WERDINGITE, A BOROSILICATE NEW TO GRANITIC PEGMATITES

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ABSTRACT

Werdingite, $(Mg,Fe)_2Al_{12}(Al,Fe)_2Si_4B_2(B,Al)_2O_{37}$, occurs in granitic pegmatites cutting granulite-facies metapelitic rocks at Cap Andrahomana, near Fort Dauphin, southeastern Madagascar (type locality of grandidierite), and at Almgjotheii, in the aureole of the Rogaland anorthosite complex, southwestern Norway. Pegmatitic werdingite is beryllian (0.19–0.55 wt% BeO by ion microprobe). It varies in Al and Si contents; a more general formula could be $(Mg,Fe,Al)_2Al_{12}(Al,Fe)_2(Si,Al)_4B_2(B,Al,Be,Si)_2O_{37}$. The proportion of Fe exceeds that of Mg in one sample from Andrahomana and in all samples from Almgjotheii; thus these samples are the Fe-dominant analogues of werdingite. At Cap Andrahomana, the maximum-phase assemblage can be given as quartz + K-feldspar + grandidierite + garnet + sillimanite + werdingite, although werdingite replaces sillimanite. Niobian ilmenite, hercynite, late biotite and late andalusite also are present. At Almgjotheii, the characteristic maximum-phase assemblage prior to extensive development of tourmaline appears to have been quartz + K-feldspar + garnet + sillimanite (andalusite) + grandidierite + Ti-rich dumortierite; werdingite is limited to assemblages with boralsilite $(Al_{16}B_6Si_2O_{37})$, grandidierite and Ti-poor dumortierite, and formed later than grandidierite. Conditions of werdingite formation at both localities are estimated to be T ≈ 600–700°C, P ≈ 3–4 kbar, $P(H_2O) < P_{total}$, that is, at lower temperature than at the peak of metamorphism that affected the country rocks. The appearance of borosilicates in pegmatites cutting granulite-facies pelitic rocks, which are generally depleted in B, can be explained by a scenario involving remobilization of B present in the pelitic precursors, incorporation of the remobilized boron in partial melts, and crystallization of the melts as pegmatite veins with borosilicates. In terms of the model system $FeO–MgO–Al_2O_3–B_2O_3–SiO_2$ open to H_2O and with quartz in excess, werdingite is restricted to assemblages richer in B_2O_3 than the tie-plane grandidierite – sillimanite and the plane grandidierite – sillimanite – garnet, which are stable instead of the join werdingite – cordierite, an assemblage not yet reported in nature or experiments. At Almgjotheii, werdingite is further restricted by the tie-plane grandidierite – dumortierite, and thus is rare in rocks with garnet and sillimanite.

Keywords: werdingite, grandidierite, boron, pegmatite, ion probe analyses, southwestern Norway, southeastern Madagascar.

SOMMAIRE

Nous documentons la présence de werdingite, $(Mg,Fe)_2Al_{12}(Al,Fe)_2Si_4B_2(B,Al)_2O_{37}$, dans des pegmatites granitiques recoupant des roches métapélitiques ré-équilibrées au faciès granulite au cap Andrahomana, près de Fort Dauphin, dans le sud-est du Madagascar (la localité-type de la grandidiérite), et à Almgjotheii, dans l'auréole métamorphique du massif anorthositique de Rogaland, dans le sud-ouest de la Norvège. Il s'agit de werdingite contenant du béryllium (0.19–0.55% BeO

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en poids, données de microsonde ionique). La teneur en Al et Si est variable; une formule plus générale serait $(Mg,Fe,Al)_2Al_{12}(Al,Fe)_2(Si,Al)_4B_2(B,Al,Be,Si)_2O_{37}$. La proportion en Fe surpasse celle en Mg dans un échantillon de Andrahomana et dans tous ceux de Almgjotheii; ces échantillons sont donc des analogues ferrifères de la werdingite. Au cap Andrahomana, l'assemblage au nombre de phases maximum serait quartz + feldspath potassique + grandidiérite + grenat + sillimanite + werdingite, quoique la werdingite remplace la sillimanite. Ilménite niobifère, hercynite, biotite et andalusite, ces deux dernières tardives, sont aussi présentes. A Almgjotheii, l'assemblage au nombre de phases maximum, stable avant le développement répandu de tourmaline, correspond à quartz + feldspath potassique + grenat + sillimanite (andalusite) + grandidiérite + dumortiérite riche en Ti; la werdingite se limite aux assemblages contenant la boralsilite ($Al_{16}B_6Si_2O_{37}$), grandidiérite et dumortiérite à faible teneur en Ti, et semble stabilisée tardivement par rapport à la grandidiérite. Aux deux endroits, les conditions de formation de la werdingite seraient: $T \approx 600–700°C$, $P \approx 3–4$ kbar, $P(H_2O) < P_{total}$, c'est-à-dire, une température plus faible que celle du paroxysme métamorphique dans l'encaissant. La présence de borosilicates dans les pegmatites recoupant les métapélites dans le faciès granulite, qui sont en général appauvries en B, pourrait s'expliquer selon une mobilisation du bore dans les précurseurs pélitiques, incorporation du bore mobilisé dans le liquide formé par fusion partielle, et cristallization de ces liquides sous forme de veines d'aspect pegmatitique avec borosilicates. En termes du système modèle $FeO–MgO–Al_2O_3–B_2O_3–SiO_2$ ouvert à H_2O et avec un excédent de quartz, la werdingite se limite aux assemblages plus riches en B_2O_3 que les compositions au delà des assemblages grandidiérite – sillimanite et grandidiérite – sillimanite – grenat, qui sont stabilisés au lieu de l'assemblage werdingite – cordiérite, qui n'a pas encore été signalé dans la nature ou dans les expériences de laboratoire. A Almgjotheii, la werdingite est de plus limitée aux compositions au delà du plan grandidiérite – dumortiérite, et est donc rare dans les roches à grenat et sillimanite.

(Traduit par la Rédaction)

Mots-clés: werdingite, grandidiérite, bore, pegmatite, analyses à la microsonde ionique, sud-ouest de la Norvège, sud-est du Madagascar.

INTRODUCTION

Borosilicates are characteristic minerals of most granitic pegmatites. Tourmaline is widespread, typically in muscovite-bearing pegmatites that cut amphibolite-facies rocks, and dumortierite is not uncommon in such pegmatites. However, tourmaline, dumortierite and other borosilicates are rare in muscovite-free pegmatites associated with upper-amphibolite to granulite-facies rocks (T in the range 700–800°C, P in the range 4–9 kbar), that is, Petr Černý's "abyssal class" of granitic pegmatites [*e.g.*, Černý 1982, 1992; these correspond to the pegmatites of maximal depths of Ginzburg *et al.* (1979)]. Examples of abyssal pegmatites with noteworthy occurrences of borosilicate minerals include not only the grandidierite-bearing pegmatites at Cap Andrahomana, Madagascar and Almgjotheii, Rogaland, Norway, to be described in more detail below, but also a pegmatite containing prismatine (reported originally as kornerupine), tourmaline and dumortierite at Homagama, Sri Lanka (Grew *et al.* 1995). Characteristic of these three pegmatites is the absence of primary muscovite, presence of sillimanite and andalusite with K-feldspar, and pelitic host-rocks containing garnet and cordierite (± sillimanite) resulting from metamorphism under granulite-facies conditions.

Werdingite, $(Mg,Fe)_2Al_{12}(Al,Fe)_2Si_4B_2(B,Al)_2O_{37}$, was originally described from a silica-undersaturated, prismatine-rich granulite-facies rock in the Namaqualand complex, Bok se Puts, South Africa, where it is inferred to have formed at 800–850°C, 4.5–6 kbar (Moore *et al.* 1990, Waters & Moore, in prep.). Grew (1996a) and

Grew *et al.* (1997) found werdingite in a specimen of silica-undersaturated grandidierite-rich rock from the Urungwe District, Zimbabwe. Grandidierite, kornerupine and tourmaline were originally described from this locality by Anderson (1975), and conditions of crystallization were estimated to have been 700–750°C, 5–6 kbar (Treloar & Kramers 1989, Munyanyiwa *et al.* 1993, Treloar 1995, in prep.). In the model system $MgO–Al_2O_3–B_2O_3–SiO_2–H_2O$, werdingite was found to be stable relative to other borosilicates ± corundum at $T > 800°C$, $P < 10$ kbar and low activities of H_2O (Werding & Schreyer 1992, 1996).

However, werdingite is not restricted to silica-undersaturated systems. In addition to discovering werdingite in the Zimbabwe rock, Grew (1996a, b) found werdingite in samples of grandidierite-bearing pegmatite from Cap Andrahomana, Madagascar, the type locality for grandidierite (Lacroix 1904, 1922). Lacroix undoubtedly saw the werdingite, which he described as a colorless mineral optically distinct from grandidierite, but he had insufficient material to fully characterize it. Huijsmans (1981) and Huijsmans *et al.* (1982) reported an "unknown mineral" in a grandidierite-bearing pegmatite from Almgjotheii, Rogaland, Norway; re-examination of this mineral showed it to consist of werdingite and boralsilite (Grew 1996a, Grew *et al.* 1998).

In the present paper, we report the occurrence of werdingite as a borosilicate new to granitic pegmatites, its composition, and the conditions of its formation in a silica-saturated environment.

GEOLOGICAL SITUATION OF THE WERDINGITE-BEARING PEGMATITES

Cap Andrahomana, Madagascar, grandidierite-bearing pegmatite

Lacroix (1922) described the grandidierite-bearing pegmatite at Andrahomana as a layer forming a series of lenses in gneiss ("banc de pegmatite formant des amandes", p. 371, vol. 2). H. Besairie (cited in Behier 1961) attempted to find Lacroix's locality and succeeded in collecting a small crystal of grandidierite from a pegmatite containing mica, garnet and tourmaline. Cordierite was found in other pegmatite veins. Besairie further reported that most pegmatites do not exceed 10 cm in thickness; the largest is a string of lenses 0.2 to 1 m thick and extends for several hundreds of meters. The host rocks consist of gneisses containing biotite, garnet and cordierite, locally grading into leptynites with negligible mica.

Almgjotheii, Norway, grandidierite-bearing pegmatite

In August, 1995, Grew (1996b, unpubl. data) re-examined the pegmatite studied by Huijsmans (1981) and Huijsmans et al. (1982) and found it to be a discordant, nearly vertical vein trending somewhat west of north, extending less than 10 m, and up to 10 cm thick. In places, the pegmatite so closely resembles the host rock that the contact was hard to pinpoint. The host rocks are gneisses containing garnet, cordierite, spinel or sillimanite or both, plus graphite in traces; a particularly graphite-rich layer crops out within 5 m

horizontally and 1–2 m structurally below the gneiss layers where the pegmatite is exposed (Huijsmans 1981, Grew, unpubl. data).

MINERALOGY OF THE WERDINGITE-BEARING PEGMATITES

Cap Andrahomana, Madagascar, grandidierite-bearing pegmatite

Five specimens of grandidierite-bearing pegmatite from Andrahomana, Madagascar were studied; all five contain werdingite (Table 1). The pegmatite consists largely of quartz and gray, perthitic K-feldspar, the latter in grains up to 4 cm across. Plagioclase is much subordinate to K-feldspar, and generally much finer grained. Werdingite is found as (1) inclusions in grandidierite (102.149) or garnet (BM1908,381), (2) independent grains, some with a distinctly prismatic habit (mostly 0.5–5 mm long, 0.1–2 mm across, e.g., Fig. 1), and (3) grains mostly 0.2–1 mm across replacing sillimanite (locally such that extinction is simultaneous) (BM1908,381; BM1927,1036; 23059, e.g., Fig. 2). Werdingite shows its characteristic yellow pleochroism, albeit pale, $-2V = 33°$ (Moore et al. 1990), high birefringence, and multiple twinning, all of which help to.distinguish it from sillimanite. A few grains of werdingite are euhedral, but most are anhedral and subequant; some grains are solitary; others, especially those replacing sillimanite, are in aggregates. It is found in direct contact with quartz, K-feldspar, sillimanite, grandidierite, hercynite and biotite.

The minerals structurally related to werdingite, that is, grandidierite, sillimanite, and andalusite (Niven et

TABLE 1. MINERALOGY OF THE ROCKS WITH WERDINGITE AND ITS Fe-DOMINANT ANALOGUE

Sections	Cap Andrahomana, Madagascar						Almgjotheii, Norway	
	102.149 1	BM1908,381 1-2	3	BM1927,1036 1-3	18877 1-2	23059 1	HE138 6	HE138 10
Quartz (Qtz)	X	X	X	X	X	X	X	X
K-feldspar (Kfs)	-	X	X	X	X	X	X	X
Plagioclase (Pl)	-	T	T	T	T	T	-	-
Garnet (Grt)	-	T	(X)	-	-	(X)	X	-
Biotite (Bt)	-	T	T	(T)	T	T	-	-
Muscovite (Ms)	-	T	-	-	-	-	T	-
Chlorite (Chl)	-	T	-	-	-	-	T	-
Sillimanite (Sil)	(T)	X	-	(X)	-	(X)	-	X
Andalusite (And)	-	T	-	T	(T)	T	(T)	T
Tourmaline (Tur)	-	-	-	-	-	-	X	X
Grandidierite (Gdd)	(X)	X	(X)	X	(X)	T	(T)†	X
Dumortierite (Dum)	-	-	-	-	-	-	T	X
Werdingite (Wrd)	(T)	X*	i	(X*)	(X)†	(X*)	(T)†	X
Corundum (Crn)	-	-	-	-	-	-	T	T
Hercynite (Hc)	-	T	T	(T)	-	-	-	-
Ilmenite	-	-	-	(T)	-	-	-	-
Unid. opaque	-	T	T	-	-	T	T	-
Apatite (Ap)	-	X	X	T	-	-	T	-
Zircon (Zrn)	-	?	-	T	-	T	-	-
Monazite (Mnz)	-	T	-	T	-	T	T	-

Note: Round brackets indicate analyzed minerals discussed in the present paper. X major constituent, T trace constituent, i included in garnet (werdingite only). *Werdingite replacing sillimanite. †Fe-dominant analogue. Unidentified opaque most likely is altered ilmenite. Data for HE138-6 and -10 are from Huijsmans (1981). Mineral abbreviations follow Kretz (1983) and Grew (1996a).
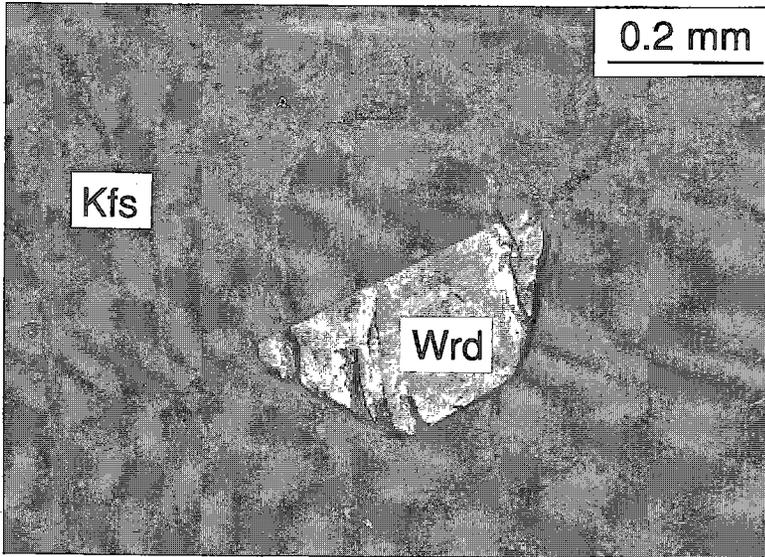
FIG. 1. Photomicrograph of twinned prism of werdingite (Wrd) in K-feldspar (Kfs), Cap Andrahomana, Madagascar. Sample 23059 (crossed nicols).
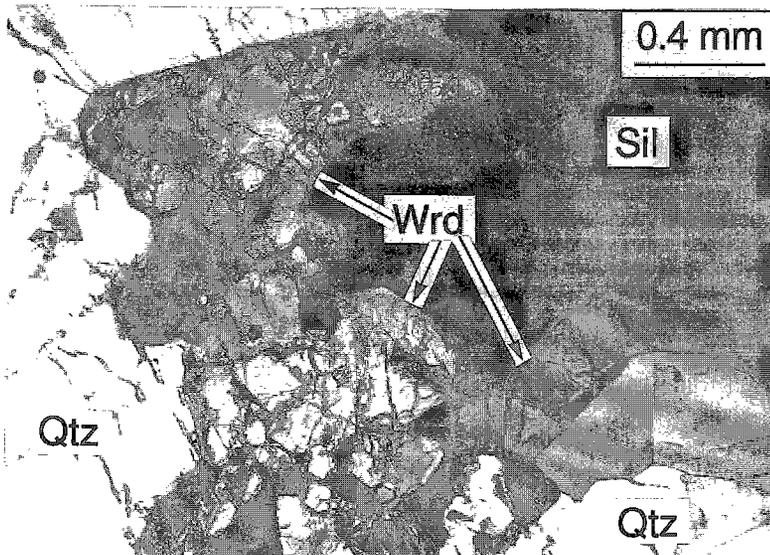
FIG. 2. Photomicrograph of twinned grains of werdingite (Wrd) replacing sillimanite (Sil, at extinction) in quartz (Qtz), Cap Andrahomana, Madagascar. Sample BM1927,1036 (crossed nicols).

al. 1991), are typically prismatic, e.g., grandidierite prisms reach 1.1 cm in length and 6 mm across, though most are much finer [Lacroix (1904, 1922) reported prisms up to 8 cm in length]. Sillimanite forms {110} prisms typically 1–5 mm long and 0.5–2 mm across, whereas andalusite appears in anhedral grains 0.3–1 mm long. Andalusite is locally in contact with K-feldspar; more commonly it is separated from K-feldspar by alteration or occurs in pockets in K-feldspar grains with plagioclase, apatite, quartz, or biotite (locally with
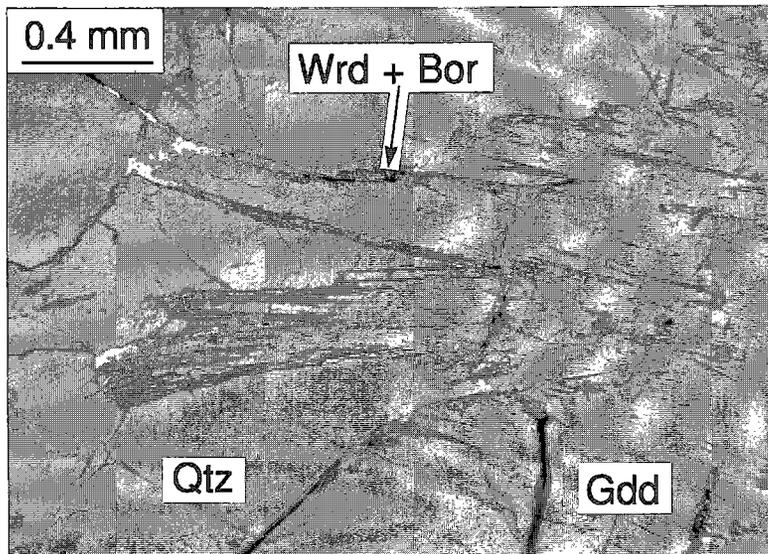
FIG. 3. Photomicrograph of intergrowths of the Fe-analogue of werdingite with boralsilite (Wrd + Bor) adjacent to grandidierite (Gdd) in quartz (Qtz), Almgjotheii, Norway. Sample HE138B, second section (plane light).

sericite). Sillimanite and andalusite are locally in parallel growth with grandidierite; andalusite encloses "islands" of grandidierite.

Grandidierite, werdingite, sillimanite and especially andalusite are partially replaced by an aggregate of fine-grained phyllosilicates distinct from muscovite. A few phyllosilicate aggregates are not obviously derived from these minerals. We cannot rule out the possibility that these aggregates are "pinite" derived from cordierite. However, as no fresh cordierite was found (also Lacroix 1904, 1922, Semroud *et al.* 1976), nor any evidence for prior presence of cordierite, such as quartz vermicules in the aggregates, it appears more likely that they are derived from alteration of K-feldspar.

Almgjotheii, Norway, grandidierite-bearing pegmatite

In hand specimens of the pegmatite, grandidierite is visible as prisms up to 1.5 cm long and 0.5 cm across, dark purple dumortierite as prisms up to 1 cm in length, and sillimanite as fibrous sprays. The dominant K-feldspar is light gray.

Werdingite has been definitively identified in only four of the 14 thin sections cut from one large specimen (HE138) collected by Huijsmans in 1979; none was found in thin sections of 15 specimens collected since then. Huijsmans (1981) confirmed the presence of werdingite by electron-microprobe analysis in section HE138-6 (Table 1), whereas a laser microspectral analysis of the "unknown mineral" in HE138-10 (J.A.

Mosk, pers. commun. to P. Maaskant, 1983) suggests that it is werdingite. In addition, the presence of werdingite was confirmed by electron-microprobe analyses in two sections cut from another fragment of HE138 in 1995-1996 (HE138B1 and HE138B2: Grew *et al.* 1998).

Werdingite (commonly intergrown with boralsilite) forms bundles typically 2-3 mm long of subparallel or somewhat radiating prisms (Fig. 3), open clusters of such prisms (Fig. 4), or intergrowths with grandidierite (Fig. 4). Prisms in the intergrowths with boralsilite commonly also show a fine ladder-like texture that presumably originated from exsolution (Grew *et al.* 1998). In contrast to the Andrahomana material, twinning is less obvious, and in places, appears to be very fine, parallel to prism length. Other minerals in contact with werdingite are plagioclase, K-feldspar, quartz, blue and purple (Ti-poor) dumortierite, and tourmaline. Tourmaline has overgrown the intergrowths of werdingite with boralsilite, and tourmaline microveinlets have penetrated the intergrowths. Huijsmans (1981) and Huijsmans *et al.* (1982) found sillimanite in contact with the unknown mineral in two sections (*e.g.*, HE138-10, Huijsmans 1981, Huijsmans *et al.* 1982, Fig. 2b), but the sections were no longer available for re-examination. The other minerals occurring in the werdingite-bearing sections appear not to have coexisted with it. Andalusite is found as corroded, partially sericitized grains in quartz surrounded by K-feldspar; it is in direct contact with K-feldspar in HE138B1. Garnet is found only in one
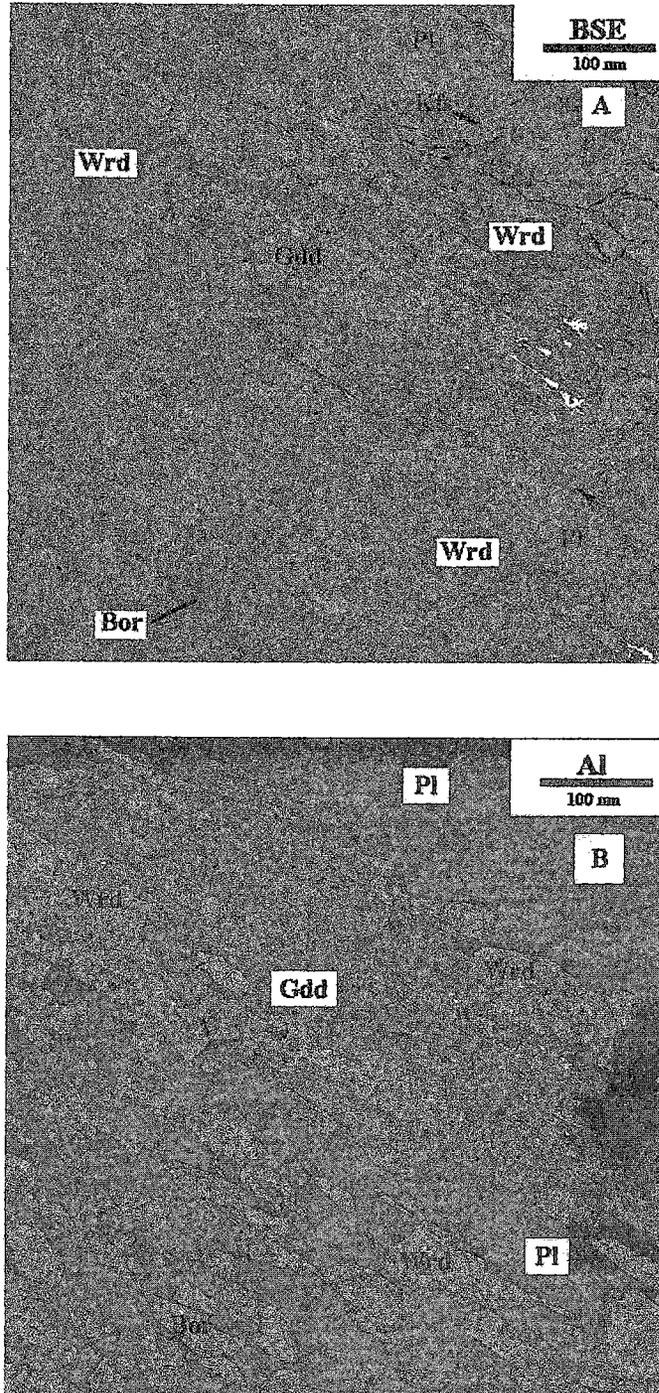
FIG. 4. Images of the Fe-analogues of werdingite (Wrd) and grandidierite (Gdd), plagioclase (Pl), K-feldspar (Kfs), and boralsilite (Bor) in sample HE138B1, Almgjotheii, Norway taken with the JEOL electron microprobe at the U.S. Geological Survey. A. Back-scattered electron (BSE) image. B. Element image for Al.

werdingite-bearing section; it occurs in quartz outside the K-feldspar grain enclosing werdingite (HE138–6, Huijsmans 1981).

CHEMICAL COMPOSITION OF THE MINERALS

Electron-microprobe analysis (EMPA)

The minerals were analyzed with an ARL SEMQ electron microprobe at the University of Maine and with a JEOL 8900 electron microprobe at the U.S. Geological Survey, Reston, Virginia. Both electron microprobes rely on wavelength-dispersion spectrometry. Operating conditions for the ARL instrument were 15 kV and 10 nA specimen current (on quartz); data were reduced using $\phi(\rho z)$ corrections, and simple silicates and oxides were used as standards. Operating conditions for the JEOL instrument were 10 kV and 30 nA beam current; data were reduced using ZAF corrections. Uvite was used as a standard for B (#NMNH C5212, McGee & Anovitz 1996, Table 2). Boron peaks were measured both from peak height and from peak integration; in the case of werdingite and grandidierite, either approach should be acceptable as both minerals, like uvite, contain only $^{[3]}B$ (see McGee & Anovitz 1996). The same two grains of werdingite in sample BM1927,1036 were analyzed by both probes. Agreement for SiO_2, Al_2O_3 and MgO is excellent, whereas Fe (as FeO) differed by 7% of the measured content: 6.42 wt% (JEOL) *versus* 5.97 wt% (ARL).

The analyses reported by Huijsmans (1981) and Huijsmans *et al.* (1982) were obtained on a Cambridge Mark 9 microprobe fitted with a Link Systems Ltd. energy-dispersion system at the Free University, Amsterdam (werdingite, grandidierite, sillimanite, andalusite at 20 kV, 15 nA) and on a Cambridge Geoscan similarly fitted (15 kV, 3–4 nA) in Manchester, U.K. (grandidierite, dumortierite).

Ion-microprobe analysis (SIMS)

The minerals were analyzed for Li, Be and B using a Cameca IMS-4f ion microprobe (secondary-ion mass spectrometry or SIMS) operated on the University of New Mexico (UNM) campus by a UNM – Sandia National Laboratories consortium. The following analytical conditions were employed: a 20 nA $^{16}O^-$, nominal 12.5 kV primary beam with a 50 V secondary beam voltage offset applied to a nominal 4.5 kV accelerating potential. The beam spot was 20 to 30 μm in diameter. A 150 μm secondary ion imaging field was used, generally in conjunction with a 33 μm field aperture. In those cases involving particularly fine-grained material, an 8 μm field aperture was used. Each spot analysis involved 20 counting cycles; in each cycle, individual peak-counting times were as follows: background (2 seconds), $^7Li^+$ (2), $^9Be^+$ (5), $^{11}B^+$ (3) and $^{30}Si^+$ (2).

TABLE 2. STANDARDS USED IN THE ION MICROPROBE ANALYSES

Standard	Li	Be	B
	wt%		
1. Lithian Schorl	0.0417	-	3.22
2. Prismatine	0.0883	(0.0079)	1.199
3. Surinamite	-	1.432	-
4. Grandidierite	-	-	3.60
5. Prismatine	-	-	1.289

Sources: 1. Harvard #112566, M. D. Dyar (personal communication 1996). 2, 4. BM1940,39, Grew *et al.* (1990), Hawthorne *et al.* (1995). Be value used only as an internal check. 3. 2292C, Grew *et al.* (1986). 5. Harvard #112233, M. Cooper (personal communication 1996)

The Li, Be, and B ion signals were normalized to ^{30}Si, and Li, Be and B contents were calculated from working curves scaled to the $^7Li/^{30}Si$, $^9Be/^{30}Si$ and $^{11}B/^{30}Si$ values of the standards (Table 2). Thus, the concentrations of these three elements are sensitive to the SiO_2 concentrations measured by EMPA. In order to minimize matrix effects in secondary-ion yield, the B standards were selected to best match the unknowns in terms of crystal structure and composition. Analyses of tourmaline, grandidierite and prismatine suggested that the matrix effect is not significant for B in the minerals analyzed in this study (see also Ottolini *et al.* 1993, Hawthorne *et al.* 1995, Hervig 1996), and thus the working curve for B was defined using all three minerals. We had less choice of standards for Be and Li; Ottolini *et al.* (1993) reported more matrix effect for Be and an even greater effect for Li. The suitability of surinamite as a Be standard is evident in comparing 12 measurements on prismatine (BM1940,39) for BeO obtained during nine sessions with a wet-chemical measurement. The SIMS measurements ranged from 0.019 to 0.032 wt% BeO and averaged 0.0275 ± 0.0042 (1 sigma) wt% *versus* 0.022 ± 0.0055 wt% BeO by wet chemistry (Grew *et al.* 1990). In the case of Li, an average of the $^7Li/^{30}Si$ values obtained on the schorl and prismatine standards was used. As these standards differ significantly in composition and crystal structure from the analyzed minerals, the tabulated Li values must be regarded as approximate, particularly those reported for biotite.

Most of the data were collected at low mass-resolution $(M/\Delta M \approx 320)$. We repeated Be analyses at selected points on biotite, werdingite, grandidierite, sillimanite, prismatine and boralsilite at a mass resolution of 1100, sufficient to separate the peaks of $^9Be^+$ and $^{27}Al^{3+}$. The primary current ranged 2 to 5 nA in this case. Even for compositional varieties of these minerals in which $2(^{27}Al^{3+}/^{30}Si^+)$ exceeds $(^9Be^+/^{30}Si^+)$, the results at high and low resolution were similar where the amount of Be exceeded 0.001 wt% BeO. That is, $^{27}Al^{3+}$ does not contribute significantly to $^9Be^+$ at > 0.001 wt% BeO (> 30 ppm Be) in minerals containing 15–70 wt% Al_2O_3.

TABLE 3. CHEMICAL COMPOSITION OF WERDINGITE AND ITS Fe-DOMINANT ANALOGUE

	Bok se Puts 22135	Cap Andrahomana					Almgjotheii		
		BM1927,1036 1 & 2, averaged		18877	23059¹		HE138B1	HE138B2	
Grain	1			1	1	2	1	1	2
Probe	JEOL	JEOL	ARL	ARL	ARL	ARL	JEOL	JEOL	JEOL
EMPA, wt %									
SiO_2	20.11	20.16	20.25	20.80	20.09	19.94	19.10	18.09	18.83
B_2O_3	10.77*	11.04*	-	-	-	-	10.83*	10.77	10.23
Al_2O_3	59.14	58.57	58.45	58.12	57.71	58.51	60.46	60.99	60.41
Fe_2O_3	2.06	2.04	1.55	0.18	0.81	0.96	-	1.27	0.48
FeO	3.12	4.59	4.57	6.74	5.19	5.04	5.98	6.29	7.57
MgO	5.01	3.36	3.44	3.09	3.50	3.43	2.24	1.69	1.46
SIMS, wt%									
Li_2O	0.003	0.008	0.008	0.009	0.009	0.008	0.004**	0.004	0.004
BeO	0.015	0.55	0.55	0.24	0.33	0.32	0.20**	0.19	0.20
B_2O_3	10.56	10.48	10.52	10.78	9.81	10.25	-	10.81	10.65
Total	100.02	99.76	99.34	99.96	97.45	98.46	98.81	99.33	99.60
Formulae per 37 O									
Si	4.032	4.065	4.092	4.199	4.155	4.075	3.884	3.684	3.837
B	3.654	3.648	3.669	3.756	3.502	3.616	3.801	3.800	3.746
Be	0.007	0.266	0.267	0.116	0.164	0.157	0.098**	0.093	0.098
Al	13.974	13.920	13.920	13.827	14.068	14.092	14.490	14.640	14.509
Fe^{3+}	0.311	0.310	0.236	0.027	0.126	0.148	-	0.195	0.074
Fe^{2+}	0.523	0.774	0.772	1.138	0.898	0.861	1.017	1.071	1.290
Mg	1.497	1.010	1.036	0.930	1.079	1.045	0.679	0.513	0.444
Li	0.002	0.006	0.007	0.007	0.007	0.007	0.003**	0.003	0.003
Total	24.0	23.999	23.999	24.0	23.999	24.001	23.972	23.999	24.001
X_{Fe2+}	0.26	0.43	0.43	0.55	0.45	0.45	0.60	0.68	0.74

Note: Ferric/ferrous ratio was calculated by normalizing cations to 24. EMPA = electron microprobe analysis, SIMS =secondary ion mass spectroscopy (ion probe). b.d. = below detection, dash = not sought. TiO_2, MnO, CaO, Na_2O, K_2O, at limit of detection; also P_2O_5, F (JEOL only). *Measured from peak height; other B_2O_3 measurements by peak integration. **Assumed values. SIMS B_2O_3 contents have been used to calculate analytical totals and formulae. ¹Grain 1 surrounds Sil 1 (Table 5), grain 2 is free standing (Fig. 1).

Several grains of werdingite were analyzed for B by both EMPA and SIMS; the SIMS results differ by ±0.5 wt% B_2O_3 relative to EMPA (Table 3); B_2O_3 contents determined by EMPA using peak integration were the same or lower, whereas those determined using peak height were higher than corresponding SIMS values. The differences are within the external precision for SIMS.

The composition of werdingite

The major constituents in pegmatitic werdingite are Be, B, Mg, Al, Si and Fe (Tables 3, 4). The other constituents sought, namely P, Ti, Mn, Ca, Na, K, F, and Cl, are at or below the limit of detection on the electron microprobe (mostly 0.01–0.05 wt%, but up to 0.1 wt% in some cases). We have calculated Fe^{3+} contents by normalizing the formula to 24 cations and 37 atoms of oxygen (see Niven *et al.* 1991). The calculated Fe^{3+} values are subject to large uncertainties, and are particularly sensitive to the measured Si content. The calculated Fe^{3+}/total Fe contents increase as follows: Urungwe, Zimbabwe granulite (Fe^{3+}/total Fe = 0: Grew *et al.* 1997) < Almgjotheii pegmatite (0–0.15, Table 3), Cap Andrahomana pegmatite (0.02– 0.29, Table 3) < Bok se Puts (type locality) granulite (0.21, Niven *et al.* 1991; 0.37, this paper, Table 3), and show a crude correlation with the degree of oxidation of the host rock. On the basis of the Fe^{3+} contents of sillimanite, andalusite, ilmenite and hercynite, which are indicators of the degree of oxidation in the rocks (*e.g.*, Grew 1980), host-rock oxidation increases as

follows: pegmatites < Urungwe granulite < Bok se Puts granulite (D.S. Waters & J.M. Moore, in prep., D.S. Waters, pers. commun. 1995, this paper, see below). The proportion of Fe^{2+} exceeds that of Mg in one sample from Andrahomana and in all samples from Almgjotheii; these samples thus are the Fe-dominant analogues of werdingite.

Be is present in all the samples of pegmatitic werdingite analyzed by SIMS, and a trace of Be was found in werdingite from the type locality (Be was not sought in holotype werdingite, Moore *et al.* 1990). Beryllium may substitute for boron on the second triangularly coordinated B site. Niven *et al.* (1991)

TABLE 4. PARTIAL CHEMICAL COMPOSITION OF WERDINGITE AND ITS Fe-DOMINANT ANALOGUE (EMPA DATA)

	Andrahomana 102.149	Almgjotheii HE138-6	
Grain	Ave. of 2	1	2
Probe	ARL	Mark	
wt %			
SiO_2	20.48	18.09	18.47
TiO_2	b.d.	b.d.	0.04
Al_2O_3	58.23	61.37	60.95
FeO	6.10	7.16	7.23
MnO	b.d.	0.05	0.04
MgO	3.42	1.36	1.52
Total	88.23	88.03	88.25

Note: b.d. = below detection. All Fe as FeO. ARL data corrected for 11 wt% B_2O_3. Mark data are from Huijsmans (1981)

FIG. 5. Plot of werdingite compositions normalized to 37 O anions and 24 cations. Sources of data are Tables 1 and 3 unless otherwise specified. 1. Type material (Moore et al. 1990, Niven et al. 1991, Waters & Moore, in prep.). 2. Sample 22135 from type locality (Grew, unpubl. notes). 3. Sample 144869, Urungwe District, Zimbabwe (Grew 1996a, Grew et al. 1997). 4. Sample BM1927,1036. 5. Sample 23059. 6. Sample 18877. 7. Sample HE138B1. 8. Sample HE138B2. Mineral abbreviations are given in Table 1; Prs: prismatine, Bor: boralsilite. The listed minerals are inferred to have either equilibrated with werdingite or formed later, but in werdingite-bearing domains.

deduced that [4]Al substitutes for B on this site concomitantly with [4]Fe^{2+} for Al on an adjacent site, resulting in a shift in the position of the bridging O(19). In the case of [4]Be → [3]B, O(19) could shift position, but Al would not be replaced, so that local charge-balance is maintained. The relationships illustrated in Figure 5 imply that incorporation of Be results in Si contents in excess of the ideal 4 Si atoms per formula unit (apfu) in the Cap Andrahomana werdingite; its (Mg + Fe^{2+}) content does not significantly exceed the ideal 2 apfu. Thus overall charge-balance could be maintained by the substitution Si + Be → 2 (Al,B).

Overall, Si increases with the divalent cations; the goodness of fit shown in Figure 5 is an artifact resulting from normalizing formulae to 24 cations and 37 atoms of oxygen. In contrast to the Tschermak substitution in other ferromagnesian silicates, in werdingite Al (in excess of 14 Al plus that replacing B, i.e., in excess of 18–B apfu) must substitute for Si and for divalent cations on the fivefold (Fe,Mg) site; no sixfold site is available (Niven et al. 1991). Less obvious is where silicon in excess of 4 Si apfu is located. Possibly, this "excess" Si substitutes for B as does [4]Al. In summary, a more general formula for werdingite could be (Mg,Fe,Al)$_2$Al$_{12}$(Al,Fe)$_2$(Si,Al)$_4$B$_2$(B,Al,Be,Si)$_2$O$_{37}$.

The composition of werdingite is sensitive to host-rock mineralogy (Fig. 5). With a few exceptions, its Si content decreases and B content increases with increasing diversity of the borosilicate assemblage and increasing B contents of these borosilicates. The werdingite samples poorest in Si and richest in B (and Al) are associated with boralsilite, Al$_{16}$B$_6$Si$_2$O$_{37}$ (ideally 18 wt% B$_2$O$_3$: Grew et al. 1998), dumortierite and grandidierite. Grandidierite is the only borosilicate associated with Si-rich werdingite.

Composition of grandidierite, sillimanite and andalusite

Boron contents of grandidierite approach the stoichiometric value of 1 B apfu (Table 5). However, Al contents are consistently less than the stoichiometric 3 Al apfu, and Fe + Mg exceed one apfu. Although these deviations could result from Fe^{3+} → Al substitution (e.g., Herd et al. 1984), Mössbauer data on grandidierite reported by Seifert & Olesch (1977) do not support this conclusion (see Grew 1996a). Fe^{2+} exceeds Mg in the samples from Almgjotheii, and consequently, these samples are the Fe^{2+}-dominant analogues of grandidierite.

In contrast to andalusite, sillimanite contains measurable Mg, B and Be (Table 6); the Almgjotheii sillimanite contains substantially more B than sillimanite from high-grade gneisses in Rogaland (0.026–0.058 wt% B$_2$O$_3$: Evers & Wevers 1984). The 0.092–0.12 wt % BeO (330–430 ppm Be) exceeds by far the only other concentrations of Be reported for sillimanite, as far as we are aware (trace – 25 ppm: Pearson & Shaw 1960, Chukhrov & Smol'yaninova 1981). The calculated formulae give B + Be + Si ≈ 1 apfu. Although Be, like B, could substitute for Si, the large difference in charge between Be and Si suggests that the mode of incorporation of Be could be complex.

Composition of the other minerals

Dumortierite from Almgjotheii includes two distinct compositional varieties: (1) rose Ti-rich dumortierite (3.59–4.60 wt% TiO$_2$) and (2) blue or purple Ti-poor dumortierite (0–0.26 wt% TiO$_2$: Huijsmans 1981, Huijsmans et al. 1982, Grew et al 1998). Both types are found in werdingite-bearing sections, but only the Ti-poor variety is intimately associated with werdingite. The tourmaline associated with werdingite is an Al-rich schorl – foitite solid solution (Grew et al. 1998). Ilmenite in BM1927, 1036 contains 1.2 wt%

TABLE 5. CHEMICAL COMPOSITION OF GRANDIDIERITE AND ITS Fe-DOMINANT ANALOGUE

	Bok se Puts 22135	Cap Andrahomana 102.149	Cap Andrahomana BM1908,381	Cap Andrahomana 18877	HE138B1	Almgjotheii HE138B2	Almgjotheii HE139B4
Probe	JEOL	ARL	ARL	ARL	JEOL	ARL	ARL
			wt %				
SiO$_2$	20.14	19.87	19.50	20.01	19.36	19.32	19.65
TiO$_2$	b.d.	b.d.	b.d.	b.d.	b.d.	0.13	b.d.
Al$_2$O$_3$	50.91	49.66	49.43	50.00	48.80	49.28	48.84
FeO	6.10	10.85	11.66	11.38	16.30	12.01	13.96
MnO	0.11	b.d.	b.d.	b.d.	0.19	0.18	0.14
MgO	10.92	7.36	6.78	7.22	4.43	6.73	5.30
	EMPA	Calc	SIMS	Calc	EMPA	SIMS	Calc
Li$_2$O	-	-	0.0002	-	-	<0.0001	-
BeO	-	-	0.002	-	-	0.001	-
B$_2$O$_3$	11.20*	11.40	11.20	11.48	11.20*	11.31	11.22
Total	99.38	99.14	98.57	100.09	100.28	98.96	99.11
			Formulae per 9 O				
Si	1.003	1.010	1.001	1.009	0.999	0.991	1.014
B	0.963	1.000	0.993	1.000	0.998	1.001	1.000
Ti	0	0	0	0	0	0.005	0
Al	2.988	2.974	2.992	2.973	2.968	2.979	2.971
Fe^{2+}	0.254	0.461	0.501	0.480	0.704	0.515	0.603
Mn	0.005	0	0	0	0.008	0.008	0.006
Mg	0.811	0.558	0.519	0.543	0.341	0.515	0.408
Total	6.024	6.003	6.006	6.005	6.018	6.014	6.002
X$_{Fe}$	0.24	0.45	0.49	0.47	0.67	0.50	0.60

Note: EMPA = electron microprobe analysis, SIMS =secondary ion mass spectroscopy (ion probe), Calc = calculated assuming stoichiometry, b.d. = below detection, dash = not sought. All Fe is presumed to be ferrous. P, F, and Cl (JEOL only), CaO, Na$_2$O, and K$_2$O at limit of or below detection. *Measured from peak height

TABLE 6. CHEMICAL COMPOSITION OF SILLIMANITE AND ANDALUSITE

Grain	Sillimanite 102.149 1	Sillimanite BM1927,1036 1	Cap Andrahomana Andalusite 18877 2	Cap Andrahomana Sillimanite 1	Cap Andrahomana Sillimanite -23059- 2	Cap Andrahomana Sillimanite 3	Almgjotheii Sillimanite* HE138B4 4	Almgjotheii Andalusite HE138B2 1
				wt %, EMPA				
SiO$_2$	35.92	35.56	37.11	35.92	35.53	35.92	35.95	36.27
Al$_2$O$_3$	62.26	61.89	62.22	62.35	62.49	62.39	62.06	62.42
Fe$_2$O$_3$	0.89	0.71	0.40	0.56	0.71	0.52	0.34	0.33
MgO	0.13	0.17	b.d.	0.11	0.14	0.09	≤0.04	≤0.03
				wt%, SIMS				
Li$_2$O	-	0.0001	0.0002	0.0002	0.0001	0.0001	0.002	<0.0001
BeO	-	0.12	<0.0001	0.092	0.12	0.10	0.073	<0.0001
B$_2$O$_3$	-	0.51	0.02	0.46	0.66	0.37	0.46	0.004
Total	99.20	98.96	99.75	99.49	99.65	99.39	98.89	99.02
				Formulae				
O	-	4.975	5.002	4.980	4.972	4.981	4.9855	4.994
Si	-	0.966	1.005	0.971	0.957	0.972	0.977	0.988
Be	-	0.008	0	0.006	0.008	0.007	0.005	0
B	-	0.024	0.001	0.021	0.031	0.017	0.022	0
Al	-	1.981	1.986	1.986	1.984	1.990	1.989	2.005
Fe^{3+}	-	0.015	0.008	0.011	0.014	0.011	0.007	0.007
Mg	-	0.007	0	0.004	0.006	0.004	0	0
Total	-	3.001	3.0	2.999	3.0	3.001	3.0	3.0

Note: EMPA = electron microprobe analysis (all ARL), SIMS =secondary ion mass spectroscopy (ion probe), b.d. = below detection, dash = not sought. TiO$_2$, MnO, CaO, Na$_2$O, K$_2$O at or below limit of detection. Formulae normalized to 3 cations; all Fe assumed to be ferric. *Not associated with werdingite; included for comparison.

TABLE 7. CHEMICAL COMPOSITION OF
GARNET AND BIOTITE
FROM CAP ANDRAHOMANA

	Garnet BM1908,381	Garnet* 23059	Biotite BM1927,1036	Biotite
	EMPA (all ARL), wt %			
SiO$_2$	37.59	37.85	36.79	37.50
TiO$_2$	b.d.	b.d.	2.07	2.48
Al$_2$O$_3$	21.07	21.11	13.33	13.25
FeO	36.18	36.06	19.80	17.73
MnO	0.35	0.38	b.d.	b.d.
MgO	4.55	4.57	11.87	12.85
CaO	0.73	0.77	b.d.	b.d.
BaO	-	-	0.03	0.04
Na$_2$O	b.d.	b.d.	0.11	0.14
K$_2$O	b.d.	b.d.	9.60	9.52
F	-	-	4.27	4.33
Cl	-	-	2.11	1.63
H$_2$Ocalc	-	-	1.28	1.41
	SIMS, wt%			
Li$_2$O	-	0.003*	~0.1	~0.1
BeO	-	<0.0001*	<0.0001	0.0001
B$_2$O$_3$	-	0.007*	0.0003	0.001
O=F,Cl	-	-	-2.28	-2.19
Total	100.47	100.75	98.98	98.69
	Formulae			
O	12	12	22	22
Si	2.996	3.005	5.750	5.795
Ti	0	0	0.243	0.288
B	-	0.001	-	-
Al	1.979	1.975	2.456	2.413
Fe^{2+}	2.412	2.394	2.588	2.291
Mn	0.024	0.026	0	0
Mg	0.541	0.541	2.766	2.960
Ca	0.062	0.065	0	0
Ba	-	-	0.002	0.002
Li	-	0.001	-	-
Na	-	-	0.033	0.042
K	-	-	1.914	1.877
Total	8.014	8.008	15.752	15.668
F	-	-	2.111	2.116
Cl	-	-	0.559	0.427
OHcalc	-	-	1.330	1.457
X$_{Fe}$	0.82	0.82	0.48	0.44

Note: EMPA = electron microprobe analysis, SIMS =secondary ion mass spectroscopy (ion probe). Calc = calculated assuming stoichiometry. b.d. = below detection, dash = not sought. All Fe as FeO. *EMPA average of 2 grains: SIMS on one grain only.

TABLE 8. CHEMICAL COMPOSITION OF HERCYNITE
FROM CAP ANDRAHOMANA (SAMPLE BM1927,1036)

	1	2	Formulae per 4 O	
Electron microprobe (ARL), wt %			Al	1.937	1.936
			V	0.001	0
Al$_2$O$_3$	57.38	56.75	Fe^{3+}	0.062	0.064
V$_2$O$_3$	0.04	b.d.	Fe^{2+}	0.780	0.836
Fe$_2$O$_3$	2.89	2.92	Mn	0.003	0.002
FeO	32.55	34.53	Mg	0.143	0.112
MnO	0.12	0.10	Zn	0.074	0.050
MgO	3.36	2.59	Total	3.000	3.000
ZnO	3.51	2.34			
Total	99.85	99.23	X$_{Fe}$	0.85	0.88

Note: b.d.: below detection. TiO$_2$, Cr$_2$O$_3$ and NiO at limit of detection. The Fe^{2+}/Fe^{3+} value is calculated by normalization to three cations.

Nb$_2$O$_5$ and 0.2 wt% Ta$_2$O$_5$. A preliminary analysis of lamellae exsolved from this ilmenite gave a columbite-like composition, Fe$_{0.96}$Mg$_{0.05}$Mn$_{0.01}$Zn$_{0.01}$Ti$_{0.15}$Nb$_{1.80}$Ta$_{0.05}$W$_{0.01}$O$_6$.

Distribution of the elements and comparisons

A major difference among the pegmatites is the extent of chemical heterogeneity. Although biotite and hercynite vary somewhat from grain to grain in sample BM1927,1036 (Tables 7, 8), the other ferromagnesian minerals are relatively homogeneous in the Andrahomana pegmatite. The composition of garnet in two samples is virtually identical (Table 7). Taking all the samples together, total Fe as FeO in werdingite ranges from 5.90 to 6.90 wt%, and MgO, from 3.09 to 3.50 wt% (Tables 3, 4). In sample #18877, the $X(Fe^{2+})$ of werdingite exceeds that of grandidierite, although

overall, the relations $0.43 < X(Fe^{2+})$ in Wrd < 0.55 and $0.45 < X(Fe^{2+})$ in Gdd < 0.49 apply. Uncertainty in estimating Fe^{3+}/Fe^{3+} ratio undoubtedly contributes to variation in the $X(Fe^{2+})$ of werdingite. Thus, grandidierite and werdingite compositions appear to vary little from sample to sample, and the $X(Fe^{2+})$ of both minerals are roughly equal. Taking all the samples together, $X(Fe^{2+})$ increases as follows: Bt ≈ Gdd ≈ Wrd ≪ Grt < Hc.

In contrast, ferromagnesian minerals are compositionally heterogeneous in the Almgjotheii pegmatite, and Fe^{2+}–Mg distribution is variable. The $X(Fe^{2+})$ of grandidierite ranges 0.41 to 0.81 from one section to another in HE138 (Huijsmans 1981, Huijsmans *et al.* 1982, this paper, Table 5), and grandidierite has a higher $X(Fe^{2+})$ than werdingite in HE138B1, but a lower $X(Fe^{2+})$ than werdingite in HE138B2.

The grandidierite and werdingite at both localities are noteworthy for their high $X(Fe^{2+})$ compared to the same minerals in metamorphic rocks, *e.g.*, #22135 (Tables 3, 5); indeed, the Fe-dominant analogues are present. The almandine content of the Andrahomana garnet is among the highest reported (79%, Table 7; *cf.* Deer *et al.* 1982). Whereas our data on #22135 suggest nearly equal distribution of Fe^{2+} and Mg between werdingite and grandidierite in granulites, data on another sample from the type locality (Moore *et al.* 1990, Niven *et al.* 1991) and on a granulite from Zimbabwe (Grew *et al.* 1997) show grandidierite to be more magnesian than werdingite. The discrepancy could result from the difficulty in calculating a Fe^{3+}/Fe^{2+} for werdingite from considerations of stoichiometry. More precise measurement of this ratio is needed before Fe^{2+}–Mg distribution can be determined with more certainty.

X-RAY-DIFFRACTION DATA

The unit-cell parameters of werdingite in sample BM1927,1036, determined from 25 reflections with an Enraf–Nonius CAD4 4-circle diffractometer (Mo$K\alpha$ radiation) at the University of Michigan are as follows:

a 7.9745(9), *b* 8.1318(8), *c* 11.3736(14) Å, α 110.46(1)°, β110.86(1)°, γ 84.63(1)°, and *V* 645.30(14) Å³. Compared to the cell of the type werdingite [*V* = 650.5(3) Å³], whose cell parameters were determined with the same make of instrument (Moore *et al.* 1990, Niven *et al.* 1991), the cell of the Andrahomana werdingite is smaller in all dimensions, with negligible differences in the angles, and its cell volume is 0.8% less. The higher B content of the Andrahomana werdingite may explain the difference, although the cell volume of synthetic werdingite, which has an even higher B content (3.87 B *apfu*: Werding & Schreyer 1992), is only 0.2% less [*V* = 649.1(5)Å³].

CONDITIONS OF FORMATION

Pegmatites at both localities were intruded into granulite-facies rocks. No geothermobarometric data are available specifically for Cap Andrahomana, which is located in the area mapped as the Tranomaro Group of the Androyan Complex. The Tranomero Group was affected by an event that peaked at between 800 and 875°C at a pressure between 4 and 5 kbar, resulting in the widespread development of Hc + Qtz, followed by nearly isobaric retrogression to 700–750°C (Paquette *et al.* 1994). Quartz and hercynite are locally in direct contact in the pegmatite. However, the presence of zinc in the hercynite (2.34–3.51 wt% ZnO, Table 8) has stabilized Hc + Qtz at lower temperatures in the pegmatite than in the Zn-free system.

The geological situation and evolution of the Andrahomana pegmatite are not precisely defined. There is no clearcut evidence for two generations of andalusite, and thus andalusite is most likely a late phase throughout. The high F and Cl contents in late biotite (Table 7) attests to reduced activities of H_2O even late in the pegmatite's evolution. Werdingite formed after sillimanite, probably under conditions comparable to those at Almgjotheii, that is T in the approximate range 600–700°C, P ≈ 4 kbar, P(H_2O) < P$_{total}$; *i.e.*, late in the retrograde stage reported by Paquette *et al.* (1994).

The Almgjotheii pegmatite is located between the orthopyroxene-in and osumilite-in isograds in the contact aureole of the Rogaland intrusive complex (Tobi *et al.* 1985, Huijsmans *et al.* 1982). The rocks in the aureole have been affected by five metamorphic events, including *M2*, a thermal event caused by diapiric emplacement of the complex, specifically, the anorthositic masses, and *M3*, which is correlated with deformation during final stages of emplacement of the anorthosite (Maijer *et al.* 1981, Maijer 1987). Temperatures during *M2* increased from 700°C at the orthopyroxene-in isograd to 1050°C close to the intrusive contact (Jansen *et al.* 1985, Schumacher & Westphal 1996), and P in the range 4–6 kbar appears to be the estimate most compatible with available geothermometric, mineralogical and fluid-inclusion

data (Jansen *et al.* 1985, Vander Auwera & Longhi 1994, Schumacher & Westphal 1996, Holland *et al.* 1996, *cf.* Wilmart & Duchesne 1987). Conditions for *M3* are estimated to be in the range 500–700°C and 2.5–4 kbar (Jansen *et al.* 1985, Wilmart & Duchesne 1987). Huijsmans *et al.* (1981, 1982) inferred that the pegmatite was emplaced during *D3*, the deformation accompanying *M3*. The pegmatite appears to be the result of partial melting during *M3*. Remobilization of the melt was facilitated by shear zones developed during *D3*, as was the case observed for granitic veins cutting charnockitic migmatite in the Rogaland aureole (Huijsmans *et al.* 1981, Fig. 7).

The mineralogy of the Almgjotheii pegmatite is consistent with the temperature range estimated for *M3* in the aureole. The association And + Kfs at P ≥ 2.5 kbar implies $X(H_2O)$ < 0.7 in the associated fluid phase (Kerrick 1972), that is, relatively dry conditions. The sequence andalusite → sillimanite → andalusite (see below) implies that the pegmatite was heated after emplacement, consistent with *M3* being a discrete metamorphic event. We infer that the Fe-dominant analogue of werdingite and boralsilite formed at T ≈ 600–700°C, P ≈ 3–4 kbar.

At both localities, werdingite and its Fe-dominant analogue are estimated to have formed at temperatures below the minimum of 775°C at 3 kbar at which Werding & Schreyer (1992, 1996) hydrothermally synthesized the Mg end-member. The lower temperatures inferred for natural werdingite are not surprising, given the substantial differences in physicochemical conditions between the pegmatite (high Fe/Mg, quartz in excess) and the experiments (Fe absent, quartz absent).

INTERPRETATION OF THE PEGMATITE ASSEMBLAGES

Semroud *et al.* (1976) proposed the following sequence of crystallization for the Andrahomana pegmatite: (1) hercynite, garnet, (2) grandidierite, sillimanite, (3) andalusite, biotite. Werdingite appears to be earlier than andalusite and biotite and later than sillimanite even though in rare cases werdingite is enclosed in grandidierite and garnet. Nonetheless, garnet occurs in close proximity to werdingite, with no evidence that garnet and werdingite were not stable together. The maximum-phase assemblage can be given as Qtz + Kfs + Gdd + Grt + Sil + Wrd (Fig. 6).

On the basis of the four sections containing the Fe-dominant analogue of werdingite and boralsilite (HE138B), as well as sections of samples obtained from D. Visser and collected by Grew in 1995, we propose the following sequence of crystallization of the Almgjotheii pegmatite (*cf.* Huijsmans *et al.* 1982): (1) rose-colored Ti-rich dumortierite (Dum I), andalusite I, sillimanite (?), grandidierite (and its Fe-dominant analogue), garnet; (2) Fe-dominant analogue of werdingite, boralsilite, blue and purple Ti-poor dumortierite (Dum II), sillimanite,
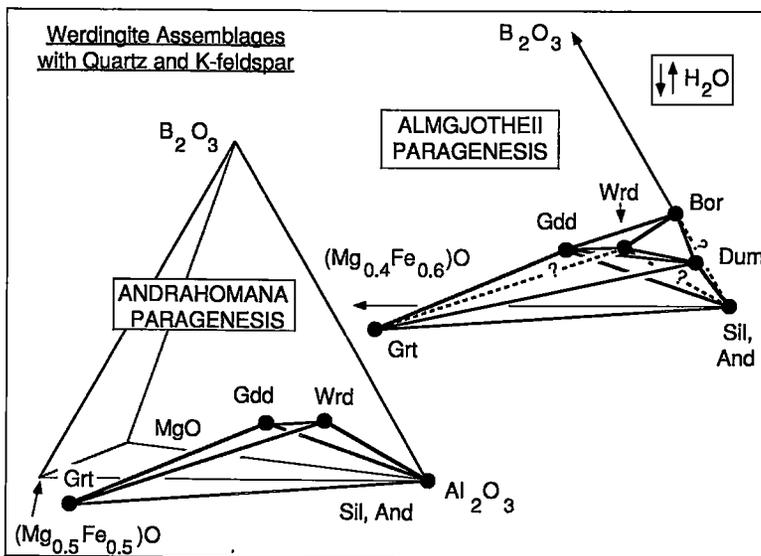
FIG. 6. Mineral parageneses at Cap Andrahomana, Madagascar and Almgjotheii, Rogaland, Norway in terms of the $FeO–MgO–B_2O_3–Al_2O_3–SiO_2$ system open to H_2O and with quartz in excess. The front faces of the tetrahedra are sections at the approximate Fe/Mg value of the ferromagnesian borosilicates. Mineral compositions are idealized from Tables 3–6 (for dumortierite, see text). Mineral abbreviations are given in Table 1. Bor: boralsilite ($Al_{16}B_6Si_2O_{37}$). Compatibilities are drawn for X_{Fe} increasing as follows: Gdd ≤ Wrd < Grt.

grandidierite II (?) grading into (3) tourmaline, corundum, hercynite, sillimanite, andalusite II, more dumortierite II, and (4) hydrous phyllosilicates, including sericite, chlorite, and margarite.

The characteristic maximum-phase assemblage prior to extensive development of tourmaline at Almgjotheii appears to have been Qtz + Kfs + Grt + Sil (And) + Gdd + Ti-rich Dum (Fig. 6). Textural relations suggest that the Fe-dominant analogue of werdingite is limited to assemblages with boralsilite, Fe-dominant analogue of grandidierite and Ti-poor dumortierite, e.g., Qtz + Kfs + Gdd + Dum + Wrd (HE138–6, Huijsmans 1981) or Pl + Gdd + Bor + Wrd (Fig. 4). Evidence for assemblages with garnet or sillimanite is equivocal. Most coarse-grained andalusite (up to 1 cm long) is an early phase; some of this andalusite is mantled by prismatic sillimanite. Andalusite also occurs with tourmaline around the Fe-dominant analogue of grandidierite (Fe-Gdd), as does sillimanite and hercynite, suggesting a reaction open to H_2O, Na_2O and CaO:

Fe-Gdd + Qtz → Tur + And or Sil ± Hc

Corundum is invariably enclosed in tourmaline (in one exceptional case, it is enclosed in andalusite) and could have formed by a reaction not involving quartz:

Fe-Gdd → Tur + Crn ± Hc

The Andrahomana and Almgjotheii pegmatites have the following features in common: (1) absence of primary tourmaline (indeed, no tourmaline at all at Andrahomana), (2) presence of andalusite, including early andalusite at Almgjotheii, (3) absence of primary muscovite and stable coexistence of sillimanite and andalusite with K-feldspar, (4) presence of minerals containing Be, W, Nb, and Ta, e.g., wolframite (Almgjotheii) and niobian ilmenite (Andrahomana), and (5) absence of cordierite. The pegmatites formed at temperatures below those at which the country rocks originally crystallized so that andalusite appeared at one or more stages of their evolution. Yet the activity of H_2O remained sufficiently low for And + Kfs to be stable, and hydrous phyllosilicates crystallized only near the conclusion of their development. Important differences between the two pegmatites are (1) the absence of primary minerals with hydroxyl in the Andrahomana pegmatite, and (2) the greater complexity of the Almgjotheii assemblage.

The assemblages can be explained in terms of the model system $FeO–MgO–Al_2O_3–B_2O_3–SiO_2$ open to H_2O and with quartz in excess (Figs. 6, 7). BeO, TiO_2 and Fe_2O_3 are the most abundant minor constituents,
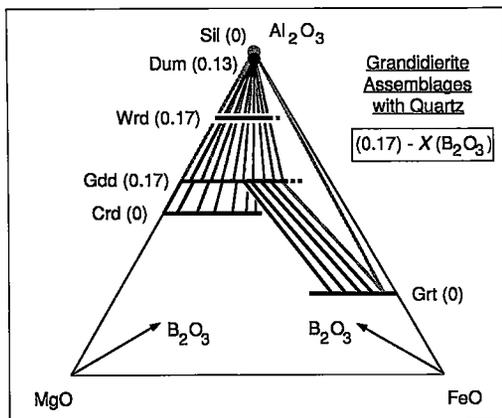
FIG. 7. Schematic representation of the compatibilities of grandidierite and its Fe-analogue in the FeO–MgO–B$_2$O$_3$–Al$_2$O$_3$–SiO$_2$ system with quartz in excess. Abbreviations: Table 1. The B$_2$O$_3$ apex can be visualized as lying above the triangle. Relative heights are indicated in parentheses [mole fraction B$_2$O$_3$ = B$_2$O$_3$/(B$_2$O$_3$ + Al$_2$O$_3$ + MgO + FeO)]. Sillimanite composition and tie lines involving sillimanite are shown in gray.

but as a first approximation, their effect on the illustrated relationships is presumed not to be significant. The mineralogy of both pegmatites reflects their marked peraluminous character, probably a result of muscovite being absent, so that Al in excess of that needed for feldspar is available for ferromagnesian and Al-rich borosilicates. The absence of cordierite is surprising; at a P near 4–5 kbar, a member of the cordierite – sekaninaite solid solution would be expected. The chemographic relationships illustrated in Figure 7 imply that the B$_2$O$_3$ contents of the pegmatite were sufficient for the bulk composition to lie "above" (*i.e.*, at higher B$_2$O$_3$ contents than) the 3-phase plane Grt + Gdd + Sil and the tie-plane Gdd + Sil. As a result, Wrd appears with Gdd + Sil ± Grt. At B$_2$O$_3$ contents "below" these planes, the assemblages Gdd + Crd + Sil ± Grt are predicted, and these have been found in a few migmatites (Grew 1996a). The wide range of the ratio Fe/Mg in Gdd overall [0.02 < *X*(Fe) < 0.81: Grew (1996a); *X*(Fe) = 0 in synthetic grandidierite, Werding & Schreyer (1996)] implies that the Gdd + Sil ± Grt joins act as barriers to a Wrd–Crd join at all Fe/Mg values where Wrd is stable [*X*(Fe) in Wrd between 0 and 0.74, including synthetic werdingite, Werding & Schreyer 1992, 1996; Moore *et al.* 1990; this paper, Table 3].

The scarcity (absence?) of assemblages of the Fe-dominant analogue of Wrd with Sil or Grt at Almgjotheii could be explained by the tie-plane Gdd + Dum acting as a barrier, breached in only a few cases, if at all. With these possible exceptions,

werdingite and its Fe-dominant analogue and boralsilite would only appear if the bulk B$_2$O$_3$ content lies "above" the Gdd–Dum tie-plane. Apparently, such high B$_2$O$_3$ contents are rare, and thus grandidierite and dumortierite (Dum I) are more abundant, together with garnet and sillimanite.

ORIGIN OF THE BORON ENRICHMENT

In general, granulite-facies rocks are depleted in boron; B contents of such rocks rarely exceed 5 ppm (Leeman & Sisson 1996). However, the pelitic host-rocks of the werdingite-bearing pegmatites probably contained boron prior to granulite-facies metamorphism; B contents of representative pelitic sediments ranges between 30 and 250 ppm (Leeman & Sisson 1996). At Cap Andrahomana, boron in the pelitic precursors could have been remobilized during metamorphism, entered pegmatite-forming melts, and subsequently precipitated out either in tourmaline or in grandidierite and werdingite. There is not enough information on the area to further specify this process. In the aureole of the Rogaland intrusive complex, borosilicates are reported to be very rare. The only other known occurrence involves tourmaline in a pegmatite 40 km northwest of Almgjotheii (Huijsmans *et al.* 1982). Thus, had the precursors of the Rogaland rocks contained significant B, it was largely lost during metamorphism. Traces of B were retained in sillimanite, which contains non-negligible amounts (0.026–0.058 wt% B$_2$O$_3$ or 80–180 ppm B, Evers & Wevers 1984). A noteworthy feature of the host gneisses intersected by the Almgotheii pegmatite is the abundance of graphite. Douthitt (1985) reported that graphite and other carbonaceous materials in metasediments contain up to 100 ppm B, possibly as finely admixed tourmaline. Thus the unusual abundance of graphite in the host rocks at Almghotheii could explain why the Almghotheii pegmatite contains boron minerals, whereas other pegmatites (with the one exception noted above) in the Rogaland area do not. A scenario for the Almgjotheii pegmatite is breakdown of the tourmaline admixed with graphite with release of boron, incorporation of the remobilized boron in a partial melt, and crystallization of the melt as a pegmatite vein with borosilicates. The presence of minerals containing Be, W, Nb and Ta suggests that these elements were remobilized along with B, and to some extent concentrated, during the metamorphism and associated anatexis.

ACKNOWLEDGEMENTS

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