

Nomenclature and classification of the aeschynite-group minerals

ZHEYING ZHU^{1,*}, HONG YU^{1,†}, CAN RAO², ZHENYU CHEN¹, BIN WU^{3,‡}, RUCHENG WANG^{4,5}, AND DENGHONG WANG¹

¹MNR Key Laboratory of Metallogeny and Mineral Assessment, Institute of Mineral Resource CAGS, Beijing 100037, China

²Key Laboratory of Geoscience Big Data and Deep Resource of Zhejiang Province, School of Earth Sciences, Zhejiang University, Hangzhou 310027, China

³National Key Laboratory of Uranium Resources Exploration-Mining and Nuclear Remote Sensing, East China University of Technology, Nanchang 330013, China

⁴State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, Xianlin University Town, Nanjing 210023, China

⁵Frontiers Science Center for Critical Earth Material Cycling, Nanjing University, Nanjing 210023, China

ABSTRACT

The nomenclature and classification of the aeschynite-group minerals were reassessed in accordance with the latest IMA-CNMNC rules governing end-member formulas. The aeschynite group minerals have the general formula AB_2O_6 , where the *A* site is occupied by the rare earth elements (REEs) (mainly lanthanides and Y), Ca, Th, and U, and the *B* site is occupied by Ti, Nb, or Ta. These minerals have isostructural crystal structures, which are currently assigned to the orthorhombic crystal system with the standard space group *Pnma* (#62) and H-M symbol $2/m\ 2/m\ 2/m$. Based on the newly adopted IMA-CNMNC guidelines (i.e., valency-imposed double-site occupancy), the substitution mechanism in the aeschynite group can be expressed as: ${}^A\text{REEs}^{3+} + {}^B\text{Ti}^{4+} \leftrightarrow {}^A\text{Ca}^{2+} + {}^B(\text{Nb,Ta})^{5+}$. Consequently, to preserve electroneutrality, the end-member compositions of the aeschynite group correspond to vigezzite CaNb_2O_6 , rynersonite CaTa_2O_6 , aeschynite $\text{REE}(\text{TiNb})\text{O}_6$, and tantal aeschynite $\text{REE}(\text{TiTa})\text{O}_6$. The “aeschynite” and “niobaeschynite” series (e.g., $-\text{[Ce]}$) have identical end-member components $[\text{Ce}(\text{TiNb})\text{O}_6]$ and $[\text{Ce}(\text{NbTi})\text{O}_6]$, and do not form a distinct solid-solution series. Therefore, niobaeschynite is discredited and subsumed into the aeschynite group, as the root-name aeschynite was established earlier. In total, seven valid end-members of the aeschynite group are proposed here: rynersonite CaTa_2O_6 ; vigezzite CaNb_2O_6 , aeschynite-(Ce) $\text{Ce}(\text{TiNb})\text{O}_6$, aeschynite-(Nd) $\text{Nd}(\text{TiNb})\text{O}_6$, aeschynite-(Y) $\text{Y}(\text{TiNb})\text{O}_6$, tantal aeschynite-(Y) $\text{Y}(\text{TiTa})\text{O}_6$, and tantal aeschynite-(Ce) $\text{Ce}(\text{TiTa})\text{O}_6$. The IMA-CNMNC-endorsed nomenclature and classification scheme for the aeschynite group fully capture the chemical diversity of the aeschynite-group minerals and convey the key chemical insights of the group to mineralogists, economic geologists, and industrial practitioners.

Keywords: Aeschynite group, dominant-valency rule, site-total-charge approach, nomenclature, classification

INTRODUCTION

The aeschynite-group minerals (AGMs) are a series of complex oxides, with the general formula AB_2O_6 . The large-cation *A* site is occupied by rare earth elements (REEs), calcium (Ca), thorium (Th), and uranium (U), whereas titanium (Ti), niobium (Nb), tantalum (Ta), and tungsten (W) occupy the *B* site. The acronym “REEs” is used in accordance with the International Union of Pure and Applied Chemistry (IUPAC) definition: the rare earth elements (REEs) are a group of 17 chemical elements comprising the 15 lanthanides plus Sc and Y. However, in this paper, the “REEs” refer specifically to the lanthanides and Y (excluding Sc), which is also denoted as “Ln + Y.” The AGMs occur mainly in rare-metal deposits, such as granitic pegmatites enriched in Nb-Y-F (e.g., Foord and Mrose 1978; Černý and Ercit 2005; Guastoni et al. 2008), alkaline to agpatic igneous

rocks (e.g., Liu et al. 2025), carbonatites (e.g., Yang et al. 2001), kimberlite (e.g., Edwards et al. 1992), hydrothermal veins (e.g., Trimouns, France, Alps, Deliens 1991), and trachytic rocks (Wang et al. 2021).

The chemical variability of several AGMs results from multiple homovalent and heterovalent substitutions, is well documented, and is formally recognized in the official International Mineralogical Association Commission on New Minerals, Nomenclature and Classification (IMA-CNMNC) list of mineral names. To date, aeschynite-group nomenclature has largely followed the dominant-constituent rule (Nickel 1992; Nickel and Grice 1998), which is inconsistent with the updated IMA CNMNC definition of an end-member (Hawthorne 2002). Furthermore, many “ideal formulae” listed for AGMs in the IMA-CNMNC database are empirically simplified representations rather than rigorously derived end-member formulas. Accordingly, this paper used the IMA-CNMNC-approved voting proposal “Nomenclature and classification of the aeschynite group,” adopted in May 2025 (MEMORANDUM 134-SM25;

* Corresponding author E-mail: zhuzheyin_nju@163.com Orcid <https://orcid.org/0009-0007-7076-4769>

† Orcid <https://orcid.org/0000-0001-7831-1106>

‡ Orcid <https://orcid.org/0000-0002-8958-3702>

Bosi et al. 2025), to clarify, revise, and formally redefine the nomenclature and classification of the aeschynite group in strict accordance with these standards (Hatert and Burke 2008; Bosi et al. 2019a, 2019b). Given the widespread occurrence of AGMs in Nb-Ta deposits, their nomenclature and classification are important from mineralogical, petrological, geochemical, and applied geological perspectives.

HISTORICAL NOMENCLATURE OF THE AESCHYNITE GROUP

The nomenclature of minerals in the aeschynite group has been a persistent historical issue. The aeschynite (often erroneously spelled “eschynite”) was first found by J.N. Menge in 1825 at the Gadolinite Pit, Ilmen, Ural, Russia. It was initially thought to be gadolinite, but later the material was analyzed by Victor Hartwall in the laboratory of the Swedish chemist Jöns Jacob Berzelius and recognized as a new mineral. Berzelius (1830) first gave it the name zirconia titanate, and later aeschynite, derived from the Greek word αἰσχύνη (“aeschyne”) for “shame,” which alludes to the fact that early chemists had difficulty separating Ti from Zr in some samples and from the dominant lanthanide element in the mineral (Hintze 1938). Rammelsberg (1875) published the original analysis of Berzelius: SnO₂ 0.5 wt%, TiO₂ 56 wt%, ZrO₂ 20 wt%, Ce₂O₃ 15 wt%, Fe₂O₃ or FeO 2.6 wt%, and CaO 3.8 wt%. Obviously, this aeschynite was a complex oxide of Ti, Zr, and Ce, containing minor Ca, Fe, and Sn.

In addition, the terms “blomstrandine,” “sinicite,” and “priorite” are synonymous with aeschynite, and “priorite” is regarded as being aeschynite-(Y) (Černý and Ercit 1989). Brögger (1879) showed that priorite is a titanitanoniobate of Y, Er, Ca, Fe, and Th, and presented a crystallographic description of priorite from the Urstad Feldspar Mine, Hidra, Vest-Agder, Norway. Priorite was named in honor of G.T. Prior, who was the first person to investigate and document the occurrence of this mineral, which originated from natural rocks. Initially, Brögger (1879) considered priorite to be identical to aeschynite from Miask, Russia. Blömstrandine was then reported and named by Brögger (1906) in honor of Christian Wilhelm Blömstrand, a professor of chemistry at the University of Lund, who undertook the chemical analysis. Brögger (1906) also presented detailed compositional data for both “blomstrandin” and priorite in a comparative table and classified blomstrandin from Hitterö as an “yttrium-Aeschynit” (Table 1).

Subsequently, the concept of the aeschynite-priorite series was adopted, in which the Ce-dominant mineral is aeschynite, and the Y-dominant minerals are priorite and blomstrandin (Adamson 1942; Komkov 1959; Fleischer 1966). Both blomstrandin and priorite are thus justifiably classified as aeschynite-(Y) using the nomenclature of Levinson (1966), given that the root-name “aeschynite” was established earlier. The names priorite and blomstrandine have been formally discredited and are no longer in use.

Rosenblum and Mosier (1975) noted that lyndochite is an Nb-rich variety of aeschynite, originally described by Ellsworth (1927) from a granitic pegmatite dike in Lyndoch Township, Ontario, Canada (the Quadeville Beryl Mine), where it was identified as a Th-rich mineral of the euxenite group and named after

TABLE 1. Blomstrandin-priorite-aeschynite composition from Brögger (1906)

Type locality	Blomstrandin		Priorite Swaziland	Aeschynite Miask
	Hitterö	Arendal		
Nb ₂ O ₅ (wt%)	17.99	23.35	36.68	32.51
Ta ₂ O ₅	0.89	1.15	–	–
TiO ₂	32.91	27.39	21.89	21.2
SnO ₂	0.12	0.18	0.29	–
SiO ₂	0.38	0.4	2.12	–
ZrO ₂	–	1.33	–	–
UO ₂	4.01	5.35	0.49	–
UO ₃	–	–	2.14	–
ThO ₂	7.69	4.28	0.61	17.55
(Y,Er) ₂ O ₃	28.76	25.62	17.11	3.1
(Ce,La,Di) ₂ O ₃	1.97	2.48	4.32	19.41
FeO	1.48	1.43	5.63	3.71
MnO	0.27	0.3	0.19	–
CaO	1.02	1.8	4.12	2.5
ZnO	–	0.09	–	–
PbO	0.06	0.84	–	–
MgO	0.04	0.15	0.22	–
Na ₂ O	0.22	0.9	–	–
K ₂ O	0.19	0.18	–	–
H ₂ O	1.88	2.56	3.69	–
Total	99.88	99.78	99.5	99.98

Note: –: compositions below the detection limit or undetected.

its type locality. Subsequently, Butler (1957) reclassified lyndochite into the aeschynite group based on compositional data, which was a revision later corroborated by Fleischer (1966) and Černý and Ercit (1989). Deliens (1991) subsequently discredited the name lyndochite and introduced the name nioboeschynite-(Y) for the same material. Ercit (2002) reinstated lyndochite as the name of a thorium variety of euxenite, citing new chemical evidence and having identified analytical and interpretive errors in the earlier reclassifications by Butler (1957) and Fleischer (1966).

Levinson (1966) subdivided the aeschynite-priorite series into aeschynite-(Ce), aeschynite-(Nd), and aeschynite-(Y) based on the suffix denoting the dominant REE (Nickel and Mandarino 1987). Chi (1974) named aeschynite-(Y) as taiyite. Tantaloeschynite (REE,Ca)(Ta,Ti,Nb)₂O₆ (Adusumilli et al. 1974) and nioboeschynite-(Ce) (Ce,Ca)(Nb,Ti)₂O₆ (Rosenblum and Mosier 1975) were defined as the end-members having Ta or Nb as the dominant cation instead of Ti. The term tantaloeschynite-(Y) was first applied as tantal-aeschynite, but was changed to tantaloeschynite by the IMA in 2008 (Burke 2008). Nioboeschynite-(Ce) was originally named nioboeschynite (Fleischer 1962), subsequently renamed nioboeschynite-(Ce) (Nickel and Mandarino 1987), and finally named nioboeschynite-(Ce) (Burke 2008). Following this, vigezzite (named after its locality) (Ca,Ce)(Nb,Ta,Ti)₂O₆ (Graeser et al. 1979) and rynersonite (named after the owner of the San Diego Mine) Ca(Ta,Nb)₂O₆ (Foord and Mrose 1978) were defined for the end-member in which Ca is dominant in the A site and pentavalent Nb or Ta is dominant in the B site, which both belong to the aeschynite group and have an identical space group. Bermanec et al. (2008) discovered nioboeschynite-(Y) and named it based on the dominant Nb in the B site and dominant Y in the A site. Recently, the Ta-dominant aeschynite mineral with Ce in the A site was approved by the IMA Committee and named tantaloeschynite-(Ce) (Zhu et al. 2024). The term “aeschynite group” then appeared in

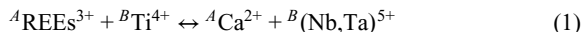
Fleischer's Glossary of Mineral Species 2008 (Back and Mandarino 2008) and its subsequent editions, and is now a common term in the literature. Given a classification based on end-members containing dominant elements, the AGMs were then divided into five subgroups: rynersonite, vigezzite, and aeschynite in which Ti is dominant over Nb or Ta; nioboeschynite in which Nb is dominant over Ti and Ta; and tantaloeschynite in which Ta is dominant in the *B* site.

APPLYING THE IMA RECOMMENDATIONS TO THE AESCHYNITE GROUP

Current IMA Rule for Nomenclature

The primary criterion for mineral nomenclature is based on the prevalence of a chemical constituent at a specific crystallographic site (Nickel and Grice 1998; Hatert and Burke 2008). Nickel (1992) called it the 50% rule for short, which was improved into the 100%/n rule, where *n* represents the number of components (Wenk and Bulakh 2004), and the dominant-constituent rule. This rule was strictly enforced for the majority of approved new mineral proposals, but some exceptions were granted when incorporating heterovalent substitutions at two sites, resulting in end-members defined by double-site occupancy constrained by valency (Hawthorne 2002). Thus, the dominant-valency approach was proposed to identify mineral species via the dominant end-member charge arrangement, and later gave rise to the site total-charge (STC) approach (Bosi et al. 2019a, 2019b). The STC approach enforces formula electroneutrality and defines end-member formulas following Hawthorne (2002) by determining the dominant end-member charge arrangement from the empirical formula and deriving the corresponding dominant end-member formula. Until now, the dominant-valency principle, combined with the STC approach, has been used to redefine numerous mineral groups and super-groups, including arrojadite (Cámara et al. 2006; Chopin et al. 2006; de Wit and Mills 2022), epidote (Armbruster et al. 2006), tourmaline (Henry et al. 2011), gadolinite (Bačík et al. 2017), perovskite (Mitchell et al. 2017), tetrahedrite (Biagioni et al. 2020), columbite super-group (Chukanov et al. 2023), pyrochlore super-group minerals (Bhattacharjee et al. 2022).

Using the dominant-valency approach to address heterovalent substitution in the two sites of the AGMs, the dominant substitution mechanism (Škoda and Novák 2007; Bermanec et al. 2008) is as follows:



According to the substitution, the root-charge arrangements consistent with end-members are vigezzite (CaNb_2O_6) and rynersonite (CaTa_2O_6), which can be derived from REE(TiNb) O_6 or REE(TiTa) O_6 via substitution, in which the REE-bearing end-member requires Nb^{5+} or Ta^{5+} to achieve charge balance with Ti^{4+} (Hawthorne 2002; Hatert and Burke 2008). This section uses the initial aeschynite compositions from type (and other representative) localities and applies both the dominant-valency and STC approaches to determine the end-member formulas of the AGMs (Bosi et al. 2019a).

Approved Minerals Belonging to AGMs

Rynersonite

Rynersonite was first described by Foord and Mrose (1978) as a new species isostructural with synthetic CaTa_2O_6 . It was discovered in the Himalayan pegmatite-aplite dike system and Mesa Grande district, San Diego County, California. It occurs as creamy-white to reddish-pink felted masses of fibrous to lath-like crystals with individual laths <0.5 mm in length and 0.05 mm in thickness, and forms as an alteration product of stibicolumbite-stibiotantalite, intimately associated with minor amounts of antimonian microlite and fersmite. The mineral is rich in Ca (CaO 13–13.8 wt%), Ta (Ta_2O_5 58.4–66.6 wt%), and Nb (Nb_2O_5 14.2–22.7 wt%). The formulas were calculated as $\text{Ca}_{1.11}(\text{Ta}_{1.44}\text{Nb}_{0.51})\text{O}_6$, $\text{Ca}_{1.16}(\text{Ta}_{1.24}\text{Nb}_{0.69})\text{O}_6$, and $\text{Ca}_{1.05}(\text{Ta}_{1.21}\text{Nb}_{0.77})\text{O}_6$, with the Ta:Nb ratio ranging from 0.74:0.26 to 0.61:0.39, which is also reflected by variations in mineral color. However, only the last of these three derived formulas is charge-balanced. Thus, only the third formula was used to calculate the end-member composition of rynersonite. For the resulting formula $\text{Ca}_{1.05}(\text{Ta}_{1.21}\text{Nb}_{0.77})\text{O}_6$, the STC of the *A* site is +2.10 (close to +2) and of the *B* site is +9.9 (close to +10). This composition is consistent with the charge arrangement of the rynersonite end-member [i.e., $A(2^+)B(5_2^+)\text{O}_6$]. Given the predominance of Ta over Nb in the *B* site, the definitive end-member formula of rynersonite is CaTa_2O_6 .

Rynersonite is scarce, but has also been discovered in the Wampewo pegmatites, Uganda, where it has exceptionally high Ta (Ta_2O_5 = 74.6 wt%) and low Nb (Nb_2O_5 = 10.23 wt%) contents (Von Knorring and Fadipe 1981). It also occurs as inclusions in wodginite and manganotantalite in the petalite pegmatites of the Vishnyakovskoye field, Russia (Makagon 2007), where the Ta# values [$\text{Ta}/(\text{Ta}+\text{Nb})$] are 0.73–0.74 (Novák et al. 2003). Along with microlite and stibiotantalite, rynersonite underwent hydrothermal alteration during various stages of subsolidus re-equilibration of the pegmatites (Staněk 1963; Ercit et al. 1993; Novák and Šrein 1998). In contrast, at Chvalovice, rynersonite occurs as a primary mineral enclosed in amblygonite, has Ta# = 0.68–0.71, and contains minor to trace amounts of W, Pb, Sn, Fe, and Mn (Novák and Černý 1998). Refer to the Online Materials¹ for more details on the calculation process.

Vigezzite

Vigezzite, with a simplified formula of $(\text{Ca,Ce})(\text{Nb,Ta,Ti})_2\text{O}_6$, was first discovered near Orcesco, Valle Vigezzo, Novara, Northern Italy (Graeser et al. 1979). It occurs as flat prismatic crystals up to 2–3 mm long, with an orange-yellow color and elongate along the *a*-axis and flattened on (010). The associated minerals are typical Nb minerals, such as pyrochlore, columbite, and fersmite, intergrown within an albitic rock of presumably pegmatitic origin. The average of 12 spot analyses reported by Graeser et al. (1979) indicates the empirical formula as $(\text{Ca}_{0.82}\text{Ce}_{0.24})_{\Sigma 1.06}(\text{Nb}_{0.9}\text{Ta}_{0.62}\text{Ti}_{0.5})_{\Sigma 2.02}\text{O}_6$, exhibiting heterogeneity in composition with the Nb# ratio [$\text{Nb}/(\text{Nb}+\text{Ta})$] ranging from 0.55 to 0.62. For the *A* site, the STC is +2.36 (close to +2), and divalent Ca predominates over trivalent Ce. For the *B* site, the STC is +9.6 (close to +10) and the total occupancy of pentavalent Nb and Ta (1.52 atoms per

formula unit, apfu) exceeds that of quadrivalent Ti (0.5 apfu). Considering the possible end-member charge arrangements (Table 2), the $A(2^+)B(5^+)O_6$ prevails over $A(3^+)B(4^+5^+)O_6$ and $A(4^+)B(4^+)O_6$ in terms of a higher apfu. The end-member CaNb_2O_6 yields an aggregate charge arrangement of 0.45 apfu (limited by the amount of Nb), which is larger than that of CaTa_2O_6 (0.31 apfu; limited by the amount of Ta). As such, the end-member formula of vigezzite is CaNb_2O_6 .

Guastoni et al. (2008) subsequently documented the occurrence of vigezzite in the Alpe Rosso pegmatite of the Vigizzo Valley, Western Alps, Italy. The vigezzite crystals were embedded in massive albite, associated with albite and tremolite, and described as brown to reddish, millimeter-sized, platy prisms with occasional dark cores resulting from thorium enrichment. The vigezzite displays significant compositional variations from core to rim, with Nb_2O_5 contents of 27.51–36.25 wt%, Ta_2O_5 contents of 32.60–42.04 wt%, TiO_2 of 6.16–10.46 wt%, and CaO of 8.69–13.61 wt% (Guastoni et al. 2008). The cores are distinguished by substantial enrichment of REEs, with Ce_2O_3 up to 4.51 wt%, Nd_2O_3 up to 1.39 wt%, Sm_2O_3 up to 0.88 wt%, and Gd_2O_3 up to 0.51 wt%. In certain localized areas of the dark reddish cores, ThO_2 can be up to 8.65 wt%. Representative vigezzite and thorian vigezzite were calculated to have formulas of $(\text{Ca}_{0.981}\text{Mn}_{0.008}\text{Ce}_{0.002})_{\Sigma 0.991}(\text{Nb}_{1.577}\text{Ta}_{0.377}\text{Ti}_{0.062})_{\Sigma 2.016}\text{O}_6$ and $(\text{Ca}_{0.638}\text{Th}_{0.126}\text{Ce}_{0.098}\text{Fe}_{0.035}\text{Nd}_{0.033}\text{Sm}_{0.02}\text{Gd}_{0.009})_{\Sigma 0.959}(\text{Nb}_{0.835}\text{Ta}_{0.675}\text{Ti}_{0.528})_{\Sigma 2.038}\text{O}_6$, respectively. By using the same approach as above, the end-members of vigezzite all belong to CaNb_2O_6 (Table 2).

Aeschnite-(Ce)

Berzelius (1830) reported the composition of aeschnite-(Ce) as follows: 29.64 wt% Nb_2O_5 ; 21.81 wt% TiO_2 ; 18.49 wt% Ce_2O_3 ; 15.75 wt% ThO_2 ; 5.60 wt% $(\text{La},\text{Dy})_2\text{O}_3$; 1.12 wt% $(\text{Y},\text{Er})_2\text{O}_3$; 3.17 wt% FeO ; and 2.75 wt% CaO . This mineral exhibits metamictization and has a loss-on-ignition value of 1.07 wt%, possibly reflecting the presence of F or OH^- . The empirical formula is $(\text{Ce}_{0.42}\text{Th}_{0.22}\text{Ca}_{0.18}\text{Fe}_{0.16}^{2+}\text{La}_{0.13}\text{Y}_{0.04})_{\Sigma 1.15}(\text{Ti}_{1.02}\text{Nb}_{0.83})_{\Sigma 1.95}(\text{O},\text{F},\text{OH})_{\Sigma 6.00}$ (Berzelius 1830). Either F or OH^- is possibly incorporated into the O site, and their contents could not be determined accurately. Applying the dominant-valency rule and STC approach, though the $^A[\text{STC}]$ and $^B[\text{STC}]$ is +3.33 (close to +3) and +8.23 (close to +8), $[A(3^+)B(4^+5^+)O_6]$ occupy the 0.59 apfu (limited by the amounts of Ln+Y), higher than $[A(2^+)B(5^+)O_6]$ (0.34 apfu) and $[A(4^+)B(4^+)O_6]$ (0.22 apfu) (Table 3). At the A site, Ce dominates the trivalent elements, and tetravalent Ti and pentavalent Nb both occupy the B site to maintain electroneutrality. Thus, the end-member formula of aeschnite-(Ce) is $\text{Ce}(\text{TiNb})\text{O}_6$.

The composition of nioboaeschnite-(Ce) from the Vishnev Mountains was first reported by Zhabin et al. (1960), and is characterized by a higher Nb than Ti content in the B site, with $\text{Nb}_2\text{O}_5 = 41.41$ wt%, $\text{TiO}_2 = 18.73$ wt%, and $\text{Nb}:\text{Ti} = 1.05:0.79$. It also contains 28.17 wt% REE_2O_3 (primarily Ce_2O_3), 4.82 wt% CaO , and a small amount of Fe ($\text{Fe}_2\text{O}_3 = 2.75$ wt%). Its chemical formula is $(\text{REE}_{0.61}\text{Ca}_{0.31}\text{Fe}_{0.14}\text{Th}_{0.03})_{1.09}(\text{Nb}_{1.12}\text{Ti}_{0.84}\text{Si}_{0.02}\text{Al}_{0.02})_{2.00}(\text{O},\text{OH})_6$ (Zhabin et al. 1960). $^A[\text{STC}]$ and $^B[\text{STC}]$ were calculated as +2.99 (close to +3) and +9.10 (close

TABLE 2. List of the site total charges of vigezzite and possible charge and atomic arrangements

Empirical formula	Vigezzite (Graeser et al. 1979)		Vigezzite (Guastoni et al. 2008)	
	$(\text{Ca}_{0.82}\text{Ce}_{0.24})_{\Sigma 1.06}(\text{Nb}_{0.9}\text{Ta}_{0.62}\text{Ti}_{0.5})_{\Sigma 2.02}\text{O}_6$ +2.1 (close to +2) +9.9 (close to +10)	$(\text{Ca}_{0.981}\text{Mn}_{0.008}\text{Ce}_{0.002})_{\Sigma 0.991}(\text{Nb}_{1.577}\text{Ta}_{0.377}\text{Ti}_{0.062})_{\Sigma 2.016}\text{O}_6$ +1.98 (close to +2) +10.02 (close to +10)	$(\text{Ca}_{0.638}\text{Th}_{0.126}\text{Ce}_{0.098}\text{Fe}_{0.035}\text{Nd}_{0.033}\text{Sm}_{0.02}\text{Gd}_{0.009})_{\Sigma 0.959}(\text{Nb}_{0.835}\text{Ta}_{0.675}\text{Ti}_{0.528})_{\Sigma 2.038}\text{O}_6$ +2.33 (close to +2) +9.66 (close to +10)	$(\text{Ca}_{0.638}\text{Th}_{0.126}\text{Ce}_{0.098}\text{Fe}_{0.035}\text{Nd}_{0.033}\text{Sm}_{0.02}\text{Gd}_{0.009})_{\Sigma 0.959}(\text{Nb}_{0.835}\text{Ta}_{0.675}\text{Ti}_{0.528})_{\Sigma 2.038}\text{O}_6$ +2.33 (close to +2) +9.66 (close to +10)
$^A[\text{STC}]$	0.31 (limited by the amount of Ta)	0.19 (limited by the amount of Ta)	0.34 (limited by the amount of Ta)	0.34 (limited by the amount of Ta)
$^B[\text{STC}]$	0.45 (limited by the amount of Nb)	0.79 (limited by the amount of Nb)	0.79 (limited by the amount of Nb)	0.42 (limited by the amount of Nb)
CaTa_2O_6	0.24 (limited by the amount of Ce)	0.002 (limited by the amount of Ce)	0.002 (limited by the amount of Ce)	0.098 (limited by the amount of Ce)
CaNb_2O_6	0.24 (limited by the amount of Ce)	0.002 (limited by the amount of Ce)	0.002 (limited by the amount of Ce)	0.098 (limited by the amount of Ce)
End-member formula	CaNb_2O_6	CaNb_2O_6	CaNb_2O_6	CaNb_2O_6

TABLE 3. List of the site total charges and possible atomic arrangements of aeschynite and nioboaeschynite minerals

	Aeschynite-(Ce) (Berzelius 1830)	Nioboaeschynite-(Ce) (Zhabin et al. 1960)	Aeschynite-(Nd) (Zhang and Tao 1982)	"Nioboaeschynite-(Nd)" (Yang et al. 2001)	Aeschynite-(Y) (Brögger 1906)	Nioboaeschynite-(Y) (Guastoni et al. 2019)
Empirical formula	[1]	[2]	[3]	[4]	[5]	[6]
$A[STC]$	+3.33	+2.99	+3.01	+2.87	+3.47	+2.98
$B[STC]$	+8.23	+9.1	+8.49	+9.08	+8.5	+9.06
$[A(2^{+})B(5^{+})O_6]$	0.34 (limited by the amounts of Ca+Fe)	0.45 (limited by the amounts of Ca+Fe)	0.08 (limited by the amounts of Ca+Mg)	0.151 (limited by the amounts of Ca+Fe+Sr+Ba)	0.13 (limited by the amounts of Ca+Fe)	0.316 (limited by the amounts of Ca+Mn)
$[A(3^{+})B(4^{+}5^{+})O_6]$	0.59 (limited by the amounts of Ln+Y)	0.61 (limited by the amounts of Ln+Y)	0.80 (limited by the amounts of Ln+Y)	0.85 (limited by the amounts of Ln+Y)	0.45 (limited by the amounts of Nb+Ta)	0.53 (limited by the amounts of Y+Ln)
$[A(4^{+})B(4^{+})O_6]$	0.22 (limited by the amounts of Th)	0.03 (limited by the amounts of Th)	0.11 (limited by the amounts of Th)	0.004 (limited by the amounts of Th)	0.15 (limited by the amounts of Th+U)	0.189 (limited by the amounts of Th+U)
End-member formula	Ce(TiNb)O ₆	Ce(NbTi)O ₆	Nd(TiNb)O ₆	Nd(NbTi)O ₆	Y(TiNb)O ₆	Y(NbTi)O ₆

Notes:

[1] $(Ce_{0.42}Th_{0.22}Ca_{0.18}Fe_{0.12}La_{0.13}Y_{0.04})_{\Sigma 1.15}(Ti_{1.02}Nb_{0.83})_{\Sigma 1.95}(O.F.OH)_{\Sigma 6.00}$.[2] $(TREe_{0.61}Ca_{0.31}Fe_{0.14}Th_{0.03})_{\Sigma 1.09}(Nb_{1.12}Ti_{0.84}Si_{0.02}Al_{0.02})_{\Sigma 2.00}(O.OH)_{\Sigma 6}$.[3] $(Nd_{0.4}Ce_{0.16}Pr_{0.06}Sm_{0.1}Eu_{0.01}Gd_{0.03}Y_{0.04}Th_{0.11}Ca_{0.05}Mg_{0.03}Na_{0.01})_{\Sigma 1.00}(Ti_{1.29}Nb_{0.58}Fe_{0.06}Al_{0.05}Ta_{0.02})_{\Sigma 2.00}(O_{5.45}OH_{0.55})_{\Sigma 6.00}$.[4] $(Nd_{0.294}Ce_{0.287}Ca_{0.12}Y_{0.066}Pr_{0.058}Sm_{0.055}La_{0.042}Gd_{0.035}Fe_{0.016}Dy_{0.013}Sr_{0.01}Ba_{0.005}Th_{0.004})_{\Sigma 1.005}(Nb_{1.02}Ti_{0.987}Si_{0.008})_{\Sigma 2.015}O_6$.[5] $(Y_{0.83}Th_{0.17}Ca_{0.06}Fe_{0.07}U_{0.05}LREe_{0.04}Na_{0.02})_{\Sigma 1.19}(Ti_{1.34}Nb_{0.44}Ta_{0.01}Si_{0.02})_{\Sigma 1.81}(O.OH)_{\Sigma 6}$.[6] $[(Y_{0.19}Ln_{0.34})_{\Sigma 0.53}Ca_{0.31}Th_{0.18}U_{0.099}Mn_{0.006}La_{0.104}(Nb_{0.94}Ti_{0.92}Ta_{0.07}Fe_{0.11})_{\Sigma 2.04}O_6]$.

to +9), respectively (Table 3). This suggests the formula is $A(3^{+})B(4^{+}5^{+})O_6$ and, adopting the updated methodology endorsed by the IMA, the ideal formula is $Ce(NbTi)O_6$. Given the same end-member components $Ce(TiNb)O_6$ and $Ce(NbTi)O_6$ of aeschynite-(Ce) and nioboaeschynite-(Ce), which represent the same compound, they are equivalent to each other. Because aeschynite-(Ce) was established first, nioboaeschynite-(Ce) is here reclassified as a synonym of aeschynite-(Ce).

Aeschynite-(Nd)

Aeschynite containing Nd as the dominant REE was described by Zhang and Tao (1982) in the giant Bayan Obo Fe-REE-Nb-bearing carbonatite deposit, China. It was first reported to occur in veins within slates and metamorphosed dolomite, associated with aegirine, riebeckite, barite, fluorite, albite, phlogopite, and magnetite. In terms of chemical composition, it contains up to 18.45 wt% Nd_2O_3 , 33.69 wt% Nb_2O_5 , 28.65 wt% TiO_2 , and minor Ta_2O_5 , with a calculated empirical formula of $(Nd_{0.4}Ce_{0.16}Pr_{0.06}Sm_{0.1}Eu_{0.01}Gd_{0.03}Y_{0.04}Th_{0.11}Ca_{0.05}Mg_{0.03}Na_{0.01})_{\Sigma 1.00}(Ti_{1.29}Nb_{0.58}Fe_{0.06}Al_{0.05}Ta_{0.02})_{\Sigma 2.00}(O_{5.45}OH_{0.55})_{\Sigma 6.00}$ (ΣY includes Y and Dy). Applying the dominant-valency rule, $A[STC]$ is calculated to be +3.01 (close to +3), and the A site is occupied mainly by trivalent REEs ($\Sigma REEs = 0.80$ apfu), with Nd being predominant (0.4 apfu). However, $B[STC]$ is +8.49 (close to +8), and the aggregate-charge arrangement $A(3^{+})B(4^{+}5^{+})O_6$ is more abundant (limited by the amounts of REEs; Table 3). As such, the ideal formula of aeschynite-(Nd) is $Nd(TiNb)O_6$, corresponding to the Nd analog of aeschynite-(Ce).

Although the term "nioboaeschynite-(Nd)" has not yet been approved by the IMA, it was reported in the East Orebody of the Bayan Obo Fe-REE-Nb deposit (Yang et al. 2001). This mineral was taken from a single aegirine-fluorite-dolomite-aeschynite vein that crosscuts banded aegirine-magnetite-fluorite ores. The aeschynite aggregate exhibits heterogeneity and is characterized by variations in brightness in backscattered electron (BSE) images. Nioboaeschynite-(Nd) is reported to contain 36.39 wt% Nb_2O_5 , 21.18 wt% TiO_2 , 13.30 wt% Nd_2O_3 , and 12.63 wt% Ce_2O_3 , with low contents of Ta_2O_5 , leading to the empirical formula of $(Nd_{0.294}Ce_{0.287}Ca_{0.12}Y_{0.066}Pr_{0.058}Sm_{0.055}La_{0.042}Gd_{0.035}Fe_{0.016}Dy_{0.013}Sr_{0.01}Ba_{0.005}Th_{0.004})_{\Sigma 1.005}(Nb_{1.02}Ti_{0.987}Si_{0.008})_{\Sigma 2.015}O_6$. $A[STC]$ and $B[STC]$ are +2.87 (close to +3) and +9.08 (close to +9), respectively. The sum of trivalent REEs is 0.85 apfu and much higher than those of divalent elements ($Ca + Fe + Sr + Ba = 0.151$ apfu) or tetravalent elements ($Th = 0.004$ apfu). The Nd content (0.294 apfu) is slightly higher than that of Ce (0.287 apfu; Table 3), resulting in the dominant occupation of the A site by Nd. Both Nb (1.02 apfu) and Ti (0.987 apfu) occupy the B site to maintain the charge balance. However, when calculated into an ideal formula, the result $Nd(NbTi)O_6$ is the same as for aeschynite-(Nd), indicating nioboaeschynite-(Nd) is the Nd analog of nioboaeschynite-(Ce), and thus corresponds to aeschynite-(Nd).

Aeschynite-(Y)

Aeschynite-(Y) is widely distributed in granite and granite pegmatites (Brögger 1906; Guastoni et al. 2019), as well as in

ankerite-dolomitic carbonatites, associated with euxenite, monazite, xenotime, fergusonite, and synchynsite. Brögger (1906) initially presented the chemical composition of blomstrandine, which was determined using wet chemical analytical methods. The analysis (Table 1) yielded a composition of $(Y,Er)_2O_3 = 28.76$ wt%, $TiO_2 = 32.91$ wt%, $Nb_2O_5 = 17.99$ wt%, and minor ThO_2 (7.69 wt%) and UO_2 (4.01 wt%), with a formula of $(Y_{0.83}Th_{0.1}Ca_{0.06}Fe_{0.07}U_{0.05}LREE_{0.04}Na_{0.02})_{\Sigma 1.19}(Ti_{1.34}Nb_{0.44}Ta_{0.01}Si_{0.02})_{\Sigma 1.81}(O,OH)_6$, based on a total of 3 cations. $A[STC]$ and $B[STC]$ are +3.47 (close to +3) and +8.5 (close to +9), respectively, and the aggregate-charge arrangement $A(3^+)B(4^+5^+)O_6$ is also more abundant (0.45 apfu, limited by the amounts of Nb+Ta) than $A(2^+)B(5^+)O_6$ (0.13 apfu, limited by the amounts of Ca+Fe), and $A(4^+)B(4^+)O_6$ (0.15 apfu, limited by the amounts of Th+U, Table 3). Y (0.83 apfu) is dominant over the other trivalent elements and occupies the *A* site, while Nb and Ti occupy the *B* site, leading to the ideal formula $Y(TiNb)O_6$.

Nioboeschynite-(Y) was also approved by the IMA and distinguished from aeschynite-(Y) by its higher Nb content as compared with Ti. Bermanec et al. (2008) declared it a new mineral species and proposed its ideal chemical formula is $[(Y,Ln),Ca,Th](Nb,Ta,Ti,Fe)_2(O,OH)_6$, which is a simplified and not ideal formula. As such, the ideal formula of nioboeschynite-(Y) should be redefined. The empirical formula of nioboeschynite-(Y) derived from the data of Bermanec et al. (2008) is $[(Y_{0.19}Ln_{0.34})Ca_{0.31}Th_{0.18}U_{0.009}Mn_{0.006}]_{\Sigma 1.04}(Nb_{0.94}Ti_{0.92}Ta_{0.07}Fe_{0.11}^{3+})_{\Sigma 2.04}O_6$ based on six O atoms (without H_2O). $A[STC]$ and $B[STC]$ are +2.98 (close to +3) and +9.06 (close to +9), respectively, and the aggregate-charge arrangement $A(3^+)B(4^+5^+)O_6$ is also more abundant (0.53 apfu; limited by the amounts of Y+Ln; Table 3). In the *A* site, trivalent elements are dominant, with Y (0.188 apfu) > Ce (0.109 apfu) and Nd (0.106 apfu), leading to the end-member of nioboeschynite-(Y) having the formula $Y(NbTi)O_6$, equivalent to that of aeschynite-(Y), and thus should be classified as aeschynite-(Y).

Tantaloeschynite-(Y)

Adusumilli et al. (1974) reported two compositions for Ta-rich aeschynite. One was from the Raposa pegmatite, northeastern Brazil, and contains 39.3 wt% Ta_2O_5 , 18.7 wt% Nb_2O_5 , and 11.7 wt% TiO_2 . The corresponding empirical formula

was recalculated based on 6 O atoms as $[(Ca_{0.47}(Y,Ln)_{0.425}(Th,U)_{0.11})_{\Sigma 1.005}(Ti_{0.62}Ta_{0.75}Nb_{0.59}Fe_{0.05}^{3+})_{\Sigma 2.015}O_6]$ with atomic of Ti:Ta:Nb = 0.62:0.75:0.59, which was named tantal-aeschynite. The Y+Ln content (0.425 apfu) is lower than that of Ca (0.47 apfu) in the *A* site, suggesting it cannot be classified as a REE mineral, based on the dominant-valency rule. In the *A* site, divalent Ca is the dominant constituent, while the STC is +2.655 and close to +3. However, the empirical formula yields $A(2^+)B(5^+)O_6$ (0.47 apfu, limited by the amounts of Ca) as the dominant end-member, compared to $A(3^+)B(4^+5^+)O_6$ (0.425 apfu, limited by the amounts of Y+Ln) and $A(4^+)B(4^+)O_6$ (0.11 apfu, limited by the amounts of Th+U; Table 4). This result demonstrates that the end-member is $CaNb_2O_6$, the Nb-dominant analog of rhyersonite, rather than the Ca-analog of aeschynite.

In fact, the presence of $A(4^+)$ cations must be considered in the calculation of the STC due to the existence of the end-member $A(4^+)B(4^+)O_6$ (e.g., $ThTi_2O_6$). This leads to an increase in the STC in the *A* site and a decrease in the *B* site in the empirical formula. However, the STC in the *B* site is +9.33, closer to +9 than +8. As such, the dominant end-member is $CaTa_2O_6$, because Ta > Nb, which is consistent with rhyersonite, rather than tantaloeschynite-(Y) (Table 5). Owing to its high Y content ($Y_2O_3 = 4.6$ wt%), the mineral from the Raposa pegmatite in Brazil may represent a metamict variety of Y-bearing rhyersonite.

The composition of Ta-rich aeschynite from Siberia was also reported by Adusumilli et al. (1974), which contains 32.13 wt% Ta_2O_5 , 17.87 wt% Nb_2O_5 , and 18.22 wt% TiO_2 . The empirical formula was calculated based on a total of 3 cations as $[Ca_{0.28}(Y,Ln)_{0.56}Al_{0.08}Fe_{0.06}Th_{0.02}Sr_{0.01}]_{\Sigma 1.01}(Ti_{0.89}Ta_{0.57}Nb_{0.53}Si_{0.02})_{\Sigma 2.01}(O_{5.76}OH_{0.24})_{\Sigma 6.00}$, with an atomic Ti:Ta:Nb = 0.89:0.565:0.525. It was named tantalian aeschynite by Adusumilli et al. (1974) because Ti is dominant over Ta in the *B* site. However, the sum of pentavalent cations (Ta + Nb = 1.09 apfu, with Ta > Nb) is higher than that of Ti^{4+} and Si^{4+} (0.905 apfu), leading to the charge-unbalanced formula of $(YT_a_2O_6)^{\Sigma 1+}$. The end-member formula requires valency-imposed double-site occupancy for electroneutrality reasons [i.e., $Y(TiTa)O_6$]. In this case, the STC of the *B* site (+9.07) indicates the presence of Ti^{4+} in the end-member formula. Meanwhile, the end-member of $[A(3^+)B(4^+5^+)O_6]$ is predominant (0.425 apfu, limited by the amounts of Ln+Y) (Table 4). Thus, this Ta-rich aeschynite is consistent with tantaloeschynite-(Y) $Y(TiTa)O_6$ and, as a structural member of

TABLE 4. List of the site total charges and possible atomic arrangements of tantaloeschynite minerals

	Tantaloeschynite-(Y) (Adusumilli et al. 1974)		Tantaloeschynite-(Ce) (Zhu et al. 2024)
Type locality	Raposa pegmatite, Brazil	Siberian material	Huangshan pegmatite, China
Empirical formula	$[Ca_{0.47}(Y,Ln)_{0.425}(Th,U)^{4+})_{0.11}]_{\Sigma 1.005}(Ti_{0.62}Ta_{0.75}Nb_{0.59}Fe_{0.05}^{3+})_{\Sigma 2.015}O_6$	$[Ca_{0.28}(Y,Ln)_{0.56}Al_{0.08}Fe_{0.06}Th_{0.02}Sr_{0.01}]_{\Sigma 1.01}(Ti_{0.89}Ta_{0.57}Nb_{0.53}Si_{0.02})_{\Sigma 2.01}(O_{5.76}OH_{0.24})_{\Sigma 6.00}$	$(Ce_{0.38}Ca_{0.37}Nd_{0.12}La_{0.07}Pr_{0.04}Sm_{0.01}Eu_{0.01}Fe_{0.01})_{\Sigma 1.00}(Ti_{0.92}Ta_{0.72}Nb_{0.21}Si_{0.08}W_{0.01}Al_{0.01})_{\Sigma 1.95}(O_{5.41}F_{0.09}OH_{0.51})_{\Sigma 6.00}$
$A[STC]$	+2.66	2.7	+2.67
$B[STC]$	+9.33	9.14	+8.98
$[A(2^+)B(5^+)O_6]$	0.47 (limited by the amount of Ca)	0.35 (limited by the amount of Ca+Fe+Sr)	0.39 (limited by the amount of Ca)
$[A(3^+)B(4^+5^+)O_6]$	0.425 (limited by the amount of Ln+Y)	0.425 (limited by the amount of Ln+Y)	0.63 (limited by the amount of Ln)
$[A(4^+)B(4^+)O_6]$	0.11 (limited by the amount of Th+U)	0.02 (limited by the amount of Th)	
End-member formula	$CaTa_2O_6$	$Y(TaTi)O_6$	$Ce(TaTi)O_6$

the aeschynite group, represents a new type locality in Siberia (excluding the Raposa deposit), requiring formal definition (Kometova et al. 1963). Subsequently, an occurrence of tantalaeschynite-(Y), with the correctly assigned formula, was discovered in Paszowice Quarry, Jawor County, Lower Silesian Voivodeship, Poland (Szeleg and Ciurla 2004).

Tantalaeschynite-(Ce)

The new mineral species tantalaeschynite-(Ce) was defined by Zhu et al. (2024) and approved by the IMA in 2024. It was discovered in the Huangshan pegmatite, Jiangxi Province, South China. Given that Nb⁵⁺ and Ta⁵⁺ have similar crystal-chemical behavior with nearly the same ionic radius (0.64 Å; Shannon 1976), when Nb is substituted for Ta, aeschynite-(Ce) becomes tantalaeschynite-(Ce) with a formula of Ce(TiTa)O₆. As such, tantalaeschynite-(Ce) is the Ta analog of aeschynite-(Ce), and also the Ce analog of tantalaeschynite-(Y). The newly discovered tantalaeschynite-(Ce) occurs as subhedral-anhedral, granular, and tabular crystals in radiating clusters, which are associated with anorthite, titanite, and microlite. Using the IMA-CNMNC approach, the tantalaeschynite-(Ce) has the empirical formula (Ce_{0.38}Ca_{0.37}Nd_{0.12}La_{0.07}Pr_{0.04}Sm_{0.01}Eu_{0.01}Fe_{0.01})Σ1.00(Ti_{0.92}Ta_{0.72}Nb_{0.21}Si_{0.08}W_{0.01}Al_{0.01})Σ1.95(O_{5.41}F_{0.09}OH_{0.51})Σ6.00. In the *A* site, the sum of trivalent atoms (ΣREE = 0.63 apfu) is higher than that of divalent atoms (Ca + Fe = 0.39 apfu), and Ce³⁺ is the dominant REE. The STC in the *A* site is +2.67 and close to +3. In that case, the *A* site contains mostly Ce³⁺. In the *B* site, based on Hatert and Burke (2008), the sum of pentavalent atoms (Nb + Ta = 0.95 apfu) is slightly higher than that of Ti⁴⁺ (0.94 apfu). However, the simple application of the dominant-valency rule leads to the unbalanced charge formula (CeTa₂O₆)^{Σ1+}. As such, the end-member formula is controlled by the valency-imposed double-site occupancy to be Ce(Ti⁴⁺Ta⁵⁺)O₆. The STC of the *B* site (+8.98) is closer to +9 than +10, supporting the presence of tetravalent ions in the *B* site that maintain the charge balance. As such, the end-member formula of tantalaeschynite-(Ce) is Ce(TiTa)O₆ (Table 4).

CRYSTAL STRUCTURE OF AESCHYNITE-GROUP MINERALS

Structure of AGMs

To date, the IMA has approved nine minerals exhibiting the orthorhombic aeschynite structure (Table 5), with the standard space group of *Pnma* (#62) and Hermann-Mauguin (H-M) symbol of 2/*m* 2/*m* 2/*m*. This is consistent with the same bonding scheme derived from the atomic arrangement of these minerals, as required by the CNMNC recommendations on polymorphs (Nickel and Grice 1998).

Rynersonite

Foord and Mrose (1978) refined the cell data of rynersonite and reoriented the original cell data into the space group *Pmnb* (*b,a,-c*), with *a* = 7.505(1) Å, *b* = 11.063(2) Å, *c* = 5.370(1) Å, and *Z* = 4. The rynersonite unit cell exhibits distorted [TaO₆] clusters with octahedral symmetry, with all Ta-O bonds having variable bond lengths and angles between atoms (Fig. 1a) (Jahnberg et al. 1963). The Ca atoms are coordinated with eight

TABLE 5. Structure and end-members of the aeschynite group minerals

Name	Ideal formula	Crystal system	Space group	<i>a</i> (Å)	<i>b</i> (Å)	<i>c</i> (Å)	<i>V</i> (Å ³)	<i>Z</i>	References	Previous ideal formula	Remark
Vigezzite	CaNb ₂ O ₆	Orthorhombic	<i>Pnma</i> (#62)	11.065	7.527	5.343	444.998	4	Graessner et al. (1979); Gluseppiti and Tadini (1990)	(Ca,Ce)(Nb,Ta,Ti) ₂ O ₆	
Rynersonite	CaTa ₂ O ₆	Orthorhombic	<i>Pnma</i> (#62)	11.063	7.505	5.370	445.859	4	Jahnberg et al. (1963); Foord and Morse (1978)	CaTa ₂ O ₆	
Aeschynite-(Ce)	Ce(TiNb)O ₆	Orthorhombic	<i>Pnma</i> (#62)	10.958	7.538	5.396	445.717	4	Berzelius (1830); Zhabin et al. (1960); Morrison et al. (2012)	(Ce,Ca,Fe,Th)(Ti,Nb) ₂ (O,OH) ₆	Including "niobaeschynite-(Ce)", Ce(NbTi)O ₆
Aeschynite-(Nd)	Nd(TiNb)O ₆	Orthorhombic	<i>Pnma</i> (#62)	10.999	7.513	5.353	442.348	4	Zhang and Tao 1982; Mandarino and Back (2004)	(Nd,Ln,Ca)(Ti,Nb) ₂ (O,OH) ₆	
Aeschynite-(Y)	Y(TiNb)O ₆	Orthorhombic	<i>Pnma</i> (#62)	10.862	7.483	5.15	418.594	4	Brögger (1906); Bonazzi and Menchetti (1999); Bermanec et al. (2008)	(Y,Ln,Ca,Th)(Ti,Nb) ₂ (O,OH) ₆	Including "niobaeschynite-(Y)", Y(TiNb)O ₆
Tantalaeschynite-(Y)	Y(TiTa)O ₆	Orthorhombic	<i>Pnma</i> (#62)	10.983	7.463	5.308	435.076	4	Adusumilli et al. (1974)	Y(Ta,Ti,Nb) ₂ O ₆	
Tantalaeschynite-(Ce)	Ce(TiTa)O ₆	Orthorhombic	<i>Pnma</i> (#62)	10.969	7.551	5.421	449.005	4	Thorogood et al. (2010); Zhu et al. (2024)	Ce(TiTa)O ₆	

^aThe terms "niobaeschynite-(Ce)" and "niobaeschynite-(Y)" were enclosed in quotation marks as they are proposed to be discredited.

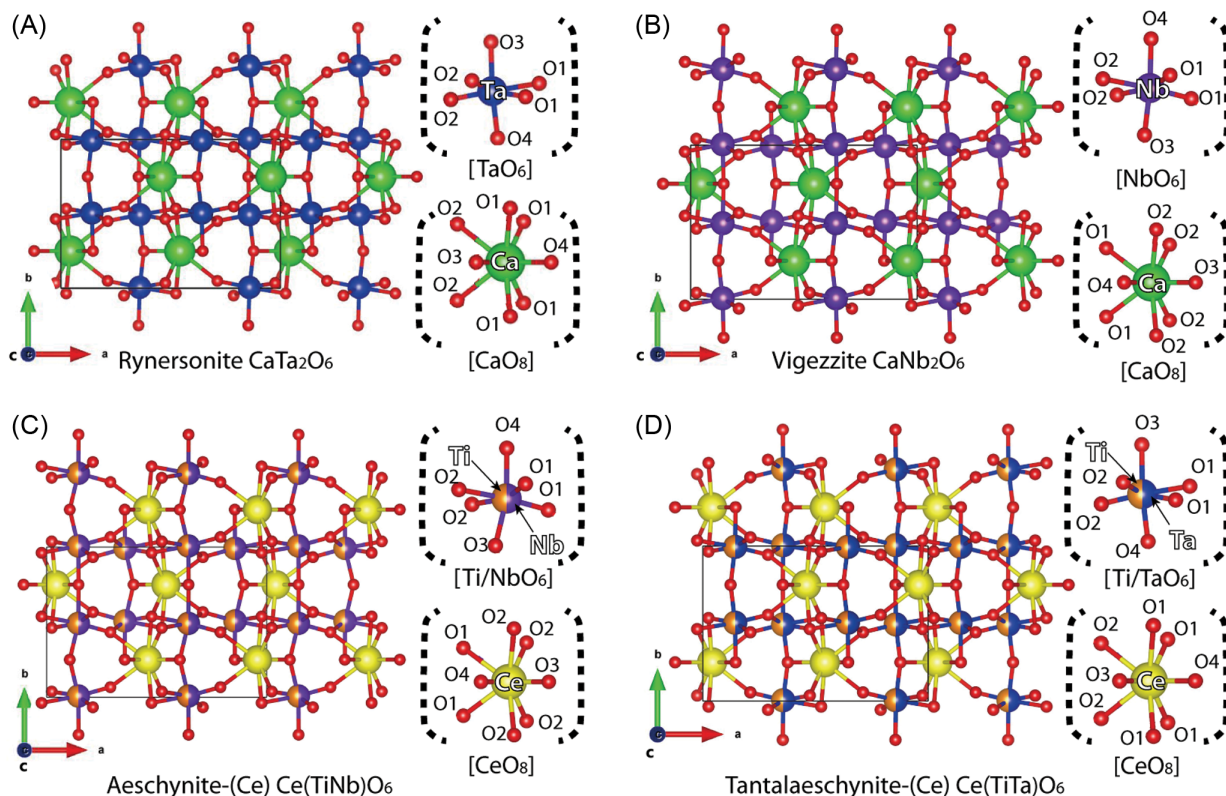


FIGURE 1. The structure of (a) rynersonite, (b) vigezzite, (c) aeschnite-(Ce), and (d) tantaloeschnite-(Ce). All the unit cells are viewed in the *c* direction. The other aeschnite-(Nd) and aeschnite-(Y) share the same crystal structure as aeschnite-(Ce), with Nd and Y occupying the Ce site via isomorphic substitution. Similarly, tantaloeschnite-(Y) is structurally identical to tantaloeschnite-(Ce), with Y substituting for Ce. (Color online.)

O atoms, resulting in distorted [CaO₈] clusters. Refer to the Online Materials¹ for more structure details.

Vigezzite

The structure of vigezzite was initially determined by Giuseppetti and Tadini (1990), resulting in the assignment of the *Pnma* (#62) space group, with *a* = 11.065 Å, *b* = 7.527 Å, *c* = 5.343 Å, and *Z* = 4. In vigezzite, the morphological prism axis is parallel to the crystallographic *a*-axis (Fig. 1b).

Aeschnite-(Ce)

The structure of aeschnite was first determined by Berzelius (1830), who confirmed that aeschnite-(Ce) belongs to the orthorhombic crystal system and *Pnma* (*a,b,c*) space group, with cell parameters of *a* = 10.958 Å, *b* = 7.538 Å, *c* = 5.396 Å, and *Z* = 4. The crystals are prismatic, parallel to [001], tabular on {010}, and striated on {010} parallel to [100]. The structure of nioboeschnite-(Ce) from the Vishnev Mountains, as defined by Aleksandrov (1962), is orthorhombic, with a *Pbnm* (*c,a,b*) space group, and *a* = 5.37 Å, *b* = 11.085 Å, *c* = 7.56 Å, and *Z* = 4. The crystal parameters of non-metamict nioboeschnite-(Ce) from Alaka are orthorhombic, with the standard space group of *Pnma* (#62, *a,b,c*) and *a* = 11.085 Å, *b* = 7.585 Å, and *c* = 5.396 Å. The unit cell of nioboeschnite-(Ce) resembles that of aeschnite-(Ce) (Fig. 1c), and is characterized by edge-sharing dimers of [(NbTi)O₆] octahedra that share corners to form a three-dimensional framework,

with *A* sites located in channels parallel to the *b* axis. In addition, the refinement revealed a splitting of the *A* site, with Ca displaced slightly from Ce (0.266 Å apart), presumably due to the crystal-chemical differences between the Ce³⁺ and Ca²⁺ cations (Morrison et al. 2012).

Aeschnite-(Nd)

Structural data for aeschnite-(Nd) are scarce, and it has been reported to be in the orthorhombic system and *Pbnm* (*c,a,b*) space group, with lattice parameters of *a* = 10.999 Å, *b* = 7.513 Å, and *c* = 5.353 Å (Mandarino and Back 2004; Škoda and Novák 2007). Following reorientation, this standard space group transforms to *Pnma* (#62, *a,b,c*). Subsequently, the structure of synthetic Nd_{2/3}Gd_{1/3}TiNbO₆ obtained by John et al. (2011) was incorrectly proposed to represent the structure of aeschnite-(Nd). It was proposed that its space group is *Pncm*, along with lattice parameters of *a* = 5.30 Å, *b* = 11.01 Å, and *c* = 7.47 Å. Apparently, the space group *Pncm*, like *Pmna* (#53), differs from the space group of the other aeschnite minerals (*Pnma* #62). Given the lack of a detailed description of the space group in John et al. (2011), it is recommended that this incorrect space group assignment be removed. Therefore, the structure of aeschnite-(Nd) is the orthorhombic system, *Pnma* (*a,b,c*) space group, and lattice parameters of *a* = 10.999 Å, *b* = 7.513 Å, and *c* = 5.353 Å, which are identical to those of aeschnite-(Ce), with Nd substituting for Ce in the [CeO₈] polyhedra.

Aeschnynite-(Y)

This end-member also belongs to the orthorhombic system (Brögger 1879). Deliens (1991) determined the space group of titanian aeschnynite-(Y) to be *Pbnm* (*c,a,b*), with $a = 5.174$ Å, $b = 10.76$ Å, $c = 7.59$ Å, and $Z = 4$. Subsequently, five non-metamict aeschnynite-(Y) samples from the Western Alps were assigned to the standard *Pnma* space group (#62), with $a = 10.862$ Å, $b = 7.483$ Å, $c = 5.150$ Å, and an orientation of *a,b,c* (Bonazzi and Menchetti 1999). The incorporation of Y into the unit cell results in an isostructural crystal structure similar to those of aeschnynite-(Ce) and aeschnynite-(Nd). Nioboeschnynite-(Y) is naturally metamict, and its structure was obtained after heating at 1000 °C, with it crystallizing into an orthorhombic structure and a space group of *Pbnm*, with $a = 5.279(3)$ Å, $b = 10.966(5)$ Å, $c = 7.443(3)$ Å, and $Z = 4$ (Bermanec et al. 2008). After changing the orientations, the standard space group of nioboeschnynite-(Y) is *Pnma* (#62), with $a = 10.966(5)$ Å, $b = 7.443(3)$ Å, and $c = 5.279(3)$ Å. Structurally, both aeschnynite-(Y) and nioboeschnynite-(Y) have the same structure with [TiNbO₆] octahedra and [YO₈] polyhedra, reflecting their common structure.

Tantaloeschnynite-(Y)

The real tantaloeschnynite-(Y) from Siberia also belongs to the orthorhombic system, space group *Pnma* (62#), and has unit-cell dimensions of $a = 10.983$ Å, $b = 7.463$ Å, $c = 5.308$ Å, and $Z = 4$ (Adusumilli et al. (1974).

Tantaloeschnynite-(Ce)

has the same structure as synthetic Ce(Ti,Ta)O₆ with a space group of *Pnma* (#62) and $a = 10.969(4)$ Å, $b = 7.551(9)$ Å, $c = 5.421(7)$ Å, $V = 449.1(3)$, and $Z = 4$ (Thorogood et al. 2010), based on results from transmission electron microscopy (TEM) and aberration-corrected transmission electron microscopy (AC-STEM). Tantaloeschnynite-(Ce) is the Ta analog of nioboeschnynite-(Ce), in which Ta substitutes for Nb in the *B* site (Fig. 1d) (Zhu et al. 2024).

Metamictization and Related Hydrothermal Alteration of AGMs

Complex Nb-Ta-Ti-REE oxide minerals, including those of AGMs, are typically metamict or have undergone hydrothermal alteration in natural samples, with only a small proportion of the documented minerals being non-metamict (e.g., Guastoni et al. 2019). As such, determining the crystal structure of such metamict minerals is a significant analytical challenge.

Early studies of metamict minerals recognized that thermal treatment at appropriate temperatures can restore their crystallinity, thereby yielding diagnostic X-ray diffraction patterns (e.g., Arnott 1950; Berman 1955; Lima de Faria 1958; Zhang and Tao 1982). Zhang and Tao (1982) performed structural analysis on a metamict sample following annealing at 800 °C and compared the X-ray powder diffraction patterns before and after heating, showing that the diffraction pattern of the annealed material was consistent with that of reference aeschnynite-(Y). To undertake X-ray diffraction analysis of metamict Nb-Ta-Ti-REE

oxide minerals, Tomašić et al. (2004, 2006) proposed a heating protocol using variable temperatures (400, 500, 650, 800, and 1000 °C) to enhance the crystallinity, and Raman spectroscopy to then identify diagnostic vibrational bands that are characteristic of metamict aeschnynite-(Y) and euxenite-(Y). Moreover, a transformation from the aeschnynite- to euxenite-type structure was observed for both minerals, but this transition remained incomplete in aeschnynite-(Y) at 1000 °C, whereas it was fully completed in euxenite-(Y). Therefore, thermal annealing improves the crystallinity, enabling reliable structural determination. However, excessive temperatures (≥ 1000 °C) trigger irreversible phase transformations in these radiation-damaged oxides.

Capitani et al. (2016) examined (Y-REE-U-Th)-(Nb-Ta-Ti) oxides from the Garnet Codera pegmatite, upper Codera Valley (Central Italian Alps) using scanning and transmission electron microscopy (SEM, TEM), wavelength- and energy-dispersive spectroscopy (WDS, EDS), and electron diffraction tomography (EDT). In TEM images, U-rich, highly damaged domains contain nanoparticles that were interpreted as the breakdown products of metamictization, while lower-U domains retain a single-crystal character. Their refined structure matched the aeschnynite group rather than ixiolite or columbite. This confirms that TEM can identify localized non-metamict domains within X-ray-amorphous materials.

In summary, two experimentally established approaches enable the structural characterization of metamict and hydrothermally altered minerals: (1) thermal annealing to restore the long-range crystalline order, and (2) electron diffraction techniques and TEM, which can resolve local structural domains at the nanoscale. For the AGMs, thermal annealing remains the main method for determining the crystal structures, as most natural specimens exhibit significant radiation-induced amorphization and few specimens retain sufficient crystallinity to permit direct structural analysis without prior annealing.

Presence of Silica in the Structure

Detectable Si contents are a relatively common feature of AGMs, although Si incorporation into the crystal structure of AGMs has not been previously documented. However, its occurrence and structural role in the structurally related pyrochlore super-group Nb-Ta-Ti-REE oxides have long been debated and remain only partially resolved (Atencio et al. 2010). Various mechanisms have been proposed to account for Si in natural pyrochlores, including the presence of Si as dispersed crystalline or amorphous silicate inclusions (Hogarth 1977; Hogarth and Horne 1989; Voloshin et al. 1989), as well as its incorporation as a structurally essential constituent. Despite the absence of tetrahedral sites suitable for Si in the pyrochlore structure, octahedral Si is structurally plausible, and the primary constraint on the occurrence of [6]Si in crystal structures is the steric crowding of cations around O anions (O'Keeffe and Hyde 1981). Using TEM-EDS and crystal-chemical constraints, Bonazzi et al. (2006) demonstrated that 30–50% of the Si detected by electron microprobe analysis (EMPA) occupies octahedral sites in the pyrochlore structure, whereas 50–70% is concentrated in radiation-damaged domains of the material.

Whether Si is incorporated into pyrochlore super-group structures warrants further investigation, but low Si contents can either be accommodated in the *B* site or represent minor contaminant phases.

The aeschynite-group and pyrochlore super-group minerals are characterized by an *A* site occupied by large [8]-coordinated cations (e.g., REE³⁺ and Ca²⁺) and a *B* site occupied by high-field-strength [6]-coordinated cations (e.g., Ti⁴⁺, Nb⁵⁺, and Ta⁵⁺). Although Si⁴⁺ (ionic radius = 0.40 Å) is sufficiently small to occupy both sites, substitution in the large *A* site would introduce a significant charge imbalance and cationic repulsion, given the dominance of divalent and trivalent cations in this site. In contrast, incorporation in the *B* site is charge-balanced and crystallographically favorable, consistent with the preferential occupancy of Si in the *B* site of AGMs. Reported SiO₂ contents in AGMs are generally low [e.g., SiO₂ ≤ 1.14 wt% in tantaloeschynite-(Ce); Zhu et al. 2024], and TEM reveals no nano-silica inclusions. It indicates the existence of limited *B*-site substitution, though still below the detection limit of site-specific analytical techniques, such as electron energy-loss spectroscopy (EELS) or atomically resolved energy-dispersive X-ray spectroscopy (EDS). Therefore, although crystal-chemical considerations strongly support Si assignment to the *B* site, direct experimental confirmation awaits analysis of either higher-Si analogs or more advanced micro-analytical methods.

Dimorphism of AGMs

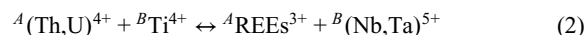
Euxenite, fersmite, and tanteuxenite-(Y) belong to the euxenite group and are provisionally assigned to the columbite super-group and *Pbcn* polymorphs of AGMs (Chukanov et al. 2023). They share the same end-member formulas as AGMs but exhibit distinct crystallization structures.

Fersmite is dimorphic with vigezzite (CaNb₂O₆), but the two minerals have distinct crystal structures. Unlike vigezzite, the synthetic analog of fersmite is orthorhombic with a space group of *Pcan* (#60), and *a* = 5.75 Å, *b* = 14.03 Å, *c* = 5.20 Å, and *Z* = 4 (Cummings and Simonsen 1970).

Euxenite-(Y) is dimorphic with aeschynite-(Y), sharing the same end-member formula of Y(NbTi)O₆. Most euxenite-(Y) is metamict, and the unit-cell parameters of synthetic euxenite-(Y) are *a* = 14.64 Å, *b* = 5.55 Å, and *c* = 5.20 Å, with a space group of *Pbcn* (#60) and *Z* = 4 (Weitzel and Schröcke 1980). Polycrase-(Y) was considered to be an analog of euxenite-(Y) with Ti > Nb in terms of atomic units (Johnsen et al. 1999). Non-metamict polycrase-(Y) with unit-cell parameters of *a* = 14.82 Å, *b* = 5.66 Å, and *c* = 5.22 Å was described by Guastoni et al. (2019). Given the common end-member formula Y(NbTi)O₆, euxenite-(Y) and polycrase-(Y) are considered to be the same mineral species, and the older name euxenite-(Y) should have priority usage (Chukanov et al. 2023).

Tanteuxenite-(Y), renamed tanteuxenite, is dimorphous with tantaloeschynite-(Y), with the same end-member formula of Y(TaTi)O₆. It is generally metamict and was first discovered in Western Australia (Simpson 1928). Tanteuxenite-(Y) is also orthorhombic with a space group of *Pbcn* (#60), and *a* = 14.574(3) Å, *b* = 5.555(1) Å, and *c* = 5.184(4) Å.

Another substitution mechanism addressing heterovalent substitution in the two sites of the AGMs also exists:



This substitution 2 yields the theoretical end-member composition ThTi₂O₆ and UTi₂O₆, corresponding to thorutite and brannerite/uranopolycrase, respectively. Both thorutite and brannerite crystallize in the monoclinic crystal system (space group *C2/m*), while uranopolycrase belongs to the orthorhombic crystal system (space group *Pbcn*); neither falls within the aeschynite group (Hess and Wells 1920; Gotman and Khapaev 1958).

SUMMARY OF THE APPROVED REPORT

Establishment of the Aeschynite Group

The nomenclature of AGMs has been updated to comply with the latest IMA-CNMNC rules on end-member formulas (valency-imposed double-site occupancy and site total-charge approach) and to uphold electroneutrality. The AGMs have a general formula of AB₂O₆, in which the *A* site is occupied by the REEs, Ca²⁺, Th⁴⁺, and U⁴⁺, while the *B* site is occupied by Ti⁴⁺, Nb⁵⁺, and Ta⁵⁺. The bonding scheme leads to similar crystal structures as those currently classified in the orthorhombic crystal system, a standard space group of *Pnma* (#62), and a H-M symbol of *2/m 2/m 2/m*. Consequently, seven end-members of the aeschynite group are approved by the IMA: rynersonite, vigezzite, aeschynite-(Ce), aeschynite-(Nd), aeschynite-(Y), tantaloeschynite-(Y), and tantaloeschynite-(Ce) (Table 2).

Redefined Species

The end-member formulas of the AGMs are redefined as follows: vigezzite CaNb₂O₆, rynersonite CaTa₂O₆, aeschynite-(Ce) Ce(TiNb)O₆, aeschynite-(Nd) Nd(TiNb)O₆, aeschynite-(Y) Y(TiNb)O₆, tantaloeschynite-(Y) Y(TiTa)O₆, and tantaloeschynite-(Ce) Ce(TiTa)O₆.

Discreditation of Nioboeschynite Subtypes

Nioboeschynite-(Ce) and nioboeschynite-(Y) are discredited for the following reasons: (1) nioboeschynite-(Ce) and nioboeschynite-(Y) have the same end-member formulas as aeschynite-(Ce) and aeschynite-(Y), respectively, with no distinct solid-solution series; and (2) nioboeschynite and aeschynite share the same orthorhombic crystal system, standard space group of *Pnma* (#62), and H-M symbol of *2/m 2/m 2/m*. Given that aeschynite-(Ce) and aeschynite-(Y) are established mineral species, nioboeschynite-(Ce) and nioboeschynite-(Y) are reclassified as aeschynite-(Ce) and aeschynite-(Y), respectively.

IMPLICATIONS

The recent nomenclature rules approved by the IMA in 2019, including coupled heterovalent substitutions at two sites, the dominant-valency rule, and the site total-charge approach, provide a robust and practical framework for determining the end-member compositions of AGMs. To date, the AGMs consist of seven officially recognized end-members: rynersonite CaTa₂O₆,

vigezzite CaNb_2O_6 , aeschynite-(Ce) $\text{Ce}(\text{Ti,Nb})\text{O}_6$, aeschynite-(Nd) $\text{Nd}(\text{Ti,Nb})\text{O}_6$, aeschynite-(Y) $\text{Y}(\text{Ti,Nb})\text{O}_6$, tantaloeschynite-(Y) $\text{Y}(\text{Ti,Ta})\text{O}_6$, and tantaloeschynite-(Ce) $\text{Ce}(\text{Ti,Ta})\text{O}_6$. The nioboerschynite is formally subsumed within the broader aeschynite series, sharing the same ideal structural formula, which resolves the long-term ambiguity in the definition and distinction of the nioboerschynite and aeschynite. Critically, this IMA-endorsed nomenclature and classification enable unambiguous identification of the actual ideal formulas and correct type localities, and precise mineral species assignment for the complex and naturally occurring members of the aeschynite group. Therefore, consistent implementation of this updated nomenclature is essential to standardize the mineral classification in AGMs studies.

Rare metals, including Nb and Ta, are critical raw materials with industrial and technological applications, which are increasingly of interest to geologists and materials scientists. This new study of the nomenclature of AGMs also enables geologists and related researchers to more effectively classify and identify complex Nb-Ta-Ti-bearing minerals. Consequently, this will facilitate mineral identification and descriptions, and ultimately enhance our understanding of related ore-forming processes.

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