

## Recommended nomenclature of epidote-group minerals

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**Abstract:** Epidote-group minerals are monoclinic in symmetry and have topology consistent with space group  $P2_1/m$  and the general formula  $A_2M_3[T_2O_7][TO_4](O,F)(OH,O)$ . Zoisite is an orthorhombic polymorph of clinozoisite  $Ca_2Al_3[Si_2O_7][SiO_4]O(OH)$  and is thus not considered a member of the epidote-group. Epidote-group minerals are divided into three subgroups. (1) Members of the **clinozoisite subgroup** are derived from the mineral clinozoisite  $Ca_2Al_3[Si_2O_7][SiO_4]O(OH)$  by homovalent substitutions only. The key cation- and anion-sites are  $A1 = M^{2+}$ ,  $A2 = M^{2+}$ ,  $M1 = M^{3+}$ ,  $M2 = M^{3+}$ ,  $M3 = M^{3+}$ ,  $O4 = O^{2-}$ ,  $O10 = (OH)$ . In other words, the dominant valence as listed above must be maintained. (2) Members of the **allanite subgroup** are REE-rich minerals typified by the eponymous mineral "allanite". This subgroup may be derived from clinozoisite by homovalent substitutions and **one** coupled heterovalent substitution of the type  $A_2(REE)^{3+} + M^3M^{2+} \rightarrow A_2Ca^{2+} + M^3M^{3+}$ . Thus the valences on the key sites are:  $A1 = M^{2+}$ ,  $A2 = M^{3+}$ ,  $M1 = M^{3+}$ ,  $M2 = M^{3+}$ ,  $M3 = M^{2+}$ ,  $O4 = O^{2-}$ ,  $O10 = (OH)$ . (3) Members of the **dollaseite subgroup** are REE-rich minerals typified by the eponymous mineral "dollaseite". This subgroup may be derived from clinozoisite by homovalent substitutions and **two** coupled heterovalent substitutions of the type  $A_2(REE)^{3+} + M^3M^{2+} \rightarrow A_2Ca^{2+} + M^3M^{3+}$  and  $M^1M^{2+} + O^4F^- \rightarrow M^1M^{3+} + O^4O^{2-}$ . Thus the valences on the key sites are:  $A1 = M^{2+}$ ,  $A2 = M^{3+}$ ,  $M1 = M^{2+}$ ,  $M2 = M^{3+}$ ,  $M3 = M^{2+}$ ,  $O4 = F^-$ ,  $O10 = (OH)$ .

The key cation-sites M3 and A1 (and, in principle, M2) determine the root name. In both clinozoisite and allanite subgroups no prefix is added to the root name if  $M1 = Al$ . The prefixes ferri, mangani, chromo, and vanado indicate dominant  $Fe^{3+}$ ,  $Mn^{3+}$ ,  $Cr^{3+}$ , and  $V^{3+}$  on M1, respectively. In the dollaseite subgroup no prefix is added to the root name if  $M1 = Mg$ . Otherwise a proper prefix must be attached; the prefixes ferro and mangano indicate dominant  $Fe^{2+}$  and  $Mn^{2+}$  at M1, respectively. The dominant cation on A2 (other than Ca) is treated according to the *Extended Levinson* suffix designation. This simple nomenclature requires renaming of the following approved species: Niigataite (old) = **clinozoisite-(Sr) (new)**, hancockite (old) = **epidote-(Pb) (new)**, tweddillite (old) = **manganipiemontite-(Sr) (new)**. Minor modifications are necessary for the following species: Strontio Piemontite (old) = **piemontite-(Sr) (new)**, androsite-(La) (old) = **manganiandrosite-(La) (new)**. Before a mineral name can be assigned, the proper subgroup has to be determined. The determination of a proper subgroup is made by the dominating valence at M3, M1, and A2 expressed as  $M^{2+}$  and or  $M^{3+}$ , not by a single, dominant ion (*i.e.*,  $Fe^{2+}$ , or Mg, or Al). In addition, the dominant valence on O4:  $X^-$  or  $X^{2-}$  must be ascertained.  $[M^{2+}]_{A2} > 0.50$ ,  $[M^{3+}]_{M3} > 0.50 \rightarrow$  clinozoisite subgroup,  $[M^{3+} + M^{4+}]_{A2} > 0.50$ ,  $[M^{2+}]_{M3} > 0.50 \rightarrow$  allanite subgroup,  $\{[M^{2+}]_{M3+M1} - [M^{3+} + M^{4+}]_{A2}\} > 0.50$  and  $[X^-]_{O4} > 0.5 \rightarrow$  dollaseite subgroup. Coupled heterovalent substitutions in epidote-group minerals require a special application of the so-called 50 % rule in solid-solution series. (1) Clinozoisite subgroup: The dominant **trivalent** cation on M3 determines the name, whereas the A2 cation appearing in the suffix has to be selected from among the **divalent** cations. (2) Allanite and dollaseite subgroups: For the sites involved in the charge compensation of a heterovalent substitution in A2 and O4 (*i.e.* M3 in the allanite subgroup; M3 and M1 in the dollaseite subgroup), identification of the relevant end-member formula must take into account the **dominant divalent charge-compensating octahedral cation ( $M^{2+}$ )** and not the dominant cation in these sites.

Formal guidelines and examples are provided in order to determine a mineral "working name" from electron-microprobe analytical data.

**Key-words:** Nomenclature, epidote-group minerals, clinozoisite, allanite, dollaseite.

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## 1. Introduction

### 1.1. Some obvious problems

Deer *et al.* (1986) concluded in their Rock-forming Minerals: “There is no universally accepted nomenclature of the monoclinic Fe–Al members of the epidote group. Some earlier names, e.g. fouquéite for compositions containing up to about 10 mol. % of the  $\text{Ca}_2\text{Fe}_3\text{Si}_3\text{O}_{12}(\text{OH})^1$  component, have fallen into disuse and clinozoisite is now used to describe those members of the series that are optically positive, corresponding with approximately 15 mol.%  $\text{Ca}_2\text{Fe}_3\text{Si}_3\text{O}_{12}(\text{OH})$ . For the more iron-rich, optically negative members, the name pistacite is used by some authors; the majority, however, describe those members with between 15 and 33 mol.%  $\text{Ca}_2\text{Fe}_3\text{Si}_3\text{O}_{12}(\text{OH})$  as epidote. This common use of the name is preferred in spite of its use to designate the group as a whole. The optical distinction of members of the clinozoisite-epidote series around the 15 mol.% composition is difficult, and in the absence of a chemical analysis is generally based on color and pleochroism. Where the composition is known it is usually expressed in terms of the theoretical pistacite end-member,  $p_s = 100 \times \text{Fe}^{3+}/(\text{Fe}^{3+} + \text{Al})$ .”

The nomenclature problems discussed by Deer *et al.* (1986) were only partly solved after publication of the criteria for new mineral names (Nickel & Mandarino, 1987). Are these “rules” only applicable to new minerals (the corresponding paragraph was entitled “criteria for new mineral names”)? What about the “grandfathered” mineral names epidote and clinozoisite described in the past and generally believed to represent valid species names? How are the boundaries between epidote and clinozoisite defined?

Of the 22 “piemontite” analytical data reported by Deer *et al.* (1986) only seven meet the minimum criterion of  $\text{Fe} < \text{Mn} > 0.5$  required to satisfy the rule given by Nickel & Mandarino (1987): “At least one major structural site is occupied by a different chemical component.”

Ercit (2002), in his article “The mess that is allanite”, asks the provocative question: What is “allanite”? He states that the name “allanite” is often incorrectly used to describe any REE-bearing epidote. Investigators were additionally confused by introduction of new mineral names for REE-bearing epidote-group minerals such as dissakisite-(Ce), dollaseite-(Ce), khristovite-(Ce), and androsite-(La). Until 1988, the mineralogy of REE-rich epidote-group minerals was very simple because there was only the one official root name allanite with the end-member formula  $\text{CaREEAl}_2\text{Fe}_2^{2+}[\text{Si}_2\text{O}_7][\text{SiO}_4]\text{O}(\text{OH})$ . An additional source of confusion (Ercit, 2002) is that cations in the formula of REE-rich epidote-group minerals are commonly grouped rather than assigned to specific sites. However, specific site assignments determine the species. In the absence of appropriate guidelines, Ercit (2002) discusses several approaches for using electron-microprobe analytical data to calculate formulae of REE-bearing epidote-group minerals. Then he

uses analytical data from the literature to obtain a simplified end-member formula corresponding to a mineral name. There are two major criticisms to his approach: (1) Analytical data from the literature that had been obtained on metamict materials were used, which do not fulfill the criterion that a mineral be crystalline; (2) Standard guidelines for mineral nomenclature (Nickel & Grice, 1998) were uncritically applied, resulting in end-member formulae [e.g.,  $\text{CaLaAl}_2\text{V}^{3+}[\text{Si}_2\text{O}_7][\text{SiO}_4]\text{O}(\text{OH})$ ] that are not charge-balanced and thus meaningless.

### 1.2. Objectives

The Commission on New Minerals and Mineral Names (CNMMN) of the International Mineralogical Association (IMA) established at the beginning of 2003 the Subcommittee on Epidote-Group Mineral Nomenclature. This subcommittee defined following aims: (1) Development of a consistent nomenclature system to minimize proliferation of unrelated mineral names; (2) to explain appropriate use of existing and new names within this mineral group by defining simple rules for nomenclature based on chemistry and ion (cation and anion) order; (3) to provide a simple but powerful scheme to derive a “working name” of an epidote-group mineral based on electron-microprobe analytical data.

Finally, this report supplies an Appendix with specifically selected chemical data of epidote-group minerals representing either borderline cases, or incomplete or erroneous analytical data, or data originating from partly metamict minerals. These examples have been chosen to demonstrate naming of epidote-group minerals in non-trivial cases.

It is not the intent of this nomenclature recommendation to provide a complete view of chemical variations reported for epidote-group minerals. For additional references on this subject we refer to Liebscher & Franz (2004).

## 2. Historical synopsis

### 2.1. Epidote and clinozoisite

**Epidote**, a monoclinic mineral with the idealized formula  $\text{Ca}_2\text{Al}_2\text{Fe}^{3+}[\text{Si}_2\text{O}_7][\text{SiO}_4]\text{O}(\text{OH})$ , was named by Haüy (1801). The type locality is Bourg d’Oisans, Dauphiné, France. The name comes from the Greek *epi* over plus *dotós* given (verbid of *didóni*), i.e., given besides, “increased”. A related noun is *epidosis*, i.e. “increase”. This refers to Haüy’s observation that the base of the mineral’s prism has one side longer than the other. The rationale for the name epidote may appear quaint to us today, but it has to be understood in the context of criteria for distinguishing minerals at the beginning of the 19<sup>th</sup> century (mainly crystal forms, density, and optical properties, as well as chemical composition). Dana (1896) stated that Haüy set aside several older names: Thallite, derived from the Greek noun *thallos* meaning young twig (alluding to the green color), was rejected because of color variation; delphinite,

<sup>1</sup>Given as  $\text{Ca}_2\text{FeAl}_2\text{Si}_3\text{O}_{12}(\text{OH})$  in the text by Deer *et al.* (1986). However, it is clear from the molar percentage values (15–33) cited by these authors for the epidote (*sensu stricto*) compositional range that they are actually referring to a  $\text{Ca}_2\text{Fe}_3\text{Si}_3\text{O}_{12}(\text{OH})$  component.

and arendalite (also named akanticonite) were rejected because they were derived from specific localities. A synonym for epidote, pistacite, comes from the Greek for pistachio nut, a reference to the distinctive yellowish-green color of some epidote. The name pistacite was introduced by Ludwig (1803-1804), who extended the systematic nomenclature of Abraham Gottlob Werner (1750-1817). This timing gives epidote precedence. Pistacite is not listed among accepted mineral names (in spite of its frequent use) by Hey (1955) but referenced as synonym of epidote. Other obsolete names (Dana, 1896) are oisanite, puschkinite (six other spellings have also been used, e.g., pushklinite in Dufrénoy, 1856), achmatite, beustite and escherite. Withamite was used for a strongly pleochroic deep crimson and straw yellow epidote-group mineral from Glen Coe, Strathclyde (Argyllshire), Scotland, UK and sometimes referred to as piemontite. However, chemical analyses gave only 0.24 wt.% MnO – equivalent to 0.27 wt. % Mn<sub>2</sub>O<sub>3</sub> – (Dana, 1896). Thus this low Mn<sup>3+</sup> content is already sufficient for piemontite-like pleochroism. Subsequent chemical analyses of “withamite” (Hutton, 1938) clearly suggest its identity with epidote. Withamite from the Yamanaka mine (Japan) described by Yoshimura & Momoi (1964) is manganian clinozoisite.

Weiss (1820) presented the first complete indexing of crystal faces of monoclinic epidote, which may be considered the beginning of systematic crystallographic work on this mineral group. Dufrénoy (1856) used epidote as the group name and distinguished thallite (green iron-bearing epidote) and zoisite on the basis of different cleavage and habit. Ito (1950) and Ito *et al.* (1954) first deduced the correct atomic arrangement in epidote, which they showed to contain both single SiO<sub>4</sub> tetrahedra and double-tetrahedral Si<sub>2</sub>O<sub>7</sub> groups (*cf.* Ito, 1947). Systematic structural studies by Dollase (1968, 1969, 1971) clarified the crystal-chemical relationships of the epidote group.

The name **clinozoisite** was given by Weinschenk (1896) to Fe-poor epidote from Prägraten, Tyrol, Austria. The name is for the polymorphism with zoisite, Ca<sub>2</sub>Al<sub>3</sub>[Si<sub>2</sub>O<sub>7</sub>][SiO<sub>4</sub>]O(OH) (see below). However, Lacroix (1889) was probably the first to describe this mineral under the name fouquéite. We quote Dana (1896): “Composition like zoisite from which it differs in form; it appears to be an epidote essentially, containing but little iron... Occurs in anorthite-gneiss at Salem, and less often at Kandy, Ceylon. The rock also contains ordinary epidote (but not immediately associated with fouquéite)... Named for M. Fouqué.” The analysis reported by Lacroix (1889) is given in Table 1.

According to the structural studies of Ito *et al.* (1954) and Dollase (1968, 1969, 1971) monoclinic members of the epidote group have three distinct octahedral sites (M1, M2, M3), each contributing with the same multiplicity to the formula. If one of these sites in an unnamed mineral were found to be dominantly occupied by a chemical component that is not dominant at the equivalent site in an existing mineral, then the unnamed would be a new mineral species with its own name (Nickel & Mandarino, 1987). Application of this rule requires detailed crystal-chemical knowledge of the various mineral groups and particularly of the cation site-preference. In the epidote group, if by chance ferric iron did not order onto the largest and most distorted octahedral site M3, but were randomly distributed over the three available sites, the composition Ca<sub>2</sub>Al<sub>2</sub>Fe<sup>3+</sup>[Si<sub>2</sub>O<sub>7</sub>][SiO<sub>4</sub>]O(OH) could not be given an independent mineral name. Instead, it would have to be called ferrian clinozoisite because Al would be dominant at all three octahedral sites (M1, M2, M3). However, structure refinements and spectroscopic investigations of epidote-group minerals have consistently shown a strong preference of Fe<sup>3+</sup> for M3 (*e.g.*, Ito *et al.*, 1954; Dollase, 1971, 1973). Thus, the old name epidote is retained.

Table 1. Historical chemical data (wt.%) of epidote (Laspeyres, 1879), fouquéite (Lacroix, 1889), and piemontite (Rammelsberg, 1875), all data cited from Dana (1896).

Sample	Epidote (Bourg d’Oisans)	Fouquéite = Clinozoisite (Sri Lanka)	Piemontite (St. Marcel)
SiO <sub>2</sub>	36.49	38.6	38.64
Al <sub>2</sub> O <sub>3</sub>	22.45	32.5	15.03
Fe <sub>2</sub> O <sub>3</sub>	14.93	2.1	8.38
Mn <sub>2</sub> O <sub>3</sub>	0.03		15.00
CaO	23.52	23.9	22.19
LOI	1.91	2.7	1.78
Sum	99.35	99.8	101.02
Si	2.94	2.97	3.16
Al	2.13	2.94	1.45
Fe	0.91	0.12	0.52
Mn	0.00		0.93
Ca	2.02	1.97	1.94
O(calc.)	12.45	12.50	12.61

Formula normalized on 8 cations. LOI – loss on ignition.

## 2.2. Zoisite

Originally this mineral was named saualpite for the locality Saualpe in Carinthia, Austria, where it occurs in eclogites. The name zoisite was chosen by A.G. Werner in 1805 to honor Siegmund Zois, Baron von Edelstein (1747-1819), the Austrian mineral collector from whom Werner obtained the holotype specimen from Saualpe (Dana, 1896). **Zoisite** is the orthorhombic polymorph of clinozoisite. Other obsolete names or synonyms cited by Dana (1896) are: Illuderite, lime-epidote, thulite, unionite. Hey (1955) also cited chrome-zoisite and manganese-zoisite. Tanzanite is a gem name for vanadium-bearing zoisite from Tanzania, which turns from brown into blue upon heat-treatment at 400-500°C. A dense green chromium-bearing zoisite in a zoisite amphibolite associated with mostly non-transparent ruby also from Tanzania was named “anyolite” meaning green in the language of the Massai (Eppler, 1984). Ito (1950) first proposed a structural model for zoisite, which was subsequently confirmed by Fesenko *et al.* (1955) and Dollase (1968). Zoisite is the only orthorhombic mineral species originally assigned to the epidote group.

## 2.3. Piemontite, strontioziemontite, and tweddillite

A Mn-rich, epidote-related mineral from Praborna mine, St. Marcel, Aosta Valley, in the Italian Western Alps, was named **piemontite** (originally “*Piemontii*”) by Kenngott (1853). The English spelling of the Italian word Piemonte is Piedmont, and Dana (1896) arbitrarily anglicized the mineral name to piemontite. However, the Italian region of the type locality, St. Marcel, was called Piemonte when the mineral was first described, and for this reason the name piemontite is correct. Today, St. Marcel belongs to Valle d’Aosta, which was established as an autonomous region in 1945. Dufrénoy (1856) stated that the “variété manganésifère” from Piemonte is named “piemontite”. Hey (1955) considered both piemontite and manganepidote to be synonyms of piemontite.

Dollase (1969) demonstrated by single-crystal X-ray structure refinement that Mn<sup>3+</sup> in piemontite, ideally Ca<sub>2</sub>Al<sub>2</sub>Mn<sup>3+</sup>[Si<sub>2</sub>O<sub>7</sub>][SiO<sub>4</sub>]O(OH), is preferentially ordered on the octahedral M3 site, thus confirming the interpretation of spectroscopic data by Burns & Strens (1967). Nonetheless, there seems to be a general problem



with the assignment of the name piemontite (Catti *et al.*, 1989). Dana (1896) included under the name piemontite monoclinic, dark-red epidote-group minerals with characteristic red – pink to amethyst – orange to yellow pleochroism, even if the molar  $Mn_2O_3$  content was less than  $Fe_2O_3$  content. Mottana & Griffin (1986) showed that piemontite from the type locality (the Praborna manganese mine) is rather heterogeneous. Nonetheless, the compositions of most samples fall in the vicinity of Al:Mn = 2:1 with a general trend of some excess Mn extending to Al:Mn = 1.3:1. In addition, Mottana & Griffin (1986) found that piemontite from St. Marcel is frequently strontian piemontite with up to 0.47 Sr pfu. Catti *et al.* (1989) and Ferraris *et al.* (1989) reported structural data on this strontian piemontite.

**Strontioepiemontite**, ideally  $CaSrAl_2Mn^{3+}[Si_2O_7][SiO_4]O(OH)$ , is the analogue of piemontite with Sr dominant in the structural site A2, as shown by X-ray single-crystal structure refinement (Bonazzi *et al.*, 1990). It is a low-temperature metamorphic product and occurs in the manganese ore at Molinello and Cassagna mines of Val Graveglia, Northern Apennines, Italy.

**Tweddillite**,  $CaSrMn^{3+}AlMn^{3+}[Si_2O_7][SiO_4]O(OH)$ , is a mineral related to strontioepiemontite (Armbruster *et al.*, 2002). It is found as a hydrothermal alteration product of primary manganese ore in the Wessels mine of the Kalahari manganese field, Republic of South Africa. It was named tweddillite in honor of S. M. Tweddill, the first curator (from 1897 to 1916) of the Museum of the Geological Survey at Pretoria, RSA. Definition of this new mineral species was justified, as shown by structure refinement, because  $Mn^{3+}$  dominates both octahedral M1 and M3 sites, different from just M3 in strontioepiemontite and piemontite.

## 2.4. “Tawmawite” and mukhinite

The name “tawmawite” was introduced by Bleeck (1907) in his description of jadeite deposits in Upper Burma (now Myanmar). Tawmaw was a major jadeite mining-district in this area at the beginning of the 20<sup>th</sup> century. Bleeck (1907) described “tawmawite” as an emerald green, chromium-rich epidote mineral. However, the chemical analysis did not correspond to epidote-group stoichiometry, mainly due to contamination with chromite. The existence of a mineral with idealized composition  $Ca_2Al_2Cr^{3+}[Si_2O_7][SiO_4]O(OH)$  has been shown by electron-microprobe analyses of epidote-group minerals occurring as inclusions in calcic plagioclase in a kyanite amphibolite from Southern Alps, New Zealand (Grapes, 1981), and in a quartzite from Outokumpu, Finland (Treloar, 1987). Chromium-rich epidote-group minerals are commonly zoned on a very fine scale (oscillatory zoning) so that determination of specific site preference of Cr using crystal-structure refinement has not been possible to date. Burns & Strens (1967) provided spectroscopic evidence that  $Fe^{3+}$ , and  $Mn^{3+}$  in epidote-group minerals order preferentially on M3, but assumed that  $Cr^{3+}$  orders preferentially on M1. However, Liebscher (2004) concluded that the derived  $\Delta_{oct}$  with the position of  $\nu_{II}$  (Burns & Strens, 1967) results in a Racah parameter *B* that is higher than that of the free  $Cr^{3+}$  ion and therefore physically meaningless. The interpretation of the spectra by Burn & Strens (1967) is thus open to question. Armbruster & Lahti (in prep.) have recently performed a combined electron microprobe - crystal-structure study on  $V^{3+}$ -rich “tawmawite” from Outokumpu, Finland, first described by Eskola (1933). Preliminary results indicate that Cr is disordered over M3 and M1 (with a slight preference for M3), which cast doubts on the species character of “tawmawite” if the Cr content is below 1 Cr pfu. To our knowledge the highest Cr content in chromian clinozoisite was reported as 15.37 wt.%  $Cr_2O_3$  (Treloar, 1987), corresponding to 0.98 Cr pfu, which is still slightly below the limit

required for highly disordered partition of Cr between M1 and M3. On the basis of available data “tawmawite” cannot be considered a valid species. Such samples have to be described as chromian (or better  $Cr^{3+}$ -rich) clinozoisite until new evidence is presented.

**Mukhinite**,  $Ca_2Al_2V^{3+}[Si_2O_7][SiO_4]O(OH)$ , was described by Shepel & Karpenko (1969) from marbles (Gornaya Shoriya, Kemerovo Oblast, Siberia, Russia). The name is for the geologist A.S. Mukhin of the West Siberian Geological Survey. In the absence of crystallographic data ordering of  $V^{3+}$  on M3 may be assumed by analogy with  $Fe^{3+}$ . Structural data including cation site-distributions are highly desirable for mukhinite.

## 2.5. Hancockite and niigataite

**Hancockite** is another old name. Penfield & Warren (1899) named a Pb-rich monoclinic epidote-group mineral discovered at Franklin, N.J., USA after Elwood P. Hancock (1836-1916) of Burlington, N.J., a collector of Franklin minerals. At the type locality the mineral contains appreciable amounts of Sr, and of  $Mn^{3+}$ , the latter being responsible for the strong red color (Dunn, 1985). Holtstam & Langhof (1994) reported a second occurrence of this very rare species from Jakobsberg, Filipstad, Sweden (skarn enclosed in dolomitic marble). Hancockite,  $CaPbAl_2Fe^{3+}[Si_2O_7][SiO_4]O(OH)$ , may be considered an epidote (*sensu stricto*) with Ca on A2 substituted by Pb.

**Niigataite**,  $CaSrAl_3[Si_2O_7][SiO_4]O(OH)$ , is related to clinozoisite but with Ca on the A2 site substituted by Sr (shown by single-crystal X-ray structure refinement). The name is for the Japanese prefecture where the mineral was discovered. Niigataite was found in a boulder of prehnite rock, where the mineral occurs interstitially with diaspore and chlorite in close association with strontian clinozoisite (Miyajima *et al.*, 2003).

## 2.6. REE-rich epidote-group minerals

In the following text REE represents the lanthanides (elements 57 to 71) and Y because of its chemical similarity to the lanthanides.

Historically, “allanite” (Thomson, 1810) is the second monoclinic mineral of the epidote group with a name that is still in use. The name is for Thomas Allan (1777-1833), a Scottish mineralogist who discovered the mineral. The type material is allegedly from Iglorsoit, East Greenland. However, studies of Giesecke’s diaries from 1806 suggest that the type locality is most likely Qaqarssuatsiaq, Aluk, East Greenland (Petersen & Johnsen, 2005). Dana (1896) listed following synonyms or varieties of “allanite”: Cerine, bucklandite, tautolite, uralorthite, bagrationite, orthite, xanthorthite, pyroorthite, and wasite. Those names describe partly altered “allanites” or solid-solution members between “allanite” and epidote from specific localities with more or less characteristic crystal forms. In addition, the Y-rich minerals muromontite (5.52 %  $BeO$ ) and bodenite were considered varieties of “allanite” (Dana, 1896). The latter two names are nowadays no longer listed among minerals and their relation to “allanite” is also under question [for a discussion on muromontite and Be in “allanite” *cf.* Grew (2002)]. Nagatelite is supposedly a phosphatian “allanite” (Iimori *et al.*, 1931). However, X-ray diffraction data are mandatory to confirm this relationship. Hey (1955) referenced also treanorite as synonym for “allanite” and additionally the following “allanite” varieties: Cerepidote, cerorthite, yttrio-orthite, magnesium-orthite, and mangan-orthite. The “orthite” vs. “allanite” controversy was resolved in 1986 by the Commission on New Minerals and Mineral Names, IMA, in favor of “allanite”. Taking into account Levison’s

nomenclature (1966) for rare-earth minerals, the mineral from Greenland originally described by Thomson (1810) is actually **allanite-(Ce)** and, citing that priority, the CNMMN formally approved the name allanite-(Ce) (Nickel & Mandarino, 1987). Cerium is the dominant REE in most “allanite”. However, chemical data are available in the literature for La- and Y-dominant “allanite”, which should be properly considered as distinct mineral species. Their status has not until recently been formally approved, although the corresponding mineral names allanite-(La) and allanite-(Y) have been in circulation (Levinson, 1966) and are included in the IMA list of minerals. With the aim of securing official status for such unapproved epidote-group minerals, Orlandi & Pasero (2006) recently defined the “new” mineral **allanite-(La)**, which has now the status of an IMA-approved species (proposal # 2003-065).

Lombaardite was first described by Nels *et al.* (1949) from the Zaaiplaats tin mine, central Transvaal, and re-examined by Neumann & Nilssen (1962) reporting *ca.* 10–15 wt.% (REE)<sub>2</sub>O<sub>3</sub>. Neumann & Nilssen (1962) suggested that lombardite is very similar or even identical to a Y<sub>2</sub>O<sub>3</sub> dominant “allanite” (with 22.16 wt.% (REE)<sub>2</sub>O<sub>3</sub> including 5.39 wt.% Y<sub>2</sub>O<sub>3</sub>) from a pegmatite at Åskagen, Värmland, Sweden. Thus the Åskagen, Värmland, sample represents **allanite-(Y)**.

“Allanite” is characterized by one coupled heterovalent substitution where the higher charge of (REE)<sup>3+</sup> replacing Ca on the A2 site (Dollase, 1971) is compensated by ferrous iron occupying the octahedral M3 site. Peacor & Dunn (1988) restudied material first investigated by Geijer (1927), which was originally named “magnesium orthite” and therefore considered the Mg-dominant analogue of “allanite”. However, chemical analyses accompanied by crystal-structure refinement showed that the true composition of this material is close to CaREEMgAlMg[Si<sub>2</sub>O<sub>7</sub>][SiO<sub>4</sub>]F(OH), an epidote-group mineral characterized by two different types of coupled heterovalent substitutions: (1) A<sup>2</sup>(REE)<sup>3+</sup> + M<sup>3</sup>Mg → A<sup>2</sup>Ca + M<sup>3</sup>Al and (2) M<sup>1</sup>Mg + O<sup>4</sup>F → M<sup>1</sup>Al + O<sup>4</sup>O<sup>2-</sup>. This new type of REE-rich epidote-group mineral was given the root name dollaseite in honor of Wayne Dollase for his crystal chemical research on epidote-group minerals. The type material for **dollaseite-(Ce)** is from the Östanmossa mine, Norberg district, Sweden, originally studied by Geijer (1927).

However, Geijer (1927) also analyzed Mg-rich material with F < 0.5 apfu, which seemed close to the Mg analogue of “allanite”. Subsequently, in a literature review Grew *et al.* (1991) found several reports of “allanite” analogues with Mg > Fe<sup>2+</sup> and compositionally distinct from “dollaseite”. The corresponding mineral with the end-member formula CaCeAl<sub>2</sub>Mg<sup>2+</sup>[Si<sub>2</sub>O<sub>7</sub>][SiO<sub>4</sub>]O(OH) was named **dissakisite-(Ce)** from the Greek *dissakis* = “twice over” in reference to the Mg equivalent of “allanite” being described twice. The type material was found in marble from Balchen Mountain in the eastern Sør Rondane Mountains, Queen Maud Land, Antarctica. The type material of the newly discovered **dissakisite-(La)** is from a peridotite body of the Ulten zone, Austroalpine domain, Eastern Alps (Tumiati *et al.*, 2005).

Sokolova *et al.* (1991) described the structure of a Ce-rich epidote-group mineral from the Inyl’chek Massif, Kyrgyzstan (former Kirghiz SSR), which was also F-rich and thus closely related to “dollaseite” but with the octahedral M3 site dominated by Mn<sup>2+</sup>. Pautov *et al.* (1993) later defined this mineral as a new species, **khristovite-(Ce)**, CaCeMgAlMn<sup>2+</sup>[Si<sub>2</sub>O<sub>7</sub>][SiO<sub>4</sub>]F(OH), which was named after the Russian geologist Evgenia Vladimirovicha Khristova.

It has been known for a long time that piemontite may incorporate significant amounts of REE (for a literature review see Bonazzi *et al.*, 1992). Bonazzi *et al.* (1996) defined a new end-member from Andros Island, Cyclades, Greece named **androsite-(La)** with the

end-member composition Mn<sup>2+</sup>LaMn<sup>3+</sup>AlMn<sup>2+</sup>[Si<sub>2</sub>O<sub>7</sub>][SiO<sub>4</sub>]O(OH). This REE-rich epidote-group mineral with La on A2 has the smaller of the two A sites (A1) occupied by Mn<sup>2+</sup> and the largest octahedral site (M3) also occupied by Mn<sup>2+</sup>, whereas the M1 octahedron is dominated by Mn<sup>3+</sup>. In addition, epidote-group minerals with compositions corresponding to **vanadoandrosite-(Ce)** and **(mangani)androsite-(Ce)** (Cenki-Tok *et al.*, 2006) have been approved by CNMMN (IMA 2004-015 and IMA 2002-049).

**Ferriallanite-(Ce)**, ideally, CaCeFe<sup>3+</sup>AlFe<sup>2+</sup>[Si<sub>2</sub>O<sub>7</sub>][SiO<sub>4</sub>]O(OH), is the analogue of allanite-(Ce) with Fe<sup>3+</sup> dominant in the octahedral M1 site. It is of metasomatic origin and occurs in an alkaline granitic pegmatite of Mount Ulyn Khuren in the Altai Range, Mongolia (Kartashov *et al.*, 2002). Furthermore, ferriallanite-(Ce), previously reported as “cerine” or iron-rich “allanite” is the most common lanthanide mineral next to cerite-(Ce) at the Bastnäs Fe-Cu-REE deposit, Skinnskatteberg, Västmanland, Sweden (Holtstam *et al.*, 2003).

## 2.7. Epidote modules in polysomatic series

As exemplified by the minerals gatelite-(Ce) (Bonazzi *et al.*, 2003) and västmanlandite-(Ce) (Holtstam *et al.*, 2005) the epidote-type structure (*E*) easily matches with that of törnebohmite, (REE)<sub>2</sub>Al[SiO<sub>4</sub>]<sub>2</sub>(OH), (*T*) to form a polysomatic series (*E*, *ET*, *T*). Sequences in addition to *ET* are to be expected because *E* and *T* modules fit together in any order and the *E-T* interface does not require significant structural distortions. Both gatelite-(Ce) and västmanlandite-(Ce) represent iso-topological *ET* type polysomes distinct by space-group symmetry and composition of the epidote-type module. The *E* module in gatelite-(Ce) is of dissakisite-(Ce) composition whereas the *E* module in västmanlandite-(Ce) is of dollaseite-(Ce) composition. To clarify the structural relationship between *E* and *T* modules Bonazzi *et al.* (2003) have chosen a unit-cell setting for gatelite-(Ce) where **a**<sub>gat.</sub> ≈ 2**a**<sub>epi.</sub> ≈ [201]<sub>tör.</sub>; **b**<sub>gat.</sub> ≈ **b**<sub>epi.</sub> ≈ **b**<sub>tör.</sub>; **c**<sub>gat.</sub> ≈ (**c**<sub>epi.</sub> + **c**<sub>tör.</sub>); β<sub>gat.</sub> ≈ β<sub>epi.</sub>. Unfortunately, a corresponding setting was not used for västmanlandite-(Ce) by Holtstam *et al.* (2005). Their original setting, *a* = 8.939, *b* = 5.706, *c* = 15.855 Å, β = 94.58°, space group *P*2<sub>1</sub>/*m* may be transformed by the matrix [-100 | 010 | 101] to obtain a setting in space group *P*2<sub>1</sub>/*m* with *a* = 8.939, *b* = 5.706, *c* = 17.568 Å, β = 115.90° corresponding to gatelite-(Ce) with *a* = 17.770, *b* = 5.651, *c* = 17.458 Å, β = 116.18° (space group *P*2<sub>1</sub>/*a*).

## 3. Recommended nomenclature

### 3.1 Definition of an epidote-group mineral

The oldest, still accepted mineral name of the mineral group under review is epidote (Haüy, 1801). For this reason the name epidote is used to not only describe a mineral species of idealized Ca<sub>2</sub>Al<sub>2</sub>Fe<sup>3+</sup>[Si<sub>2</sub>O<sub>7</sub>][SiO<sub>4</sub>]O(OH) composition but also to designate the entire group. The subcommittee discussed the point whether zoisite should be regarded a member of the epidote group (*e.g.*, Franz & Liebscher, 2004). However, given that *ca.* 20 mineral species are presently recognized as isostructural with epidote but zoisite stands alone, the subcommittee decided to limit the epidote group to closely related species having monoclinic symmetry so as to avoid having to mention repeatedly the one exception having orthorhombic symmetry. Exclusion of zoisite from the epidote group has

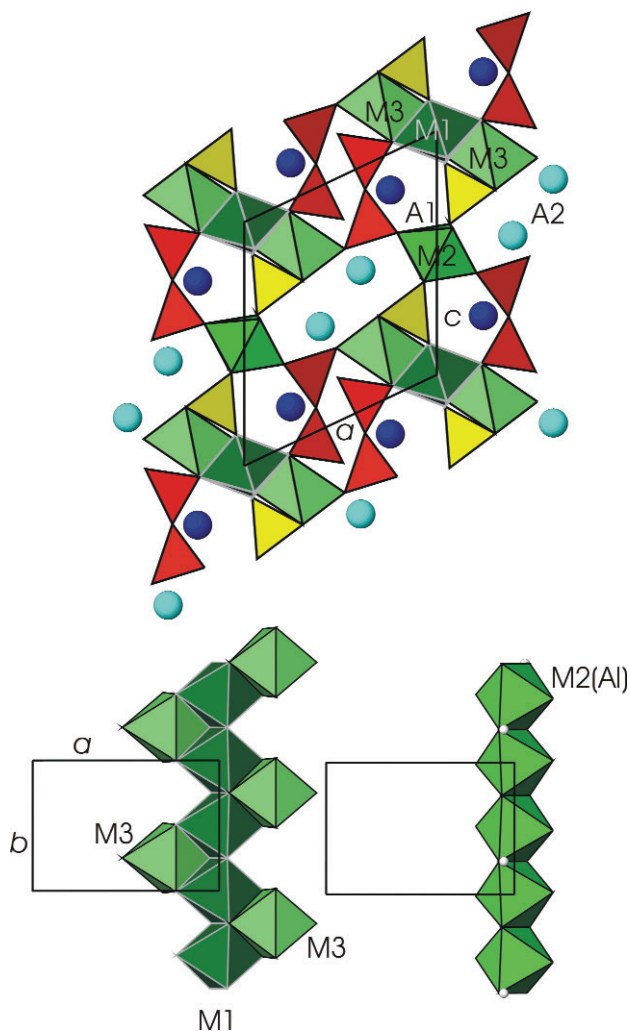


Fig. 1, Top: Polyhedral model of the clinozoisite structure (space group  $P2_1/m$ ) projected along the  $b$ -axis.  $TO_4$  tetrahedra are in yellow,  $T_2O_7$  groups are in red, octahedra in green, A sites are shown as blue spheres (A1 dark blue, A2 light blue); Bottom: Linkage of octahedral sites forming chains parallel to the  $b$ -axis. H atoms on the chain formed by M2 octahedra are shown as small white spheres.

a historical precedent (Tschermak, 1905) and was followed in the most recent edition of Strunz Mineralogical Tables (Strunz & Nickel, 2001).

### Definition

An epidote-group mineral is described with the generic formula  $A_2M_3[T_2O_7][TO_4](O,F)(OH,O)$ . The monoclinic crystal structure is composed of  $T_2O_7$  (usually  $Si_2O_7$ ) and  $TO_4$  (usually  $SiO_4$ ) units linked to two kinds of chains (parallel to the  $b$ -axis) built by edge-sharing octahedra (Fig. 1). One chain consists of M2 octahedra while the other chain is formed by M1 octahedra with M3 octahedra attached on alternate sides along its length. M octahedra are mainly occupied by trivalent ions such as Al,  $Fe^{3+}$ ,  $Mn^{3+}$ ,  $Cr^{3+}$ ,  $V^{3+}$ . Divalent cations (*e.g.*, Mg,  $Fe^{2+}$ ,  $Mn^{2+}$ ) may occupy M sites (preferentially M3) if various heterova-

lent substitutions come into play. M2 has a strong preference for Al whereas the occupancy of M1 and M3 depends on competing ions. Usually an OH group is bonded to the M2 cation. The overall structural arrangement gives rise to two types of cavities, a smaller one named A1, usually occupied by Ca or  $Mn^{2+}$  and a larger one named A2, usually occupied by Ca, Sr, Pb, and REE. The resulting connectivity (topology) is consistent with space group  $P2_1/m$ .

The  $P2_1/m$  structure of epidote-group minerals displays ten symmetry independent anion sites, commonly labelled O1 – O10. In natural samples the site O10 represents O bonded to H (hydroxyl group) whereas the O4 site may be occupied by  $O^{2-}$  (clinozoisite and allanite subgroups) or by  $F^-$  (dollaseite subgroup).

### Annotation

Zoisite is a polymorph of clinozoisite  $Ca_2Al_3[Si_2O_7][SiO_4]O(OH)$  of orthorhombic symmetry (space group  $Pnma$ ) with only one type of edge-sharing octahedral chain and M3 octahedra attached only on one side along its length. Alternatively, zoisite and clinozoisite may even be interpreted to have polytypic relations (Ito, 1950; Merlino, 1990).

### 3.2. Definition of subgroups

For better and easier distinction of epidote-group minerals we introduce three subgroups based on the existing accepted mineral species. Additional subgroups may be defined if new species are not accommodated in the following three.

Members of the **clinozoisite subgroup** are derived from the mineral clinozoisite  $Ca_2Al_3[Si_2O_7][SiO_4]O(OH)$  solely by homovalent substitutions. The key cation and anion sites are A1 =  $M^{2+}$ , A2 =  $M^{2+}$ , M1 =  $M^{3+}$ , M2 =  $M^{3+}$ , M3 =  $M^{3+}$ , O4 =  $O^{2-}$ , O10 = (OH) $^-$ . In other words, the dominant valence as listed above must be maintained.

Members of the **allanite subgroup** are REE-rich minerals typified by the eponymous mineral “allanite”. This subgroup is derived from clinozoisite by homovalent substitutions and **one** coupled heterovalent substitution of the type  $A_2(REE)^{3+} + M_3M^{2+} \rightarrow A_2Ca^{2+} + M_3M^{3+}$ . Thus the valences on the key sites are: A1 =  $M^{2+}$ , A2 =  $M^{3+}$ , M1 =  $M^{3+}$ , M2 =  $M^{3+}$ , M3 =  $M^{2+}$ , O4 =  $O^{2-}$ , O10 = (OH) $^-$ .

Members of the **dollaseite subgroup** are REE-rich minerals typified by the eponymous mineral “dollaseite”. This subgroup is derived from clinozoisite by homovalent substitutions and **two** coupled heterovalent substitutions of the type  $A_2(REE)^{3+} + M_3M^{2+} \rightarrow A_2Ca^{2+} + M_3M^{3+}$  and  $M_1M^{2+} + O_4F^- \rightarrow M_1M^{3+} + O_4O^{2-}$ . Thus the valences on the key sites are: A1 =  $M^{2+}$ , A2 =  $M^{3+}$ , M1 =  $M^{2+}$ , M2 =  $M^{3+}$ , M3 =  $M^{2+}$ , O4 =  $F^-$ , O10 = (OH) $^-$ .

### 3.3. Role of $U^{4+}$ and $Th^{4+}$ in the allanite and dollaseite subgroups

Gieré & Sorensen (2004) reviewed  $Th^{4+}$  and  $U^{4+}$  contents in “allanite”. According to their literature review



the maximum reported ThO<sub>2</sub> content is 4.9 wt.% corresponding to *ca.* 0.07 Th pfu. The maximum UO<sub>2</sub> content is 0.82 wt.% in a crystal containing additionally 1.09 wt.% ThO<sub>2</sub>, corresponding to 0.02 apfu each. Thus, Th and U are minor constituents of the actinides (ACT) group of elements. The recommended chemical criterion to assign minerals to the allanite and dollaseite subgroups is REE + ACT > 0.5 pfu. The major argument for adding U and Th to REE is that the coupled heterovalent substitution mechanism is presumably: A<sub>2</sub>(Th<sup>4+</sup>,U<sup>4+</sup>) + 2 M<sub>3</sub>M<sup>2+</sup> → A<sub>2</sub>Ca + 2 M<sub>3</sub>M<sup>3+</sup>. *Comment:* The IMA CNMMN guidelines for new minerals also list Sc<sup>3+</sup> together with Y<sup>3+</sup> and lanthanides as candidates for which the Levinson extension should be used. However, Sc<sup>3+</sup> has also a strong preference for octahedral sites (*E.g.*, bazzite is a beryl analogue where Sc replaces Al). For this reason a special treatment of Sc-rich epidote-group minerals seems necessary, and, if such compositions were found in nature, the Sc distribution will have to be studied.

### 3.4. Derivation of mineral names

Considering members of the clinozoisite subgroup, most frequent are homovalent substitutions on M3 by Fe<sup>3+</sup>, V<sup>3+</sup>, Cr<sup>3+</sup>, and Mn<sup>3+</sup> (replacing Al) as well as on A2 by Sr, Pb<sup>2+</sup>, and less commonly, Ba (replacing Ca). These substitutions, in principle, yield 20 combinations each corresponding to a distinct mineral species. If we further consider that homovalent substitutions may also occur on M1 as exemplified by the mineral tweddillite (Armbruster *et al.*, 2002) and that Mn<sup>2+</sup> can also substitute for Ca on A1, the number of potential species increases further. For this reason we believe that the free choice of a mineral name needs to be restricted in order to avoid proliferation of unrelated mineral names. Relationships among minerals should be evident in the names. For example, the chemical relation between piemontite and strontioziemontite is obvious, whereas the name tweddillite obscures its relation to strontioziemontite.

In the recommended new nomenclature the key cation-sites M3 and A1 (and, in principle, M2) determine the root name. If the dominant cations at A1, M3 (and M2) exactly match those of an approved species, **the same root name must be given**. If at one of these sites the dominant cation is different a new root name may be suggested.

In both clinozoisite and allanite subgroups no prefix is added to the root name if M1 = Al. In the dollaseite subgroup no prefix is added to the root name if M1 = Mg. Otherwise a proper prefix derived from the name of a chemical element must be attached. The prefixes ferri, mangani, chromo, and vanado indicate dominant Fe<sup>3+</sup>, Mn<sup>3+</sup>, Cr<sup>3+</sup>, and V<sup>3+</sup> on M1, respectively (clinozoisite and allanite subgroups). The prefixes ferro and mangano indicate dominant Fe<sup>2+</sup> and Mn<sup>2+</sup> at M1, respectively (dollaseite subgroup). The dominant cation on A2 in the clinozoisite subgroup (other than Ca) is defined as *extended Levinson suffix* (Levinson, 1966; Bayliss & Levinson, 1988). Note that A2 in the allanite and dollaseite subgroups is occupied by REE. Thus for those minerals Levinson suffixes *per se* apply to the dominant REE. This simple nomenclature requires complete renaming of following species:

Table 2. Clinozoisite subgroup: accepted mineral species (in bold) along with selected examples of recommended names for possible new members of epidote-group minerals.

Name	Old name	A1	A2	M1	M2	M3	O4	O10
<b>Clinozoisite</b>		Ca	Ca	Al	Al	Al	O	OH
<b>Clinozoisite-(Sr)*</b>	<i>Niigataite</i>	Ca	Sr	Al	Al	Al	O	OH
Clinozoisite-(Pb)		Ca	Pb	Al	Al	Al	O	OH
<b>Epidote</b>		Ca	Ca	Al	Al	Fe <sup>3+</sup>	O	OH
<b>Epidote-(Pb)*</b>	<i>Hancockite</i>	Ca	Pb	Al	Al	Fe <sup>3+</sup>	O	OH
Epidote-(Sr)		Ca	Sr	Al	Al	Fe <sup>3+</sup>	O	OH
Ferriepidote		Ca	Ca	Fe <sup>3+</sup>	Al	Fe <sup>3+</sup>	O	OH
Ferriepidote-(Sr)		Ca	Sr	Fe <sup>3+</sup>	Al	Fe <sup>3+</sup>	O	OH
Ferriepidote-(Pb)		Ca	Pb	Fe <sup>3+</sup>	Al	Fe <sup>3+</sup>	O	OH
Vanadoepidote		Ca	Ca	V <sup>3+</sup>	Al	Fe <sup>3+</sup>	O	OH
Vanadoepidote-(Sr)		Ca	Sr	V <sup>3+</sup>	Al	Fe <sup>3+</sup>	O	OH
Vanadoepidote-(Pb)		Ca	Pb	V <sup>3+</sup>	Al	Fe <sup>3+</sup>	O	OH
<b>Mukhinite</b>		Ca	Ca	Al	Al	V <sup>3+</sup>	O	OH
Mukhinite-(Sr)		Ca	Sr	Al	Al	V <sup>3+</sup>	O	OH
Mukhinite-(Pb)		Ca	Pb	Al	Al	V <sup>3+</sup>	O	OH
Tawmawite #		Ca	Ca	Al	Al	Cr <sup>3+</sup>	O	OH
Chromotawmawite		Ca	Ca	Cr <sup>3+</sup>	Al	Cr <sup>3+</sup>	O	OH
<b>Piemontite</b>		Ca	Ca	Al	Al	Mn <sup>3+</sup>	O	OH
<b>Piemontite-(Sr)*</b>	<i>Strontioziemontite</i>	Ca	Sr	Al	Al	Mn <sup>3+</sup>	O	OH
Piemontite-(Pb)		Ca	Pb	Al	Al	Mn <sup>3+</sup>	O	OH
Manganipiemontite		Ca	Ca	Mn <sup>3+</sup>	Al	Mn <sup>3+</sup>	O	OH
<b>Manganipiemontite-(Sr)*</b>	<i>Tweddillite</i>	Ca	Sr	Mn <sup>3+</sup>	Al	Mn <sup>3+</sup>	O	OH
new root name		Mn <sup>2+</sup>	Ca	Mn <sup>3+</sup>	Al	Mn <sup>3+</sup>	O	OH

*Notes:* \* recommended new mineral names for accepted species; # not a valid species until clear evidence for Cr > 0.5 pfu on M1 or M3 is presented.

Niigataite (old) = **clinozoisite-(Sr) (new)**,  
 hancockite (old) = **epidote-(Pb) (new)**,  
 tweddillite (old) = **manganipiemontite-(Sr) (new)**.

Fortunately, two of these species were very recently described and all three species are rare, so that the mineralogical community is not familiar with the original names. Minor modifications are necessary for following species:

Strontioziemontite (old) = **piemontite-(Sr) (new)**,  
 androsite-(La) (old) = **manganianandrosite-(La) (new)**.

*Comments:* “Androsite” is an example for a root name derived from the occupancy of two key sites A1 (Mn<sup>2+</sup>) and M3 (Mn<sup>2+</sup>). Additional root names are required for corresponding compositions with either A1 occupied by Ca or M3 occupied by any other divalent cation.

Kartashov *et al.* (2002) list analytical data for a mineral of idealized composition CaCeFe<sup>3+</sup><sub>2</sub>Fe<sup>2+</sup> [Si<sub>2</sub>O<sub>7</sub>][SiO<sub>4</sub>]O(OH) but the available data were not considered sufficient for naming a new species. On the one hand, such a hypothetical mineral would qualify for a new root name due to its unique occupancy of M3 and M2. The strong relation to ferriallanite-(Ce) could also be expressed by the possible name “ferriferriallanite-(Ce)” where the dominant occupancy on M2 is expressed by a second prefix. If the two prefixes are identical an alternate choice could be the name “diferriallanite-(Ce)”. Because there are yet no accepted examples for such species with M2 ≠ Al we defer the naming decision to the authors proposing the new species and to the CNMMN members reviewing the proposal. We believe that awkward doubly prefixed names should be the exception rather than the rule in epidote-group minerals.

Table 3. Allanite subgroup: accepted mineral species (in bold) along with selected examples of recommended names for possible new members of epidote-group minerals.

Name	Old name	A1	A2	M1	M2	M3	O4	O10
<b>Allanite-(Ce), -(La), -(Y)</b>		Ca	(REE) <sup>3+</sup>	Al	Al	Fe <sup>2+</sup>	O	OH
<b>Ferriallanite-(Ce)</b>		Ca	Ce <sup>3+</sup>	Fe <sup>3+</sup>	Al	Fe <sup>2+</sup>	O	OH
Vanadoallanite-(REE)		Ca	(REE) <sup>3+</sup>	V <sup>3+</sup>	Al	Fe <sup>2+</sup>	O	OH
Chromoallanite-(REE)		Ca	(REE) <sup>3+</sup>	Cr <sup>3+</sup>	Al	Fe <sup>2+</sup>	O	OH
<b>Dissakisite-(Ce), -(La)</b>		Ca	(REE) <sup>3+</sup>	Al	Al	Mg	O	OH
Ferridissakisite-(REE)		Ca	(REE) <sup>3+</sup>	Fe <sup>3+</sup>	Al	Mg	O	OH
Vanadodissakisite-(REE)		Ca	(REE) <sup>3+</sup>	V <sup>3+</sup>	Al	Mg	O	OH
Mangandissakisite-(REE)		Ca	(REE) <sup>3+</sup>	Mn <sup>3+</sup>	Al	Mg	O	OH
Chromodissakisite-(REE)		Ca	(REE) <sup>3+</sup>	Cr <sup>3+</sup>	Al	Mg	O	OH
Androsite-(REE) (new def.)		Mn <sup>2+</sup>	(REE) <sup>3+</sup>	Al	Al	Mn <sup>2+</sup>	O	OH
<b>Manganiandrosite-(La)*, -(Ce)■</b>	<i>androsite</i>	Mn <sup>2+</sup>	(REE) <sup>3+</sup>	Mn <sup>3+</sup>	Al	Mn <sup>2+</sup>	O	OH
Ferriandrosite-(REE)		Mn <sup>2+</sup>	(REE) <sup>3+</sup>	Fe <sup>3+</sup>	Al	Mn <sup>2+</sup>	O	OH
<b>Vanadoandrosite-(Ce)■</b>		Mn <sup>2+</sup>	Ce <sup>3+</sup>	V <sup>3+</sup>	Al	Mn <sup>2+</sup>	O	OH
Chromoandrosite-(REE)		Mn <sup>2+</sup>	(REE) <sup>3+</sup>	Cr <sup>3+</sup>	Al	Mn <sup>2+</sup>	O	OH
New root names		Ca	(REE) <sup>3+</sup>	Al	Al	Mn <sup>2+</sup>	O	OH
		Ca	(REE) <sup>3+</sup>	Fe <sup>3+</sup>	Fe <sup>3+</sup>	Fe <sup>2+</sup>	O	OH
		Mn <sup>2+</sup>	(REE) <sup>3+</sup>	Al	Al	Mg <sup>2+</sup>	O	OH
		Mn <sup>2+</sup>	(REE) <sup>3+</sup>	Al	Al	Fe <sup>2+</sup>	O	OH

Notes: \* recommended new mineral names for accepted species; ■ approved by CNMMN (Cenki-Tok *et al.*, 2006); vanadoandrosite-(Ce) has originally been approved as vanadio-androsite-(Ce).

Table 4. Dollaseite subgroup: accepted mineral species (in bold) along with selected examples of recommended names for possible new members of epidote-group minerals.

Name	A1	A2	M1	M2	M3	O4	O10
<b>Dollaseite-(Ce)</b>	Ca	Ce <sup>3+</sup>	Mg	Al	Mg	F	OH
<b>Khristovite-(Ce)</b>	Ca	Ce <sup>3+</sup>	Mg	Al	Mn <sup>2+</sup>	F	OH
Ferrokhrystovite-(REE)	Ca	(REE) <sup>3+</sup>	Fe <sup>2+</sup>	Al	Mn <sup>2+</sup>	F	OH
Manganokhrystovite-(REE)	Ca	(REE) <sup>3+</sup>	Mn <sup>2+</sup>	Al	Mn <sup>2+</sup>	F	OH
New root name	Ca	(REE) <sup>3+</sup>	Mg	Al	Fe <sup>2+</sup>	F	OH
New root name	Mn <sup>2+</sup>	(REE) <sup>3+</sup>	Mg	Al	Mn <sup>2+</sup>	F	OH

Occupancy of the *key sites* and recommended names for all hitherto defined epidote-group minerals and for some examples of possible compositions not yet found are summarized in Tables 2-4. In addition, cell dimensions of approved species are given in Table 5.

*Comment:* In particular, our subcommittee discussed the use of proper prefixes for V<sup>3+</sup> and Cr<sup>3+</sup>. The ending for both prefixes should be -o because V<sup>3+</sup> and Cr<sup>3+</sup> are the predominant low valences of V and Cr in mineral formulas (V<sup>2+</sup>, although reported in minerals, is not considered a potential constituent because it is so rare). We have chosen the prefix “chromo” for Cr<sup>3+</sup> by analogy with

Table 5. Cell dimensions of epidote-group minerals (space group *P2<sub>1</sub>/m*).

Name	<i>a</i> (Å)	<i>b</i> (Å)	<i>c</i> (Å)	β (°)	<i>V</i> (Å <sup>3</sup> )	Ref.
Clinozoisite	8.861	5.5830	10.141	115.46	453.0	Pawley <i>et al.</i> 1996
Clinozoisite-(Sr)	8.890	5.5878	10.211	115.12	459.3	Miyajima <i>et al.</i> 2003
Epidote	8.908	5.663	10.175	115.35	463.9	Bonazzi & Menchetti 1995
Epidote-(Pb)	8.958	5.665	10.304	114.4	476.2	Dollase 1971
Mukhinite	8.90	5.61	10.15	115.5	457	Shepel & Karpenko 1969
Piemontite	8.844	5.577	10.167	115.54	460.6	Langer <i>et al.</i> 2002
Piemontite-(Sr)	8.870	5.681	10.209	114.88	466.7	Bonazzi <i>et al.</i> 1990
Manganipiemontite-(Sr)	8.932	5.698	10.310	114.56	477.3	Armbruster <i>et al.</i> 2002
Allanite-(Ce)	8.927	5.761	10.150	114.77	474.0	Dollase 1971
Allanite-(La)	8.914	5.726	10.132	114.87	469.1	Orlandi & Pasero 2006
Allanite-(Y) <sup>s</sup>	-	-	-	-	-	
Ferriallanite-(Ce)	8.962	5.836	10.182	115.02	482.6	Kartashov <i>et al.</i> 2002
Manganiandrosite-(La)	8.896	5.706	10.083	113.88	468.0	Bonazzi <i>et al.</i> 1996
Manganiandrosite-(Ce)	8.901	5.738	10.068	113.43	471.8	Cenki-Tok <i>et al.</i> , 2006
Vanadoandrosite-(Ce)	8.856	5.729	10.038	113.09	468.5	Cenki-Tok <i>et al.</i> , 2006
Dissakisite-(Ce)	8.905	5.684	10.113	114.62	465.3	Rouse & Peacor 1993
Dissakisite-(La)	8.962	5.727	10.235	115.19	475.3	Tumiati <i>et al.</i> 2005
Dollaseite-(Ce)	8.934	5.721	10.176	114.31	474.0	Peacor & Dunn 1988
Khristovite-(Ce)	8.903	5.748	10.107	113.41	474.6	Pautov <i>et al.</i> 1993

<sup>s</sup>refined cell dimensions for allanite-(Y) are not available. However, Neumann & Nilssen (1962) published an X-ray powder pattern, indicating that the cell dimensions of allanite-(Y) are similar to other “allanites”. All mineral names are according to the new nomenclature suggested in this paper.



the common use of this Greek root meaning color in scientific terms (chromophore, chromosome, *etc.*). For  $V^{3+}$  we have agreed on “vanado” although we were aware that the element name is derived from the goddess Vanadis in Norse mythology. “Vanado” was preferred over “vanadio” because this prefix implies “vanadii” would be the prefix for  $V^{4+}$ . Both prefixes would lead to awkward mineral names, in particular if the root name begins with a vowel. We also discussed the possibility of hyphenation between prefix and root name for certain epidote-group mineral names and concluded that hyphenation should be avoided. Nevertheless, we concur with the IMA CNMMN guidelines (Nickel & Grice, 1998) and recommend that a hyphen be used if an unhyphenated name is awkward and the hyphen assists in deciphering the name.

### 3.5. Definition of new species of epidote-group minerals

The definition of mineral species of the epidote-group of minerals depends on the preferred occupancy of various structural sites. Therefore, submission of any new species to CNMMN **must** be accompanied by crystal-structure refinement and/or spectroscopic experiments indicating the extent of order of a chemical species on a given structural site. Exceptions are permissible only for new species distinguished by REE cation, or for simple compositions where the cation distribution is unambiguous from the chemical composition alone. In such cases high-quality chemical data would be considered sufficient. Given the role of F in the dollaseite subgroup, a fluorine analysis is mandatory for epidote-group minerals.

It is emphasized that all new species, for which names (*e.g.*, “clinozoisite-(Pb)”, “epidote-(Sr)”, for additional examples see Tables 2-4) are already defined in this recommended nomenclature, require approval of a formal new-mineral proposal submitted to IMA CNMMN.

### 3.6. Assigning subgroups and mineral names to solid-solution members

#### 3.6.1. Assigning subgroups

In order to name an epidote-group mineral, priority should be given to the choice of subgroup, then root name, and last the specific name. The starting point will be a table reporting the cations on A1, A2, M1, M2 and M3 and the anions on O4 and O10 (*key sites*).

For a proper subgroup assignment one has to determine the dominant valence at M3, M1 and A2 expressed as  $M^{2+}$  and  $M^{3+}$ , **not** just specify a single dominant ion (*i.e.*,  $Fe^{2+}$  or Mg or Al). In addition, the dominant valence on O4:  $X^-$  or  $X^{2-}$  must be evaluated.

$[M^{2+}]_{A2} > 0.50$ ,  $[M^{3+}]_{M3} > 0.50 \rightarrow$  clinozoisite subgroup,  
 $[M^{3+} M^{4+}]_{A2} > 0.50$ ,  $[M^{2+}]_{M3} > 0.50 \rightarrow$  allanite subgroup,  
 $\{[M^{2+}]_{M3+M1} - [M^{3+} M^{4+}]_{A2}\} > 0.50$  **and**  $[X^-]_{O4} > 0.5 \rightarrow$  dollaseite subgroup.

*Comment:* The structural refinement of both dollaseite-(Ce) and kristovite-(Ce) convincingly showed F<sup>-</sup> to be ordered at the O4 site. Thus, the presence of more than 0.5 F per formula unit corresponds to the dollaseite subgroup. Assigning F to O4 and not to O10 has major implications; substitution of F<sup>-</sup> for O<sup>2-</sup> reduces total negative charge and thus must be balanced by decreasing the  $M^{3+}$ :  $M^{2+}$  value.

The above definition of the dollaseite subgroup may at first glance appear unduly complex. A simpler scheme based solely on cation occupancy would be:

$[M^{2+}]_{A2} > 0.5$ ,  $[M^{3+}]_{M1} > 0.5$ ,  $[M^{3+}]_{M3} > 0.5 \rightarrow$  clinozoisite subgroup (with  $[X^-]_{O4} < 0.5$  implicit),  
 $[M^{3+} M^{4+}]_{A2} > 0.5$ ,  $[M^{3+}]_{M1} > 0.5$ ,  $[M^{2+}]_{M3} > 0.5 \rightarrow$  allanite subgroup (with  $[X^-]_{O4} < 0.5$  implicit),  
 $[M^{3+} M^{4+}]_{A2} > 0.5$ ,  $[M^{2+}]_{M1} > 0.5$ ,  $[M^{2+}]_{M3} > 0.5 \rightarrow$  dollaseite subgroup (with  $[X^-]_{O4} > 0.5$  implicit).

The above alternate scheme is not recommended although it is correct for ideal end-members. For members with  $0.5 < (REE)^{3+} \ll 1.0$  the scheme might fail. There are only two structure refinements addressing cation order on M1 and M3 in dollaseite subgroup minerals (Peacor & Dunn, 1988; Sokolova *et al.*, 1991). These are not sufficient for us to provide a more rigorous definition of the dollaseite subgroup.

#### 3.6.2. Assigning mineral names

As mentioned in the introduction, the traditional distinction between clinozoisite and epidote is based on their optical character. Clinozoisite was defined as optically positive whereas epidote was shown to be optically negative. The change over occurs at ~ 40 % epidote component ( $Ca_2Al_2Fe^{3+}[Si_2O_7][SiO_4]O(OH)$ ). In a similar way, the name piemontite has been commonly assigned to monoclinic, Mn-bearing epidote-group minerals exhibiting the characteristic pleochroism, even if the molar  $Mn_2O_3$  content is less than  $Fe_2O_3$  content.

There is a wealth of optical data on epidote-group minerals, recently summarized by Franz & Liebscher (2004). Crystal optics is a fundamental tool in analyzing and describing rocks and minerals, and good optical data may be used in some cases to identify a species or even to quantify a solid-solution member. Nevertheless, binary behaviour should not be assumed *a priori* for complex systems such as the epidote-group minerals. If the chemical composition becomes too complex optical data are ambiguous and have their limitations in mineral identification. As an example, different species of the allanite and dollaseite subgroups are very difficult to distinguish on optical grounds. For a proper evaluation of capabilities and limitations of optical methods for the identification of epidote-group minerals comparative studies are necessary.

The subcommittee, therefore, strongly recommends that optical criteria alone not be used for distinguishing epidote-group minerals. Although optical tests (*e.g.*, determination of the optical sign, optical orientation or pleochroism) are useful for preliminary species identification, we recommend that electron-microprobe analytical data be used to determine a mineral name of a solid-solution member. The dominant cation at *key structural sites*, with the restriction described below, determines the name (*e.g.*, Nickel & Grice, 1998; Nickel, 1992).

##### 3.6.2.1. Clinozoisite subgroup

If only homovalent substitutions take place, the dominant cation at *key structural sites* simply determines the name. Coupled heterovalent substitutions in epidote-group minerals require a special treatment of the so-called 50 %

rule in a solid-solution series. Even for the REE-bearing minerals, the A2 cation appearing in the suffix has to be selected from among the divalent cations in order to name a species belonging to the clinozoisite group. The root name depends on the dominant trivalent cation on M3.

*Example:*

Consider the A2 occupancy (0.35 Ce, 0.05 La, 0.30 Ca, 0.20 Sr, 0.10 Pb). Because  $(\text{REE})^{3+} < 0.5$  the mineral belongs to the clinozoisite subgroup. Although Ce is the dominant cation on A2, the critical cation is Ca, the dominant divalent cation. No suffix is needed in this case because a suffix is only added for a dominant A2 cation other than Ca.

The above hypothetical mineral might have the M3 site occupied by 0.4 Mg, 0.25 Fe<sup>3+</sup>, 0.35 Al. Because this mineral is a member of the clinozoisite subgroup the dominant M<sup>3+</sup> ion (*i.e.* Al, not Mg) is decisive for the root name of the species. Formal derivation of the proper name gives clinozoisite. The adjectival modifiers cerian and magnesian (Schaller, 1930; Bayliss *et al.*, 2005) may be added to emphasize the high Ce and Mg contents.

This deviation from the common procedure of naming minerals is necessary because strict adherence to the rule based on the dominant ionic species leads to inconsistencies and unbalanced formulas. For example, the above mineral would have the idealized formula CaCeAl<sub>2</sub>Mg[Si<sub>2</sub>O<sub>7</sub>][SiO<sub>4</sub>]O(OH), which is the same as the formula for dissakisite-(Ce), a member of the allanite subgroup. If 0.1 Fe<sup>2+</sup> were to replace 0.1 Mg, M3 composition becomes 0.3 Mg, 0.1 Fe<sup>2+</sup>, 0.25 Fe<sup>3+</sup>, 0.35 Al, and the idealized formula becomes CaCeAl<sub>3</sub>[Si<sub>2</sub>O<sub>7</sub>][SiO<sub>4</sub>]O(OH). The latter formula is not charge balanced and thus nonsensical. Furthermore, the requirement to name clinozoisite-subgroup minerals on the basis of dominant M<sup>2+</sup> on A2 and dominant M<sup>3+</sup> on M3 reduces proliferation of unwanted mineral names.

### 3.6.2.2. Allanite and dollaseite subgroups

For the sites involved in the charge compensation of a heterovalent substitution in A2 (*i.e.* M3 in the allanite subgroup, and also M1 in the dollaseite subgroup), the identification of the relevant end-member formula **must** take into account the dominant *charge-compensating* octahedral cation (M<sup>2+</sup>) and **not** the dominant cation in these sites.

*Example:*

An allanite-subgroup mineral where M3 is not dominated by a single divalent cation but by several, so that a trivalent cation is the most abundant one: *e.g.*, Ca(La<sub>0.6</sub>Ca<sub>0.4</sub>)Al<sub>2</sub>(Fe<sup>2+</sup><sub>0.3</sub>Mg<sub>0.2</sub>Mn<sup>2+</sup><sub>0.1</sub>Al<sub>0.4</sub>)[Si<sub>2</sub>O<sub>7</sub>][SiO<sub>4</sub>]O(OH) [*One might be tempted to write a meaningless, non-charge-balanced end-member CaLaAl<sub>3</sub>[Si<sub>2</sub>O<sub>7</sub>][SiO<sub>4</sub>]O(OH).*]

Within the framework proposed above, the correct way to proceed is: First assign the mineral to the allanite subgroup ( $[\text{M}^{3+}]_{\text{A2}} > 0.5$ ,  $[\text{M}^{2+}]_{\text{M3}} > 0.5$ ,  $[\text{F}^-]_{\text{O4}} < 0.5$ ). Thus the end-member formula is: CaLaAl<sub>2</sub>M<sup>2+</sup>[Si<sub>2</sub>O<sub>7</sub>][SiO<sub>4</sub>]O(OH). Fe<sup>2+</sup> is dominant among the M<sup>2+</sup> cations (*i.e.* Fe<sup>2+</sup> is the dominant *charge-compensating* cation). Thus the mineral would properly be named allanite-(La). Likewise, another allanite-subgroup mineral with the same formula except for 0.4 Al replaced by 0.4 Cr must be given the same name, *i.e.* allanite-(La). The adjectival modifier Cr-rich (chromian) may be added to distinguish this mineral from Cr-poor allanite-(La).

## 4. Deriving a mineral name from electron-microprobe analytical data

One of the pitfalls in epidote-group mineralogy has been the derivation of a mineral name from chemical data.

There are four major problems. (1) Rules of finding a proper root name depend on the subgroup because of interference between homovalent and coupled heterovalent substitutions (discussed above). Thus, before a mineral name can be assigned, the subgroup has to be determined. (2) Epidote-group minerals are frequently mixed-valence Fe and/or Mn compounds and the charge of the respective cations has to be calculated on the basis of assumed negative charges. (3) Frequent oscillatory zoning may be masked if the zoning is perpendicular to the incident electron beam. (4) Minerals of the allanite and dollaseite subgroups are commonly metamict, in some cases with complete loss of crystallinity (for a review, see Gieré & Sorensen, 2004). Strongly metamict materials significantly deviate in composition and stoichiometry from their non-metamict equivalents. Metamictization is accompanied with hydration, swelling, and selective leaching. The transition from an ideal crystal to amorphous material during metamictization is continuous. The question of crystal quality remains open if electron-microprobe analytical data are applied without accompanying diffraction experiment.

A central question intimately associated with the problem of metamictization concerns the existence of significant vacancies, in particular on the A sites. This issue becomes important when discussing how the mineral formula should be normalized. Ercit (2002) states two arguments in favor of A-site vacancies: (1) the structure refinement of Sokolova *et al.* (1991) and (2) the electron-microprobe analyses by Peterson & MacFarlane (1993) and Chesner & Ettliger (1989).

Ad (1). We believe that the structure refinement by Sokolova *et al.* (1991) on a very Mn-rich sample does not unambiguously demonstrate the presence of vacancies on A sites if the cation distribution is critically scrutinized. Normalization of the corresponding electron-microprobe analysis to Si = 3 leads to an excess of M-type cations. Coordination of the A1 site, for which vacancies are assumed, is approximately six-fold, which is characteristic of Mn<sup>2+</sup> on A1 (Bonazzi & Menchetti, 2004). Furthermore, the determined scattering power at A1 is 23 electrons, which is intermediate between Ca (20 electrons) and Mn (25 electrons).

Ad (2). Allanites from granitic pegmatites and uraniumiferous calcite veins in the Grenville Province of the Canadian Shield (Peterson & MacFarlane, 1993) contain up to 4.16 wt. % ThO<sub>2</sub> and are mostly metamict. Thus the analyzed deficit of A-site cations might be associated with partial metamictization. Interestingly, significant A-site vacancies were also calculated from electron-microprobe analytical data (Chesner & Ettliger, 1989) on young (75 000 y. to 1.2 m.y.) volcanic allanites (ThO<sub>2</sub> up to 2.17 wt.%). These allanites appear optically rather fresh and metamictization is certainly not advanced. Thus the A-site substitution vector  $(\text{REE})^{3+}_{2/3} + \text{Vac}_{1/3} \leftrightarrow \text{Ca}$  should not be ignored.

### 4.1. Formula normalization

We recommend normalization of electron-microprobe analytical data on the basis of  $\Sigma(\text{A}+\text{M}+\text{T}) = 8$ . This method,

however, is inadequate whenever **A-site vacancies** are present or if not all elements have been analyzed. In either case, the assumption  $\Sigma$  cations = 8.0 leads to  $Si > 3.00$  apfu. If Si becomes  $> 3.05$  apfu, the formula may be renormalized on  $Si = 3$ . One should be aware that normalization to 3 Si transfers all errors of the Si determination to the other cations in the formula, resulting in larger absolute errors on the number of cations (Ercit, 2002). We discourage normalization on  $\Sigma (M+T) = 6$  because  $Mn^{2+}$  and probably also  $Fe^{2+}$  (to a lesser extent) may occupy M1, M3, and A1 (Bonazzi *et al.*, 1996)

#### 4.2. Determination of negative charges

Because refinement of the dollaseite-(Ce) and kristovite-(Ce) structures convincingly showed F<sup>-</sup> to be ordered at the O4 site, the total sum of negative charge should be assumed as follows:  $\Sigma$  (anion charge) = 2 (12 - x) + x + 1, where x = F + Cl (apfu).

*Comment:* Significant amounts of Cl have been rarely reported, except for Cl up to 0.86 wt.% (0.126 apfu) in the halogen-bearing “allanite” from the Hemlo area, Ontario (Pan & Fleet, 1990). We have no knowledge about the role of Cl in the epidote structure. By analogy with F, we recommend the simplest scheme: Assign Cl to the O4 site.

#### 4.3. Charge-balance of the empirical formula

The  $Fe^{2+}/Fe^{3+}$  and  $Mn^{2+}/Mn^{3+}$  values are varied until  $\Sigma$  (cation charge) equals  $\Sigma$  (anion charge), oxidizing first  $Fe^{2+}$ , then  $Mn^{2+}$ , in order to account for their different redox potentials. The assignment of all Mg to the M sites also contributes to the balancing of excess positive charge in the REE-bearing members. One must be aware that this step introduces considerable errors if not all cations have been analyzed (one possible indicator is  $Si > 3.05$  apfu). Furthermore, this step assumes that there is no “oxyallanite” component.

#### 4.4. Assignment of ionic species to the various key sites

i) All Si is assigned to the T sites. If  $Si < 3.00$  apfu (or  $Si^{4+}+P^{5+}+Be^{2+}+B^{3+} < 3.00$  apfu),  $[IV]Al$  is calculated as 3 - Si. However, if Si is *significantly*<sup>2</sup> below 3.00, the analysis is probably not reliable.

ii) If there is sufficient Al after step i), the M2 site is fully occupied by Al. Otherwise, any deficit (1 - Al) is to be compensated by  $Fe^{3+}$ .

iii) Any excess (oct - 2) of octahedral cations (oct = Al,  $Fe^{3+}$ ,  $Mn^{3+}$ ,  $V^{3+}$ ,  $Cr^{3+}$ ,  $Ti^{4+}$ ,  $Sn^{4+}$ ,  $Fe^{2+}$ ,  $Mn^{2+}$ , Mg,  $Cu^{2+}$ , ...) is to be assigned to A1. Priority must be given to  $Mn^{2+}$ . If the amount of  $Mn^{2+}$  is not sufficient preference should be given to  $Fe^{2+}$  or other available cations with large ionic radii.

iv) The A1 site is filled with Ca to sum up to 1.0 apfu. (minor Na will also be assigned to A1). Exception: If

Table 6. Effective octahedral ionic radii in Å (Shannon, 1976).

Ion	Octahedral radius (Å)
Al <sup>3+</sup>	0.535
Ti <sup>4+</sup>	0.605
Cr <sup>3+</sup>	0.615
V <sup>3+</sup>	0.640
Fe <sup>3+</sup>	0.645 <sup>1</sup> (high spin)
Mn <sup>3+</sup>	0.645 <sup>1</sup> (high spin)
Sn <sup>4+</sup>	0.690
Mg	0.720
Cu <sup>2+</sup>	0.730
Zn	0.740
Fe <sup>2+</sup>	0.780 (high spin)
Mn <sup>2+</sup>	0.830 (high spin)

<sup>1</sup>to avoid ambiguity  $Mn^{3+}$  (Jahn-Teller distortion) should be regarded larger than  $Fe^{3+}$  although the average ionic radii are equal.

$\Sigma(REE+ACT+Ba+Sr+Pb^{2+}) > 1.0$ , excess cations may be assigned to A1 (preferentially those with the smaller ionic radii).

v) All (REE)<sup>3+</sup> (together with Th<sup>4+</sup> and U<sup>4+</sup>) are assigned to A2. Larger divalent cations such as Sr, Pb<sup>2+</sup>, Ba, and K are also added to this site. Remaining Ca is added to A2.

*Comment:* In the absence of knowledge on octahedral REE in allanite and dollaseite-subgroup minerals we ignore this possibility in this simplified procedure. Cressey & Steel (1988), on the basis of  $L_{III}$  edge extended X-ray absorption fine structure (EXAFS), suggested that Lu in synthetic dissakisite-(La) is located at the M3 site and that Gd and Er reside at the A2 and A1 sites, respectively. These results, while interesting, require confirmation.

vi) If any, F and Cl must be assigned to the O4 site.

vii) The remaining 2.00 octahedral cations are assigned to M3 and M1. In the lack of structural information, a sequence based on **decreasing ionic radii** could be written to fill first M3 and then M1. Octahedral ionic radii according to Shannon (1976) are listed in Table 6.

*Comment:* In particular, we do not know how  $M^{2+}$  is ordered between M1 and M3 if O4 is partly occupied by F. Because M1 has two bonds to O4 whereas M3 has only one, we would expect that M1 would have a rather strong selectivity for  $M^{2+}$  if O4 = F. The method must be certainly refined if additional information on cation order in minerals of this subgroup is available.

#### 4.5. Subgroup and root name

Before a name can be given to a mineral species the subgroup has to be determined (see above). In case of dollaseite-subgroup minerals, assigning an individual name may fail for compositions  $0.5 < REE + ACT \ll 1$  and  $1 \gg (F \text{ on } O4) > 0.5$ . This shortcoming results from our

<sup>2</sup>A good and complete electron-microprobe analysis of an epidote-group mineral should reproduce the stoichiometric constraints within 1 % relative, i.e.  $Si = 2.97$  to  $3.03$  pfu. Thus, analyses yielding  $< 2.97$  Si pfu may indicate T-site substitution. However, Si values below 2.9 pfu should be regarded as anomalous and probably erroneous. Si values  $> 3.03$  pfu may indicate either A-site vacancies (partial metamictization?) or incomplete analyses.



limited knowledge about order of  $M^{2+}$  between M1 and M3 for this subgroup. In the Appendix several examples are presented to illustrate how a “working name” can be derived from an electron-microprobe analysis. The term “working name” is used to emphasize that a strongly simplified scheme for the naming procedure was applied. The “working name” may be used in any mineralogical or petrological investigation as long as the derived mineral name agrees with the recommendations of this IMA CNMMN subcommittee. No quotation marks are needed in case the name is already that of an approved species; otherwise they are mandatory. Of course, the “working name” procedure is not sufficient to define a new species of the epidote-group minerals.

#### 4.6. Usage of the term “pistacite”

The term “pistacite” is not an accepted mineral name and should therefore not be used as a synonym for epidote. There is a tradition among petrologists to name the hypothetical composition  $Ca_2Fe^{3+}_3[Si_2O_7][SiO_4]O(OH)$  “pistacite” component in clinzoisite – epidote solid solutions. If the term “pistacite” is used in this sense it should be written in quotation marks accompanied by the word *component* to indicate its theoretical meaning [“pistacite” component]. We firmly discourage from using “pistacite” component and recommend an alternative, less confusing expression  $X_{Fe} = Fe^{3+}/(Fe^{3+} + Al)$  to quantify a solid-solution member.

#### 4.7. Usage of the term “oxyallanite”

It has been shown by several investigators (e.g., Dollase, 1973; Bonazzi & Menchetti, 1994) that “allanite” dehydroxylates in air between ca. 600 and 700°C where charge balance is maintained by oxidation of ferrous to ferric iron according to:  $M^3Fe^{2+} + O^{10}OH^- \rightarrow M^3Fe^{3+} + O^{10}O^{2-} + 1/2 H_2$ . This substitution has been achieved experimentally, but it has not yet been demonstrated to occur in nature. The term “oxyallanite” may be used for the theoretical end-member  $CaREEAl_2Fe^{3+}[Si_2O_7][SiO_4]O_2$ . If the term “oxyallanite” is used in this sense it should be written in quotation marks accompanied by the word *component* to indicate its theoretical meaning [“oxyallanite” component]. A recommended more descriptive term is oxidized or dehydroxylated allanite-(REE).

### 5. Metamictization

Metamictization is a major problem in assigning a proper species name, in particular for REE-bearing epidote-group minerals. Metamict samples tend to be more reactive than well-crystallized minerals (for a review see Gieré & Sorensen, 2004) and exhibit anion- and cation-exchange properties (e.g., possibly leading to vacancies on A sites). There is no sharp borderline between a completely X-ray amorphous substance (due to metamictization) and a mineral with a well-ordered crystal lattice. Subsequent heat-treatment under inert conditions to reestablish an ordered crystal lattice seems to be questionable if the

resulting “mineral” adopts a composition that is characteristic of a partly ion-exchanged poorly crystalline (metastable) substance, but not of the original mineral. There is at least some suspicion that such “mineral” compositions are influenced by the experimenter and are not an unaltered product of nature. These problems are not specific of epidote-group minerals but are much more prominent in other mineral groups with higher concentrations of radioisotopes. For this reason the issue of metamictization is out of the scope of this subcommittee and should be treated in a general way by a different working group. We recommend exercising caution with compositions of “partly” metamict epidote-group minerals in naming new species, even if the “faulty” lattice has been mended by subsequent heat treatment.

### 6. Appendix

Some selected electron-microprobe analytical data cited from the literature are summarized in Table 7. Those data have been selected because they represent either borderline compositions (approximately intermediate between two species), or the data are incomplete and/or erroneous, or they originate from partly metamict samples. The aim of this appendix and the data in Table 7 is to demonstrate how a mineral name (Table 8) can be derived in non-trivial cases, based on the formal ion assignment to the *key sites* as discussed in Chapter 4.

The selected analytical data by Chessner & Ettliger (1989) and Treloar & Charnley (1987) had to be normalized to Si = 3 because normalization on  $\Sigma(A + M + Z)$  yielded  $Si > 3.05$ . The Chessner & Ettliger (1989) data suggest either A-site vacancies or incomplete analyses of A-site cations, whereas the Treloar & Charnley (1987) analytical data on dissakisite-(Ce) (originally described as allanite) from Outokumpu (Finland) indicate significant M-site vacancies, which are most probably related to incomplete analyses. In particular, the presence of V in the Outokumpu deposit suggests that  $V^{3+}$  could have been incorporated in the epidote-group minerals, but Treloar & Charnley (1987) did not analyze V. Another indication of missing cations in the analytical data of Treloar & Charnley (1987) is the sum of positive charges, which is insufficient to balance 25 negative charges even if all iron is calculated as ferric. A less likely alternative is significant F replacing O on O4 and thus lowering the sum of negative charges. F on O4, however, would not explain the low sum of M cations. There is also a deficit of positive charges (with all Fe as ferric) in some analytical data of “epidote-(Sr)” reported by Ahijado *et al.* (2005) (e.g., analysis Nr. 8). Furthermore, analysis ACNF-8 (Table 7) gives only 2.847 Si pfu, which is anomalously low and probably is an analytical artifact.

*What to do if subgroup and/or mineral name assignment fails?*

(1) Poor or incomplete analyses or analyses from metamict materials are not expected to lead to the correct species name. There are several indicators for questionable analytical data such as  $Si > 3.0$  or  $Si < 2.9$ , vacancies on M sites, or unbalanced charge ( $\Delta$  charge). (2a) Border-line case ( $REE + ACT > 0.5$ , close to 0.5 apfu): It may happen that, due to small amounts of Na, and/or vacancies on the A sites, and/or minor amounts of tetrahedral Al, the charge balance of the formula requires  $M^3[M^{3+}]$  to slightly exceed  $M^3[M^{2+}]$  even if  $A_2[REE + ACT] > 0.5$ . In other words, the dominant valence on M3 is not in agreement with the definition of the allanite subgroup (example: Analysis PF6 in Tables 7 and 8).

*Solution.* Priority must be given to the A2 key site. Because  $A_2[REE + ACT] > 0.5$  and  $O^4F < 0.5$  the mineral is assigned to the allanite

Table 7. Formula calculation based on electron-microprobe analytical data.

Analysis	PF1 <sup>1</sup>	PF2 <sup>1</sup>	PF6 <sup>1</sup>	PF8 <sup>1</sup>	PF11 <sup>1</sup>	ACNF -2 <sup>2</sup>	ACNF -8 <sup>2</sup>	Analysis	BAOZ -11 <sup>3</sup>	BAOZ -C3-7 <sup>3</sup>	OTT 16 -1 <sup>4</sup>	MTT 8 -1 <sup>4</sup>	YTT 51A5 -2 <sup>4</sup>	TC3 <sup>5</sup>	TC9 <sup>5</sup>
SiO <sub>2</sub>	34.38	33.62	33.52	32.14	31.23	34.76	32.80	SiO <sub>2</sub>	31.81	30.77	32.61	31.40	31.21	34.39	34.90
TiO <sub>2</sub>	0.49	0.31	0.44	0.21	0.34	0.00	0.06	TiO <sub>2</sub>	0.03	0.04	0.89	0.78	0.90		
Al <sub>2</sub> O <sub>3</sub>	13.93	16.88	18.16	15.61	18.33	19.35	17.79	Al <sub>2</sub> O <sub>3</sub>	14.34	13.41	13.99	13.70	13.15	18.55	18.89
Cr <sub>2</sub> O <sub>3</sub>	0.71	0.70	0.82	0.40	0.42			Cr <sub>2</sub> O <sub>3</sub>						4.91	4.95
V <sub>2</sub> O <sub>3</sub>	8.89	8.06	6.78	8.46	0.97			Fe <sub>2</sub> O <sub>3</sub>	7.52	7.62					
Fe <sub>2</sub> O <sub>3</sub>						15.42	18.42	Mn <sub>2</sub> O <sub>3</sub>	13.93	13.27					
FeO*	11.42	6.55	4.39	8.34	9.58			FeO*			15.57	16.10	15.48	2.84	2.70
MgO	0.09	1.25	0.62	0.4	0.14	0.00	0.05	MgO	0.56	0.54	0.84	0.41	0.90	3.01	2.92
MnO	1.90	1.40	1.14	1.26	1.21	0.14	0.44	MnO			0.66	0.67	0.99		
CaO	17.78	14.24	14.82	11.76	10.99	15.91	16.13	ZnO	0.74	0.69					
SrO						10.76	11.64	CaO	12.08	11.16	9.95	9.13	9.54	13.95	14.19
BaO						0.10	0.04	PbO	6.08	9.86					
Na <sub>2</sub> O	0.06	0.12	0.06	0.17	0.14	0.00	0.01	Na <sub>2</sub> O	0.19	0.13					
K <sub>2</sub> O						0.01	0.01	K <sub>2</sub> O	0.02	0.00					
La <sub>2</sub> O <sub>3</sub>	3.88	6.74	7.48	4.23	4.95			La <sub>2</sub> O <sub>3</sub>	3.88	4.55	5.77	4.80	5.95	9.24	9.21
Ce <sub>2</sub> O <sub>3</sub>	3.54	5.56	6.78	8.76	12.18			Ce <sub>2</sub> O <sub>3</sub>	3.11	1.20	11.25	10.81	11.76	9.43	9.08
Pr <sub>2</sub> O <sub>3</sub>	0.20	0.33	0.38	1.43	1.06			Pr <sub>2</sub> O <sub>3</sub>			1.09	1.21	1.17		
Nd <sub>2</sub> O <sub>3</sub>	0.50	1.00	0.78	3.95	4.32			Nd <sub>2</sub> O <sub>3</sub>	1.57	1.07	3.61	4.51	3.83	1.29	1.31
Sm <sub>2</sub> O <sub>3</sub>	0.10	0.21	0.21	0.57	0.61			Sm <sub>2</sub> O <sub>3</sub>			0.47	0.80	0.46	0.24	0.24
Gd <sub>2</sub> O <sub>3</sub>				0.28	0.52			Dy <sub>2</sub> O <sub>3</sub>							
Dy <sub>2</sub> O <sub>3</sub>				0.30	0.34			Y <sub>2</sub> O <sub>3</sub>			0.29	0.48	0.43	0.14	0.16
Y <sub>2</sub> O <sub>3</sub>	0.11	0.14	0.17	0.12	0.12			ThO <sub>2</sub>			1.75	2.17	1.83		
F	nd	0.31	0.28	nd	0.19			Total	95.86	94.31	98.74	96.97	97.60	97.99	98.55
O=F	0	0.13	0.12	0	0.08			Norm.	Σ = 8	Σ = 8	Si = 3	Si = 3	Si = 3	Si = 3	Si = 3
Total	97.98	97.29	96.71	98.39	97.56	96.45	97.39	Si	3.012	3.035	3.0	3.0	3.0	3.0	3.0
Norm.	Σ = 8	Σ = 8	Σ = 8	Σ = 8	Σ = 8	Σ = 8	Σ = 8	Ti	0.002	0.003	0.062	0.056	0.065		
Si	2.977	2.997	3.023	2.972	2.965	3.003	2.847	Al	1.600	1.559	1.518	1.543	1.491	1.907	1.914
Al	0.023	0.003	0	0.028	0.035	0	0.153	Cr						0.339	0.336
Σ Z	3	3	3.023	3	3	3.003	3	Fe <sup>3+</sup>	0.536	0.566	1.080	0.912	0.735	0.207	0.194
Ti	0.032	0.021	0.030	0.015	0.024	0.00	0.004	Fe <sup>2+</sup>			0.117	0.375	0.509		
Al	1.399	1.770	1.930	1.673	2.016	1.970	1.667	Mg	0.079	0.079	0.115	0.058	0.129	0.391	0.374
Cr	0.049	0.049	0.059	0.029	0.032			Mn <sup>3+</sup>	0.576	0.579					
V	0.617	0.576	0.490	0.627	0.074			Mn <sup>2+</sup>	0.155	0.164	0.051	0.054	0.081		
Fe <sup>3+</sup>	0.636	0.045		0.040	0.004	1.002	1.203	Zn	0.052	0.050					
Fe <sup>2+</sup>	0.191	0.373	0.331	0.561	0.757			Σ M	3.000	3.000	2.943	2.998	3.010	2.844	2.818
Mg	0.012	0.166	0.083	0.055	0.020		0.006	Mn <sup>2+</sup>	0.273	0.253					
Mn <sup>2+</sup>	0.064	0	0.077	0	0.073			Ca	1.226	1.179	0.981	0.935	0.982	1.304	1.307
Mn <sup>3+</sup>						0.010	0.032	Pb	0.155	0.262					
Σ M	3	3	3	3	3	2.982	2.912	Na	0.035	0.025					
Mn <sup>2+</sup>	0.075	0.106	0.010	0.099	0.024			REE	0.299	0.246	0.761	0.793	0.835	0.651	0.632
Fe <sup>2+</sup>		0.070		0.044				Th			0.037	0.047	0.040		
Ca	1.650	1.360	1.432	1.165	1.118	1.472	1.500	REE+Th	0.299	0.246	0.798	0.840	0.875	0.651	0.632
Sr						0.539	0.585	Σ A	1.988	1.965	1.779	1.775	1.857	1.955	1.939
Ba						0.003	0.001	Σ cat.charge	25	25	25	25	25	24.70	24.59
Na	0.01	0.015	0.011	0.030	0.026		0.001	Σ an.charge	25	25	25	25	25	25	25
K						0.001	0.001	Δ charge	0	0	0	0	0	-0.30	-0.41
REE	0.265	0.449	0.525	0.662	0.832										
Σ A	2.000	2.000	1.978	2.000	2.000	2.015	2.088								
F	0	0.087	0.080	0	0.057										
Σ cat.charge	25	24.91	25.10	25	24.94	24.99	24.75								
Σ an.charge	25	24.91	24.92	25	24.94	25	25								
Δ charge	0	0	+0.18	0	0	-0.01	-0.25								

<sup>1</sup>Pan & Fleet (1991); <sup>2</sup>Ahijado *et al.* (2005); <sup>3</sup>Bermanec *et al.* (1994); <sup>4</sup>Chesner & Ettliger (1989); <sup>5</sup>Treloar & Charnley (1987); \* total iron content given as FeO. All calculations were done for three decimals to reduce rounding errors (although only two decimals may be significant).

Table 8. Distribution of ions on key sites and derivation of mineral name based on electron-microprobe analytical data listed in Table 7.

	A1	A2	M1	M2	M3	O4	<i>subgroup mineral name</i>
PF1 <sup>1</sup>	2+	2+	3+	3+	3+	2-	<i>clinozoisite</i>
	0.075 Mn <sup>2+</sup> 0.010 Na <u>0.925 Ca</u>	<u>0.726 Ca</u> 0.265 REE	<u>0.520 V<sup>3+</sup></u> 0.049 Cr 0.032 Ti 0.399 Al	Al	0.064 Mn <sup>2+</sup> 0.191 Fe <sup>2+</sup> 0.012 Mg <u>0.636 Fe<sup>3+</sup></u> 0.097 V <sup>3+</sup>	0.000 F	vanadoepidote*
PF2 <sup>1</sup>	2+	2+	3+	3+	2+ !!	2-	<i>clinozoisite</i> <sup>s</sup>
	0.106 Mn <sup>2+</sup> 0.070 Fe <sup>2+</sup> 0.015 Na <u>0.809 Ca</u>	<u>0.551 Ca</u> 0.449 REE	0.160 V <sup>3+</sup> 0.049 Cr 0.021 Ti <u>0.770 Al</u>	Al	0.373 Fe <sup>2+</sup> 0.166 Mg 0.045 Fe <sup>3+</sup> <u>0.416 V<sup>3+</sup></u>	0.087 F	mukhinite <sup>s</sup>
PF6 <sup>1</sup>	2+	3+	3+	3+	3+ !!	2-	<i>allanite</i> <sup>s</sup>
	0.010 Mn <sup>2+</sup> 0.011 Na <u>0.979 Ca</u>	0.453 Ca <u>0.525 REE</u> 0.022 #	0.040 Cr 0.030 Ti <u>0.930 Al</u>	Al	0.077 Mn <sup>2+</sup> <u>0.331 Fe<sup>2+</sup></u> 0.083 Mg 0.490 V <sup>3+</sup> 0.019 Cr	0.080 F	(V <sup>3+</sup> -rich) allanite-(La) <sup>s</sup>
PF8 <sup>1</sup>	2+	3+	3+	3+	2+	2-	<i>allanite</i>
	0.099 Mn <sup>2+</sup> 0.044 Fe <sup>2+</sup> 0.030 Na <u>0.827 Ca</u>	0.338 Ca <u>0.662 REE</u>	0.283 V <sup>3+</sup> 0.029 Cr 0.015 Ti <u>0.673 Al</u>	Al	<u>0.561 Fe<sup>2+</sup></u> 0.055 Mg 0.040 Fe <sup>3+</sup> 0.344 V <sup>3+</sup>	0.000 F	(V <sup>3+</sup> -rich) allanite-(Ce)
PF11 <sup>1</sup>	2+	3+	3+	3+	2+	2-	<i>allanite</i>
	0.024 Mn <sup>2+</sup> 0.026 Na <u>0.950 Ca</u>	0.168 Ca <u>0.832 REE</u>	1.000 Al	Al	0.073 Mn <sup>2+</sup> <u>0.757 Fe<sup>2+</sup></u> 0.020 Mg 0.004 Fe <sup>3+</sup> 0.074 V <sup>3+</sup> 0.032 Cr 0.024 Ti 0.016 Al	0.057 F	allanite-(Ce)
ACNF-2 <sup>2</sup>	2+	2+	3+	3+	3+	2-	<i>clinozoisite</i>
	0.001 Na <u>0.999 Ca</u>	0.473 Ca <u>0.539 Sr</u> 0.003 Ba 0.001 K	0.012 Fe <sup>3+</sup> <u>0.970 Al</u> 0.018 #	Al	0.010 Mn <sup>3+</sup> <u>0.990 Fe<sup>3+</sup></u>	0.000 F	epidote-(Sr)*
ACNF-8 <sup>2</sup>	2+	2+	3+	3+	3+	2-	<i>clinozoisite</i>
	0.001 Na <u>0.999 Ca</u>	0.501Ca <u>0.585 Sr</u> 0.001Ba 0.001K	0.241Fe <sup>3+</sup> <u>0.667Al</u> 0.004 Ti 0.088 #	Al	0.006 Mg 0.032 Mn <sup>3+</sup> <u>0.962 Fe<sup>3+</sup></u>	0.000 F	epidote-(Sr)*
BAOZ-11 <sup>3</sup>	2+	2+	3+	3+	3+	2-	<i>clinozoisite</i>
	0.273 Mn <sup>2+</sup> 0.035 Na <u>0.692 Ca</u>	<u>0.534 Ca</u> 0.299 REE 0.155 Pb 0.012 #	0.398 Fe <sup>3+</sup> 0.002 Ti <u>0.600 Al</u>	Al	0.155 Mn <sup>2+</sup> <u>0.576 Mn<sup>3+</sup></u> 0.052 Zn 0.079 Mg 0.138 Fe <sup>3</sup>	0.000 F	piemontite
BAOZ-C3-7 <sup>3</sup>	2+	2+	3+	3+	3+	2-	<i>clinozoisite</i>
	0.253 Mn <sup>2+</sup> 0.025 Na <u>0.722 Ca</u>	<u>0.457 Ca</u> 0.246 REE 0.262 Pb 0.035 #	0.438 Fe <sup>3+</sup> <u>0.559 Al</u>	Al	0.164 Mn <sup>2+</sup> <u>0.579 Mn<sup>3+</sup></u> 0.050 Zn 0.079 Mg 0.128 Fe <sup>3+</sup>	0.000 F	piemontite
OTT16-1 <sup>4</sup>	2+	3+	3+	3+	3+!!	2-	<i>allanite</i> <sup>s</sup>
	<u>0.981 Ca</u> 0.019 #	<u>0.798</u> REE + Th 0.202 #	0.363 Fe <sup>3+</sup> 0.062 Ti <u>0.518 Al</u> 0.057 #	Al	0.051 Mn <sup>2+</sup> <u>0.117 Fe<sup>2+</sup></u> 0.115 Mg 0.717 Fe <sup>3+</sup>	0.000 F	allanite-(Ce) <sup>s</sup>



Table 8. (continued)

	A1	A2	M1	M2	M3	O4	subgroup mineral name
MTT8-1 <sup>4</sup>	2+	3+	3+	3+	3+!!	2-	<i>allanite</i> <sup>s</sup>
	0.935 Ca 0.065 #	0.840 REE + Th 0.160 #	0.399 Fe <sup>3+</sup> 0.056 Ti 0.543 Al 0.002 #	Al	0.054 Mn <sup>2+</sup> 0.375 Fe <sup>2+</sup> 0.058 Mg 0.513 Fe <sup>3+</sup>	0.000 F	allanite-(Ce) <sup>s</sup>
YTT51A5-2 <sup>4</sup>	2+	3+	3+	3+	2+	2-	<i>allanite</i>
	0.982 Ca 0.018 #	0.875 REE + Th 0.125 #	0.454 Fe <sup>3+</sup> 0.065 Ti 0.491 Al	Al	0.081 Mn <sup>2+</sup> 0.509 Fe <sup>2+</sup> 0.129 Mg 0.281 Fe <sup>3+</sup>	0.000 F	allanite-(Ce)
TC-3 <sup>5</sup>	2+	3+	3+	3+	3+ !!	2-	<i>allanite</i> <sup>s</sup>
	1.000 Ca	0.304 Ca 0.651 REE 0.045 #	0.844 Al 0.156 #	Al	0.391 Mg 0.207 Fe <sup>3+</sup> 0.339 Cr 0.063 Al	0.000 F	dissakisite-(Ce) <sup>s</sup>
TC-9 <sup>5</sup>	2+	3+	3+	3+	3+ !!	2-	<i>allanite</i> <sup>s</sup>
	1.000 Ca	0.307 Ca 0.632 REE 0.061 #	0.818 Al 0.182 #	Al	0.374 Mg 0.194 Fe <sup>3+</sup> 0.336 Cr 0.096 Al		dissakisite-(La) <sup>s</sup>

Note: \* Recommended names: However, these names are not acceptable without corresponding new mineral approval by IMA CNMMN; <sup>s</sup>subgroup and/or name assignment fails with the standard procedure (for solution see appendix).

<sup>1</sup>Pan & Fleet (1991); <sup>2</sup>Ahijado *et al.* (2005); <sup>3</sup>Bermanec *et al.* (1994); <sup>4</sup>Chesner & Ettliger (1989); <sup>5</sup>Treloar & Charnley (1987).

subgroup and the species name is determined by the dominant M<sup>2+</sup> on M3.

(2b) Border-line case (REE + ACT < 0.5, close to 0.5 apfu); it may happen that, due to small amounts of Th<sup>4+</sup> on the A2 site, and/or Si slightly exceeding 3.00, and/or minor amounts of octahedral Ti<sup>4+</sup>, Sn<sup>4+</sup>, and/or significant F on O4, the charge balance of the formula requires M<sup>3</sup>[M<sup>2+</sup>] to slightly exceed M<sup>3</sup>[M<sup>3+</sup>] even if A<sup>2</sup>[REE<sup>3+</sup>] < 0.5 (example: Analysis PF2 in Tables 7 and 8).

*Solution.* Priority must be given to the A2 key site. Because A<sup>2</sup>[REE + ACT] < 0.5 the mineral is assigned to the clinozoisite subgroup and the species name is determined by the dominant M<sup>3+</sup> on M3.

(3) A<sup>2</sup>[REE + ACT] partly charge-balanced by vacancies: We may suspect a certain degree of metamictization (examples OTT16-1 and MTT8-1 in Tables 7 and 8).

*Solution:* In analogy to (2a).

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