

Article

Nomenclature of the monazite supergroup minerals

Pavel Uher¹ , Frédéric Hatert² , Martin Ondrejka¹, Peter Bačík^{1,3} , Jiří Sejkora⁴ , Radek Škoda⁵  and Martin Števko^{3,4} 

¹Department of Mineralogy, Petrology and Economic Geology, Faculty of Natural Sciences, Comenius University, Bratislava, Slovakia; ²Laboratoire de Minéralogie et de Cristallochimie, Université de Liège, Liège, Belgium; ³Earth Science Institute, Slovak Academy of Sciences, Bratislava, Slovakia; ⁴Department of Mineralogy and Petrology, National Museum, Prague, Czech Republic; and ⁵Department of Geological Sciences, Faculty of Science, Masaryk University, Brno, Czech Republic

Abstract

The monazite supergroup minerals represent anhydrous phosphates, less frequently arsenates, silicates and chromates with general formula ABX_4 , monoclinic symmetry, space group $P2_1/n$ (14), and $Z = 4$. The *A* site is occupied usually by REE (La^{3+} to Gd^{3+}) and other large divalent to tetravalent cations (mainly Ca^{2+} , Pb^{2+} , Bi^{3+} , Th^{4+} and U^{4+}) in nine-fold coordination. The *B*-site is filled with cations in tetrahedral coordination (mainly P^{5+} and As^{5+} , in specific cases also Si^{4+} , Cr^{6+} and other cations). The anionic *X* site is usually occupied by O^{2-} but may be replaced to a small extent by F^- or an $(OH)^-$ anion. The supergroup is divided into one group: monazite (phosphates, arsenates, vanadates), and two unassigned members: huttonite (silicates) and crocoite (chromates, sulfates). Recently, eleven valid mineral species of the monazite supergroup were approved by the IMA-CNMNC: monazite-(La), monazite-(Ce), monazite-(Nd), monazite-(Sm), monazite-(Gd), cheralite, gasparite-(La), gasparite-(Ce), rooseveltite, huttonite, and crocoite. In addition, mineral analyses and synthesized compounds indicate the potential existence of several other new members of the monazite supergroup in natural environments.

Keywords: monazite supergroup; monazite group; huttonite; crocoite; ABX_4 ; nomenclature; classification

(Received 20 August 2025 UTC; revised 9 November 2025 UTC; accepted 9 November 2025 UTC; Accepted Manuscript published online: 19 November 2025 UTC)

Introduction

Monazite *sensu lato* is a widespread accessory mineral of various igneous and metamorphic rocks, some hydrothermal systems, and rarely it is an authigenic or clastic mineral in sediments. Moreover, monazite is a principal ore mineral of rare-earth elements (REE, *lanthanoids*), particularly Ce^{3+} and other REE^{3+} cations with larger ionic radii ('light' REE, especially La to Nd), the key elements in modern industry and technology. Monazite is stable over a very wide range of *P*–*T* conditions, including ultra-high-pressure diamond-bearing metamorphic rocks (e.g. Petřík *et al.*, 2019; Závada *et al.*, 2021) to nearly surface authigenic associations (e.g. Čopjaková *et al.*, 2011), it has also been described from extraterrestrial lunar rocks (Kartashov *et al.*, 2006) and Martian meteorites (Liu *et al.*, 2016). Internal textures, variations of chemical composition, and alteration products of monazite reflect crystal and host-rock evolution and, therefore, monazite represents one of the most important indicators of geological processes and *P*–*T*–*X* conditions. Moreover, due to the common presence of radioactive Th and U in their structure, monazite is widely used in petrochronology for

dating of magmatic and metamorphic processes in the parental rocks (e.g. Engi, 2017).

Cerium is the dominant REE cation in almost all natural monazites, therefore, the end-member formula for its overwhelmingly most common member is expressed as $CePO_4$. However, advanced analytical techniques since the second half of the 20th Century has also revealed monazites with different dominant REE cations (La^{3+} , Nd^{3+} , Sm^{3+} and Gd^{3+}) or $Ca^{2+} + Th^{4+}$ substituting for REE. Such monazite compositions with another dominant cation represent independent mineral species with proper names and end-member formulae. For the naming of essential REE minerals, the Levinson rules were approved by the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association (IMA-CNMNC), and they have been widely used. Here, the dominant REE cation is written as a suffix of the chemical abbreviation of the dominant element (Levinson, 1966; Bayliss and Levinson, 1988).

Consequently, except for the most widespread monazite-(Ce) member, we have recognized several other rare monazite species with dominant La, Nd, Sm and Gd. The La-dominant composition of monazite was first noted by Borovsky and Gerasimovskiy (1945) and defined as the independent mineral monazite-(La) by Levinson (1966). The Nd-dominant member was firstly described by Maksimović and Pantó (1980), but it was approved as a new mineral monazite-(Nd) only after its crystal structure was determined (Graesser and Schwander, 1987). Later, monazite-(Sm)

Corresponding author: Pavel Uher; Email: pavel.uher@uniba.sk

Associate Editor: Anthony R. Kampf

Cite this article: Uher P, Hatert F, Ondrejka M., Bačík P, Sejkora J., Škoda R. and Števko M. (2026) Nomenclature of the monazite supergroup minerals. *Mineralogical Magazine*, 1–14. <https://doi.org/10.1180/mgm.2025.10178>

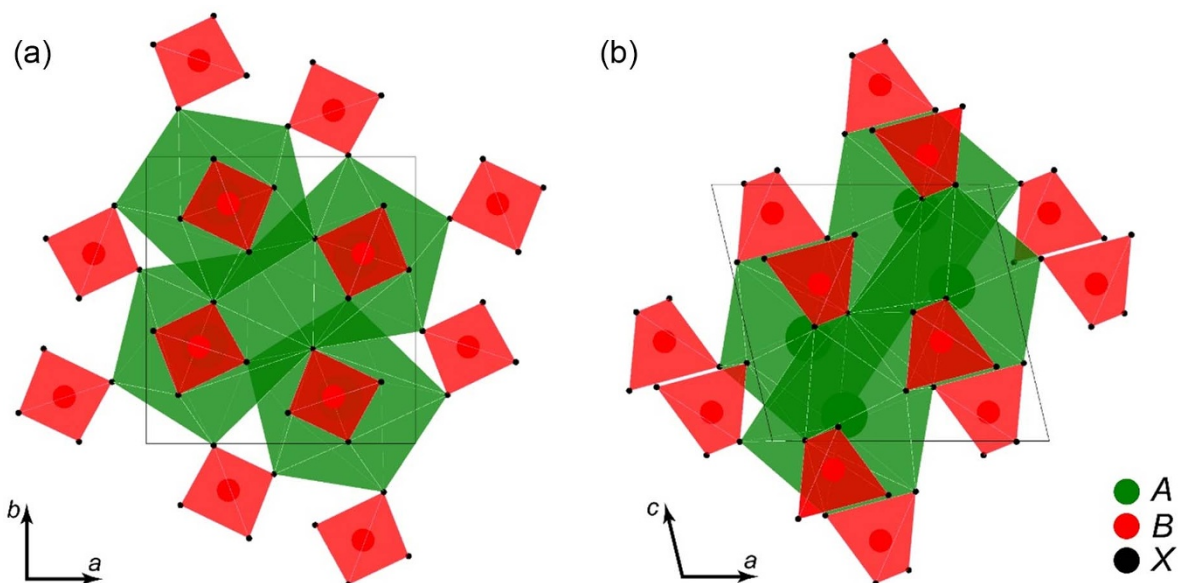


Figure 1. Monazite-type structure viewed in the (a) *c*- and (b) *b*-axis direction.

(Masau *et al.*, 2002) and more recently monazite-(Gd) (Ondrejka *et al.*, 2023a, 2023b) were discovered and both have been approved as independent mineral species.

The monazite-(Ce), monazite-(La), monazite-(Nd), ‘brabantite’, cheralite, gasparite-(Ce) and rooseveltite were classified as members of the monazite group in the phosphates mineral class (Strunz and Nickel, 2001) or monazite group (without rooseveltite) in the anhydrous phosphates class (Gaines *et al.*, 1997). However, a consistent nomenclature and classification system of the monazites and isostructural minerals following the CNMNC IMA rules (Mills *et al.*, 2009) was missing until now. This present contribution brings such recommended nomenclature of the monazite supergroup minerals including basic characterization of their members, naming rules, classification scheme, and recommended formula calculation. The new nomenclature and classification of the monazite

supergroup has been approved by the International Mineralogical Association (IMA) Commission on New Minerals, Nomenclature and Classification (CNMNC) (Bosi *et al.*, 2025).

Monazite structure and site occupancy

The crystal structures of the trivalent La, Ce, Pr and Nd phosphates were determined by X-ray diffraction techniques in 1944 for the Manhattan Project (Mooney, 1948). Monazite and isostructural minerals form compounds with general ABX_4 stoichiometry, monoclinic symmetry, space group $P2_1/n$ (14), and $Z = 4$. The monazite-type crystal structure (Fig. 1) consists of irregular 9-coordinated cations of the *A* site, which are linked together by isolated distorted BX_4 tetrahedra, the AX_9 polyhedra and BX_4 tetrahedra form chains sharing *X* edges along the *c* axis, and the

Table 1. Nomenclature and classification of the monazite-supergroup minerals. Valid members are in bold font, and potential (hypothetical) members are in italics

Group	Class	Species name	Formula
Monazite	Phosphates, arsenates and vanadates	monazite-(La)	LaPO₄
		monazite-(Ce)	CePO₄
		monazite-(Nd)	NdPO₄
		monazite-(Sm)	SmPO₄
		monazite-(Gd)	GdPO₄
		cheralite	Ca_{0.5}Th_{0.5}PO₄
		<i>new root name</i>	<i>Ca_{0.5}U_{0.5}PO₄</i>
		<i>new root name</i>	<i>Si_{0.5}Th_{0.5}PO₅</i>
		gasparite-(La)	LaAsO₄
		gasparite-(Ce)	CeAsO₄
		<i>gasparite-(Nd)</i>	<i>NdAsO₄</i>
		rooseveltite	BiAsO₄
		<i>new root name-(La)</i>	<i>LaVO₄</i>
Unassigned	Silicates	huttonite	ThSiO₄
	Chromates	crocoite	PbCrO₄
	Sulfates	<i>clinoanhydrite</i>	<i>CaSO₄</i>

Table 2. The substitution mechanisms of the monazite-supergroup minerals

Substitution	References
$\text{Ce}^{3+} \leftrightarrow (\text{La}, \text{Pr}, \text{Nd}, \text{Sm}, \text{Gd}, \text{Y}, \text{other REE})^{3+}$	all authors
$\text{P}^{5+} \leftrightarrow (\text{As}, \text{V})^{5+}$	Ondrejka <i>et al.</i> (2007); Vereshchagin <i>et al.</i> (2019)
$2\text{REE}^{3+} \leftrightarrow (\text{Ca}, \text{Sr})^{2+} + (\text{Th}, \text{U})^{4+}$	Franz <i>et al.</i> (1996); Chakhmouradian and Mitchell (1998); Förster (1998); Williams <i>et al.</i> (2007); Uher <i>et al.</i> (2013)
$2\text{REE}^{3+} + \text{vacancy} \leftrightarrow 3\text{Ca}^{2+}$	Catlos and Miller (2017)
$\text{REE}^{3+} + (\text{P}, \text{As})^{5+} \leftrightarrow (\text{Th}, \text{U})^{4+} + \text{Si}^{4+}$	Della Ventura <i>et al.</i> (1996); Franz <i>et al.</i> (1996); Förster (1998); Williams <i>et al.</i> (2007); Uher <i>et al.</i> (2013)
$\text{REE}^{3+} + (\text{P}, \text{As})^{5+} \leftrightarrow (\text{Ca}, \text{Sr})^{2+} + \text{S}^{6+}$	Chakhmouradian and Mitchell (1998, 1999); Ondrejka <i>et al.</i> (2007); Williams <i>et al.</i> (2007); Pršek <i>et al.</i> (2010); Krenn <i>et al.</i> (2011); Laurent <i>et al.</i> (2016); Broom-Fendley <i>et al.</i> (2020)
$\text{REE}^{3+} + \text{Si}^{4+} \leftrightarrow \text{Ca}^{2+} + \text{P}^{5+}$	Catlos and Miller (2017)
$2\text{P}^{5+} \leftrightarrow \text{Si}^{4+} + \text{S}^{6+}$	Williams <i>et al.</i> (2007)
$\text{REE}^{3+} + \text{O}^{2-} \leftrightarrow (\text{Ca}, \text{Sr})^{2+} + (\text{OH}, \text{F})^-$	Chakhmouradian and Mitchell (1999); Broom-Fendley <i>et al.</i> (2020)
$(\text{PO}_4)^{3-} \leftrightarrow (\text{SiO}_3)^{2-} + \text{F}^-$	Williams <i>et al.</i> (2007)
$\text{REE}^{3+} + \text{P}^{5+} \leftrightarrow \text{Th}^{4+} + \text{S}^{6+}$	Broom-Fendley <i>et al.</i> (2020)
$2\text{P}^{5+} \leftrightarrow \text{S}^{4+} + \text{S}^{6+}$	Broom-Fendley <i>et al.</i> (2020)
$\text{O}^{2-} \leftrightarrow \text{S}^{2-}$	Broom-Fendley <i>et al.</i> (2020)

X atom is coordinated to one *B* and two *A* atoms (e.g. Ueda, 1967; Ni *et al.*, 1995; Boatner, 2002; Clavier *et al.*, 2011; Zaman and Antao, 2020).

The cation and anion site occupancy of ABX_4 in the monazite-type structure minerals is the following (less represented and rare or questionable cations and anions are listed in () and [] parentheses, respectively):

A-site cations: La^{3+} , Ce^{3+} , Nd^{3+} , Sm^{3+} , Gd^{3+} (+ small amounts of Y^{3+} and other REE^{3+}), Ca^{2+} , Pb^{2+} , (Sr^{2+}) , Bi^{3+} , Th^{4+} , U^{4+} , (U^{5+}) , U^{6+} , [vacancy, Na^+ , K^+ , Mg^{2+} , Fe^{2+} , Cu^{2+} , Zn^{2+} , Ni^{2+} , Ba^{2+} , Sc^{3+} , Al^{3+} , Fe^{3+} , Sb^{3+} , Zr^{4+}];

B-site cations: P^{5+} , As^{5+} , (V^{5+}) , Si^{4+} , (S^{4+}) , Cr^{6+} , (S^{6+}) , Se^{6+} , Te^{6+} ;

X-site anions: O^{2-} (F^- , OH^- , S^{2-}), $[\text{Cl}^-]$.

Naming of minerals

Monazite, the first discovered mineral of the supergroup, was described from Miass (Russia) and named by Johann Friedrich August Breithaupt (1829) from the Greek word *μονάζω* (to be solitary) in allusion to the rarity of its presence in the first known occurrences. Six years before, a new mineral from Dauphiné (France) was named ‘turnerite’ by Levy (1823); later, ‘turnerite’ was identified as a synonym or variety of monazite (e.g. Miers, 1885; Gliszczynski, 1939). However, the commonly used term monazite takes precedence over the currently unused archaic term ‘turnerite’, regardless of its time priority.

The root name monazite plus element suffixes $-(\text{La})$, $-(\text{Ce})$, $-(\text{Nd})$, $-(\text{Sm})$ and $-(\text{Gd})$ conform to the Levinson rule for REE phosphate minerals with the monazite-type structure and the La, Ce, etc. dominant monazite members (Levinson, 1966; Bayliss and Levinson, 1988). Therefore, monazite-(La), monazite-(Ce), monazite-(Nd), monazite-(Sm) and monazite-(Gd) have been described and approved as valid mineral species names up to the present (Table 1). The same method is applied for gasparite members, the REE-dominant arsenate phases with monazite-type structure: gasparite-(La) and gasparite-(Ce). Therefore, for any new mineral with the monazite-type structure and dominance of another as previously described *A*-site REE cation, the root name monazite or gasparite (or new root name) plus the suffix of dominant REE abbreviation is used, for example *gasparite*-(Nd).

For related monazite-structure minerals without dominant REE occupancy of *A* site, independent root names without suffixes are applied: rooseveltite, cheralite, huttonite, crocoite, or new root

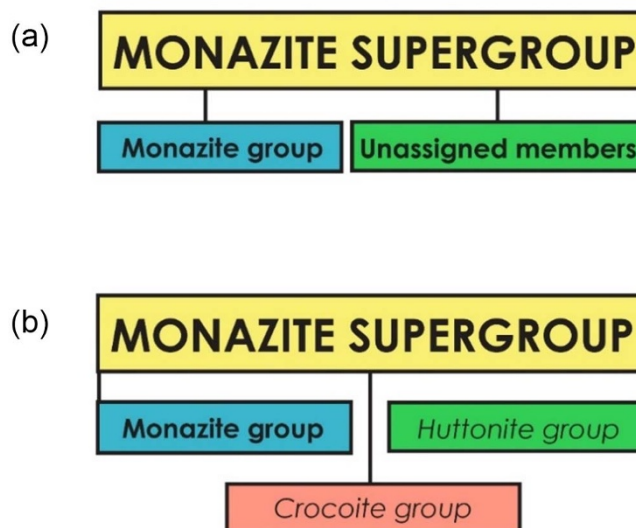


Figure 2. Classification scheme of the monazite supergroup: (a) with a currently defined group and unassigned members; and (b) with hypothetical groups.

names for future new members (Table 1). For a potential (hypothetical) mineral with a dominant CaSO_4 molecule and monazite-type structure, the name *clinoanhydrite* is proposed in our nomenclature to emphasize its monoclinic symmetry and dimorphous relation to anhydrite, the orthorhombic modification of CaSO_4 (see also text below).

Classification of the monazite-supergroup minerals

The minerals with ABX_4 stoichiometry and monazite structure contain various tetrahedrally coordinated *B*-site cations with the same or different valency (P^{5+} , As^{5+} , V^{5+} , Si^{4+} , Cr^{6+} , S^{6+}) and consequently, they belong to different mineral classes according to the system of Strunz and Nickel (2001): phosphates, arsenates, silicates, chromates and potentially also vanadates and sulfates (Table 1). Similarities of ionic radii between most *A*- or *B*-site cations enable broad isomorphic homovalent and coupled heterovalent substitutions within the monazite-type structure (Table 2). Such closely related isostructural minerals, which formally belong to several groups in various chemical classes, could be classified into the same unit, named *supergroup*, with the following definition (Mills *et al.*, 2009): “A mineral supergroup consists of two or more groups which

have essentially the same structure and composed of chemically similar elements. Generally, a supergroup will contain members from the same mineral class (e.g., the epidote supergroup); however, in rare cases, a supergroup may also contain groups belonging to different classes, as for example, in the alunite supergroup. A supergroup may also contain isolated mineral species which do not belong to any mineral group, as for example, vanadinite, which is the only vanadate in the apatite supergroup". Since the 2010s, this hierarchy between supergroup and its groups belonging to different mineral classes has been applied to several important mineral nomenclatures and classifications: the apatite (Pasero *et al.*, 2010), pyrochlore (Atencio *et al.*, 2010), alunite (Bayliss *et al.*, 2010), garnet (Grew *et al.*, 2013), gadolinite (Bačík *et al.*, 2017), spinel (Bosi *et al.*, 2019), and other mineral supergroups.

Consequently, the newly defined monazite supergroup (Table 1, Fig. 2) includes the monazite group (phosphates, arsenates, vanadates) and unassigned members huttonite (silicates) and crocoite (chromates, sulfates). The group is defined by the charge of the cation at the *B* site and corresponding mineral class, which is following dividing into mineral species (Table 1). Because only one possible group with *B* occupied by a cation with a charge of +5 contains more than one valid mineral species, only the monazite group can be defined now. However, other hypothetical groups can be established, including the huttonite ($B = 4+$) or crocoite groups ($B = 6+$), if additional new members are described with a composition meeting the classification criteria (Fig. 2).

Some aspects of natural monazite-supergroup chemical composition

A site: REE, Zr and Sc

The monazite-type structure is accommodated for the preferable implementation of REE with larger ionic radii ('light' REE, mainly La to Nd) and with nine-fold coordination with oxygen anions in contrast to eight-fold coordinated REE cations in the tetragonal zircon-type structure (Ushakov, 2001; Boatner, 2002; Clavier *et al.*, 2011). Consequently, synthetic La to Gd orthophosphates, La to Nd arsenates, and LaVO_4 are stable monazite-structure compounds, and Tb to Ho orthophosphates and Ce to Nd vanadates are rather metastable in this structure (Kolitsch and Holtstam, 2004; Clavier *et al.*, 2011, and references therein). Chemical compositions of natural monazites and gasparites are in accordance with this behaviour, and mineral species with dominant LaPO_4 to GdPO_4 , LaAsO_4 and CeAsO_4 molecules have been described. Moreover, the composition corresponding to Nd-dominant gasparite (NdAsO_4) with the empirical formula $[(\text{Nd}_{0.60}\text{Pr}_{0.19}\text{Ca}_{0.09}\text{La}_{0.06}\text{Y}_{0.03}\text{Ce}_{0.02}\text{Th}_{0.01}\text{Gd}_{0.01})_{\Sigma 0.98}(\text{As}_{0.94}\text{V}_{0.07})_{\Sigma 1.01}\text{O}_4]$ is also known (Cabella *et al.*, 1999).

Miscibility between larger ('light', La^{3+} to Eu^{3+}) and smaller ('heavy', Gd^{3+} to Lu^{3+} and Y^{3+}) REE cations increases and the miscibility gap decreases, with the growth of temperature, and this phenomenon is successfully applied as a geothermometer (Heinrich *et al.*, 1997; Gratz and Heinrich, 1997, 1998; Pyle *et al.*, 2001; Mogilevsky, 2007). Consequently, the monazites, which originated under high-temperature conditions, can accommodate more Y and other smaller REE³⁺ cations in their structure. For example, monazite-(Ce) from high-temperature granulite contains 21–42 mol.% of the (Y, HREE) PO_4 component [6.5–14 wt.% Y_2O_3 , 6–11 wt.% $(\text{Gd}-\text{Yb})_2\text{O}_3$], which corresponds to the minimum precipitation temperature of ca. 1050°C (Krenn and Finger, 2010).

Low contents of zirconium (up to 0.02 Zr atoms per formula unit, ≤ 0.9 wt.% ZrO_2) have been documented rarely in several electron probe microanalyses of monazite-(Nd) (Graeser and Schwander, 1987), monazite-(Ce) (Bea, 1996; Santos *et al.*, 2018) and monazite-(Sm) (Masau *et al.*, 2002). Such relatively low Zr concentrations are limited by the relatively small size of the Zr^{4+} ionic radius for its effective accommodation in the monazite-type structure. The even smaller Sc^{3+} cation is usually below the detection limit of the WDS analyses of monazites.

A site: Actinides (Th, U), Ca, Sr and Pb

Some members of the monazite supergroup commonly contain appreciable contents of the actinide elements, thorium and uranium. In huttonite, Th^{4+} is an essential cation and, together with Ca^{2+} in cheralite, can be an important substituent in monazite-(Ce), which commonly forms a solid solution with both huttonite and cheralite (e.g. Kucha, 1980; Della Ventura *et al.*, 1996; Förster, 1998).

Concentrations of uranium, on the other hand, are usually relatively low due to the restricted accommodation of a smaller U^{4+} cation into the monazite structure in comparison with the larger Th^{4+} cation. The content of U in magmatic and metamorphic monazites reaches usually up to 1 wt.% UO_2 (below 0.01 U atoms per formula unit). However, some accessory monazite-(Ce) in pegmatites and granites contain high amounts of uranium (~5 to 16 wt.% UO_2 , Gramaccioli and Segalstad, 1978; Mannucci *et al.*, 1986; Bea, 1996; Uher *et al.*, 2013), even up to 23.1 wt.% UO_2 or ≤ 0.21 U apfu (Pérez-Soba *et al.*, 2014). Such monazite-(Ce) shows incorporation of the U^{4+} cation mainly through the $\text{Ca}_{0.5}\text{U}_{0.5}\text{PO}_4$ molecule, a uranium-analogue of cheralite (Gramaccioli and Segalstad, 1978; Uher *et al.*, 2013; Pérez-Soba *et al.*, 2014). Besides dominant U^{4+} , part of the uranium in monazite could be present in U^{5+} and U^{6+} form (up to 22 % of total U cation; Puchkova *et al.*, 2016).

Natural monazites usually show no irradiation-induced amorphization of the crystal structure (metamictization) due to radioactive decay of Th and U admixtures, a phenomenon common in zircon and other actinide-bearing minerals. The ability of the monazite structure for α -healing, a mechanism of defect recovery due to the electronic energy loss of α particles (^4He nuclei), explains the absence of the monazite structure amorphization (Seydoux-Guillaume *et al.*, 2018) and its gradual structural restoration by the ^4He ions (Nasdala *et al.*, 2020).

Calcium in monazite (as Ca^{2+} cation) is usually accommodated via a coupled CaThREE_{-2} cheralite substitution. Monazite rich in Ca and Th (sometimes referred to as cheralitic monazite) and cheralite itself are relatively common accessory minerals in granitic pegmatites and aplites (e.g. Gramaccioli and Segalstad, 1978; Bea, 1996; Förster, 1998; Pérez-Soba *et al.*, 2014; Uher *et al.*, 2014; Sobocký *et al.*, 2020). Some Ca-rich and Th,U-low monazites suggest Ca accommodation via $\text{Ca}_3\text{REE}_{-2}$ and/or $\text{CaPRE}_{-1}\text{Si}_{-1}$ substitution mechanisms (Catlos and Miller, 2017).

The Sr^{2+} cation rarely occurs in the monazite-group minerals, it attains up to 8.7 wt.% SrO or 0.18 apfu Sr (Chakhmouradian and Mitchell, 1998, 1999; Del Blanco *et al.*, 1998; Bulakh *et al.*, 2000; Pršek *et al.*, 2010; Nikolenko *et al.*, 2018; Broom-Fendley *et al.*, 2020). These Sr-rich monazite-(Ce) compositions also show an usually elevated content of sulfur in $(\text{SO}_4)^{2-}$ form (see below) and represent metamorphic, hydrothermal, or low-temperature secondary monazite in specific lithologies, such as carbonatites, kimberlites, or magnetite-rich metamorphic rocks.

Moreover, a composition with a dominant $\text{Sr}_{0.5}\text{Th}_{0.5}\text{PO}_4$ molecule and empirical formula $(\text{Sr}_{0.20}\text{Ca}_{0.12}\text{Th}_{0.32})_{\Sigma 0.64}(\text{Ce}_{0.22}\text{Nd}_{0.08}\text{Pr}_{0.04}\text{La}_{0.01})_{\Sigma 0.35}\text{P}_{1.00}\text{O}_4$ was described as a low-temperature secondary mineral in carbonatite (Chakhmouradian and Mitchell, 1998).

The concentration of Pb in monazite members is usually negligible (up to 0.5 wt.% PbO). The isotopic composition of Pb in the monazite-group minerals indicates it is almost completely radiogenic isotopes (^{206}Pb , ^{207}Pb , and ^{208}Pb), products of U and Th radioactive decay, whereas the content of non-radiogenic lead (^{204}Pb isotope) is very low, usually less than $1\text{ }\mu\text{g}\cdot\text{g}^{-1}$ or ppm (Parrish, 1990; Montel *et al.*, 1996). Consequently, old Archean to Proterozoic monazites, especially Th- and U-rich, could contain a significant content of Pb, for example up to 3.7 wt.% PbO for 2.4 Ga old metamorphic monazite-(Ce) with 28 wt.% ThO_2 and 1.2 wt.% UO_2 (Zhu and O'Nions, 1999). In rare cases, a relatively high Pb content (up to 0.5 wt.% PbO) in Th-poor monazite-(Ce) indicates a presence of non-radiogenic ('common') Pb, entered the monazite structure as the PbSO_4 molecule (Krenn *et al.*, 2011). Similarly, high lead content in U,Th-poor rooseveltite (up to 6.4 wt.% PbO; Krinov *et al.*, 2011) represents undoubtedly a non-radiogenic lead, most probably incorporated as the Pb^{2+} cation in the structure. A divalent A-site Pb^{2+} cation in the monazite structure has been documented by XANES and XPS studies (Dubrill *et al.*, 2009; Tang *et al.*, 2020).

A site: Fe, Al, and other elements

Some electron probe microanalyses of the monazite-group minerals reported elevated contents of Fe. These monazite analyses contain ~0.5 to 9.6 wt.% FeO (up to 0.31 Fe apfu; e.g. Bulakh *et al.*, 2000; Janots *et al.*, 2006; Pršek *et al.*, 2010; Bowins and Crockett, 2011; Čopjaková *et al.*, 2011; Starijaš Mayer *et al.*, 2014; Enkhbayar *et al.*, 2016; Broom-Fendley *et al.*, 2020). However, calculation of such Fe-rich compositions gave usually non-stoichiometric formulae with an apparent excess of A-site cations (commonly ΣA -cations attain 1.1 to 1.2 apfu), corresponding roughly to the Fe content. Consequently, the presence of micro- to nanoinclusions of Fe-(hydro)oxide phases or Fe-bearing minerals [e.g. allanite-(Ce), Starijaš Mayer *et al.*, 2014] is the most plausible explanation of such high iron content in the monazites measured.

Analyses of monazite-(Ce) and monazite-(La) infrequently also show an elevated content of aluminium with Al_2O_3 values reaching 0.5 to 1.4 wt.% (Bea, 1996; Bulakh *et al.*, 2000; Čopjaková *et al.*, 2011; Starijaš Mayer *et al.*, 2014; Santos *et al.*, 2018), rarely up to 6.7 wt.% Al_2O_3 (Janots *et al.*, 2006; Bowins and Crockett, 2011). Similarly, as in the case of Fe, a small Al^{3+} cation is not incorporated in the monazite structure, and admixture of some Al-rich minerals is the most probable reason for elevated measured Al in monazite. For example, an admixture of closely associated allanite-(Ce) caused high Al content in monazite (Starijaš Mayer *et al.*, 2014).

Magnesium (0.1–0.8 wt.% MgO; 0.01–0.05 apfu Mg) and Na (0.1–0.2 wt.% Na_2O ; ≤ 0.01 apfu Na) were detected in monazite-(Ce) from the NWA 7034 Martian regolith breccia meteorite (Liu *et al.*, 2016). Sulfatation Sr-enriched monazite-(Ce) contains up to 0.3 wt.% Na_2O (Enkhbayar *et al.*, 2016; Broom-Fendley *et al.*, 2020). Moreover, 0.7 wt.% K_2O (0.04 apfu K) was detected in U-rich monazite-(Ce) from a granitic pegmatite (Gramaccioli and Segalstad, 1978).

Arsenate minerals of the monazite group sometimes display 0.1 to 3.3 oxide wt.% of Pb, Fe, Ni, Co, Cu and Zn (rooseveltite:

Krinov *et al.*, 2011; Sejkora *et al.*, 2019), or Mn [1.3 wt.% MnO, 0.05 apfu Mn in gasparite-(La), Vereschagin *et al.*, 2019], probably in the form of divalent cations in A site. However, they could be also related to micro- or nano-inclusions of various minerals.

B site: V, Cr and S

Valid members of the monazite supergroup minerals (Table 1) are usually phosphates and arsenates, rarely silicates (huttonite) and chromates (crocoite). Some gasparite compositions also revealed high contents of V^{5+} , replacing dominant As^{5+} and P^{5+} in the B site, as in vanadium-rich gasparite-(La) with up to 11.2 wt.% V_2O_5 (~0.3 apfu V; Cabella *et al.*, 1999; Vereschagin *et al.*, 2019).

Crocoite, PbCrO_4 (Beudant 1832) represents the only known chromate mineral with a monazite-type structure. Its structural identity with monazite has been known for a long time (Gliszczynski, 1939; Effenberger and Pertlik, 1986; Errandonea *et al.*, 2015). However, natural crocoite shows near end-member composition without recognized elevated contents of REE, P, As or other elements typical for members of the monazite-supergroup minerals and their possible solid solution is probably very restricted, apparently due to relatively different Pb^{2+} and Cr^{6+} versus REE^{3+} (Th^{4+} , U^{4+} , Ca^{2+} , Bi^{3+}) and P^{5+} (As^{5+} , V^{5+} , Si^{4+}) ionic radii. Dissimilar parental lithologies also play a role; crocoite occurs in oxidation zones of sulfidic minerals with the influence of (ultra)basic Cr-rich rocks, whereas other monazite-structure minerals are found usually in Cr-poor felsic rocks (mainly granites, pegmatites, carbonatites, metamorphic rocks).

Sulfur is not a common substituent in natural monazite-structure minerals. However, this B-site element has been repeatedly determined in secondary, hydrothermal, or low-temperature monazite-(Ce), from altered carbonatites, kimberlites, rhyolites, quartz veins, and various ore-bearing metamorphic assemblages in concentration up to 11.2 wt.% SO_3 or ≤ 0.30 apfu S (Chakhmouradian and Mitchell, 1999; Bulakh *et al.*, 2000; Ondrejka *et al.*, 2007; Repina, 2008; Pršek *et al.*, 2010; Krenn *et al.*, 2011; Enkhbayar *et al.*, 2016; Nikolenko *et al.*, 2018; Broom-Fendley *et al.*, 2020). Moreover, a slightly elevated S content was also determined in primary magmatic monazite where it is probably connected with a specific oxidized environment during its crystallization from a melt with higher oxygen fugacity ($f\text{O}_2$) and S activity (Ondrejka *et al.*, 2013).

The sulfur in monazite occurs in the sulfate form (S^{6+}O_4) $^{2-}$ replacing P, As, or Si along the $\text{REE}^{3+} + (\text{P}, \text{As})^{5+} \leftrightarrow (\text{Ca}, \text{Sr})^{2+} + \text{S}^{6+}$ or $2\text{P}^{5+} \leftrightarrow \text{Si}^{4+} + \text{S}^{6+}$ substitutions (Table 2). The monoclinic CaSO_4 compound with the monazite structure was synthesized at high pressure (over 2 GPa) and room to high-temperature experiments (e.g. Borg and Smith, 1975; Crichton *et al.*, 2005; Ma *et al.*, 2007; Bradbury and Williams, 2009; Gracia *et al.*, 2012). In addition to the mentioned predominant sulfate form, the X-ray photoelectron spectroscopy measurements also indicate a subordinate presence of four-valent sulfur in the sulfite anionic group (S^{4+}O_3) $^{2-}$, possibly along the $2\text{P}^{5+} \leftrightarrow \text{S}^{4+} + \text{S}^{6+}$ substitution in sulfur-rich monazite-(Ce) (Broom-Fendley *et al.*, 2020; Table 2).

X site: Fluorine, hydroxyl and sulfide anions

Oxygen is the fairly dominant anion of the monazite-structure X-site position. However, some electron probe microanalyses of monazite-(Ce), gasparite-(Ce) and huttonite revealed a noticeable amount of the fluorine anion, replacing oxygen, 0.4–1.5 wt.% or ≤ 0.2 apfu F (Kucha, 1980; Andreoli *et al.*, 1994; Baldwin *et al.*, 2006; Ondrejka *et al.*, 2007; Hetherington and Harlov,

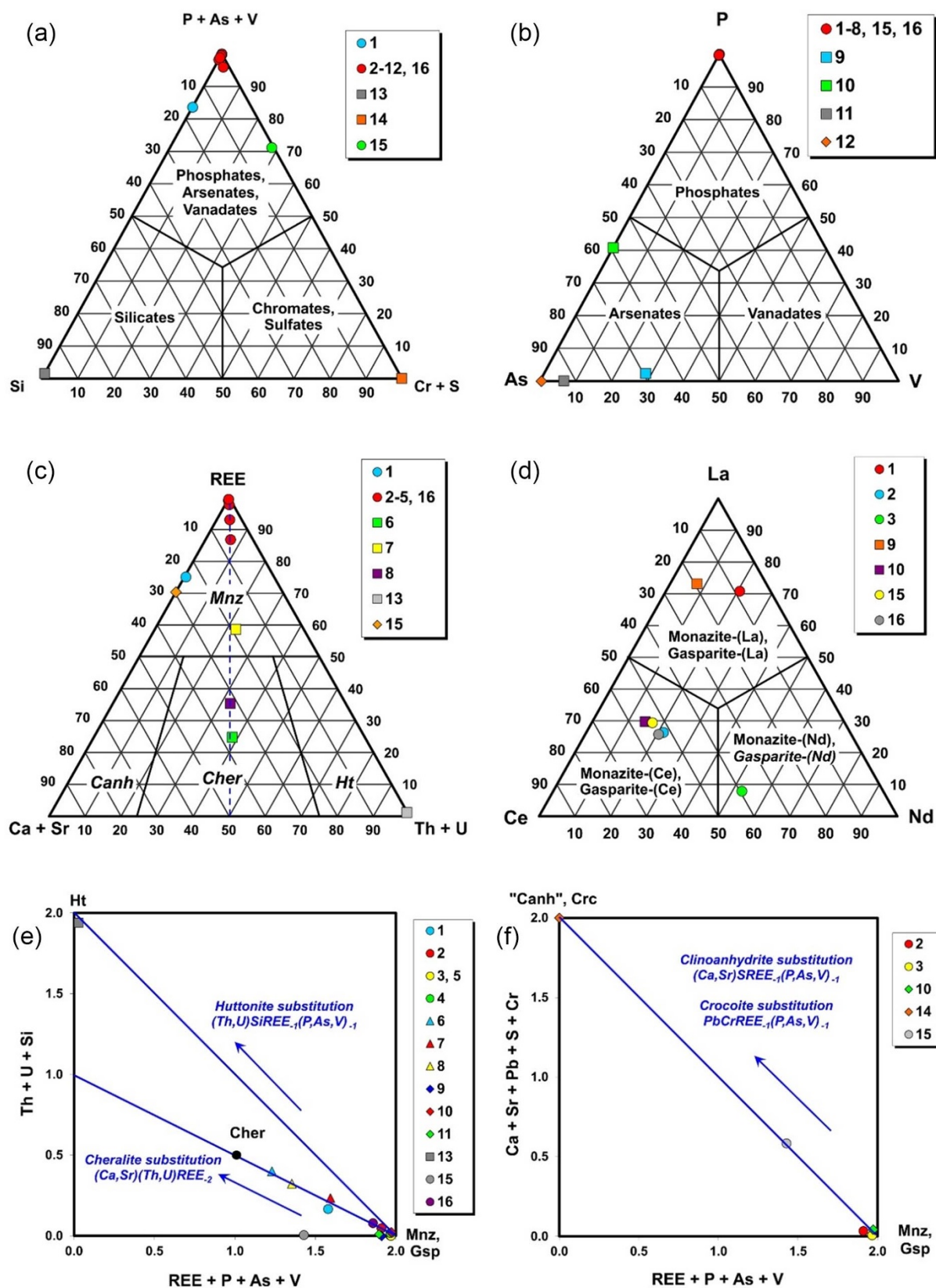


Figure 3. The proposed classification and substitution diagrams of the monazite-supergroup minerals. The numbers correspond to the analyses in [Appendix 1](#).

Table 3. Valid mineral species of the monazite supergroup and their basic data

Species name	Formula	<i>a</i> (Å)	<i>b</i> (Å)	<i>c</i> (Å)	β (°)	Type locality (country)	Reference
Monazite-(La)	LaPO ₄	6.83	7.07	6.50	103.3	Kounrad (Kazakhstan)	Borovsky and Gerasimovsky (1945); Strunz and Nickel (2001)
Monazite-(Ce)	CePO ₄	6.79	7.02	6.47	103.4	Miass (Russia)	Breithaupt (1829); Strunz and Nickel (2001)
Monazite-(Nd)	NdPO ₄	6.745	6.964	6.435	103.65	Punta Clogstafel or Monte Giove (Italy)	Graeser and Schwander (1987) www.mindat.org
Monazite-(Sm)	SmPO ₄	6.725	6.936	6.448	104.02	Annie Claim #3 (Canada)	Masau <i>et al.</i> (2002)
Monazite-(Gd)	GdPO ₄	6.703	6.914	6.383	103.8	Prakovce, Zimná Voda (Slovakia)	Ondrejka <i>et al.</i> (2023a)
Cheralite	Ca _{0.5} Th _{0.5} PO ₄	6.751	6.962	6.468	103.53	Kuttakuzhi (India)	Bowie and Horne (1953); Bowles <i>et al.</i> (1980)
Gasparite-(La)	LaAsO ₄	6.958	7.167	6.716	104.41	Ushkatyn-III (Kazakhstan); Vanni glacier (Switzerland)	Vereshchagin <i>et al.</i> (2019)
Gasparite-(Ce)	CeAsO ₄	6.937	7.137	6.738	104.69	Pizzo Cervandone (Italy)	Graeser and Schwander (1987)
Rooseveltite	BiAsO ₄	6.879	7.159	6.732	104.84	Santiaguillo (Bolivia)	Herzenberg (1946); Bedlivy and Mereiter (1982)
Huttonite	ThSiO ₄	6.80	6.96	6.54	104.55	Gillespie's Beach (New Zealand)	Pabst and Hutton (1951)
Crocoite	PbCrO ₄	7.127	7.438	6.799	102.43	Berezovsk (Russia)	Beudant (1832); Effenberger and Pertlik (1986)

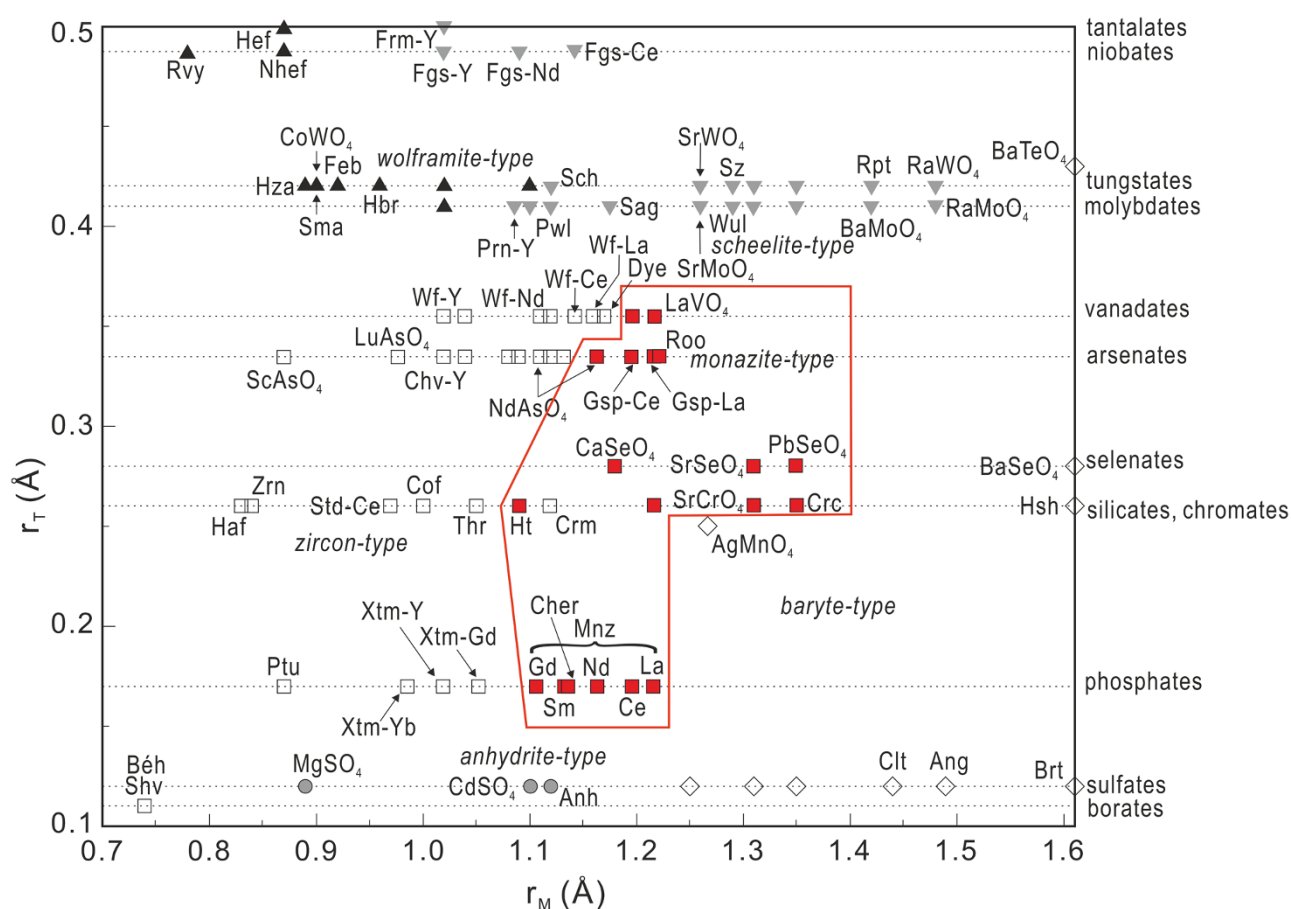


Figure 4. Mutual relationships between monazite and other ABX_4 compounds expressed by the ionic radius of the A-site cation (r_M) versus the ionic radius of the B-site cation (r_T); the effective ionic radii in corresponding coordination number are according to Shannon (1976). Mineral abbreviations (according to Warr, 2021) are the following (in alphabetical order): Ang – anglesite, Anh – anhydrite, Béh – béhierite, Brt – baryte, Cher – cheralite, Chv-Y – chernovite-(Y), Clt – celestine, Cof – coffinite, Crc – crocoite, Crm – chromite, Dye – dreyerite, Feb – ferberite, Fgs-Ce – fergusonite-(Ce), Fgs-Nd – fergusonite-(Nd) (not IMA approved mineral), Fgs-Y – fergusonite-(Y), Frm-Y – formantite-(Y), Gsp-Ce – gasparite-(Ce), Gsp-La – gasparite-(La), Haf – hafnion, Hef – heftetjernite, Hsh – hashemite, Ht – huttonite, Hza – huanzalaite, Mnz-Ce – monazite-(Ce), Mnz-Gd – monazite-(Gd), Mnz-La – monazite-(La), Mnz-Nd – monazite-(Nd), Mnz-Sm – monazite-(Sm), Nhef – nioboheftetjernite, Prn-Y – paraniite-(Y), Ptu – pretulite, Pwl – powellite, Roo – rooseveltite, Rpt – ronpetersonite, Rvy – rossovskyite, Sag – suseinargiuite, Sch – scheelite, Shv – schiavinatoite, Sma – sanmartinite, Std-Ce – stetindite-(Ce), Sz – stolzite, Thr – thorite, Wf-Ce – wakefieldite-(Ce), Wf-La – wakefieldite-(La), Wf-Nd – wakefieldite-(Nd), Wf-Y – wakefieldite-(Y), Wul – wulfenite, Xtm-Gd – xenotime-(Gd), Xtm-Y – xenotime-(Y), Xtm-Yb – xenotime-(Yb), Zrn – zircon.

2008; Bowins and Crocket, 2011; Catlos and Miller, 2017; Broska and Kubiš, 2018; Santos *et al.*, 2018; Broom-Fendley *et al.*, 2020; Maraszewska *et al.*, 2023). The presence of a hydroxyl anion in natural monazite causes defects attributed mainly to

post-crystallization hydration of a radiation-damaged structure, along with heterovalent substitution (Abe *et al.*, 2017). The entry of F^- or $(OH)^-$ anions into structure of the monazite-supergroup minerals has been explained by the $REE^{3+} + O^{2-} \leftrightarrow (Ca, Sr)^{2+} + (OH, F)^-$ (Chakhmouradian and Mitchell, 1999; Broom-Fendley *et al.*, 2020) or $(PO_4)^{3-} \leftrightarrow (SiO_3)^{2-} + F^-$ (Williams *et al.*, 2007) substitution mechanisms (Table 2). The X-ray photoelectron spectroscopy also reveals a rare presence of sulfide (S^{2-}) anion in monazite-(Ce), possibly along the $O^{2-} \leftrightarrow S^{2-}$ substitution (Broom-Fendley *et al.*, 2020; Table 2).

Calculation of monazite-supergroup mineral formulae

The ABX_4 stoichiometry of the monazite-supergroup minerals enables the following procedures for the calculation of chemical analyses (in wt.%) into the mineral formulae (in apfu):

- (1) Normalization on the basis of 4 oxygen atoms ($X = 4\ O$).
- (2) Normalization on the basis of $(A + B) = 2$ cations.
- (3) Normalization on the basis of $B = 1$ cation.
- (4) Normalization on the basis of $A = 1$ cation.

Procedure (1) is recommended for most of the monazite-supergroup members where nearly the whole X -anion site is occupied by O^{2-} and the content of other anions (F^- , OH^- and S^{2-}) is negligible. However, procedures (2) to (4) are suitable for monazite compositions with the presence of the above-mentioned anions other than O^{2-} . If some additional A -site elements are possibly present but were not analysed (e.g. some REE, especially in older analyses), we recommend using the procedure (3), based on the sum of the B -site cations (P^{5+} , As^{5+} , V^{5+} , Si^{4+} , S^{6+} , Cr^{6+} , etc.). Conversely, procedure (4) is recommended when some smaller amount of the B -site element (e.g. As and V in phosphate members) is expected but missing in the given analysis. The monazite-supergroup minerals have $Z = 4$ (number of chemical formula units per one unit cell); therefore, all above-mentioned calculations can be multiplied by 4, and the formulae will be based on 16 oxygen atoms (1), $(A + B) = 8$ cations (2), $B = 4$ cations (3), or $A = 4$ cations (4). Representative chemical analyses of the monazite-supergroup minerals with their formula calculation (based on $B = 1$ cation) are in Appendix 1, and the proposed classification and substitution diagrams of the monazite-supergroup minerals are shown in Fig. 3.

Moreover, molecular amounts of the monazite (super)group end-members can be calculated, especially for common magmatic and metamorphic monazite-(Ce) with detectable contents of Si, Th and Ca (huttonite and cheralite components). The procedure for such mole fraction calculation is described in Pyle *et al.* (2001).

Valid, potential, and discredited members of the monazite supergroup

The following eleven valid mineral species of the monazite supergroup are known (see List of minerals at www.cnmnc.units.it/imalist.htm [accessed on July 1, 2026]): monazite-(La), monazite-(Ce), monazite-(Nd), monazite-(Sm), monazite-(Gd), cheralite, gasparite-(La), gasparite-(Ce), rooseveltite, huttonite, and crocoite (Table 3). Rooseveltite, huttonite and crocoite are grandfathered minerals, cheralite is a redefined member, monazite-(Ce) and monazite-(La) are renamed species, while monazite-(Nd), monazite-(Sm), monazite-(Gd), gasparite-(La) and gasparite-(Ce) are IMA approved mineral species. In addition, mineral analyses

and synthesized compounds indicate the potential existence of several other new members (mineral species) of the monazite supergroup in natural environments. They include at least minerals with $Ca_{0.5}U_{0.5}PO_4$ (U-analogue of cheralite), $Sr_{0.5}Th_{0.5}PO_4$ (Sr-analogue of cheralite), $NdAsO_4$ [gasparite-(Nd)], $LaVO_4$ [vanadate analogue of monazite-(La) or gasparite-(La)], and $CaSO_4$ (clinoanhydrite), a monazite-structured dimorph of anhydrite) end-member compositions, see above paragraphs. Minerals of the monazite supergroup discredited by the CNMNC IMA include 'brabantite', 'cheralite-(Ce)', and 'tombarthite-(Y)'. 'Brabantite' was originally described and approved as a new mineral with the end-member formula $CaTh[PO_4]_2$ (Rose, 1980). However, it represents only a synonym of cheralite, the previously described mineral (Bowie and Horne, 1953). Consequently, according to the IMA rules, the name cheralite has priority over 'brabantite', which was later discredited (Linthout, 2007). Moreover, 'cheralite-(Ce)' with suffix '-(Ce)' was also discredited as a separate mineral species because Ce or other REE is not a dominant (essential) element in its end-member formula and the mineral denoted as 'cheralite-(Ce)' (e.g. Förster, 1998) represents only Ca-Th-rich monazite-(Ce) composition (Burke, 2006). Consequently, the term cheralite (without the suffix) is the only valid mineral name with the dominant $Ca_{0.5}Th_{0.5}PO_4$ end-member formula. 'Tombarthite-(Y)', originally named 'tombarthite', was described and approved by IMA as a new mineral, hydrated silicate of dominant Y [approximately with $(Y, REE, Ca, Fe, Mn, Th)(Si, H_4)_4(O, OH)_4$ formula], with unit-cell parameters similar to monazite (Neumann and Nilssen, 1968). However, a recent study of the 'tombarthite-(Y)' neotype material revealed its mixture character with dominant thalénite-(Y), xenotime-(Y), and kainosite-(Y), and consequently 'tombarthite-(Y)' was discredited as a valid mineral (Friis, 2018).

Relationships with the other mineral (super)groups

The monazite supergroup minerals represent natural compounds with general ABX_4 stoichiometry and monoclinic symmetry, space group $P2_1/n$ (14), and $Z = 4$. Their large divalent to tetravalent A -site cation is coordinated by nine X -site anions (usually O^{2-}), whereas the B -site cation shows tetrahedral coordination. Many minerals reveal the analogous ABX_4 stoichiometry with a large A -site cation (commonly Ca^{2+} , Pb^{2+} , REE^{3+} , Zr^{4+} , Th^{4+} , U^{4+}), a B -site cation in 4-fold coordination (usually Si^{4+} , P^{5+} , As^{5+} , V^{5+} , Nb^{5+} , Ta^{5+} , S^{6+} , W^{6+}) and oxygen as the fairly dominant X -site anion.

The monazite supergroup minerals show the closest compositional and structural relationships with the tetragonal zircon and xenotime groups, tetragonal scheelite group [including fergusonite-(Y) and formantite-(Y)], orthorhombic baryte and anhydrite groups, and to a lesser extent with members of the rhabdophane and gypsum groups (ABO_4 + molecular H_2O minerals). However, they show different structural and bond-valence arrangements, reflected in different symmetry and space groups. Mutual relationships between monazite and other ABX_4 compounds, expressed in P - T stability fields, crystal structure, and chemistry, have been discussed in numerous experimental studies (e.g. Clavier *et al.*, 2011 and references therein) and are illustrated in Fig. 4.

Acknowledgements. We thank all members of the IMA CNMNC for their constructive criticism and comments during the approval procedure. We thank two anonymous reviewers, as well as principal editor Stuart Mills and associate editor for their useful comments. This work was supported by the Slovak

Research and Development Agency under the contract APVV-22-0092 and by the Ministry of Culture of the Czech Republic (long-term project DKRVO 2024-2028/1.II.c; National Museum, 00023272) for JS.

Competing interests. The authors declare none.

References

- Abe T., Kuribayashi T. and Nakamura M. (2017) Infrared spectroscopic study of OH defects in monazite. *European Journal of Mineralogy*, **29**, 949–957.
- Andreoli M.A.G., Smith C.B., Watkeys M., Moore J.M., Ashwal L.D. and Hart R.J. (1994) The geology of the Steenkampskraal monazite deposit, South Africa; implications for REE-Th-Cu mineralization in charnockite-granulite terranes. *Economic Geology*, **89**, 994–1016.
- Atencio D., Andrade M.B., Christy A.G., Gieré R. and Kartashov P.M. (2010) The pyrochlore supergroup of minerals: Nomenclature. *The Canadian Mineralogist*, **48**, 673–698.
- Bačík P., Miyawaki R., Atencio D., Cámara F. and Fridrichová J. (2017) Nomenclature of the gadolinite supergroup. *European Journal of Mineralogy*, **29**, 1067–1082.
- Baldwin J.A., Bowring S.A., Williams M.L. and Mahan K.H. (2006) Geochronological constraints on the evolution of high-pressure felsic granulites from an integrated electron microprobe and ID-TIMS geochemical study. *Lithos*, **88**, 173–200.
- Bayliss P. and Levinson A.A. (1988) A system of nomenclature for rare-earth mineral species: Revision and extension. *American Mineralogist*, **73**, 422–423.
- Bayliss P., Kolitsch U., Nickel E.H. and Pring A. (2010) Alunite supergroup: recommended nomenclature. *Mineralogical Magazine*, **74**, 919–927.
- Bea F. (1996) Residence of REE, Y, Th and U in granites and crustal protoliths; implications for the chemistry of crustal melts, *Journal of Petrology*, **37**, 521–552.
- Bedlvy D. and Mereiter K. (1982) Structure of α -BiAsO₄ (Rooseveltite). *Acta Crystallographica*, **B38**, 1559–1561.
- Beudant F.S. (1832) Crocoite. *Traité de Minéralogie*, **2**, 669–670 [in French].
- Boatner L.A. (2002) Synthesis, structure, and properties of monazite, pre-tulite, and xenotime. Pp. 87–121 in: *Phosphates: geochemical, geobiological and materials importance. Reviews in Mineralogy and Geochemistry*, **48** (M. Kohn, J. Rakovan and J.M. Hughes, editors). Mineralogical Society of America, Washington, D.C., USA.
- Borg I.Y. and Smith D.K. (1975) A high pressure polymorph of CaSO₄. *Contributions to Mineralogy and Petrology*, **50**, 127–133.
- Borovsky I.B. and Gerasimovsky V.I. (1945) Rare earths in minerals. *Comptes Rendu (Doklady) de l'Académie des Sciences de l'URSS*, **49**, 353–356.
- Bosi F., Biagioni C. and Pasero M. (2019) Nomenclature and classification of the spinel supergroup. *European Journal of Mineralogy*, **31**, 183–192.
- Bosi F., Hatert F., Pasero M. and Mills S.J. (2025) IMA Commission on New Minerals, Nomenclature and Classification (CNMNC) - Newsletter 85. *Mineralogical Magazine*, **89**, 454–458.
- Bowie S.H.U. and Horne J.E.T. (1953) Cheralite, a new mineral of the monazite group. *Mineralogical Magazine*, **30**, 93–99.
- Bowins R.J. and Crockett J.H. (2011) Monazite, xenotime and REE minerals in Archean banded iron-formation from the Sherman and Adams mines, Ontario, Canada. *The Canadian Mineralogist*, **49**, 749–763.
- Bowles J.F.W., Jobbins E.A. and Young B.R. (1980) A re-examination of cheralite. *Mineralogical Magazine*, **43**, 885–888.
- Bradbury S.E. and Williams Q. (2009) X-ray diffraction and infrared spectroscopy of monazite-structured CaSO₄ at high pressures: implications for shocked anhydrite. *Journal of Physics and Chemistry of Solids*, **70**, 134–141.
- Breithaupt A. (1829) On monazite, a new species in mineral realm. *Journal für Chemie und Physik*, **55**, 301–303 [in German].
- Broom-Fendley S., Smith M.P., Andrade M.B., Ray S., Banks D.A., Loye E., Atencio D., Pickles J.R. and Wall F. (2020) Sulfur-bearing monazite-(Ce) from the Eureka carbonatite, Namibia: oxidation state, substitution mechanism, and formation conditions. *Mineralogical Magazine*, **84**, 35–48.
- Broska I. and Kubiš M. (2018) Accessory minerals and evolution of tin-bearing S-type granites in the western segment of the Gemeric Unit (Western Carpathians). *Geologica Carpathica*, **69**, 483–497.
- Bulakh A.G., Nesterov A.R., Zaitsev A.N., Pilipiuk A.N., Wall F. and Kirillov A.S. (2000) Sulfur-containing monazite-(Ce) from late-stage mineral assemblages at the Kandaguba and Vuoriyarvi carbonatite complexes, Kola peninsula, Russia. *Neues Jahrbuch für Mineralogie – Monatshefte*, **2000**, 217–233.
- Burke E.A.J. (2006) A mass discreditation of GQN minerals. *The Canadian Mineralogist*, **44**, 1557–1560.
- Cabella R., Lucchetti G. and Marescotti P. (1999) Occurrence of LREE- and Y-arsenates from a Fe-Mn deposit, Ligurian Briançonnais Domain, Maritime Alps, Italy. *The Canadian Mineralogist*, **37**, 961–972.
- Carlos E.J. and Miller N.R. (2017) Speculations linking monazite compositions to origin: Llallagua tin ore deposit (Bolivia). *Resources*, **6**, 36.
- Chakhmouradian A.R. and Mitchell R.H. (1998) Lueshite, pyrochlore and monazite-(Ce) from apatite-dolomite carbonatite, Lesnaya Varaka complex, Kola Peninsula, Russia. *Mineralogical Magazine*, **62**, 769–782.
- Chakhmouradian A.R. and Mitchell R.H. (1999) Niobian ilmenite, hydroxylapatite and sulfatite monazite; alternative hosts for incompatible elements in calcite kimberlite from Internatsional'naya, Yakutia. *The Canadian Mineralogist*, **37**, 1177–1189.
- Clavier N., Podor R. and Dacheux N. (2011) Crystal chemistry of the monazite structure. *Journal of the European Ceramic Society*, **31**, 941–976.
- Čopjaková R., Novák M. and Franců E. (2011) Formation of authigenic monazite-(Ce) to monazite-(Nd) from Upper Carboniferous graywackes of the Drahany Upland: roles of the chemical composition of host rock and burial temperature. *Lithos*, **127**, 373–385.
- Crane M.J., Leverett P., Shaddick L.R., Williams P.A., Klopogge J.T. and Frost R.L. (2001) The PbCrO₄-PbSO₄ system and its mineralogical significance. *Neues Jahrbuch für Mineralogie – Monatshefte*, **2001**, 505–519.
- Crichton W.A., Parise J.B., Antao S.M. and Grzechnik A. (2005) Evidence for monazite-, barite- and AgMnO₄ (distorted barite)-type structures of CaSO₄ at high pressure and temperature. *American Mineralogist*, **90**, 22–27.
- Del Blanco M., Costas Ulbrich M., Echeveste H. and Vlach S.R.F. (1998) Monazite-(Nd) with Sm from the Los Diques carbonatite dykes, north-east part of the Sierra de Cobres, Salta, Argentina). *IV Reunion de Mineralogia y Metalogenia Universidad Nacional der Sur - Bahía Blanca. MINMET'98-EDIUNS*, 63–69 [in Spanish].
- Della Ventura G., Mottana A., Parodi G.C., Raudsepp M., Bellatreccia F., Caprilli E., Rossi P. and Fiori S. (1996) Monazite-huttonite solid-solutions from the Vico Volcanic Complex, Latium, Italy. *Mineralogical Magazine*, **60**, 751–758.
- Dubail J., Farges F., Gautron L., Harfouche M., Borca C. and Grolimund D. (2009) Pb in naturally irradiated monazites and zircons. *Journal of Physics Conference Series*, **190**, 012180.
- Effenberger H. and Pertlik F. (1986) Four monazite type structures: comparison of SrCrO₄, SrSeO₄, PbCrO₄ (crocoite), and PbSeO₄. *Zeitschrift für Kristallographie*, **176**, 75–83.
- Engi M. (2017) Petrochronology based on REE-minerals: monazite, allanite, xenotime, apatite. Pp. 365–418 in: *Petrochronology: Methods and Applications* (M.J. Kohn, M. Engi and P. Lanari, editors). Reviews in Mineralogy and Geochemistry, **83**. Mineralogical Society of America, Chantilly, Virginia, USA.
- Enkhbayar D., Seo J., Choi S.-G., Lee Y.J. and Batmunkh E. (2016) Mineral chemistry of REE-rich apatite and sulfur-rich monazite from the Mushgai Khudag, alkaline volcanic-plutonic complex, South Mongolia. *International Journal of Geosciences*, **7**, 20–31.
- Errandonea D., Muñoz A., Rodríguez-Hernández P., Proctor J.E., Sapiña F. and Bettinelli M. (2015) Theoretical and experimental study of the crystal structures, lattice vibrations, and band structures of monazite-type PbCrO₄, PbSeO₄, SrCrO₄, and SrSeO₄. *Inorganic Chemistry*, **54**, 7524–7535.
- Förster H.-J. (1998) The chemical composition of REE-Y-Th-U-rich accessory minerals in peraluminous granites of the Erzgebirge-Fichtelgebirge region, Germany. Part I: the monazite-(Ce)-brabantite solid solution series. *American Mineralogist*, **83**, 259–272.

- Förster H.-J., Harlov D.E. and Milke R. (2000) Composition and Th – U – total Pb ages of huttonite and thorite from Gillespie's Beach, South Island, New Zealand. *The Canadian Mineralogist*, **38**, 675–684.
- Franz G., Andrehs G. and Rhede D. (1996) Crystal chemistry of monazite and xenotime from Saxothuringian-Moldanubian metapelites, NE Bavaria, Germany. *European Journal of Mineralogy*, **8**, 1097–1118.
- Friis H. (2018) Discreditation of tombarthite-(Y). *Mineralogical Magazine*, **82**, 1131–1139.
- Gaines R.V., Skinner H.C.W., Foord E.E., Mason B. and Rosenzweig A. (1997) *Dana's New Mineralogy*, 8th edition. John Wiley & Sons, Inc., New York, 1819 pp.
- Gliszczynski S. von (1939) Contribution to the "isomorphism" of monazite and crocoite. A critical statement. *Zeitschrift für Kristallographie, Mineralogie und Petrographie*, **101**, 1–16 [in German].
- Gracia L., Beltrán A., Errandonea D. and Andrés J. (2012) CaSO_4 and its pressure-induced phase transitions. A density functional theory study. *Inorganic Chemistry*, **51**, 1751–1759.
- Graeser S. and Schwander H. (1987) Gasparite-(Ce) and monazite-(Nd): two new minerals to the monazite group from the Alps. *Schweizerische Mineralogische und Petrographische Mitteilungen*, **67**, 103–113.
- Gramaccioli C.M. and Segalstad T.V. (1978) A uranium- and thorium-rich monazite from a south-alpine pegmatite at Piona, Italy. *American Mineralogist*, **63**, 757–761.
- Gratz R. and Heinrich W. (1997) Monazite-xenotime thermobarometry: experimental calibration of the miscibility gap in the binary system CePO_4 - YPO_4 . *American Mineralogist*, **82**, 772–780.
- Gratz R. and Heinrich W. (1998) Monazite-xenotime thermometry. III. Experimental calibration of the partitioning of gadolinium between monazite and xenotime. *European Journal of Mineralogy*, **10**, 579–588.
- Grew E.S., Locock A.J., Mills S.J., Galuskina I.O., Galuskin E.V. and Hälenius U. (2013) Nomenclature of the garnet supergroup. *American Mineralogist*, **98**, 785–811.
- Heinrich W., Andrehs G. and Franz G. (1997) Monazite-xenotime miscibility gap thermometry. I. An empirical calibration. *Journal of Metamorphic Geology*, **15**, 3–16.
- Herzenberg R. (1946) Rooseveltite. New minerals in Bolivia. *Boletín Técnico, Universidad Técnica de Oruro*, **1**, 10–11 [in Spanish].
- Hetherington C.J. and Harlov D.E. (2008) Metasomatic thorite and uraninite inclusions in xenotime and monazite from granitic pegmatites, Hydra anorthosite massif, southwestern Norway: mechanics and fluid chemistry. *American Mineralogist*, **93**, 806–820.
- Janots E., Negro F., Brunet F., Goffé B., Engi M. and Bouybaouène M.L. (2006) Evolution of the REE mineralogy in HP-LT metapelites of the Sebti complex, Rif, Morocco: monazite stability and geochronology. *Lithos*, **87**, 214–234.
- Kartashov P.M., Bogatnikov O.A., Mokhov A.V., Gorshkov A.I., Ashikhmina N.A., Magazina L.O. and Koporulina E.V. (2006) Lunar monazites. *Doklady Earth Sciences*, **407A**, 498–502.
- Kolitsch U. and Holtstam D. (2004) Crystal chemistry of REEXO_4 compounds ($X = \text{P, As, V}$). II. Review of REEXO_4 compounds and their stability fields. *European Journal of Mineralogy*, **16**, 117–126.
- Krenn E. and Finger F. (2010) Unusually Y-rich monazite-(Ce) with 6–14 wt.% Y_2O_3 in a granulite from the Bohemian Massif: implications for high-temperature monazite growth from the monazite-xenotime miscibility gap thermometry. *Mineralogical Magazine*, **74**, 217–225.
- Krenn E., Putz H., Finger E. and Paar W.H. (2011) Sulfur-rich monazite with high common Pb in ore-bearing schists from the Schellgaden mining district (Tauern Window, Eastern Alps). *Mineralogy and Petrology*, **102**, 51–62.
- Krinov D.I., Azarova Y.V., Struzhkov S.F., Natalenko M.V. and Radchenko Y.I. (2011) On the discovery of rooseveltite, preisingerite, tröegerite and zeunerite in Bi-As-Cu-U-mineralization from the Oranzhevoye ore field, Verkhnē-Kalganinsky Massif, Magadan Region, Russia. *New Data on Minerals*, **46**, 20–24.
- Kucha H. (1980) Continuity in the monazite-huttonite series. *Mineralogical Magazine*, **43**, 1031–1034.
- Laurent A.T., Seydoux-Guillaume A.-M., Duchene S., Bingen B., Bosse V. and Datas L. (2016) Sulphate incorporation in monazite lattice and dating the cycle of sulphur in metamorphic belts. *Contributions to Mineralogy and Petrology*, **171**, 94.
- Levinson A.A. (1966) A system of nomenclature for rare-earth minerals. *American Mineralogist*, **51**, 152–158.
- Levy A. (1823) Description of a new Mineral. *The Annals of Philosophy*, **5**, 241–243.
- Linthout K. (2007) Tripartite division of the system 2REEPO_4 – $\text{CaTh}(\text{PO}_4)_2$ – 2ThSiO_4 , discreditation of brabantite, and recognition of cheralite as the name for members dominated by $\text{CaTh}(\text{PO}_4)_2$. *The Canadian Mineralogist*, **45**, 503–508.
- Liu Y., Ma C., Beckett J.R., Chen Y. and Guan Y. (2016) Rare-earth-element minerals in Martian breccia meteorites NWA 7034 and 7533: implications for fluid-rock interaction in the Martian crust. *Earth and Planetary Science Letters*, **451**, 251–262.
- Ma Y.M., Zhou Q., He Z., Li F.F., Yang K.F., Cui Q.L. and Zou G.T. (2007) High-pressure and high-temperature study of the phase transition in anhydrite. *Journal of Physics: Condensed Matter*, **19**, 425221.
- Maksimović Z. and Pantó Gy. (1980) Bastnäsite – (La) and monazite – (Nd), a new variety of monazite, from the Marmara bauxite deposit (Greece). *Bulletin de l'Académie Serbe des Sciences et des Arts, Classé des Sciences Naturelles et Mathématiques, Sciences Naturelles*, **72** (20), 35–42.
- Mannucci G., Diella V., Gramaccioli C.M. and Pilati T. (1986) A comparative study of some pegmatitic and fissure monazite from the Alps. *The Canadian Mineralogist*, **24**, 469–474.
- Maraszewska M., Broska I., Kurylo S. and Konečný P. (2023) The composite zircon-xenotime-monazite-allanite assemblage in the leucogranite from the Low Tatra Pluton, Western Carpathians: interplay of melts and fluids. *Geologica Carpathica*, **74**, 387–406.
- Masau M., Černý P., Cooper M.A., Chapman R. and Grice J.D. (2002) Monazite-(Sm), a new member of the monazite group from the Annie Claim #3 granitic pegmatite, southeastern Manitoba. *The Canadian Mineralogist*, **40**, 1649–1655.
- Miers H.A. (1885) On monazite from Cornwall, and connellite. *Mineralogical Magazine*, **6**, 164–167.
- Mills S.J., Hatert F., Nickel E.H. and Ferraris G. (2009) The standardisation of mineral group hierarchies: application to recent nomenclature proposals. *European Journal of Mineralogy*, **21**, 1073–1080.
- Mogilevsky P. (2007) On the miscibility gap in monazite-xenotime systems. *Physics and Chemistry of Minerals*, **34**, 201–214.
- Montel J.-M., Foret S., Veschambre M., Nicollet C. and Provost A. (1996) Electron microprobe dating of monazite. *Chemical Geology*, **131**, 37–53.
- Mooney R.C.L. (1948) Crystal structures of a series of rare earth phosphates. *The Journal of Chemical Physics*, **16**, 1003.
- Nasdala L., Akhmadaliev S., Burakov B.E., Chanmuang N.C. and Škoda R. (2020) The absence of metamictisation in natural monazite. *Scientific Reports*, **10**, 14676.
- Neumann H. and Nilssen B. (1968) Tombarthite, a new mineral from Høgetveit, Evje, South Norway. *Lithos*, **1**, 113–123.
- Ni Y., Hughes J.M. and Mariano A.N. (1995) Crystal chemistry of the monazite and xenotime structures. *American Mineralogist*, **80**, 21–26.
- Nikolenko A.M., Redina A.A., Doroshkevich A.G., Prokopyev I.R., Ragozin A.L. and Vladykin N.V. (2018) The origin of magnetite-apatite rocks of Mushgai-Khudag Complex, South Mongolia: mineral chemistry and studies of melt and fluid inclusions. *Lithos*, **320–321**, 567–582.
- Ondrejka M., Uher P., Pršek J. and Ozdín D. (2007) Arsenian monazite-(Ce) and xenotime-(Y), REE arsenates and carbonates from the Tisovec-Rejkovo rhyolite, Western Carpathians, Slovakia: composition and substitutions in the $(\text{REE,Y})\text{XO}_4$ system ($X = \text{P, As, Si, Nb, S}$). *Lithos*, **95**, 116–129.
- Ondrejka M., Broska I., Uher P., Kohút M., Putiš M. and Konečný P. (2013) *Accommodation of S and As by primary magmatic monazite in Western Carpathian granitic rocks: the role of minor element substitutions and redox conditions of parental melt*. Program, Abstracts and Fieldtrip Guidebook. International Workshop on the Geology and Metallogeny of Critical Metals (CM2013), Ulaanbaatar, Mongolia.
- Ondrejka M., Uher P., Ferenc Š., Majzlan J., Pollok K., Mikuš T., Milovská S., Molnárová A., Škoda R., Kopačík R., Kurylo S. and Bačík P. (2023a) Monazite-(Gd), a new Gd-dominant mineral of the monazite group from

- the Zimná Voda REE-U-Au quartz vein, Prakovce, Western Carpathians, Slovakia, *Mineralogical Magazine*, **87**, 568–574.
- Ondrejka M., Uher P., Ferenc Š., Milovská S., Mikuš T., Molnárová A., Škoda R., Kopáček R. and Bačík P. (2023b) Gadolinium-dominant monazite and xenotime: selective hydrothermal enrichment of middle REE during low temperature alteration of uraninite, brannerite and fluorapatite (the Zimná Voda REE-U-Au quartz vein, Western Carpathians, Slovakia). *American Mineralogist*, **108**, 754–768.
- Pabst A. and Hutton C.O. (1951) Huttonite, a new monoclinic thorium silicate. *American Mineralogist*, **36**, 60–69.
- Parrish R.R. (1990) U–Pb dating of monazite and its application to geological problems. *Canadian Journal of Earth Sciences*, **27**, 1431–1450.
- Pasero M., Kampf A.R., Ferraris C., Pekov I.V., Rakovan J. and White T.J. (2010) Nomenclature of the apatite supergroup minerals. *European Journal of Mineralogy*, **22**, 163–179.
- Pekov I.V. (2000) *Lovozero Massif*. Ocean Pictures Ltd., Moscow, 480 pp.
- Pérez-Soba C., Villaseca C., Orejana D. and Jeffries T. (2014) Uranium-rich accessory minerals in the peraluminous and perphosphorous Belvis de Monroy pluton (Iberian Variscan belt). *Contributions to Mineralogy and Petrology*, **167**, 1008.
- Petrík I., Janák M., Klonowska I., Majka J., Froitzheim N., Yoshida K., Sasinková V., Konečný P. and Vaculovič T. (2019) Monazite behaviour during metamorphic evolution of a diamond-bearing gneiss: a case study from the Seve Nappe Complex, Scandinavian Caledonides. *Journal of Petrology*, **60**, 1773–1796.
- Pršek J., Ondrejka M., Bačík P., Budzyń B. and Uher P. (2010) Metamorphic-hydrothermal REE minerals in the Bacúch magnetite deposit, Western Carpathians, Slovakia: (Sr,Sr)-rich monazite-(Ce) and Nd-dominant hingganite. *The Canadian Mineralogist*, **48**, 81–94.
- Puchkova E.V., Bogdanov R.V. and Gieré R. (2016) Redox states of uranium in samples of microlite and monazite. *American Mineralogist*, **101**, 1884–1891.
- Pyle J.M., Spear F.S., Rudnick R.L. and McDonough W.F. (2001) Monazite–xenotime–garnet equilibrium in metapelites and a new monazite–garnet thermometer. *Journal of Petrology*, **42**, 2083–2107.
- Repina S.A. (2008) Monazite as an indicator of formation conditions of quartz veins at the Zhelannoe Deposit, the Subpolar Urals. *Geology of the Ore Deposits*, **50**, 609–619.
- Rose D. (1980) Brabantite, $\text{CaTh}[\text{PO}_4]_2$, a new mineral of the monazite group. *Neues Jahrbuch für Mineralogie, Monatshefte*, **1980**, 247–257.
- Santos J.J.A., Conceição H., Leandro M.V.S. and Rosa M.L.S. (2018) Formation of monazite-(Ce, La) by fluid-apatite interaction: the Floresta Azul Alkaline Complex, Bahia, Brazil. *Brazilian Journal of Geology*, **48**, 721–733.
- Sejkora J., Pauliš P., Gramblička R., Malíková R., Pour O., Dolníček Z., Ulmanová J. and Vrtiška L. (2019) The recently found Bi-Co-Ni-As-U-V mineralization of the Přísečnice ore district, Krušné hory Mountains (Czech Republic). *Bulletin Mineralogie Petrologie*, **27**, 1–37 [in Czech].
- Seydoux-Guillaume A.-M., Deschanelis X., Baumier C., Neumeier S., Weber W.J. and Peugot S. (2018) Why natural monazite never becomes amorphous: experimental evidence for alpha self-healing. *American Mineralogist*, **103**, 824–827.
- Shannon R.D. (1976) Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides. *Acta Crystallographica*, **A32**, 751–767.
- Sobocký T., Ondrejka M., Uher P., Mikuš T. and Konečný P. (2020) Monazite-group minerals and xenotime-(Y) in A-type granitic rocks: chemical composition and in-situ Th–U–total Pb EPMA dating (Velence Hills, Hungary). *Acta Geologica Slovaca*, **12**, 89–106.
- Starijaš Mayer B., Krenn E. and Finger F. (2014) Microcrystals of Th-rich monazite (La) with a negative Ce anomaly in metadiorite and their role for documenting Cretaceous metamorphism in the Slavonian Mountains (Croatia). *Mineralogy and Petrology*, **108**, 231–243.
- Strunz H. and Nickel E.H. (2001) *Strunz Mineralogical Tables, 9th Edition*. E. Schweizerbart'sche Publishing, Stuttgart, 870 pp.
- Tang X., Li Q.-L., Zhang B., Wang P., Gu L.-X., Ling X.-X., Fei C.-H. and Li J.-H. (2020) The chemical state and occupancy of radiogenic Pb, and crystallinity of RW-1 monazite revealed by XPS and TEM. *Minerals*, **10**, 504.
- Twardak D., Pieczka A., Kotowski J. and Nejbert K. (2023) Mineral chemistry and genesis of monazite-(Sm) and monazite-(Nd) from the Blue Beryl Dyke of the Julianna pegmatite system at Piława Górna, Lower Silesia, Poland. *Mineralogical Magazine*, **87**, 575–581.
- Ueda T. (1967) Re-examination of the crystal structure of monazite. *Journal of the Japanese Association of Mineralogists, Petrologists, and Economic Geologists*, **58**, 170–179.
- Uher P., Plašienka D., Ondrejka M., Hraško L. and Konečný P. (2013) Uranium-rich monazite-(Ce) from the Krivá type granitic cobbles in conglomerates of the Pieniny Klippen Belt, Western Carpathians, Slovakia: composition, age determination and possible source areas. *Geological Quarterly*, **57**, 343–352.
- Uher P., Kohút M., Ondrejka M., Konečný P. and Siman P. (2014) Monazite-(Ce) in Hercynian granites and pegmatites of the Bratislava Massif, Western Carpathians: compositional variations and Th-U-Pb electron-microprobe dating. *Acta Geologica Slovaca*, **6**, 215–231.
- Ushakov S.V., Helean K.B., Navrotsky A. and Boatner L.A. (2001) Thermochemistry of rare-earth orthophosphates. *Journal of Materials Research*, **16**, 2623–2633.
- Vereshchagin O.S., Britvin S.N., Perova E.N., Brusnitsyn A.I., Polekhovskiy Y.S., Shilovskikh V.V., Bocharov V.N., van der Burgt A., Cuchet S. and Meisser N. (2019) Gasparite-(La), $\text{La}(\text{AsO}_4)$, a new mineral from Mn ores of the Ushkatyn-III deposit, Central Kazakhstan, and metamorphic rocks of the Wanní glacier, Switzerland. *American Mineralogist*, **104**, 1469–1480.
- Warr L.N. (2021) IMA–CNMNC approved mineral symbols. *Mineralogical Magazine*, **85**, 291–320.
- Williams M.L., Jercinovic M.J. and Hetherington C.J. (2007) Microprobe monazite geochronology: understanding geologic processes by integrating composition and chronology. *Annual Review of Earth and Planetary Sciences*, **35**, 137–175.
- Zaman M.M. and Antao S.M. (2020) Crystal structure refinements of four monazite samples from different localities. *Minerals*, **10**, 1028.
- Závada P., Štípská P., Hasalová P., Racek M., Jeřábek P., Schulmann K., Kylander-Clark A. and Holder R. (2021) Monazite geochronology in melt-percolated UHP meta-granitoids: an example from the Erzgebirge continental subduction wedge, Bohemian Massif. *Chemical Geology*, **559**, 119919.
- Zhu X.K. and O'Nions R.K. (1999) Zonation of monazite in metamorphic rocks and its implications for high temperature thermochronology: a case study from the Lewisian terrain. *Earth and Planetary Science Letters*, **171**, 209–220.

Appendix

Appendix 1. Representative chemical compositions (wt.%) and formulae (apfu) of the monazite-supergrout minerals (apfu)*. Mineral formulae based on *B*-site (S + Cr + P + As + V + Si) = 1 atom. Mineral abbreviations are according to Warr (2021). Valid members are written in **bold**, potential unapproved members in *italic font*

Mineral Anal. No.	Mnz-La 1	Mnz-Ce 2	Mnz-Nd 3	Mnz-Sm 4	Mnz-Gd 5	Cher 6	U Mnz-Ce 7	Sr Cher 8	Gsp-La 9	Gsp-Ce 10	Gsp-Nd 11	Roo 12	Ht 13	Crc 14	S Mnz-Ce 15	F Mnz-Ce 16
SO ₃		0.03	0.00							0.72		0.00			10.66	0.02
CrO ₃														29.94		
P ₂ O ₅	27.59	29.39	30.48	29.15	29.46	30.10	28.34	29.06	0.64	10.45	0.03	0.00	0.36	0.02	23.73	29.49
As ₂ O ₅					0.07				30.32	24.55	39.83	33.35		0.01	0.11	0.11
V ₂ O ₅									9.77	0.00	2.22	0.10				
SiO ₂	4.56	0.33	0.02	0.18	0.03	0.45	0.14			0.37	0.02	0.09	18.77		0.17	0.28
TiO ₂																
ZrO ₂																
ThO ₂	0.37	3.27	0.13	1.11	0.00	40.50	1.65	34.94	0.00	0.57	0.88		79.54		0.00	6.90
UO ₂	0.10	0.66	0.07	0.00	0.06	3.12	23.13			0.00			0.71		0.00	0.77
Al ₂ O ₃			0.00		0.02					0.07		0.00			0.00	0.00
Y ₂ O ₃	1.67	0.88	0.59	0.00	1.23	2.28	2.38		0.01	0.13	1.21		0.27		0.00	2.15
La ₂ O ₃	33.21	14.46	3.90	1.21	3.01	2.15	6.27	0.62	40.21	16.86	3.85		0.01		15.04	12.95
Ce ₂ O ₃	4.05	28.69	19.64	7.62	6.88	6.30	16.61	14.78	10.69	31.68	1.09		0.02		27.54	27.22
Pr ₂ O ₃	3.57	3.37	4.35	1.88	1.11	0.57	1.79	2.96	1.46	3.59	11.27		0.01		2.88	2.96
Nd ₂ O ₃	9.95	12.15	26.86	13.25	10.62	2.07	7.51	5.50	4.24	8.61	37.05		0.05		8.91	10.61
Sm ₂ O ₃	1.59	1.83	9.05	33.22	17.45	0.93	1.68		0.09	0.73	0.00		0.03		0.00	1.53
Eu ₂ O ₃	0.81	0.12	1.35	0.38	1.62		0.08				0.13				0.10	
Gd ₂ O ₃	1.19	1.25	3.20	11.06	23.36	1.20	1.49			0.83	0.47		0.08		0.01	1.20
Tb ₂ O ₃		0.10			1.58	0.30	0.15			0.00					0.10	0.20
Dy ₂ O ₃		0.39	0.44	0.37	2.31	0.80	0.69			0.14			0.05		0.09	0.59
Ho ₂ O ₃		0.03			0.20	0.06	0.08			0.02					0.00	0.00
Er ₂ O ₃		0.26	0.05	0.38	0.10	0.21	0.13			0.00					0.43	0.17
Tm ₂ O ₃		0.12			0.01										0.22	0.04
Yb ₂ O ₃		0.13		0.16	0.35	0.02	0.04			0.00					0.10	0.03
Lu ₂ O ₃		0.08			0.02		0.00			0.08					0.20	0.00
Bi ₂ O ₃												65.04				
FeO		0.04	0.00		0.03		0.00		0.05	0.00		0.00	0.01		0.00	0.00
MnO					0.04				1.30	0.00		0.00				0.08
CuO												0.43		0.03		
MgO												0.00				
CaO	4.57	0.76	0.13	0.27	0.10	8.87	4.34	2.81	1.33	0.38	1.78	0.47	0.02	0.00	4.45	1.48
SrO	3.18	0.03	0.05					8.33		0.00		0.00			6.48	

(Continued)

Appendix 1. (Continued.)

Mineral Anal. No.	Mnz-La 1	Mnz-Ce 2	Mnz-Nd 3	Mnz-Sm 4	Mnz-Gd 5	Cher 6	U Mnz-Ce 7	Sr Cher 8	Gsp-La 9	Gsp-Ce 10	Gsp-Nd 11	Roo 12	Ht 13	Crc 14	S Mnz-Ce 15	F Mnz-Ce 16
BaO			0.00													0.17
PbO		0.11	0.00			0.66	0.99			0.00		0.00	0.03	69.73	0.05	0.14
Na ₂ O	0.83											0.00				
K ₂ O	0.12											0.00				
F										0.37		0.00				0.82
Cl					0.04					0.04		0.00				0.02
O = F										-0.15						-0.35
O = Cl					-0.01					-0.01						0.00
Total	97.36	98.48	100.31	100.24	99.69	100.59	97.49	99.00	100.11	100.03	99.83	99.48	99.96	99.73	101.27	99.57
Atoms per formula unit																
S		0.001	0.000							0.024		0.000			0.283	0.001
Cr														0.999		0.000
P	0.837	0.986	0.999	0.993	0.997	0.983	0.994	1.000	0.024	0.392	0.001	0.000	0.016	0.001	0.709	0.986
As					0.001				0.694	0.568	0.932	0.991		0.000	0.002	0.002
V									0.283	0.000	0.066	0.004				0.000
Si	0.163	0.013	0.001	0.007	0.001	0.017	0.006			0.016	0.001	0.005	0.984		0.006	0.011
Ti																0.000
Zr																0.000
Th	0.003	0.029	0.001	0.010	0.000	0.355	0.016	0.323	0.000	0.006	0.009		0.949		0.000	0.062
U	0.001	0.006	0.001	0.000	0.001	0.027	0.213			0.000			0.008		0.000	0.007
Al			0.000		0.001					0.004		0.000			0.000	0.000
Y	0.032	0.019	0.012	0.000	0.026	0.047	0.052		0.000	0.003	0.029		0.008		0.000	0.045
La	0.439	0.211	0.056	0.018	0.044	0.031	0.096	0.009	0.649	0.275	0.064		0.000		0.196	0.189
Ce	0.053	0.416	0.278	0.112	0.101	0.089	0.252	0.220	0.171	0.513	0.018		0.000		0.356	0.394
Pr	0.047	0.049	0.061	0.028	0.016	0.008	0.027	0.044	0.023	0.058	0.184		0.000		0.037	0.043
Nd	0.127	0.172	0.371	0.190	0.152	0.029	0.111	0.080	0.066	0.136	0.592		0.001		0.112	0.150
Sm	0.020	0.025	0.121	0.461	0.240	0.012	0.024		0.001	0.011	0.000		0.001		0.000	0.021
Eu	0.010	0.002	0.018	0.005	0.022		0.001				0.002				0.001	0.000
Gd	0.014	0.016	0.041	0.147	0.310	0.015	0.020			0.012	0.007		0.001		0.000	0.016
Tb		0.001			0.021	0.004	0.002			0.000					0.001	0.003
Dy		0.005	0.005	0.005	0.030	0.010	0.009			0.002			0.001		0.001	0.007
Ho		0.000			0.003	0.001	0.001			0.000					0.000	0.000
Er		0.003	0.001	0.005	0.001	0.003	0.002			0.000					0.005	0.002
Tm		0.001			0.000										0.002	0.000
Yb		0.002		0.002	0.004	0.000	0.001			0.000					0.001	0.000
Lu		0.001			0.000		0.000			0.001					0.002	0.000
Bi												0.953				0.000

(Continued)

Appendix 1. (Continued.)

Mineral Anal. No.	Mnz-La 1	Mnz-Ce 2	Mnz-Nd 3	Mnz-Sm 4	Mnz-Gd 5	Cher 6	U Mnz-Ce 7	Sr Cher 8	Gsp-La 9	Gsp-Ce 10	Gsp-Nd 11	Roo 12	Ht 13	Crc 14	S Mnz-Ce 15	F Mnz-Ce 16
Fe		0.001	0.000		0.001		0.000		0.002	0.000		0.000	0.000		0.000	0.000
Mn					0.001				0.048	0.000		0.000				0.003
Cu												0.018		0.001		0.000
Mg												0.000				0.000
Ca	0.175	0.032	0.005	0.012	0.004	0.366	0.193	0.122	0.062	0.018	0.085	0.029	0.001	0.000	0.168	0.063
Sr	0.066	0.001	0.001					0.196		0.000		0.000			0.133	0.000
Ba			0.000													0.003
Pb		0.001	0.000			0.007	0.011			0.000		0.000	0.000	1.042	0.000	0.001
Na	0.058											0.000				0.000
K	0.005											0.000				0.000
Sum A	1.050	0.994	0.973	0.995	0.978	1.003	1.031	0.995	1.024	1.040	0.990	1.001	0.971	1.043	1.017	1.007
Sum B	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Total	2.050	1.994	1.973	1.995	1.978	2.003	2.031	1.995	2.024	2.040	1.990	2.001	1.971	2.043	2.017	2.007
F										0.052		0.000				0.103
Cl					0.003					0.003		0.000				0.001

Notes: Sample details: 1: Monazite-(La), hydrothermal in alkaline pegmatite, Lovozero Massif, Russia (Pekov, 2000). 2: Monazite-(Ce), ultra-high-pressure gneiss, Seve Nappe Complex, Norway (Petrík et al., 2019). 3: Monazite-(Nd): authigenic in graywacke, Drahany Upland, Czech Republic (Čopjaková et al., 2011). 4: Monazite-(Sm): granitic pegmatite, Piława Górna, Poland (Twardak et al., 2023). 5: Monazite-(Gd): hydrothermal quartz vein, Prakovce-Zimná Voda, Slovakia (Ondrejka et al., 2023a). 6: Cheralite, Li-mica granite, Eibenstock pluton, Germany (Förster, 1998). 7: U-rich monazite-(Ce), P-rich granite, Belvis de Monroy pluton, Spain (Pérez-Soba et al., 2014). 8: Sr-dominant cheralite, carbonatite, Lesnaya Varaka, Russia (Chakhmouradian and Mitchell, 1998). 9: Gasparite-(La), hydrothermal in calcite vein, Ushkatyn-III Mn deposit, Kazakhstan (Vereshchagin et al., 2019). FeO originally as Fe₂O₃. 10: Gasparite-(Ce): post-magmatic in altered rhyolite, Tisovec-Rejkovo, Slovakia (Ondrejka et al., 2007). 11: Nd-dominant gasparite, hydrothermal-metamorphic, Ponte dei Gonazzi Fe-Mn deposit, Italy (Cabella et al., 1999). 12: Rooseveltite, supergene in hydrothermal Bi-Co-Ni-As-U-V mineralization, Přísečnice, Czech Republic (Sejkora et al., 2019). 13: Huttonite, clastic mineral in sand, Gillespie's Beach, New Zealand (Förster et al., 2000). 14: Crocoite, supergene, oxidation zone of Pb deposit, Red Lead Mine, Dundas, Australia (Crane et al., 2001). 15: S-rich monazite-(Ce), hydrothermal in metamorphic magnetite deposit, Bacúch, Slovakia (Pršek et al., 2010). 16: F-rich monazite-(Ce), muscovite leucogranite, Zámostská Hoľa, Slovakia (Maraszewska et al., 2023). *Blank entries indicate not measured, 0.00 wt.% indicates measured but below the detection limit