | n.s. | n.s. |
| Fe ₂ O ₃ | n.s. | n.s. | 1.9 (h) | 1.7 (h) | 1.5 (h) | n.s. | n.s. | n.s. | n.s. |
| FeO | 3.97 (3.79-4.21) | 2.16 | 6.8 | 8.4 | 6.9 | 2.4 | 23.7 | 2.0 | 0.4 |
| MnO | 0.07 (0.01-0.14) | 0.24 | 0.80 | 0.74 | 0.98 | 0.2 | 0.5 | n.s. | n.s. |
| MgO | 7.46 (7.26-7.75) | 9.46 | 3.7 | 2.9 | 3.5 | 10.5 | 4.4 | 19.5 | 19.0 |
| CaO | 0.06 (0.03-0.08) | 0.13 | 0.12 | 0.14 | 0.11 | 0.1 | 0.3 | n.d. | n.s. |
| Na ₂ O | 0.22 (0.16-0.31) | 0.27 | 0.96 | 0.35 | 0.27 | 3.7 | 2.0 | 4.1 | 5.3 |
| K ₂ O | 4.12 (3.98-4.21) | 3.98 | 3.0 | 3.0 | 3.0 | 1.4 | 3.8 | 3.3 | 3.8 |
| BaO | 0.25 (0.22-0.28) | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| Total | 100.06 (99.05-101.51) | 100.03 | 100.4 | 100.6 | 100.0 | 100.0 | 96.7 | 100.3 | 99.0 |
| Na | -- | -- | -- | -- | -- | 0.49 | 0.69 | 1.03 | 1.57 |
| Ca | -- | -- | -- | -- | -- | 0.02 | 0.06 | -- | -- |
| B (IX) | □ | □ | □ | □ | □ | 0.51 | 0.75 | 1.03 | 1.57 |
| K | 0.88 | 0.84 | 0.64 | 0.65 | 0.65 | 0.30 | 0.94 | 0.70 | 0.82 |
| Na | 0.07 | 0.09 | 0.31 | 0.12 | 0.09 | 0.70 | 0.06 | 0.30 | 0.18 |
| Ca | 0.01 | 0.02 | 0.02 | 0.03 | 0.02 | -- | -- | -- | -- |
| Ba | 0.02 | -- | -- | -- | -- | -- | -- | -- | -- |
| C (XII) | 0.98 | 0.95 | 0.97 | 0.80 | 0.76 | 1.00 | 1.00 | 1.00 | 1.00 |
| Mg | 1.46 | 1.69 | 0.93 | 0.73 | 0.88 | 1.66 | -- | 1.81 | 1.86 |
| Fe ²⁺ | 0.55 | 0.30 | 0.96 | 1.19 | 0.97 | 0.33 | 2.08 | 0.28 | 0.06 |
| Mn | 0.01 | 0.03 | 0.11 | 0.11 | 0.14 | 0.03 | 0.08 | -- | -- |
| Cr | -- | -- | -- | -- | -- | 0.01 | -- | -- | -- |
| M (VI) | 2.02 | 2.02 | 2.00 | 2.03 | 1.99 | 2.03 | 2.16 | 2.09 | 1.92 |
| Al | 2.59 | 2.36 | 2.62 | 2.71 | 2.74 | 1.96 | -- | -- | 0.05 |
| Fe ³⁺ | -- | -- | 0.24 | 0.22 | 0.19 | -- | -- | -- | -- |
| Ti | 0.02 | 0.01 | 0.01 | 0.02 | 0.01 | 0.10 | -- | -- | -- |
| Mg | 0.39 | 0.63 | -- | -- | -- | 0.94 | 1.25 | 3.00 | 2.95 |
| Fe ³⁺ | -- | -- | -- | -- | -- | -- | 1.75 | -- | -- |
| T2 (IV) | 3.00 | 3.00 | 2.87 | 2.95 | 2.95 | 3.00 | 3.00 | 3.00 | 3.00 |
| Si | 10.35 | 10.60 | 10.37 | 10.33 | 10.41 | 10.23 | 11.93 | 11.87 | 11.55 |
| Al | 1.65 | 1.40 | 1.63 | 1.67 | 1.59 | 1.77 | 0.05 | 0.08 | 0.45 |
| Mg | -- | -- | -- | -- | -- | -- | 0.02 | 0.05 | -- |
| T1 (IV) | 12.0 | 12.0 | 12.0 | 12.0 | 12.0 | 12.0 | 12.0 | 12.0 | 12.0 |
| Total | 18.00 | 17.97 | 17.84 | 17.78 | 17.70 | 18.54 | 18.91 | 19.12 | 19.49 |

n.s. = Not sought.

n.d. = Sought but not detected.

(a) Average of 14 probe analyses.

(b) Chinner and Dixon (1973).

(c) Olsen and Bunch (1970).

(d) Bunch and Fuchs (1969).

(e) Dodd *et al.* (1965).(f) Fuchs *et al.* (1966).

(g) Olsen (1967).

(h) Based on assumed structural requirements (see Olsen and Bunch, 1970).

and merrihueite, three minerals of the milarite group (Forbes *et al.*, 1972) typically found in meteorites.

A comparison of the different osumilite-type compositions reveals at least two coupled (see Fig. 2) and three simple substitutions that may take place. The three simple substitutions include $Al^{3+} \rightleftharpoons Fe^{3+}$ in the T2 position, $Mg^{2+} \rightleftharpoons Fe^{2+}$ in the M position, and $Na^{+} \rightleftharpoons K^{+}$ in the C position.

The first coupled substitution involves Si^{4+} for Al^{3+} in the T1 position and $(Mg,Fe)^{2+}$ for $(Al,Fe)^{3+}$ in the T2 position (*i.e.*, $Si^{4+} + [Mg,Fe]^{2+} \rightleftharpoons 2[Al,Fe]^{3+}$). In

the Indarch roedderite and in merrihueite this substitution occurs almost to the limit where T1 contains only Si. This substitution is represented by the ordinate in Figure 2.

The second coupled substitution combines the substitutions of $(K,Na)^{+} \rightleftharpoons \square$ in the B position and $(Al,Fe)^{3+} \rightleftharpoons Si^{4+}$ in the T1 position (*i.e.*, $[K,Na]^{+} + [Al,Fe]^{3+} \rightleftharpoons \square + Si^{4+}$). This substitution is particularly evident in the roedderite from the Wichita County meteorite (Olsen, 1967). Here the extra Na (0.57) in the B site and 0.45 Al in the T1 site

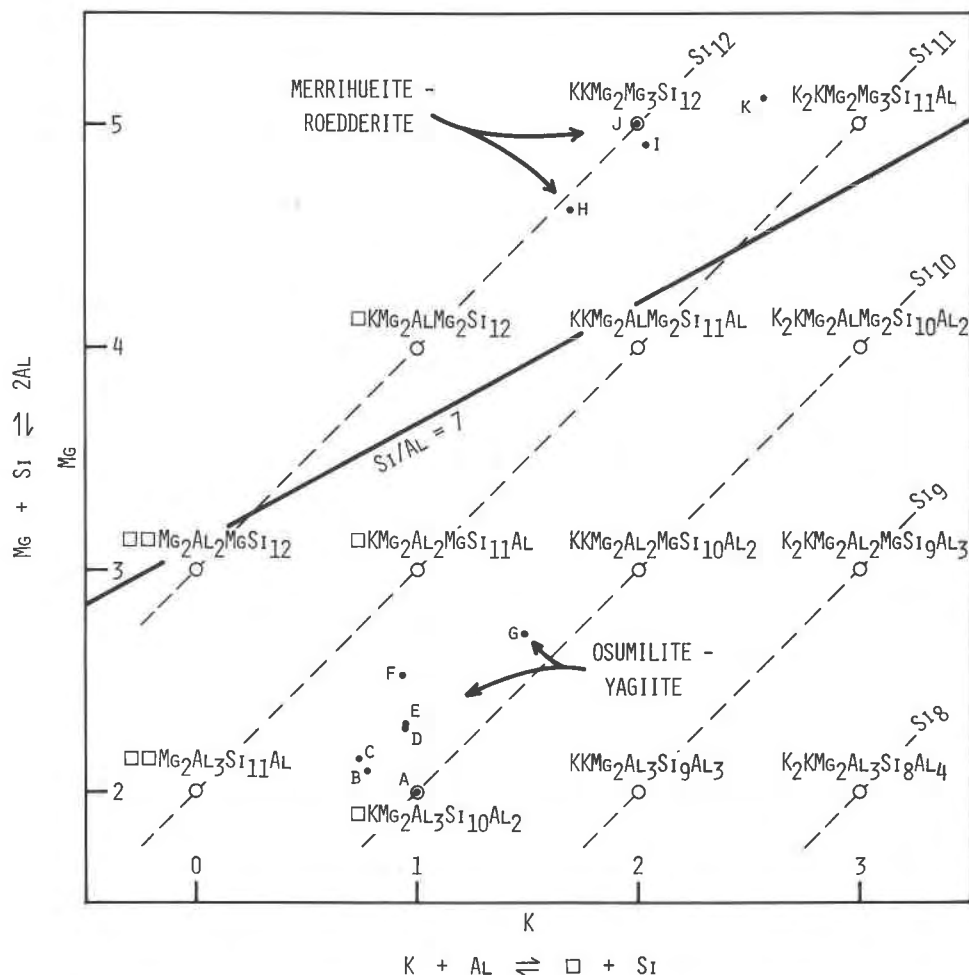


FIG. 2. Two-dimensional array of osumilite-type formulae. Only the cationic parts of the formulae are given (O_{30} has been omitted from each). In all cases $K = (Na, K)$ and $Mg = (Mg, Fe)$. Osumilite-yagiite and merrihueite-roedderite fields are shown. Mineral compositions are plotted in terms of K (i.e., $Na+K$) and Si : A = synthetic osumilite, B = Monte Arci osumilite, C = Obsidian Cliffs osumilite, D = Sakkabira osumilite, E = Nain osumilite, F = Tieveragh osumilite, G = Colomera yagiite, H = Mezö-Madaras merrihueite, I = Indarch roedderite, J = synthetic merrihueite, K = Wichita County roedderite.

approximately balance the loss of 0.45 Si in the T1 site, relative to a roedderite "end member" formula, $Na(Na,K)(Mg,Fe)_2Mg_3Si_{12}O_{30}$. This substitution is represented by the abscissa in Figure 2.

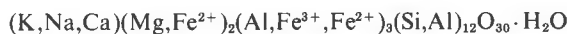
By combining the two coupled substitutions in a 1:1 ratio, a hybrid substitution, which consists of $(Mg,Fe)^{2+} + (Na,K)^+ \rightleftharpoons (Al,Fe)^{3+} + \square$, is created. This substitution is represented by the diagonal (parallel to constant Si) in Figure 2.

Olsen and Bunch (1970) suggested that as $K/(K+Na+Ca)$ increases in osumilite, the occupancy of the C site decreases (see also Forbes *et al.*, 1972). Extrapolating to $K/(K+Na+Ca) = 1$, their data imply that pure K-osumilite would have only a

60 percent occupancy of the C site. The Nain osumilite, as well as the Tieveragh osumilite, is much more K-rich than the other osumilites, yet the occupancy of the C site is nearly 100 percent (Table 4). Hence we agree with the conclusion of Chinner and Dixon (1973) that the linear plot of $K/(K+Na+Ca)$ vs $\Sigma(K+Na+Ca)$ of Olsen and Bunch (1970) is probably fortuitous.

Nomenclature

Miyashiro's (1956) original definition of osumilite involved the generalized formula:



Bunch and Fuchs (1969) defined yagiite as that part of the solid solution region with $\text{Na} > \text{K}$, $\text{Mg} > \text{Fe}$, and $\text{Si}/\text{Al} < 7$ and redefined osumilite as having $\text{K} > \text{Na}$, $\text{Fe} > \text{Mg}$, and $\text{Si}/\text{Al} < 7$, even though the type specimen was known to have Fe/Mg near unity (see Table 2).

Using the criteria of Bunch and Fuchs, the Nain osumilite fits the $\text{K} > \text{Na}$ definition of osumilite, but agrees with the $\text{Mg} > \text{Fe}$ definition of yagiite. In studying the Tieveragh osumilite, Chinner and Dixon (1973) faced the same problem, but complicated matters (see Mandarino, 1974) by unintentionally naming the Tieveragh specimen "osumilite-(K,Mg)". Nevertheless, they felt that it was "an unnecessary complication to assign new names to only slightly disparate members of relatively obscure solid solution series not readily differentiated by ordinary petrographic methods." This, of course, is underscored by the fact that the type specimen is not Fe-rich, but instead is very near the center between the Mg and Fe end members.

Figure 2 graphically displays all of the osumilite-type "end member" formulae which can be produced

by the two coupled substitutions mentioned in the previous section. The $\text{Si}/\text{Al}=7$ line separates the osumilite-yagiite field from the merrihueite-roedderite field according to the definition of Bunch and Fuchs (1969). On this diagram are plotted the compositions of known osumilite-type phases. Yagiite is related to the osumilites via the "1:1" hybrid substitution; however, it lies in essentially the same compositional field as the osumilites on this diagram.

It appears that the nomenclature and definition of osumilite are in need of clarification. The Commission on New Minerals and Mineral Names of the IMA has begun work on the problem, and to date has disapproved the name "osumilite-(K,Mg)" (A. Kato, written communications, 1975). In view of the Commission's involvement, no proposals for clarification are offered here.

Phase relations and petrogenesis

The compositions of the phases associated with the osumilite are listed in Table 5. The hercynitic spinel is not included here because textures indicate that it probably was not in equilibrium with osumilite. In addition the barian biotite is probably of secondary origin; however, its analysis is included here because of its unusual composition.² Thus the assemblage is assumed to be osumilite + quartz + hypersthene + orthoclase + cordierite + plagioclase + graphite + pyrrhotite. The components involved are SiO_2 - Al_2O_3 - MgO - FeO - K_2O - Na_2O - CaO - C - S . CaO, C, and S are accessory inert components which are essentially present only in the phases plagioclase, graphite, and pyrrhotite, respectively. By combining FeO with MgO and Na_2O with K_2O , and by projecting from quartz (SiO_2), the critical assemblage can be evaluated in a KAlO_2 - Al_2O_3 - MgO projection (Fig. 3). In this projection osumilite plots within the "3-phase" triangle, hypersthene-cordierite-orthoclase. Based on this geometry, it seems likely that the breakdown products of the osumilite would be hypersthene + cordierite + orthoclase + quartz. This is in contrast to the high-temperature breakdown products of metastable (?) synthetic osumilite (cordierite + K-feldspar + quartz) reported by Schreyer and Seifert (1967). The difference is caused by the substitution of Mg + Si for 2Al in the Nain osumilite. This moves the osumilite composition off the cordierite + K-feldspar join

TABLE 5. Compositions of Minerals Associated with the Nain Osumilite^(a)

| | Cordierite | Hypersthene | Orthoclase | Plagioclase | Biotite |
|-------------------------|------------|-------------|------------|-------------|---------|
| SiO_2 | 49.83 | 50.38 | 64.33 | 54.70 | 35.61 |
| Al_2O_3 | 33.82 | 3.75 | 18.41 | 28.25 | 13.50 |
| TiO_2 | 0.01 | 0.24 | 0.08 | 0.04 | 4.75 |
| Cr_2O_3 | 0.02 | 0.17 | n.d. | n.d. | 0.20 |
| FeO | 5.62 | 25.12 | n.d. | 0.11 | 13.36 |
| MnO | 0.08 | 0.36 | 0.06 | n.d. | 0.02 |
| MgO | 10.34 | 20.18 | n.d. | 0.02 | 15.74 |
| CaO | 0.01 | 0.17 | 0.34 | 11.04 | n.d. |
| Na_2O | 0.02 | 0.03 | 1.17 | 5.18 | 0.05 |
| K_2O | 0.02 | n.d. | 14.33 | 0.34 | 7.86 |
| BaO | n.d. | 0.07 | 0.51 | n.d. | 4.61 |
| Total | 99.77 | 100.47 | 99.23 | 99.68 | 95.70 |

| | |
|------------------------|---|
| Cordierite | $(\text{Mg}_{1.54}\text{Fe}_{0.47}^{2+}\text{Mn}_{0.01})\text{Al}_{3.99}\text{Si}_{4.99}\text{O}_{18}$ |
| Hypersthene | $(\text{Ca}_{0.01}\text{Mg}_{1.13}\text{Fe}_{0.79}^{2+}\text{Mn}_{0.01}\text{Cr}_{0.01}\text{Ti}_{0.01}\text{Al}_{0.06})_{(\text{Si}_{1.89}\text{Al}_{0.11})\text{O}_6}$ |
| Orthoclase | $(\text{K}_{0.85}\text{Na}_{0.11}\text{Ca}_{0.02}\text{Ba}_{0.01})\text{Al}_{1.01}\text{Si}_{2.99}\text{O}_8$ |
| Plagioclase | $(\text{Ca}_{0.54}\text{Na}_{0.48}\text{K}_{0.02})\text{Al}_{1.51}\text{Si}_{2.48}\text{O}_8$ |
| Biotite ^(b) | $(\text{K}_{0.77}\text{Ba}_{0.14}\text{Na}_{0.01})(\text{Mg}_{1.79}\text{Fe}_{0.85}^{2+}\text{Cr}_{0.01}\text{Ti}_{0.21})_{(\text{Si}_{2.72}\text{Al}_{1.22}\text{Ti}_{0.06})\text{O}_{10}(\text{F,OH})_2}$ |

n.d. = Sought but not detected.

(a) Each printed analysis represents the average of three or more probe analyses.

(b) Calculated on the basis of 11 oxygens.

²This biotite appears to be unique in terms of its Ba content. We know of no other biotite analysis with BaO in excess of 1 wt percent. It is also unusual in that Al + Si does not fill the tetrahedral position; either tetrahedral Fe, Ti, or Mg is required.

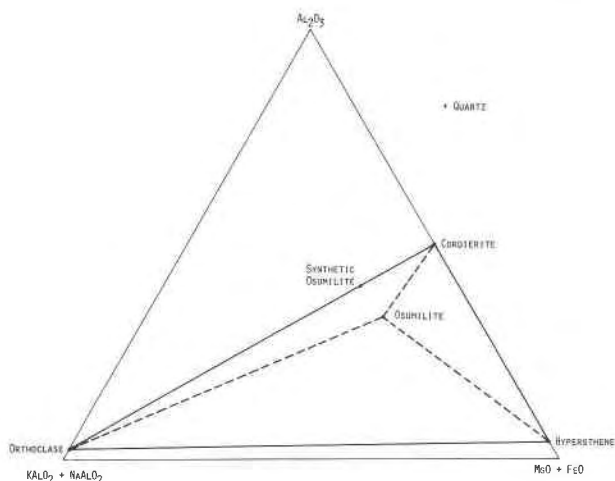


FIG. 3. Projection from quartz onto the Al_2O_3 - KAlO_2 - MgO plane. Mineral compositions for the Nain critical assemblage are from probe analyses. Synthetic osumilite is from Schreyer and Seifert (1967). (Plotted as mole percent).

(where synthetic osumilite lies in projection; Fig. 3) and into the "3-phase" field.

An orthoclase projection onto the AFM plane (Fig. 4) shows that the varying Mg/Fe ratios of these phases allow osumilite to coexist with its presumed breakdown products over a range of P - T conditions. Chinner and Dixon (1973) state that the stable occurrence of osumilite would require it to be more iron-rich than the accompanying cordierite and orthopyroxene. This presumes that Fe-rich osumilite is more stable (with respect to cordierite + orthopyroxene) than Mg-rich osumilite. Figure 4 shows instead that the Nain osumilite is more magnesian than the accompanying cordierite and hypersthene.

Included in this projection is a cordierite-garnet-hypersthene (+ quartz) assemblage from a nearby part of the Nain contact aureole, which crystallized at approximately the same P_{Total} (Berg, in preparation). With increasing pressure the garnet-cordierite-hypersthene triangle moves toward higher Mg/Fe values (Hensen and Green, 1973). If, with increasing pressure, the breakdown of the Fe-rich cordierite-hypersthene pairs proceeds at a faster rate than the production of Mg-rich cordierite-hypersthene pairs from osumilite, the cordierite-hypersthene field will shrink to a single tie-line, and the reaction, cordierite + hypersthene (+ K-feldspar + quartz) \rightarrow osumilite + garnet, will occur. This reaction seems unlikely, however, because it would result in the unusual coexistence of a mineral with tetrahedral Mg (osumilite) and a mineral with 8-

coordinated Mg (garnet). It is probable that cordierite + hypersthene will always intervene between osumilite + garnet in nature.

Based on the partitioning of Mg and Fe between garnet and cordierite (Hensen and Green, 1973) in the contact aureole of the Nain complex and the breakdown of hypersthene to olivine + quartz (Smith, 1971) in both the contact aureole and associated adamellitic rocks, Berg (in preparation) has constructed a paleogeobarometric map of the Nain complex. Using these data, the osumilite would appear to have crystallized at a P_{Total} of about 5.2 kbar. The lack of primary hydrous phases, the presence of graphite, and the lack of Fe^{3+} in ilmenites of associated granulites (Berg, in preparation) indicate that the $P_{\text{H}_2\text{O}}$ was undoubtedly much lower than P_{Total} and that f_{O_2} was very low.

Temperature, unlike pressure, can vary drastically in a contact aureole and is therefore more difficult to estimate. Based on its position in the contact aureole and temperatures determined from garnet-cordierite pairs and orthopyroxene-olivine-quartz assemblages throughout the aureole (Berg, in preparation), the osumilite probably crystallized near the high end of the temperature range 700°-900°C.

The textures and homogeneous composition described above, and the Precambrian, plutonic origin of the Nain osumilite suggest that it is a stable phase. Thus, even though Schreyer and Seifert (1967) found synthetic osumilite ($\text{KMg}_2\text{Al}_3\text{Si}_{10}\text{Al}_2\text{O}_{30}$) to be unstable or metastable from 0.5-5 kbar $P_{\text{H}_2\text{O}}$ and Sakakabira osumilite unstable at 2 kbar $P_{\text{H}_2\text{O}}$, it appears that natural osumilite can exist stably at P_{Total} near

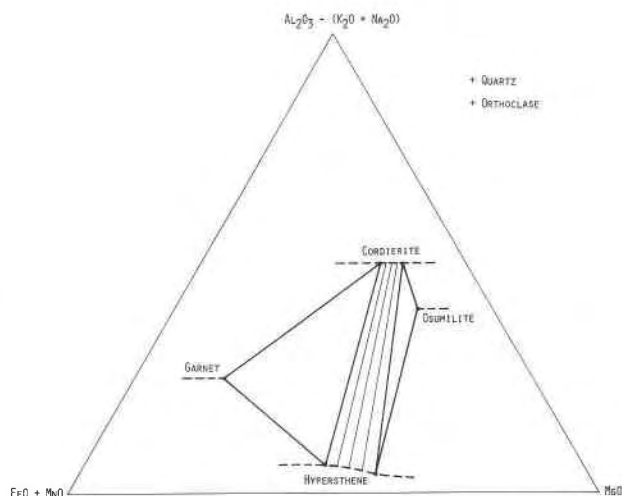


FIG. 4. AFM projection from orthoclase. Mineral compositions are from probe analyses. (Plotted as mole percent).

5 kbar and temperatures near 700°–900°C, if $P_{\text{H}_2\text{O}} \ll P_{\text{Total}}$.

Newton (1972) has shown that $P_{\text{H}_2\text{O}}$ increases the stability of cordierite. There being theoretically fewer water sites in the osumilite structure than in the cordierite structure, we suggest that H₂O lowers the free energy of cordierite relative to that of osumilite, thus stabilizing cordierite + K-feldspar + quartz (+ hypersthene) relative to osumilite. In support of the idea that H₂O would not likely increase the stability of osumilite is the fact that Seifert and Schreyer (1969) found that the osumilite-type phase merrihueite (synthetic) was stable to higher pressures and had a larger stability field under anhydrous conditions than it did under hydrous conditions. Hence, we propose that at high temperatures, pressures near 5 kbar, and near-anhydrous conditions, anhydrous osumilite is stable relative to anhydrous cordierite + orthoclase + quartz + hypersthene (Nain case), whereas under similar, but hydrous conditions, hydrous cordierite + K-feldspar + quartz (+ hypersthene) is stable relative to osumilite (as determined by Schreyer and Seifert, 1967).

Summary

Osumilite occurs with quartz, hypersthene, orthoclase, cordierite, plagioclase, graphite, and pyrrhotite in the contact aureole of the Precambrian anorthositic Nain complex, Labrador. Although experimental and other natural evidence has indicated that osumilite is a metastable low-pressure phase, the textures and chemical homogeneity of the Nain osumilite indicate that it formed as a stable phase. P - T data for the Nain complex show that the osumilite formed at a P_{Total} near 5 kbar and $T = 700^\circ\text{--}900^\circ\text{C}$. $P_{\text{H}_2\text{O}}$ was much lower than P_{Total} , and that was apparently one of the critical factors in stabilizing the osumilite under plutonic conditions.

Note added in proof

B. J. Hensen has recently informed me that he actually synthesized osumilite under approximately the same conditions as those suggested above, *i.e.*, $P_{\text{H}_2\text{O}} \ll P_{\text{Total}}$ (Hensen, 1970, Ph.D. Thesis, Australian National University, Canberra, p. 147–153). The osumilite was synthesized from the A_{70} bulk composition of Hensen and Green (1971) at 1000° and 1100°C in the pressure range of 3.6–7.2 kbar. Systematic variation in the abundance of osumilite with varying P and T and identical proportions of osumilite, cordierite, and hypersthene in runs carried out under the same conditions, but with different

starting materials, suggested to Hensen that this synthetic osumilite was a stable phase.

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