Stornesite-(Y), \((Y, Ca)[Na(Ca,Na)_3(Mg,Fe)](PO_4)_3\), the first terrestrial Mg-dominant member of the fillowite group, from granulite-facies paragneiss in the Larsemann Hills, Prydz Bay, East Antarctica

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ABSTRACT

Stornesite-(Y), end-member formula \(Y[Na_6(Ca,Na)_3]Mg_{43}(PO_4)_{36}\), is a new Y-dominant analog of the meteoritic mineral chladniite. A representative electron microprobe analysis is SiO\(_2\) = 0.02, P\(_2\)O\(_5\) = 48.11, SO\(_2\) = 0.05, MgO = 23.16, MnO = 0.24, FeO = 15.55, Na\(_2\)O = 5.04, CaO = 5.66, SrO = 0.02, Y\(_2\)O\(_3\) = 1.43, Yb\(_2\)O\(_3\) = 0.24, UO\(_2\) = 0.01, Sum = 99.53 wt%, which gives \(Y_{0.68}Yb_{0.06}Na_{8.69}Ca_{5.40}Sr_{0.01}Mg_{30.71}Fe_{11.56}Mn_{0.18}Si_{0.02}S_{0.04}P_{36.22}O_{144}\). Overall, Y + REE range from 0.542 to 0.985 atoms per formula, and atomic Mg/(Mg + Fe) ratio from 0.684 to 0.749. Single-crystal X-ray diffraction gives trigonal symmetry, \(a = 14.9628(27)\ Å, c = 42.756(11)\ Å, V = 8290(4)\ Å\(^3\), calculated density = 3.196 g/cm\(^3\), \(R^2\) = 0.05, \(ε = 1.6250(10)\) at 589 nm. Its color is pale yellow in standard thin sections. Stornesite-(Y) is found as inclusions in fluorapatite. Grains are anhedral, subhedral, or locally euhedral with hexagonal or rhombic outlines; maximum dimensions are 1 × 0.25 mm. It is inferred to have formed at 800–860 °C, 6–7 kbar by reaction of biotite with an anatectic melt locally enriched in P by interaction with fluorapatite.

Keywords: Phosphate, new mineral, Antarctica, Larsemann Hills, electron microprobe, crystal structure, granulite facies, anatexis

INTRODUCTION

The fillowite group comprises complex anhydrous phosphates that have been found only on the relative dominance of the divalent cations Mg, Ca, Mn, and Fe (Table 1). The Mg-dominant member, chladniite, has been found only in two meteorites. We report from a terrestrial environment a second Mg-dominant member, stornesite-(Y), that differs from chladniite in that Y is the dominant cation in a site occupied by Ca in a synthetic analog of chladniite (Domanskii et al. 1983) and by Mn and Ca in fillowite (Araki and Moore 1981; Ma et al. 2005) and its synthetic Ca-free analog (Keller et al. 2001). Like chladniite, stornesite-(Y) is a high-temperature mineral. It is found in a metamorphic environment, and its formation appears to be related closely to anatectic melts. The mineral and name were approved by the Commission on New Minerals and Mineral Names, International Mineralogical Association (2005-040). The name is for the locality, Stornes Peninsula, the westernmost major exposure in the Larsemann Hills, and for the dominance of Y at one site. Holotype material (sample no. 113002A) is deposited in the National Museum of Natural History (Smithsonian Institution) as catalog number NMNH 174436.

OCCURRENCE

Stornesite-(Y) has only been found enclosed in fluorapatite segregations in biotite-quartz-plagioclase paragneiss, a distinctive lithologic unit characterized by segregations of cordierite, prismaticate, grandidierite, and tourmaline in the Larsemann Hills, which are coastal exposures on Prydz Bay, East Antarctica (Carson et al. 1995; Ren et al. 2003). The holotype specimen (113002A and 113002AA) and specimen 113002C were collected at 69° 24.929' S, 76° 03.990' E about 200 m southwest of the south end of Johnston Fjord and 170 m north of Tassie Tarn on Stornes Peninsula (Fig. 1), the third specimen (121401E) at 69° 24.437' S, 76° 15.057' E on Brattnevet Peninsula, about 7 km east of the type locality. The holotype specimen is a rounded nodule of...
dark-brown fluorapatite, ~8–10 cm across. The nodule is rimmed by a discontinuous mantle of wagnerite, which is also present in the surrounding gneiss, together with minor apatite. Specimen 113002C is from a quartz veinlet up to 10 cm thick containing subordinate plagioclase and fluorapatite segregations up to 3 cm across. Specimen 121401E is from a quartz mass not exceeding 10 cm in thickness and extending about 3 m. This mass contains fluorapatite segregations up to 5 cm across, subordinate biotite and quartz fluorapatite segregation.

Stornesite-(Y) grains are anhedral, subhedral, or locally euhedral; subsequent to elongate; subhedral and euhedral grains show hexagonal outlines (Fig. 2) or rhombic with maximum dimensions of 1 × 0.25 mm. The grains occur individually in thin section, in quartz adjacent to a fluorapatite segregation.

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Stornesite-(Y) is commonly altered to Fe oxide and Ca-Na-Mg-Fe phosphates (Table 2; Figs. 4a and 6b), or intersected by trails of very fine secondary minerals (Fig. 3). Secondary fluorapatite forms microveinlets and patches in the coarse-grained fluorapatite or on its margins. The secondary fluorapatite is fine-grained and riddled with inclusions. Monazite-(Ce) and xenotime-(Y) appear in pseudomorphs after stornesite (Y) and as fine particles in secondary fluorapatite.

**PHYSICAL AND OPTICAL PROPERTIES OF STORNESITE-(Y)**

Most physical properties cannot be determined because of the small grain size and the very limited amount of available material, i.e., only a few crystals exclusively in thin sections. Cleavage was not evident in thin section. The tenacity is brittle. The density calculated from the empirical formula is 3.196 g/cm³.

Stornesite-(Y) is transparent, uniaxial (+), with \( \epsilon = 589 \text{ nm} \). Dichroism was not observed. The color is pale yellow in thin sections of standard thickness (~0.03 mm), the same as the host fluorapatite.

**CRYSTALLOGRAPHIC PROPERTIES**

Powder X-ray diffraction (XRD) data were obtained with a 57.3 mm-diameter Gandolfi camera and CuKα radiation (Table 3) at the Ruhr University.

Single-crystal X-ray studies were carried out with a 3-circle SMART BRUKER CCD 1K at the University of Bern, graphite-monochromated MoKα radiation.
studied crystal (0.07 × 0.05 × 0.03 mm) was excavated from a standard petrographic thin section using a micro-milling cutter (Medenbach 1986) and was for this reason strongly strained. Small crystal size and poor diffraction quality required an exposure time of 5 min per frame (Table 4). The structure was solved by direct methods in space group $R-3$. After it became evident that the new mineral represented a structural analog of the synthetic compound $Ca_8Na_8Mg_42(PO_4)_{36}$ (Domanskii et al. 1983), the atom labeling system of those authors was adopted. The structure was refined with the program SHELXL (Sheldrick 1993) including occupancies for all non-tetrahedral cation sites. Pairs of scattering factors, Mg-Fe and Na-Ca, were assigned for site occupancy refinement, depending on coordination number and average bond lengths. At this step it was recognized that the octahedral cation position at (0, 0, 0) displayed considerably higher scattering power than initially assumed. Given the electron microprobe analyses for sample 113002A (see below), 0.01 Yb (equivalent to 0.06 Yb per 144 O) was assigned as fixed constituent at this site and ratios of Y and Ca were varied to fill this Y2 position. Data quality did not allow to perform a full anisotropic refinement and therefore only O sites and selected cation positions (Ca1, Y2, Na1, and Ca2) were refined with anisotropic

**TABLE 2.** Minerals enclosed in fluorapatite

<table>
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<tr>
<th>Sample No.</th>
<th>Location</th>
<th>Type</th>
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<th>Type</th>
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<tr>
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<td>121401E</td>
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</table>

**Associated with stornesite-(Y)**

Stornesite-(Y) (Sto) x x x x
Fluorapatite (Ap) host host host host
Wagnerite (Wag) x x x x
Quartz (Qz) – x x x
K-feldspar (Kfs) – x x x
Biotite (Bt) – – x x
Cordierite (Cd) – – x –
Sillimanite (Sl) – – x –
Monazite-(Ce) (Mnz) x x x x
Xenotime-(Y) (Xnt) x x x x
Pyrite (Py) x – – –

**Not with stornesite-(Y)**

Plagioclase – – – x
Hercynite (Hc) – – – x
Magnetite (Mgt) x – – –
Ilmenite ("pseudorutilile") (Ilm) – – – –
Mg-dominant sarcopside† – – – –

**Secondary only**

Chlorite – – – x
Muscovite – – – x
Fluorapatite (veins and margins) x x x x
Mg-dominant wicksite† x – – –
Mélonjosephite x – – –
Jahnite-like x – – –
Isokite-like – – – x
Unid. Ca-Mg-Fe phosphate x – – –
Lazulite/souzalite-like x x x x
Cassiterite x – – –
Celestine – – – –

**Notes:** x = present.
* Holotype specimen: core of fluorapatite nodule.
† New mineral (IMA 2006-004, approved).
‡ New mineral (IMA 2005-051, approved).
§ Holotype specimen: margin of fluorapatite nodule.

**FIGURE 1.** Map of the Larsemann Hills showing the localities for stornesite-(Y) and sapphirine + quartz; the locality of sapphirine + quartz near Johnston Fjord was described by Tong and Liu (1997). BI = Bolingen Islands, LH = Larsemann Hills, BB = Brattstrand Bluffs, VH = Vestfold Hills. The index map showing an outline of Antarctica and the coast of Prydz Bay was prepared by C.J.L. Wilson.

**FIGURE 2.** Back-scattered electron images (BSE) of euhedral stornesite-(Y) in sample 113002C (a) and sample 121401E (b). Biotite (Bt) is sieved with quartz (Qz).
displacement parameters converging at $R_1 = 8.6\%$. The relatively high $R_1$ value is due to the small crystal size and poor crystal quality. In particular, weak reflections $|F_{\text{obs}}| < 6|F_{\text{calc}}|$ with overestimated observed intensities strongly contribute (43%) of the unique reflections) to the low $R_1$ value. In a test refinement these weak reflections were omitted and $R_1$ converged at $R_1 = 5.0\%$ without significant influence on structural parameters and occupancies. Results of the refinement of the full data set are given in Tables 4 and 5, and Tables 6 and 7.

Stornesite-(Y) is the fifth compound in the fluorapatite group for which the structure has been refined (Table 1). The fluorite-group structure is composed of six independent PO$_4$ tetrahedra and 14 other polyhedra, in which coordination ranges from 5 to 9 (Table 5; Fig. 7). This gives a generalized formula of M$_{46}$(PO$_4$)$_{36}$ for $Z = 3$. Of the 3 largest sites, which are seven-, eight- or ninefold-coordinated, one is occupied by Na only, whereas Na and Ca are disordered over the other two. Araki and Moore (1981) reported a fourth large site, their Na1, but refined Na occupancy at this position with fixed displacement parameter yielded $< 10\%$ Na, which is at the limit of resolution of our data, and we conclude that this site is vacant in stornesite-(Y). Magnesium and Fe are variably ordered over the 9 sites, ranging from 100% Mg at Mg3 to 55%Mg at Mg4. Two sites are distinct in being highly regular octahedral sites with their centers placed on the threefold axes. The smaller site Fe10 at (0,0,0.5) is occupied equally by Fe and Mg in stornesite-(Y), but by Ca in the synthetic analog of chladinite (Domanski et al. 1983) and by Mn in wolfsite (Araki and Moore 1981). The larger site (Y2) at (0, 0, 0) is occupied dominantly by Y in stornesite-(Y), but by Ca in the synthetic and by Mn in wolfsite. It has considerably shorter bond lengths than the other Ca sites. In stornesite-(Y), Y and Yb are fully ordered at this site, which is our rationale for recognizing stornesite-(Y) as a distinct species in the fluorite group.

1 For a copy of Tables 6 and 7, Document item AM-06-024, contact the Business Office of the Mineralogical Society of America (see inside front cover of recent issue) for price information. Deposit items may also be available on the American Mineralogist web site at http://www.minsocam.org.

### Chemical Composition and Compatibility Index of Stornesite-(Y)

Stornesite-(Y) and associated minerals were analyzed with a Cameca SX100 electron microprobe at the University of Maine using wavelength dispersive spectroscopy. Analytical conditions were 15 kV accelerating voltage, 10 nA beam current, and a 5 µm spot diameter for stornesite, silicates, and hercynite (except...
in a few cases where grains were so small that a focused beam had be used), and a 20 µm spot diameter for fluorapatite and wagnerite. All data were processed using the X-Phi correction of Merlet (1994). The standards used for the phosphates were fluorapatite (F), tugtupite (NaK), synthetic Mg3(PO4)2 (MgK), albite (AlK), albite (SiK), fluorapatite or synthetic Mg3(PO4)2 (P), barite (SiK), tugtupite (ClK), fluorapatite (CaK), rutile (TiK), rhodonite (MnK), almandine (FeK), celestine (SrL), synthetic Y-Al garnet (Y), synthetic REE phosphates (REEL), and U metal (UM). Analyses of stornesite-(Y) are averages of 12 to 25 spots, where each constituent was counted for 5 s.

Stornesite-(Y) varies in composition from grain to grain and from sample to sample (Table 8). Magnesium and Fe vary inversely in a 1:1 ratio consistent with Mg = Fe substitution and with total Mg + Fe + Mn = 43 per 144 O (Fig. 8a). Yttrium + REE range from 0.542 to 0.985 per 144 O, almost the entire theoretically possible range for stornesite-(Y). Yttrium is dominant among the Y + REE group and Yb is consistently present, whereas La, Ce, and Nd are present at or below the detection limits of the electron microprobe (compare chladnite, which range from HREE-enriched to LREE-enriched; Floss 1999). In terms of Ca (at Y2), compositions plot from the boundary with the chladnite field to near-complete absence of Ca at the Y site (Fig. 9). The scatter is most likely due to analytical uncertainties associated with the small amounts of Y and REE present and small spread in Na and Ca contents (0.8 to 1.2 atoms per 144 O for Na and Ca).

The Gladstone-Dale relation (Mandarino 1981) gives a compatibility index $1 - (K_P/K_C) = -0.030$, which is excellent.

FILLOWITE GROUP: FORMULA AND NOMENCLATURE

The formula cited in most references for the fillowite group, $Na_xCa_yM_z(PO_4)_w$ (e.g., Strunz and Nickel 2001), is oversimplified (see also Fransolet et al. 1998). A more appropriate formula based on structure refinements of fillowite, synthetic chladnite,
and stornesite-(Y) is (Ca,Mn,Y,REE)(Na□)Na(Na,Ca)M2+(PO4)36. This formula can be generalized to (M2+,Y,REE,Na)(Na,K)
□(Na,K)(M2+,Na,K)(M2+,M3+)43(PO4)36 to include galileiite,
in which Fe replaces Ca throughout, a K-dominant analog of galileiite reported from
the Sandtown IIIA meteorite (Olsen et al. 1999) would require
reviewed by other members of the working group, the final version was
published in the original journal. The authors, however, did not include the
modified version in their final publication. Instead, they cited the
draft version in their subsequent papers.

Another potential criterion for recognizing different species is
crystallographic space group. The crystallographic space group of
the new mineral is Pnma, which is different from the space group of
the known species, chladniite. This difference in space group can
be used to distinguish between different species of the stornesite-(Y)
mineral group.

The stornesite-(Y) mineral is characterized by its unique
colour and luster. The mineral exhibits a metallic luster and a
translucent to opaque appearance. The stornesite-(Y) mineral is
commonly found in granulite facies environments and is
considered to be a useful indicator of high-grade metamorphic
conditions. The mineral is also known to form inclusions in
various rock types, including gneiss, granite, and amphibolite.

In conclusion, the stornesite-(Y) mineral is a newly discovered
crystallographic and chemical mineral that exhibits unique
properties and is useful in both petrologic and geologic
applications. Further study is needed to fully understand its
occurrence, distribution, and significance.
The minerals found in the stornesite-(Y)-bearing fluorapatite segregations or in the quartz masses associated with the segregations constitute a diverse suite (Table 2). Fluorapatite grains in the segregations range from 2 mm in 121401E to 4 cm across in the holotype specimen, and are anhedral; the centimeter-sized grains in the holotype specimen show cleavage. Fluorapatite in the two specimens from the type locality contain very abundant, ß ne acicular inclusions of Fe-sul ß de parallel to c (Fig. 6); semi-quantitative EDS analyses give Fe/S ratios consistent with pyrite in some inclusions, with pyrrhotite in others. The ß uorapatite composition (Table 9) is noteworthy for its relatively high Cl, Y2O3, MgO, and FeO contents, which greatly exceed the ranges reported for most metamorphic ß uorapatite (Kapustin 1987; Povondra 1992; Bea and Montero 1999; Spear and Pyle 2002; Harlov and Förster 2002). The contents of REE + Y per formula unit average roughly 70% of the Na content (except for one spot unusually enriched in Yb, Table 9), that is, at less than the 1:1 ratio predicted by the substitution Na + (Y , REE) = 2Ca (Pan and Fleet 2002); Harlov et al. (2006) reported a similar deviation from stoichiometry in Si-poor, chlor- and ß uorapatite from a pelitic xenoliths from the Stromboli volcano, Italy. Fluorapatite with similar FeO contents has been reported from a pegmatoid in association with almandine-rich garnet (2.22 wt% FeO, Fransolet and Schreyer 1981), orthogneiss (2.38 wt% FeO, Povondra and Vrána 1993), and from pumice (1.43–2.67 wt% FeO, Heming and Carmichael 1973); however, the chlor- ß uorapatite from Stromboli is by far the richest in FeO reported to date, 4.88 wt% (Harlov et al. 2006).

In the holotype specimen, wagnerite enclosed in ß uorapatite is colorless or pale yellow in thin section, in contrast to the distinctly yellow wagnerite mantling the nodule and in enclosing gneiss, as well as wagnerite found elsewhere in the biotite-quartz-plagioclase gneiss (e.g., Ren et al. 2003, 2005). Wagnerite forms subsequent to elongated, anhedral to nearly euhedral grains some of which have exterior angles <180° (holotype specimen) and mostly range from 0.5 to 1 mm in length. Fluorapatite in the holotype and Brattnevet specimens also encloses wagnerite sheets generally 0.1 mm thick, but up to 1.2 cm across. In the Brattnevet specimen, pale yellow wagnerite commonly is associated with biotite enclosed in fluorapatite (Fig. 10). Analyzed pale wagnerite contains minor Fe and <0.1 wt% TiO2 (e.g., Table 9) in contrast to yellow Ti-bearing wagnerite such as that analyzed in...
nodules from two nearby localities and in gneiss (Ren et al. 2003, 2005). Two wagnerite crystals in the holotype specimen are the 7b polytype (Table 10), whereas two wagnerite crystals in the section containing Mg-dominant sarcopside from Brattnevet, as well as wagnerite in other samples, are the 5b polytype (Table 10; Ren et al. 2003, 2005).

Monazite-(Ce) and xenotime-(Y) occur in a variety of textures, e.g., as selvages along grain boundaries (e.g., Figs. 4b and 5) or rods in coarse fluorapatite. K-feldspar is in places microperthitic, and its intergrowth with quartz in specimens from the type locality suggests graphic granite, but microscopic in scale (Fig. 4). In the Brattnevet specimen, K-feldspar is commonly associated with biotite, vermicular hercynite, magnetite, and altered ilmenite (“pseudorutile”) in a texture suggestive of biotite breakdown (Fig. 10). K-feldspar contains 0.09–1.09 wt% P2O5, plagioclase (An17–18), 0.3 wt% P2O5 (e.g., Table 11). The EMPA data (Fig. 11) are consistent with P

### Table 9. Selected analyses of fluorapatite (Ap) and wagnerite (Wag)

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<td>0.19</td>
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<td>0.04</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Yb2O3</td>
<td></td>
<td>0.04</td>
<td>0.05</td>
<td>0.05</td>
<td>0.07</td>
<td>n.a.</td>
<td>b.d.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Lu2O3</td>
<td></td>
<td>0.10</td>
<td>b.d.</td>
<td>b.d.</td>
<td>b.d.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>H2O calc</td>
<td></td>
<td>1.36</td>
<td>1.42</td>
<td>1.42</td>
<td>1.42</td>
<td>4.22</td>
<td>4.45</td>
<td>4.37</td>
</tr>
<tr>
<td>O = F + Cl</td>
<td>7.988</td>
<td>7.992</td>
<td>7.999</td>
<td>8.002</td>
<td>2.998</td>
<td>3.023</td>
<td>3.010</td>
<td>3.010</td>
</tr>
</tbody>
</table>

Notes: n.a. = not analyzed; b.d. = below detection. All Fe as FeO. H2O calculated from stoichiometry: F + Cl + H = 1. X(Mg) = atomic Mg/(Mg+Fe).

* From 250 m E of type locality.
† From base of Gneiss Peak, 500 m ENE of type locality.

### Table 10. Wagnerite: cell parameters

<table>
<thead>
<tr>
<th>Sample</th>
<th>Polytype</th>
<th>7b</th>
<th>7b</th>
<th>5b</th>
<th>5b</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>113002A</td>
<td>113002A</td>
<td>112906H*</td>
<td>120302C*</td>
</tr>
<tr>
<td>a (Å)</td>
<td>9.6841(8)</td>
<td>9.6846(13)</td>
<td>9.659(2)</td>
<td>9.6542(12)</td>
<td></td>
</tr>
<tr>
<td>b (Å)</td>
<td>44.374(5)</td>
<td>44.364(11)</td>
<td>31.592(2)</td>
<td>31.687(7)</td>
<td></td>
</tr>
<tr>
<td>c (Å)</td>
<td>11.9191(9)</td>
<td>11.9208(15)</td>
<td>11.918(2)</td>
<td>11.9259(13)</td>
<td></td>
</tr>
<tr>
<td>β</td>
<td>108.289(7)*</td>
<td>108.31(1)*</td>
<td>108.26(2)*</td>
<td>108.251(1)*</td>
<td></td>
</tr>
<tr>
<td>V (Å³)</td>
<td>4845.1(8)</td>
<td>4843(1.5)</td>
<td>3464(2)</td>
<td>3465(1)</td>
<td></td>
</tr>
</tbody>
</table>

* From 250 m E of type locality.
† From base of Gneiss Peak, 500 m ENE of type locality.
incorporation by the substitution $\text{PA} \text{Si}_2$ (London et al. 1990).

Brown biotite associated with breakdown melt textures (e.g., Fig. 10) is rich in TiO$_2$, F, and Cl (columns 1–2, Table 12); high totals could result from overestimating unanalyzed H$_2$O assuming anion stoichiometry in Ti-rich biotite (Cesare et al. 2003). Biotite sieved with quartz (Fig. 2b) or associated with sillimanite (Fig. 5) is commonly olive-green in color and contains little Ti (column 3; Table 12).

Hercynite is also present in one quartz inclusion in specimen 121401E (Fig. 12a); it contains minor Zn and V, but negligible Cr (Table 13).

**ORIGIN OF STORNESITE-(Y) AND ASSOCIATED FERROMAGNESIAN PHOSPHATES**

The origin of stornesite-(Y) and the distinctive suite of minerals (Ti-poor wagnerite, P-bearing K-feldspar, Mg-dominant sapphire) found only as inclusions in fluorapatite must be considered as tied closely to the process by which fluorapatite and associated plagioclase-bearing quartz masses and veins were segregated. The presence of high-temperature mineral assemblages such as hercynite + quartz and K-feldspar + hercynite + magnetite (from biotite breakdown) in the fluorapatite suggests that the segregation process occurred at close to peak metamorphic temperatures rather than at lower temperatures during post-peak fluid activity on the retrograde path. One possibility is that the segregation process is genetically linked to anatectic, which pervasively affected the Larsemann Hills (e.g., Stüwe et al. 1989; Dirks et al. 1993; Carson et al. 1997), that is, the fluorapatite segregations and plagioclase-bearing quartz could be restitic bodies remaining after melt had been extracted, an origin Carson et al. (1997) ascribed to cordierite-bearing, quartz-plagioclase leucosomes in the Larsemann Hills. Relatively high FeO contents ofapatite-group minerals have only been reported in high-temperature igneous rocks (Heming and Carmichael 1973; Fransolet and Schreyer 1981) or from pelitic xenoliths that had been partially melted and metasomatized by chloride-rich fluids (Harlov et al. 2006). The association of Fe-bearing apatite-group minerals with melts in other areas suggests that the fluorapatite nodules formed in the presence of an anatectic melt at the peak temperatures of metamorphism in the Larsemann Hills.

Permeation of the fluorapatite segregations with melt is suggested by the presence of K-feldspar-quartz intergrowths, one of which is distinctly graphic (Fig. 4); these intergrowths could be crystallized entrapped melt that was not altered on the retrograde path. Phosphorus contents up to 1 wt% P$_2$O$_5$ in K-feldspar enclosed in fluorapatite (Table 11) suggests melt P$_2$O$_5$ contents might have also reached 1 wt% had these melts been peraluminous (London 1992; London et al. 1999), a reasonable assumption given the presence of sillimanite and possible cordierite in a few inclusions. Phosphorus diffuses slowly in peraluminous granitic melts (Wolf and London 1994; London 1998), and thus, very likely it became concentrated in the melt permeating the fluorapatite nodules and did not diffuse out into the main mass of melt. By analogy with the reactions proposed by London et al. (1999), the development of wagnerite coronas around biotite with breakdown textures (Fig. 10) could be attributed to reaction of biotite with a phosphate-bearing melt:

$$\text{Bt} + 2 \text{P}_2\text{O}_5 \text{(in melt)} \rightarrow \text{Kfs} + \text{Hc} + \text{Mgt} + \text{Ilm} + \text{wagnerite}$$

**FIGURE 10.** BSE image of biotite (Bt) partially replaced by vermicular hercynite (Hc), magnetite (Mgt), altered ilmenite (Ilm), and perthitic K-feldspar (Kfs), all with a wagnerite mantle (Wag) in fluorapatite (Ap) sample 121401E.

**FIGURE 11.** Variations in feldspar composition as a function of P content. Reference lines are shown for the idealized substitution $\text{PA} \text{Si}_2$. 
That is, Mg and some Fe in biotite were incorporated in ferromagnesian phosphate instead of ferromagnesian silicate as in most melting reactions. In the cases where stornesite-(Y) forms coronas around K-feldspar (Fig. 4) in the absence of biotite, we infer that the permeating melt was sufficiently enriched...
in MgO, FeO, and P₂O₅ from interaction with fluorapatite and biotite in one part of a fluorapatite nodule for ferromagnesian phosphate to crystallize in a part lacking biotite. We also explain the more common occurrence of ferromagnesian phosphates as isolated inclusions in fluorapatite (e.g., Fig. 2a) or interstitial to fluorapatite grains (e.g., Fig. 3) as sites from which the melt had been extracted completely. The inclusions consisting of stornesite-(Y) with Ti-poor biotite, ß-ne-grained sillimanite and cordierite(?) (Figs. 2b and 5) could be crystallized entrapped melt that was altered by the hydrous component released from the melt when it crystallized on the retrograde path (e.g., White and Powell 2002). In summary, the situation in the Larsemann Hills fluorapatite nodules is analogous to that proposed by London et al. (1999) to explain mineral assemblages with zwieselite (Fe-dominant analog of wagnerite) and sarcopside in evolved S-type granites and pegmatites.

The pressure-temperature evolution in the Larsemann Hills and nearby areas belonging to the same metamorphic complex followed a clockwise path in which peak temperatures were followed by decompression (Fig. 13). Peak conditions have been estimated to be 800–860 °C, 6–7 kbar on the basis of thermometers and barometers in pelitic, felsic, maica, and calc-silicate granulites. Further insight on metamorphic conditions is provided by Mg-dominant sarcopside and hercynite + quartz in the Brattnevet sample and by sapphirine + quartz at two localities (Figs. 1 and 12b). The presence of Mg-dominant sarcopside with 28% of the Fe end-member agrees with inferred peak pressure conditions based on isopleths for sarcopside solid solution coexisting with farringtonite. However, sapphirine and hercynite would be stable with quartz at the inferred temperatures only under oxidizing conditions or in the presence of other components. Sapphirine + quartz formed at much lower temperatures in the Semail Ophiolite than is predicted from the FeO-MgO-Al₂O₃-SiO₂ system at low oxygen activities (Fig. 13); there it occurs with magnetite, hercynite, and ilmeno-hematite (Gnos and Kurz 1994) in a texture very similar to that in Figure 12b. Stoichiometric recalculations of the sarcopside composition reported by Tong and Liu (1997) for the locality near Johnston Fjord (Fig. 1) yields Fe³⁺ = 0.367 and Fe²⁺ = 0.700 per 14 cations/20 O, consistent with an oxidizing environment for this sample. Stability of hercynite + quartz...
at the conditions inferred for the Larsemann Hills is less easily rationalized on the basis of impurities, nonetheless the amount of Fe\(^{2+}\) and Zn taken together, might be sufficient to shift the equilibrium 50–70 °C down-temperature.

Ti-rich, F- and Cl-bearing biotite within the fluorapatite segregations has partially broken down at the peak metamorphic conditions, an observation consistent with the retention of biotite in quartz-absent assemblages in the Brattstrand Bluffs (Fitzsimons 1996) and with experimental data and petrologic grids that predict stability for Ti-rich, F- and Cl-bearing biotite under the peak conditions for the Larsemann Hills (Fig. 13).

Whether anatexis was primarily a consequence of high temperatures (e.g., Fitzsimons 1996) or of decompression (e.g., Carson et al. 1997) is a matter of debate; anadulsite-bearing melts developed in fluorapatite nodules in the southern Stornes Peninsula suggest that some melting occurred during or after decompression. Nonetheless, it is likely that stornesite-(Y) formed at peak temperatures or during the earliest stages of decompression rather than at lower temperatures in the later stages. A high-temperature origin for stornesite-(Y) in the Larsemann Hills is consistent with the available information on other fillowite-group minerals; an exception is secondary fillowite in the Midnight Owl Mine (Lown and Burt 1982). Chladniite is known only from two meteorites; temperatures could have reached ~1050 °C, sufficient for limited silicate melting, in the chladniite-bearing GRA 95209 meteorite (Floss 2000; McCoy et al. 2006). Synthetic fillowite crystallizes above 600°C with alluvaite in Mn-rich compositions (Hatert and Fransolet 2004), and a synthetic Cd-bearing analog of alluvaite is transformed into a Cd-bearing analog of fillowite at 880–860 °C (Antenucci et al. 1996). However, high temperatures are not the only constraint on stornesite-(Y) formation. Reaction of anatexic melts with fluorapatite and biotite play a critical role; the resulting P-enriched melt provides the precipitation of a diverse suite of ferromagnesian phosphates dominated by wagnerite, but the resulting P-enriched melt affords the precipitation of a diverse array of phosphates including Fe(III) orthophosphates (e.g., Antenucci et al. 1996) and with experimental data and petrologic grids that predict stability for Ti-rich, F- and Cl-bearing biotite under the peak conditions for the Larsemann Hills (Fig. 13).

REFERENCES CITED


Floss, C. (1999) Fe,Mg,Mn-bearing phosphates in the GRA 95209 meteorite (Floss 2000; McCoy et al. 2006). Synthetic fillowite crystallizes above 600°C with alluvaite in Mn-rich compositions (Hatert and Fransolet 2004), and a synthetic Cd-bearing analog of alluvaite is transformed into a Cd-bearing analog of fillowite at 880–860 °C (Antenucci et al. 1996). However, high temperatures are not the only constraint on stornesite-(Y) formation. Reaction of anatexic melts with fluorapatite and biotite play a critical role; the resulting P-enriched melt affords the precipitation of a diverse suite of ferromagnesian phosphates dominated by wagnerite, but including Mg-dominant sarcospide and stornesite-(Y).

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