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Gatelite-supergroup minerals: recommended nomenclature and review

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Abstract: All minerals having a crystal structure and a chemical composition that can be described as a regular combination of modules of epidote-type structure (**E**) and modules of törnebohmite-type structure (**T**) fulfil the criteria of forming a mineral supergroup, named the gatelite supergroup. All members share the same general formula and topology, consisting of edge-sharing octahedral chains, cross-linked to each other by SiO_4 and Si_2O_7 groups, with the remaining large cavities occupied by Ca and REE ± Na. By analogy with the epidote supergroup, three groups are defined to accommodate the existing accepted mineral species: (i) the *gatelite group* – includes members that can be derived from the mineral gatelite-(Ce) solely by homovalent substitutions, *i.e.*, gatelite-(Ce), perbøeite-(Ce), and ferriperbøeite-(Ce); (ii) the *västmanlandite group* – includes members typified by the mineral västmanlandite-(Ce). This group is derived from gatelite-(Ce) by homovalent substitutions and one coupled heterovalent substitution of the type ${}^{M1}[M^{3+}] + {}^{O4}[O^{2-}] \rightarrow {}^{M1}[M^{2+}] + {}^{O4}[F^{-}]$. Västmanlandite-(Ce) is the unique member of this potential group; and (iii) the *alnaperbøeite group* – includes members typified by the mineral alnaperbøeite-(Ce). This group is derived from gatelite-(Ce) by homovalent substitutions and one coupled heterovalent substitution of the type ${}^{A2+A3+A4}[A^{3+}{}_{3}] + {}^{M3}[M^{2+}] \rightarrow {}^{A2+A3+A4}[A^{3+}{}_{2.5}A^{+}{}_{0.5}] + {}^{M3}[M^{3+}]$. Alnaperbøeite-(Ce) is the unique known member of this potential group. We recommend that the nomenclature of the gatelite supergroup be based on the criterion of occupancy of *key* cation sites. In particular, *A*1 and *M*3 (and, in principle, *M*2) determine the root name. If the dominant cations at *A*1, *M*3 (and *M*2) exactly match those of an approved species, the same fixed root name – modified by an appropriate prefix – is given. If the dominant cation is different at any of these sites, a new root name is assigned.The members of the gatelite supergroup are rare minerals, although the number of occurrences is increasing. They have been found in REE-rich assemblages in a variety of geological settings, including granitic NYF pegmatites, carbonatite and associated fenites, alkali-syenites, and hydrothermal-metasomatic skarns. Most frequently, they coexist with törnebohmite-(Ce), allanite- or dollaseite-group minerals, bastnäsite-(Ce), cerite-(Ce), or fluorbritholite-(Ce). Analytical data available from the literature show extensive solid solution along the ferriperbøeite-(Ce)–västmanlandite-(Ce) and the perbøeite-(Ce)–alnaperbøeite-(Ce) joins, whereas there are few or no samples testifying to västmanlandite-(Ce)–gatelite-(Ce) or perbøeite-(Ce)–ferriperbøeite-(Ce) solid solutions.The present nomenclature recommendations were approved by the International Mineralogical Association Commission on New Minerals, Nomenclature and Classification.

Key-words: gatelite supergroup; mineral nomenclature; gatelite-(Ce); västmanlandite-(Ce); perbøeite-(Ce); alnaperbøeite-(Ce); ferriperbøeite-(Ce).

1. Definition

Gatelite-(Ce) (Bonazzi *et al.*, 2003), västmanlandite-(Ce) (Holtstam *et al.*, 2005), perbøeite-(Ce) and alnaperbøeite-(Ce) (Bonazzi *et al.*, 2014), as well as the recently approved species ferriperbøeite-(Ce) (Bindi *et al.*, 2018) represent isotopological epidote–törnebohmite (**E**–**T**) type polysomes. They are distinguished by the chemical composition of the **E** module but share the same structural topology and the common general formula $A_4M_4(Si_2O_7)(SiO_4)_3(O^{2-},F^{-})(OH)_2$. From this point of view, they fulfil the criteria of forming a mineral supergroup (Mills *et al.*, 2009). Because the first member of this kind was named gatelite-(Ce), the root name of this species has priority in naming the supergroup.

The object of this paper is to present nomenclature recommendations for the supergroup, approved by the International Mineralogical Association Commission on New Minerals, Nomenclature and Classification, and give a condensed review of what is currently known about the minerals belonging to it.

2. Structure and crystal chemistry

All minerals of the gatelite supergroup have a crystal structure that can be described as a regular alternation of modules of epidote-type structure (**E**) and modules of törnebohmite-type structure (**T**). The **E** modules are (001) slabs, ~10.4 Å thick, with the general composition $A_2M1M2M3[Si_2O_7][SiO_4]X(OH)$, where $X = O^{2-}$ and/or F^{-}. The **T**-type

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modules are (-102) slabs, ~7.1 Å thick, with the composition $[REE_2Al(SiO_4)_2(OH)]$ (Fig. 1).

Specifically, the following crystallographic relations are observed: $a_{gat} \sim 2a_{epi} \sim [201]_{tör}$; $b_{gat} \sim b_{epi} \sim b_{tör}$; $c_{gat} \sim (c_{epi} + a_{tör})$. The doubling of the translation unit along the monoclinic *a*-axis in gatelite-(Ce) is due to a distortion away from the mirror symmetry normal to the *b*-axis; thus, the space group is $P2_1/a$ instead of $P2_1/m$. Such symmetry deviations are indeed very slight, so that the *hkl* reflections with $h = 2n + 1$ are relatively weak (Bonazzi *et al.*, 2003).

In the cases of perbøeite-(Ce), alnaperbøeite-(Ce) and ferriperbøeite-(Ce), no evidence of doubling of the translation unit along the *a*-axis was observed by means of X-ray diffraction, although the crystals were examined with long exposure times, whereas in västmanlandite-(Ce) only a weak, continuous streaking at $a^*/2$ was recorded (Holtstam *et al.*, 2005; Bonazzi *et al.*, 2014; Bindi *et al.*, 2018).

Thus, in all cases except for gatelite-(Ce), the structure was refined as an *average structure* in the space group $P2_1/m$ instead of $P2_1/a$, disregarding the slight distortion away from the mirror plane normal to the *b*-axis. However, whereas the continuous streaking in västmanlandite-(Ce) is due to the offset from the (010) mirror plane of two sites (*A*3 and O15, occupied by REE and oxygen, respectively), in perbøeite-(Ce), alnaperbøeite-(Ce) and ferriperbøeite-(Ce), only O15 exhibits an offset from the mirror plane. Therefore, a possible streaking at $a^*/2$ due to short-range order, if any, would be even weaker than in västmanlandite-(Ce).

All the minerals of the supergroup share the same topology, consisting of edge-sharing octahedral chains running along the monoclinic *b*-axis, cross-linked to each other by SiO_4 and Si_2O_7 groups. The remaining large cavities are occupied by Ca (*A*1) and REE ± Na (*A*2, *A*3 and *A*4).

In the $P2_1/a$ model there are four independent octahedral sites: *M*1 octahedra form branched chains with *M*3 octahedra alternately attached on opposite sides, whereas *M*2a and *M*2b octahedra (which in the $P2_1/m$ model coalesce to a unique *M*2 octahedron with double multiplicity) form single chains. As the homologue octahedron of the epidote structure, *M*3 is the largest and distorted one, and hosts always divalent cations due to the ubiquitous presence of REE^{3+} at the *A*2 site. On the other hand, the dominance of divalent cations (mainly Mg) in the *M*1 octahedron is related to the amount of F^- substituting for O^{2-} at the O4 site. As in the epidote supergroup, the amount of Mg^{2+}, Fe^{2+}, Al^{3+}, Fe^{3+} entering *M*1 and *M*3 depends on competing ions, with a preference for the larger cations to enter *M*3. *M*2a and *M*2b (or *M*2 in the $P2_1/m$ model), which replicate the *M*2 in the epidote archetype and the octahedral site in törnebohmite, are almost fully occupied by Al.

3. Definition of groups

The classification of the gatelite-type minerals is based on the **E** structural element, as the **T** module is relatively constant in composition, with only minor Al^{3+}-Fe^{3+} substitution.

Up to now, only **ET** polysomes having the **E** module with *A*2 = REE have been found, probably because the high activity of lanthanides required to form törnebohmite: gatelite-(Ce), perbøeite-(Ce), and ferriperbøeite-(Ce) have **E** modules all belonging to the allanite group; västmanlandite-(Ce) has **E** = dollaseite-(Ce), and the **E** module of alnaperbøeite-(Ce) has no known natural analogue in the epidote supergroup (*cf.* Table 1). Dollaseite-(Ce), $CaCeMg_2Al(Si_2O_7)(SiO_4)(OH)F$, is distinct from the allanite-group members by the F-content at O4 and by having divalent ions, Mg^{2+}, in both *M*1 and *M*3 (Peacor & Dunn, 1988), and forms its own group in the epidote supergroup together with khristovite-(Ce), $CaCeMgAlMn^{2+}(Si_2O_7)(SiO_4)(OH)F$ (Armbruster *et al.*, 2006).

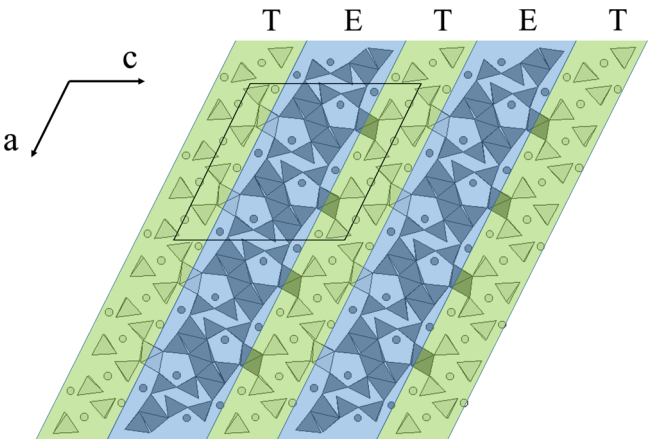

Fig. 1. Crystal structure of gatelite-group minerals seen as a regular alternation of (001) epidote-type slabs (**E**) and (-102) törnebohmite-type slabs (**T**). Unit cell corresponds to that of gatelite-(Ce) ($P2_1/a$).

By analogy with the epidote supergroup (Mills *et al.*, 2009; *cf.* Armbruster *et al.*, 2006), three groups are defined to accommodate the existing accepted mineral species with the *gatelite supergroup* established at the higher hierarchical level. Additional groups need to be introduced if new species cannot be covered by these.

(i) The *gatelite group* includes members that can be derived from the mineral gatelite-(Ce) solely by homovalent substitutions. The key cation and anion sites for this group are: *A*1 = A^{2+}; *A*2, *A*3, *A*4 = A^{3+}; *M*1 = M^{3+}; *M*2 = M^{3+}; *M*3 = M^{2+}; O4 = O^{2-}; O10 and O11 = $(OH)^-$. In other words, the dominant valence as listed above must be maintained. The three species gatelite-(Ce), perbøeite-(Ce), and ferriperbøeite-(Ce) thus constitute the presently known members of the gatelite group.

(ii) The *västmanlandite group* includes members typified by the mineral västmanlandite-(Ce). This group is derived from gatelite-(Ce) by homovalent substitutions and one coupled heterovalent substitution of the type $^{M1}[M^{3+}] + {}^{O4}[O^{2-}] \rightarrow {}^{M1}[M^{2+}] + {}^{O4}[F^-]$. Thus, the valences on the key sites are: *A*1 = A^{2+}; *A*2, *A*3, *A*4 = A^{3+}; *M*1 = M^{2+}; *M*2 = M^{3+}; *M*3 = M^{2+}; O4 = F^-; O10 and O11 = $(OH)^-$. Up to now, västmanlandite-(Ce) is the unique member of this potential group.

Table 1. Data for accepted mineral species of the gatelite supergroup, along with selected examples of recommended names for hypothetical new members (in *italics*) and the corresponding **E** module. Key sites in bold type.

Name	Ref.	End-member formula	S.G.	**E** module	Ref. (**E** module)
		[***A*1** (3REE)] [***M*1** 2*M*2 ***M*3**] $Si_2O_7(SiO_4)_3$ ***X*** $(OH)_2$			
Gatelite group					
gatelite-(Ce)	(1)	$[\mathbf{Ca}Ce_3][\mathbf{Al}\ Al_2\mathbf{Mg}]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$	$P2_1/a$	dissakisite-(La), -(Ce)	(2,3)
ferrigatelite-(Ce)		$[\mathbf{Ca}Ce_3][\mathbf{Fe^{3+}}Al_2\mathbf{Mg}]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$		*ferridissakisite-(Ce)**,$	(4)
perbøeite-(Ce)	(5)	$[\mathbf{Ca}Ce_3][\mathbf{Al}\ Al_2\mathbf{Fe^{2+}}]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$	$P2_1/m$	allanite-(La), -(Ce), -(Nd), -(Y)	(6,7,8,9)
ferriperbøeite-(Ce)	(10)	$[\mathbf{Ca}Ce_3][\mathbf{Fe^{3+}}Al_2\mathbf{Fe^{2+}}]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$	$P2_1/m$	ferriallanite-(La), -(Ce)	(11, 12)
vanadoperbøeite-(Ce)		$[\mathbf{Ca}Ce_3][\mathbf{V^{3+}}Al_2\mathbf{Fe^{2+}}]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$		vanadoallanite-(La)	(13)
new root name (A)		$[\mathbf{Ca}Ce_3][\mathbf{Al}Al_2\mathbf{Mn^{2+}}]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$		*akasakaite**	
ferriA		$[\mathbf{Ca}La_3][\mathbf{Fe^{3+}}Al_2\mathbf{Mn^{2+}}]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$		ferriakasakaite-(La)	(14,15)
manganiA		$[\mathbf{Ca}La_3][\mathbf{Mn^{3+}}Al_2\mathbf{Mn^{2+}}]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$		manganiakasakaite-(La)	(16)
new root name (B)		$[\mathbf{Mn}Ce_3][\mathbf{Al}Al_2\mathbf{Mn^{2+}}]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$		androsite-(Ce)#	(17)
ferriB		$[\mathbf{Mn}Ce_3][\mathbf{Fe^{3+}}Al_2\mathbf{Mn^{2+}}]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$		ferriandrosite-(La), -(Ce)#	(14,17)
manganiB		$[\mathbf{Mn}Ce_3][\mathbf{Mn^{3+}}Al_2\mathbf{Mn^{2+}}]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$		manganiandrosite-(La), -(Ce)	(18,19)
vanadoB		$[\mathbf{Mn}Ce_3][\mathbf{V^{3+}}Al_2\mathbf{Mn^{2+}}]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$		vanadoandrosite-(Ce)	(19)
new root name (C)		$[\mathbf{Mn}Ce_3][\mathbf{Al}Al_2\mathbf{Fe^{2+}}]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$		uedaite-(Ce)	(20)
Västmanlandite potential group					
västmanlandite-(Ce)	(21)	$[\mathbf{Ca}Ce_3][\mathbf{Mg}Al_2\mathbf{Mg}]Si_2O_7(SiO_4)_3\mathbf{F}(OH)_2$	$P2_1/m$	dollaseite-(Ce)	(22)
new root name (D)		$[\mathbf{Ca}Ce_3][\mathbf{Mg}Al_2\mathbf{Mn}](Si_2O_7)(SiO_4)\mathbf{F}(OH)_2$		khristovite-(Ce)	(23)
new root name (E)		$[\mathbf{Ca}Ce_3][\mathbf{Mg}Al_2\mathbf{Fe^{2+}}]Si_2O_7(SiO_4)_3\mathbf{F}(OH)_2$		not yet found	
ferroE		$[\mathbf{Ca}Ce_3][\mathbf{Fe^{2+}}Al_2\mathbf{Fe^{2+}}]Si_2O_7(SiO_4)_3\mathbf{F}(OH)_2$		not yet found	
Alnaperbøeite potential group					
alnaperbøeite-(Ce)	(5)	$[Ca(Ce_{2.5}Na_{0.5})][AlAl_2Al]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$	$P2_1/m$	not yet found	
new root name (F)		$[Ca(Ce_{2.5}Na_{0.5}][AlAl_2Fe^{3+}]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$		not yet found	
ferriF		$[CaCe_{2.5}Na_{0.5}][Fe^{3+}Al_2Fe^{3+}]Si_2O_7(SiO_4)_3\mathbf{O}(OH)_2$		not yet found	

*Recommended based on approved nomenclature criteria (Armbruster *et al.*, 2006);
Probably valid, but still not IMA-approved;
$ Corresponding to UM-2007-36.

References: (1) = Bonazzi *et al.* (2003); (2) = Lavina *et al.* (2006); (3) = Grew *et al.* (1991); (4) = Holtstam & Andersson (2007); (5) = Bonazzi *et al.* (2014); (6) = Orlandi & Pasero (2006); (7) = Dollase (1971); (8) = Škoda *et al.* (2012); (9) = Armbruster *et al.* (2006); (10) = Bindi *et al.* (2018); (11) = Kolitsch *et al.* (2012); (12) = Kartashov *et al.* (2002); (13) = Nagashima *et al.* (2013); (14) = Nagashima *et al.* (2015); (15) = Chukanov *et al.* (2018); (16) = Biagioni *et al.* (2017); (17) = Girtler *et al.* (2013); (18) = Bonazzi *et al.* (1996); (19) = Cenki-Tok *et al.* (2006); (20) = Miyawaki *et al.* (2008); (21) = Holtstam *et al.* (2005); (22) = Peacor & Dunn (1988); (23) = Pautov *et al.* (1993).

(iii) The *alnaperbøeite group* includes members typified by the mineral alnaperbøeite-(Ce). This group is derived from gatelite-(Ce) by homovalent substitutions and one coupled heterovalent substitution of the type $^{A2+A3+A4}[A^{3+}{}_3] + {}^{M3}[M^{2+}] \rightarrow {}^{A2+A3+A4}[A^{3+}{}_{2.5}A^{+}{}_{0.5}] + {}^{M3}[M^{3+}]$. Alnaperbøeite-(Ce) is the unique known member of this potential group.

4. Derivation of mineral names for potential new members

In line with the epidote minerals (Armbruster *et al.*, 2006), we recommend that the nomenclature of the gatelite supergroup be based on the criterion of occupancy of *key* cation sites. In particular, *A*1 and *M*3 (and, in principle, *M*2) determine the root name. If the dominant cations at *A*1, *M*3 (and *M*2) exactly match those of an approved species, *the same fixed root name is given*. If the dominant cation is different at any of these sites, a new root name is to be assigned.

In the *gatelite* and *alnaperbøeite* groups, no prefix should be added to the root name if *M*1 = Al; in the *västmanlandite* group, no prefix is added to the root name if *M*1 = Mg. Otherwise a proper prefix derived from the name of a chemical element is attached. In particular, when *M*1 = M^{3+} (*gatelite* and *alnaperbøeite* groups), the prefixes ''ferri'', ''mangani'', ''chromo'', and ''vanado'' indicate dominant Fe^{3+}, Mn^{3+}, Cr^{3+}, and V^{3+} at *M*1, respectively. When *M*1 = M^{2+} (*västmanlandite* group), the prefix ''ferro'' indicates dominant Fe^{2+} at *M*1. Finally, the dominant REE (at *A*2 + *A*3 + *A*4) is indicated with a *Levinson suffix* (Levinson, 1966; Bayliss & Levinson, 1988).

Some suggested names for hypothetical new members are listed in Table 1 along with the known IMA-approved species. Figure 2 shows the relations between the groups in the gatelite supergroup. Figure 3 shows the chemical relations between known and some potential new species in the gatelite supergroup.

5. Review of known occurrences and their geological environments

Gatelite-supergroup minerals have been found in a variety of geological settings: granitic niobium-yttrium-fluorine family (NYF) pegmatite (Tysfjord), carbonatite and associated fenites (Biraya, Ren, Anadol), alkali-syenite (Mochalin Log placer deposit), hydrothermal-metasomatic skarns (Trimouns, Bastnäs, Norberg), with an age span of nearly two billion years (see Table 2 for references). Obviously, they exist in REE-rich assemblages, and most frequently coexist with törnebohmite-(Ce), allanite- or dollaseite-group minerals, bastnäsite-(Ce), cerite-(Ce), or fluorbritholite-(Ce). Among the more abundant associated non-REE minerals are dolomite, fluorite or quartz.

The members of the supergroup are very rare minerals, although the number of observations is increasing (Table 2). On the one hand, it is important to bear in mind that some species are easily overlooked without careful mineralogical and petrological studies; for example, ferriallanite-(Ce) and ferriperbøeite-(Ce) have similar appearance (habit, colour and lustre). Furthermore, minute intergrowths of **E** with **ET** or **ET** with **T** members have been observed (Fig. 4) so that even microchemical point analyses sometimes are inadequate for identification. On the other hand, gatelite-supergroup minerals are not ubiquitous in all REE mineral assemblages of a similar kind, as some recent detailed studies suggest (*e.g.*, Allaz *et al.*, 2015).

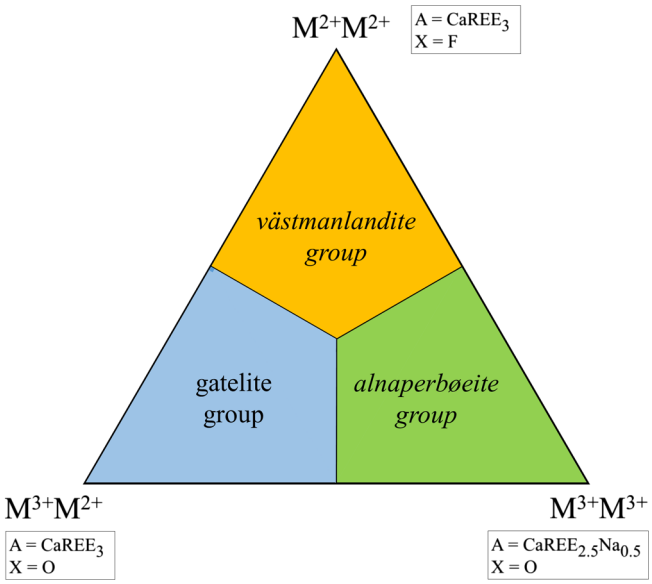

Fig. 2. Diagram distinguishing groups in the gatelite supergroup, based on *M*1 + *M*3 contents. Västmanlandite and alnaperbøeite are potential groups because both include only a single member, and thus are written in italics.

To the best of our knowledge, no experimental work has been undertaken to study the *P–T–x* stability of these minerals. Nevertheless, some analogies with the REE-rich epidote-supergroup minerals might be inferred. Allanite-(Ce) is stable up to *ca.* 800 °C at 1 kbar and to ≥1050 °C at 40 kbar (Affholter, 1987; Hermann, 2002). However, the greater amount of $(OH)^-$ groups in the gatelite-type structure possibly decreases the *T* stability in comparison with the allanite-group minerals, although there are indications that törnebohmite-(Ce) may persist to at least 800 °C (Affholter, 1987; Martin *et al.*, 2011). Studies of relevant REE-rich members of the epidote supergroup indicate that their *P–T* stability is highly dependent on bulk-rock and fluid chemistry (*e.g.*, Janots *et al.*, 2007; Budzyń *et al.*, 2017), in particular Ca and P contents. Members of the gatelite supergroup obviously need high bulk concentrations of LREE and Al for their formation, but appear to be relatively insensitive to SiO_2 activity and fO_2. From the data provided for the different natural occurrences, it appears that they have been formed as primary mineral at least in a range from 350 °C (Trimouns; Schärer *et al.*, 1999) to 750 °C (Ren; Ya'acoby, 2011). In some rocks, members of the supergroup have apparently survived regional metamorphism of up to *ca.* 600 °C/3 kbar (Bastnäs; Skelton *et al.*, 2018) and 700 °C/5–8 kbar (Ren; Ya'acoby, 2011).

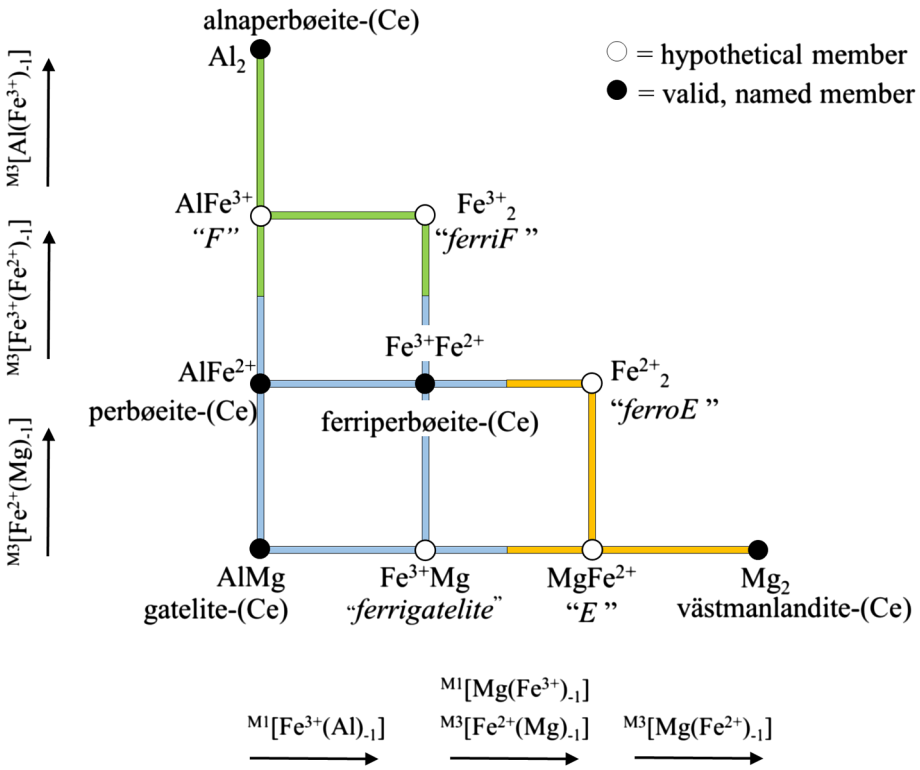

Fig. 3. Schematic representation of chemical relations in the gatelite supergroup based on *M*1 + *M*3 contents (see subtitutional vectors). Stick colours are the same as for the compositional areas of Fig. 2.

In some cases, the minerals seem to have formed at the earliest stage of REE-mineralization, more or less directly in a magmatic or hydrothermal system. In the Bastnäs-type deposits in Sweden, ferriperbøeite-(Ce) and västmanlandite-(Ce) formed at the expense of primary cerite-(Ce) or fluorbritholite-(Ce), respectively, in metasomatic reactions involving Ca–Mg minerals (dolomite, tremolite) and hydrothermal fluids (T > 400 °C) containing Si-, Fe- and Al–chloro-fluoro anion complexes (Holtstam & Andersson, 2007; Holtstam *et al*., 2014). In the Anadol deposit, perbøeite-(Ce) and associated törnebohmite-(Ce) are interpreted to have been formed by decomposition of allanite-(Ce), by reaction with high fO_2, low-T aqueous fluids, also producing REE-bearing epidote, quartz and iron hydroxide (Khomenko *et al*., 2013).

6. Mineral-chemical spectrum

The supergroup, as it is presently known, can be described by the multicomponent system Ce_2O_3–CaO–MgO–FeO–Fe_2O_3–Al_2O_3–SiO_2–H_2O (CeCMF^{2}ASH), with addition of F_2 or Na_2O to cover the exotic members västmanlandite-(Ce) or alnaperbøeite-(Ce) (Fig. 3). Analytical data available from literature sources are collected in a supplementary table (Table S1). As no vacancies at the cation positions have been demonstrated for the structure type, formulae are normalized to 13 cations. All analysed samples deviate more or less from the ideal composition, with mainly $^{M3}[MgFe^{2+}_{-1}]$, $^{M3}[AlFe^{2+}_{-1}]$, $^{M1}[MgFe^{3+}_{-1}]$, $^{M1,M2}[AlFe^{3+}_{-1}]$, $^{M1,M3}[MgAl_{-1}]$, $^{A}[Ca(REE)_{-1}]$, $^{A}[(REE)Na_{-1}]$ and $^{O4}[OF_{-1}]$ as substitution vectors. The specimens closest to end-member composition contain 84% västmanlandite (from Norberg), 80% perbøeite (type specimen), 70% ferriperbøeite (Bastnäs), 56% alnaperbøeite (type specimen), and 51% gatelite (type specimen) component, respectively. The effect of the OF_{-1} substitution is clear, largely related to the västmanlandite component, but the $(OH)F_{-1}$ substitution operating at the OH sites in this structure type cannot be excluded *a priori*. Variation at the tetrahedral sites is insignificant; the average Si content for the whole sample population is 4.97 ± 0.07 atoms per formula unit (apfu). Aluminium in *M*2, assuming perfect ordering at the smaller *M*2 octahedra, ranges from 1.67 to 2.00 apfu; structure refinements and Mössbauer spectroscopy data support the presence of minor Fe^{3+} at this site for västmanlandite-(Ce) and ferriperbøeite-(Ce) (Holtstam *et al*. 2005; Bindi *et al*., 2018).

The major chemical substitutions occur at the octahedral *M*1 and *M*3 sites. The greatest variation concerns Mg^{2+}, which ranges from 0 to 1.75 apfu. The Mg content is inversely correlated with Fe^{2+}, indicating an extensive ferriperbøeite-(Ce)–västmanlandite-(Ce) solid solution (Fig. 5). The Rödbergsgruvan sample (Table S1) is a case with near-midpoint composition, with ~57% ferriperbøeite and 43% västmanlandite. A single analysis from the Norberg mines is also special as it shows Fe^{2+} > Mg and still contains an appreciable amount of F (0.31 apfu), corresponding to a substantial fraction of unnamed $[CaCe_3][MgAl_2Fe^{2+}]Si_2O_7(SiO_4)_3F(OH)_2$ (root name "*E*"). Variation in Fe^{3+} at the *M*1–*M*3 sites is extensive (0–1.03 Fe apfu). It is noteworthy that there are no compositional points

Table 2. Reported occurrences of gatelite supergroup minerals.

Mineral	Locality	Association	Age	Ref.
Gatelite-(Ce)	*Trimouns* talc mine, Luzenac, Ariège, France (type locality)	aeschynite-(Y), törnebohmite-(Ce), dissakisite-(Ce), dolomite, talc, quartz, pyrite	100 Ma	(a)
Västmanlandite-(Ce)	*Norberg* Fe mines, Västmanland, Sweden • Malmkärra (type locality) • Johannagruvan • Hackspikgruvan	fluorbritholite-(Ce), dollaseite-(Ce), gadolinite-(Y), gadolinite-(Nd), ulfanderssonite-(Ce), tremolite, magnetite, dolomite	1.9–1.8 Ga	(b, c, d)
Perbøeite-(Ce)	*Tysfjord* granite pegmatites, Nordland, Norway • Stetind • Hundholmen (type locality) • Nedre Eivollen	törnebohmite-(Ce), allanite-(Ce), bastnäsite-(Ce), fluorthalenite-(Y), kuliokite-(Y), hundholmenite-(Y), fluorbritholite-(Y), fluorite	400 Ma	(e, f)
Alnaperbøeite-(Ce)	*Tysfjord* granite pegmatites, Nordland, Norway • Stetind (type locality) • Hundholmen • Nedre Eivollen	törnebohmite-(Ce), allanite-(Ce), bastnäsite-(Ce), fluorthalenite-(Y), kuliokite-(Y), hundholmenite-(Y), fluorbritholite-(Y), fluorite	400 Ma	(e, f)
Ferriperbøeite-(Ce)	*Bastnäs* Fe–Cu–REE mines, Riddarhyttan, Västmanland, Sweden (type locality)	cerite-(Ce), törnebohmite-(Ce), ferriallanite-(Ce), bastnäsite-(Ce), tremolite + sulfide minerals	1.9–1.8 Ga	(g, c, d)
Ferriperbøeite-(Ce)	*Rödbergsgruvan* Fe mine, Nora, Örebro, Sweden	cerite-(Ce), ferriallanite-(Ce), bastnäsite-(Ce), tremolite, zircon	1.9–1.8 Ga	(c)
Ferriperbøeite-(Ce)	*Biraya* REE-Fe ore occurrence, Vitim highland, Irkutskaya Oblast', Russia	törnebohmite-(Ce), ferriallanite-(Ce), biraite-(Ce), strontianite, calcite	500–400 Ma	(h, i)
Ferriperbøeite-(Ce)	*Ren* Carbonatite Sill, Monashee Mountains, British Columbia, Canada	biraite-(Ce) + Mg-analogue to biraite-(Ce), ferriallanite-(Ce), monazite-(Ce), winchite, dolomite, calcite, barite	700 Ma	(l)
Perbøeite-(Ce) (originally reported as gatelite-(Ce))	*Anadol* REE occurrence, Donetskaya Oblast', East Azov region, Ukraine	allanite-(Ce), törnebohmite-(Ce), britholite-(Ce), cerite-(Ce), quartz, epidote, fluorite, goethite	1.9–1.7 Ga?	(m)
Ferriperbøeite-(Ce)	*Högfors* Fe mines, Riddarhyttan, Västmanland, Sweden	cerite-(Ce), bastnäsite-(Ce), gadolinite-(Ce), ferriallanite-(Ce), monazite-(Ce), quartz, hematite	1.9–1.8 Ga	(n)
Ferriperbøeite-(Ce)/ ''ferriperbøeite-(La)''	*Mochalin Log*, Potanin Mountains, southern Urals, Chelyabinsk Oblast', Russia	bastnäsite-(La), törnebohmite-(Ce), allanite-(Ce), dissakisite-(La), monazite-(La), quartz, thorite	400 Ma	(o, p)

References: (a) = Bonazzi *et al.* (2003); (b) = Holtstam *et al.* (2005); (c) = Holtstam & Andersson (2007); (d) = Holtstam *et al.* (2014); (e) = Bonazzi *et al.* (2014); (f) = Aaroe (2017); (g) = Bindi *et al.* (2018); (h) = Gurzhiy *et al.* (2010); (i) = P.M. Kartashov, pers. comm.; (l) = Ya'acoby (2011); (m) = Khomenko *et al.* (2013); (n) = Jonsson & Högdahl (2013); (o) = webmineral.ru; (p) = R. Škoda, pers. comm.

where 2 < Al apfu < 3 (Fig. 5), which means that intermediate members of the ferriperbøeite-(Ce)–perbøeite-(Ce) solid solution have not yet been found, although the corresponding epidote-supergroup minerals (*i.e.*, members of the ferriallanite–allanite solid solution) are widely reported (Gieré & Sorensen, 2004; Vlach, 2012). There is also a limited Al–Mg substitution, similar to what occurs in the intermediate dollaseite–dissakisite compositions found in the Norberg deposits (Holtstam & Andersson, 2007). Replacement of Fe^{2+} for Al is limited to the perbøeite-(Ce)–alnaperbøeite-(Ce) join, where there is also a significant coupled Ce–Na substitution (Bonazzi *et al.*, 2014). As shown in Fig. 5, along this join Al approaches the theoretical value of 4 apfu. However, the corresponding Na content does not reach 0.5 apfu, since the substitution of trivalent REEs by divalent Ca also contributes to charge balance.

All samples representing the ferriperbøeite-(Ce)–västmanlandite-(Ce) join show a deficit of Ca (0.80–0.97 apfu), whereas the Al-rich members seem to have Ca $\geq$ 1.00 apfu, which has been ascribed to an artefact related to difficulties with analysing all REE (Bonazzi *et al.*, 2014). From structure refinements, it is shown that when extra REE atoms occur, they are accommodated at the *A*1 site in the **E** module (Holtstam *et al.*, 2005; Bindi *et al.*, 2018). Cerium is here consistently the dominant REE (atomic Ce/La = 2.71–1.05); the material from Ren is the richest in La_2O_3 (>20 wt%). The true La-analogue of ferriperbøeite-(Ce) has, however, recently been discovered at Mochalin Log (R. Škoda, pers.

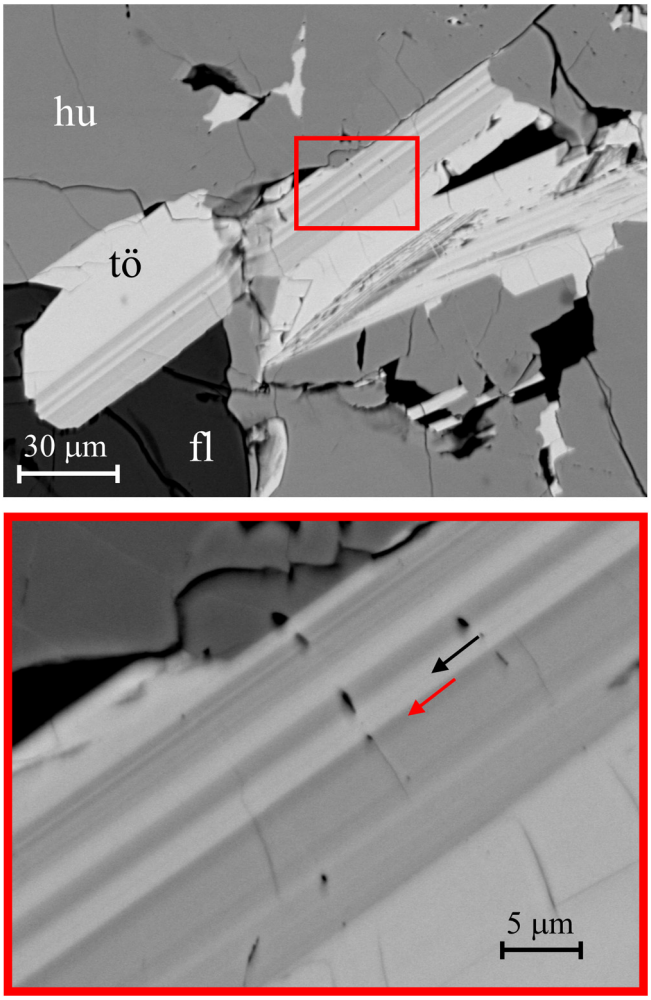

Fig. 4. SEM-BSE images showing minute lamellae of törnebohmite-(Ce) (light grey, black arrow) intergrown with lamellae of a member of the perbøeite-(Ce)–alnaperbøeite-(Ce) solid solution (dark grey, red arrow) in the samples from Stetind (Tysfjord, Norway). Intermediate grey lamellae likely correspond to intergrowths of thinner lamellae. The image at the top shows the mineral association (hu = hundholmenite-(Y); tö = törnebohmite-(Ce); fl = Y-rich fluorite).

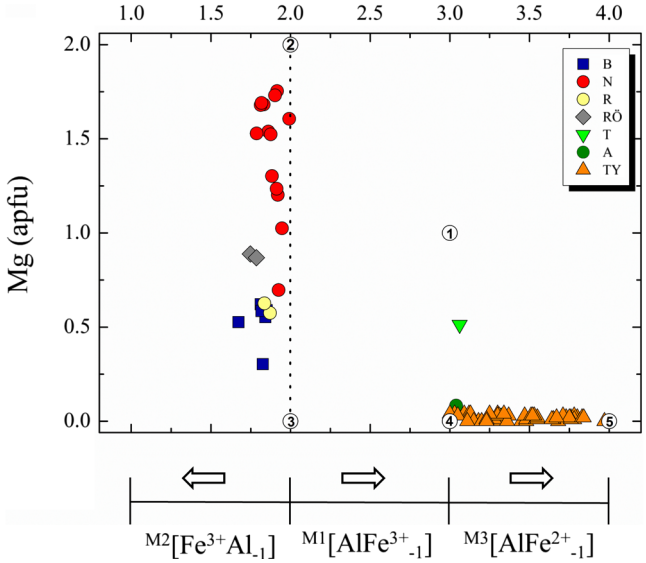

Fig. 5. Variation of Al^{3+} *vs.* Mg^{2+} (in atoms per formula unit) in gatelite-supergroup minerals. Empty circles with numbers represent ideal compositions: 1 = gatelite-(Ce); 2 = västmanlandite-(Ce); 3 = ferriperbøeite-(Ce); 4 = perbøeite-(Ce); 5 = alnaperbøeite-(Ce). Orange triangles (TY) refer to members of perbøeite-(Ce)–alnaperbøeite-(Ce) join from Tysfiord granite, Norway (Stetind + Hundholmen + Nedre Eivollen) (Table 7, Bonazzi *et al.*, 2014); the other symbols refer to chemical data reported in Table S1 as follows: B = Bastnäs, Västmanland, Sweden; N = Norberg (Malmkärra + Johanna + Hackspik) mines, Västmanland, Sweden; R = Ren, British Columbia, Canada; RÖ = Rödbergsgruvan mine, Nora, Örebro, Sweden; T = Trimouns mine, Luzenac, France; A = Anadol, East Azov region, Ukraine.

comm. 2017). Overall, there is also a significant variation in Nd_2O_3 and Sm_2O_3 contents (2.5–11.7 and 0.1–2.0 wt%, respectively). At Trimouns and Tysfjord we find Ce > Nd > La. The Tysfjord samples also have, along with a västmanlandite-(Ce) sample from Norberg (Malmkärra), the highest Y_2O_3 concentrations (0.6–1.3 wt%). The HREE (Tb–Lu) contents are, when actually measured, generally very low, with a maximum of 0.3 wt% of Er_2O_3 (Tysfjord).

It is noteworthy that no gatelite-supergroup minerals have been found to show substantial MnO contents (up to *ca.* 1 wt% for samples from Anadol, *ca.* 0.3 wt% from Trimouns, and *ca.* 0.2 wt% from Tysfjord), although Mn in both trivalent and divalent states is a major constituent for many members of the allanite group (see Table 1).

Impurities in these minerals are generally low, with 0.3 wt% P_2O_5 (Ren), 0.2 wt% TiO_2 (Ren). Actinides are mostly close to or below the electron microprobe detection limits, with the Tysfjord pegmatite samples as an exception (contains 0.1–0.4 wt% ThO_2). The presence of minor amounts of large cations such as Ba^{2+} and Pb^{2+}, are also indicated in the EDS analyses from Anadol. The cations Th^{4+}, Pb^{2+} and Ba^{2+} are preferably assigned to the *A*2–4 sites, as they occur in the epidote supergroup (Armbruster *et al.*, 2006).

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