

Original paper

Arsenogoldfieldite, $\text{Cu}_{12}(\text{As}_2\text{Te}_2)_{\Sigma 4}\text{S}_{13}$, a new tetrahedrite-group mineralJiří SEJKORA^{1,2*}, Cristian BIAGIONI^{3,4}, Zdeněk DOLNÍČEK¹, Panagiotis VOUDOURIS⁵¹ Department of Mineralogy and Petrology, National Museum, Cirkusová 1740, 193 00, Praha 9, Czech Republic; jiri.sejkora@nm.cz² Earth Science Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 840 05 Bratislava, Slovak Republic³ Dipartimento di Scienze della Terra, Università di Pisa, Via Santa Maria, 53, I-56126 Pisa, Italy⁴ Centro per l'Integrazione della Strumentazione Scientifica dell'Università di Pisa, Università di Pisa, Italy⁵ Department of Mineralogy and Petrology, Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, University Campus, 15772, Zografou, Athens, Greece

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Arsenogoldfieldite is a new mineral discovered in a sample collected from the North Star mine, Mammoth, Tintic district, Juab County, Utah, U.S.A (type locality). It occurs as anhedral grains, up to 300 μm in size, in a quartz gangue, associated with tellurium, enargite including Sn-bearing variety and supergene juabite. Arsenogoldfieldite is black, with a metallic luster. Mohs hardness is *ca.* 3½–4; calculated density is 4.954 $\text{g}\cdot\text{cm}^{-3}$. In reflected light, arsenogoldfieldite is grey with a brownish shade; it is isotropic. Internal reflections were not observed. Reflectance values for the four COM wavelengths in air [$R(\%) \lambda(\text{nm})$] are: 30.2(470); 29.9(546); 29.9 (589); and 30.4 (650). The empirical formula of arsenogoldfieldite is $\text{Cu}_{11.75}\text{Zn}_{0.03}\text{Fe}_{0.02}[(\text{As}_{1.44}\text{Sb}_{0.43}\text{Bi}_{0.13})_{\Sigma 2.00}\text{Te}_{2.00}]\text{S}_{13.11}$. The ideal formula is $\text{Cu}_{12}(\text{As}_2\text{Te}_2)\text{S}_{13}$, which requires (in wt. %) Cu 48.13, As 9.46, Te 16.11, S 26.30, total of 100.00. Arsenogoldfieldite is cubic, $I-43m$, with unit-cell parameters $a = 10.2868(4)$ Å, $V = 1088.53(13)$ Å³, $Z = 2$. The strongest reflections of the X-ray powder diffraction pattern [d , Å (I) hkl] are: 3.638 (8) 220, 2.969 (100) 222, 2.573 (9) 400, 1.8187(21) 440 and 1.5504(9) 622. According to the single-crystal X-ray diffraction data ($R = 0.0221$ on the basis of 380 unique reflections with $F_o > 4\sigma F_o$ and 22 refined parameters), arsenogoldfieldite is isotypic with other tetrahedrite-group minerals. Arsenogoldfieldite is named in agreement with the nomenclature of the tetrahedrite group as the (As/Te) end-member in the goldfieldite series. The mineral and its name have been approved by the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association (2022-084). The description of arsenogoldfieldite from the Pefka mine, Alexandroupoli, Western Thrace, Greece (cotype locality), its chemical composition and crystal structure data are also given in the paper.

Keywords: arsenogoldfieldite, new mineral, sulfosalt, crystal structure, North Star mine, Pefka mine

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1. Introduction

Tetrahedrite-group minerals are the most common sulfosalts in many hydrothermal ore deposits. These chalcogenides show the widest chemical variability among sulfosalts, as proven by the currently 40 valid mineral species. This is a consequence of the plasticity of the crystal structure of tetrahedrite isotypes, able to accommodate several homo- and heterovalent substitutions, hosting many chemical constituents typical of hydrothermal ore deposits (Moëlo et al. 2008; Biagioni et al. 2020). The general structural formula of tetrahedrite-group minerals can be written as $^{M(2)}\text{A}_6^{M(1)}(\text{B}_4\text{C}_2)_{\Sigma 6}^{X(3)}\text{D}_4^{S(1)}\text{Y}_{12}^{S(2)}\text{Z}$, where $\text{A} = \text{Cu}^+$, Ag^+ , and $\square$ (vacancy); $\text{B} = \text{Cu}^+$, and Ag^+ ; $\text{C} = \text{Zn}^{2+}$, Fe^{2+} , Hg^{2+} , Cd^{2+} , Ni^{2+} , Mn^{2+} , Cu^{2+} , Cu^+ , In^{3+} and Fe^{3+} ; $\text{D} = \text{Sb}^{3+}$, As^{3+} , Bi^{3+} , and Te^{4+} ; $\text{Y} = \text{S}^{2-}$, and Se^{2-} ; and $\text{Z} = \text{S}^{2-}$, Se^{2-} , and $\square$ (Biagioni et al. 2020).

Within this group, members of the tetrahedrite ($\text{D} = \text{Sb}$) and tennantite ($\text{D} = \text{As}$) series are the most widespread (Biagioni et al. 2020), whereas species with predomi-

nance of Te are rare (Biagioni et al. 2022) and those with Bi are exceptional (Sejkora et al. 2025). Tellurium-rich members of the tetrahedrite group have been known for a long time. The first descriptions of goldfieldite were given by Sharwood (1907) and Ransome (1909). Thompson (1946) proved this mineral to be isotypic with tetrahedrite. Kato and Sakurai (1970) and Kalbskopf (1974) found that Te does not substitute for S but replaces Sb and As. Several authors have debated the definition of goldfieldite (e.g., Trudu and Knittel 1998 and references therein) and the debate was finally solved in the nomenclature of the tetrahedrite group by Biagioni et al. (2020) taking into account the current IMA-CNMNC guidelines and in agreement with the *Report of the sulfosalt sub-committee* (Moëlo et al. 2008). Goldfieldite is defined as the Te-rich member of the tetrahedrite group having end-member formula $(\text{Cu}_4\square_2)\text{Cu}_6\text{Te}_4\text{S}_{13}$; its type locality is the Mohawk mine, Goldfield, Nevada, U.S.A. Actually, chemical data available for samples from this locality show $(\text{As} + \text{Sb} + \text{Bi})/\text{Te}$ atomic ratios close to 1,

with $\text{Sb} > (\text{As}, \text{Bi})$, i.e., close to the end-member formula $\text{Cu}_{12}(\text{Sb}_2\text{Te}_2)\text{S}_{13}$ (e.g., Ransome 1909; Lévy 1967). For this reason, Shimizu and Stanley (1991) applied the name goldfieldite to this composition. However, in order to avoid any confusion, the name goldfieldite is currently applied to the Te-pure compositional end-member, $(\text{Cu}_4\Box_2)\text{Cu}_6\text{Te}_4\text{S}_{13}$ with Te contents in the range 3–4 *apfu*, whereas new names (stibiogoldfieldite and arsenogoldfieldite) should be associated with the Sb/Te and As/Te end-members (Biagioni et al. 2020) with Te contents in the range 1–3 *apfu* and $\text{Sb} > \text{As}$ and $\text{As} > \text{Sb}$, respectively. The mineral corresponding to the end-member $\text{Cu}_{12}(\text{Sb}_2\text{Te}_2)\text{S}_{13}$ was found during the examination of some specimens classified as goldfieldite from the Mohawk mine, U.S.A. and was defined as the new mineral stibiogoldfieldite (Biagioni et al. 2022). Later, Te-rich stibiogoldfieldite in association with Se-bearing danto-paite from the same occurrence was described by Musetti et al. (2024), improving our understanding of the crystal chemistry of goldfieldite-series minerals.

During the study of samples labeled as *goldfieldite* from the North Star mine, the phase with composition close to the end-member $\text{Cu}_{12}(\text{As}_2\text{Te}_2)\text{S}_{13}$ was found and characterized. This new mineral and its name were approved by the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association (IMA 2022-084), its mineral symbol is *Asgf*. Arsenogoldfieldite is named in agreement with the nomenclature of the tetrahedrite group (Biagioni et al. 2020) as the (As/Te) end-member in the goldfieldite series. The holotype material (polished section) is deposited in the mineralogical collection of the Department of

Mineralogy and Petrology of the National Museum in Prague, Cirkusová 1740, 193 00 Praha 9, Czech Republic (catalogue number PIP 28/2022). The crystal used for the single-crystal X-ray diffraction study is kept in the mineralogical collection of the Museo di Storia Naturale of the Università di Pisa, Via Roma 79, Calci (PI), Italy, under catalogue number 20018. In addition, a sample of arsenogoldfieldite from the Pefka mine, Alexandroupoli, Greece, was examined and designated as cotype specimen. It is deposited in the collections of the Museo di Storia Naturale of the Università di Pisa, Via Roma 79, Calci (PI), under catalogue number 20020.

In this paper the description of arsenogoldfieldite and its crystal structure from both occurrences are reported, along with a discussion on some crystal-chemical and nomenclature issues.

2. Occurrence and mineral description

2.1. Occurrence

Arsenogoldfieldite was found at the so-called “Upper dumps” of the North Star mine, Mammoth, Tintic district, Juab County, Utah, U.S.A. (GPS coordinates: 39° 55' 14" N, 112° 6' 26" W). The North Star mine exploited a Au–Ag–Cu–Pb hydrothermal vein deposit located in contact-metamorphosed dolostone and was the largest producer of gold in the Tintic district. The North Star mine was discovered in 1885, closed in 1900, and reported to be inaccessible since 1911. The main ore minerals were galena, cerussite, and enargite in quartz and

baryte gangue (Lindgren and Loughlin 1919). The full list of minerals recorded from this area (more than 110 species) is given on mindat.org at <https://www.mindat.org/loc-182908.html>. Arsenogoldfieldite occurs in quartz gangue in association with tellurium, enargite including its Sn-bearing variety and supergene juabite. It is a product of hydrothermal activity.

An additional finding of arsenogoldfieldite from the Pefka mine, Alexandroupoli, Western

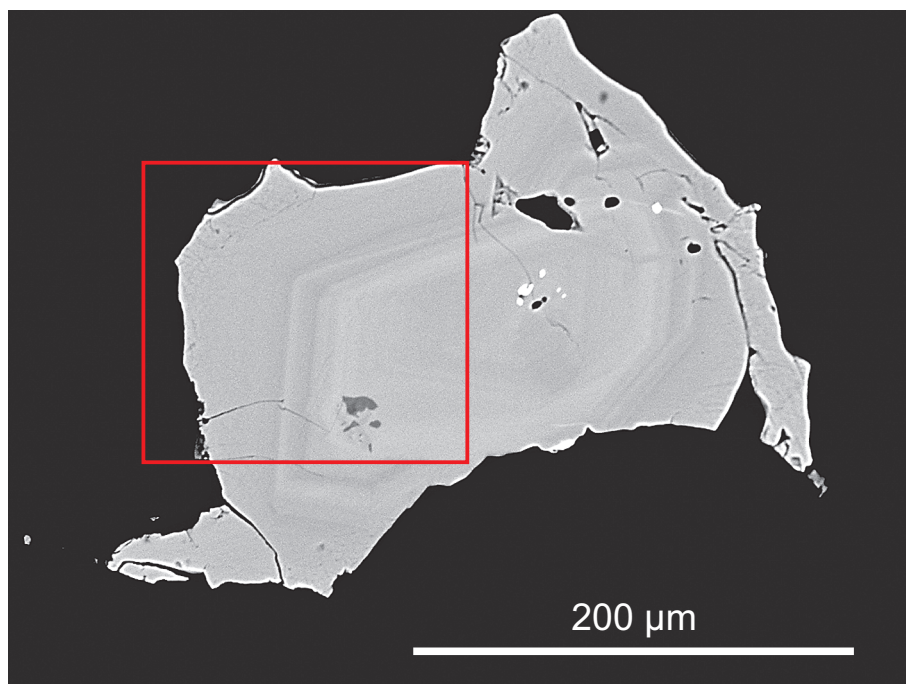


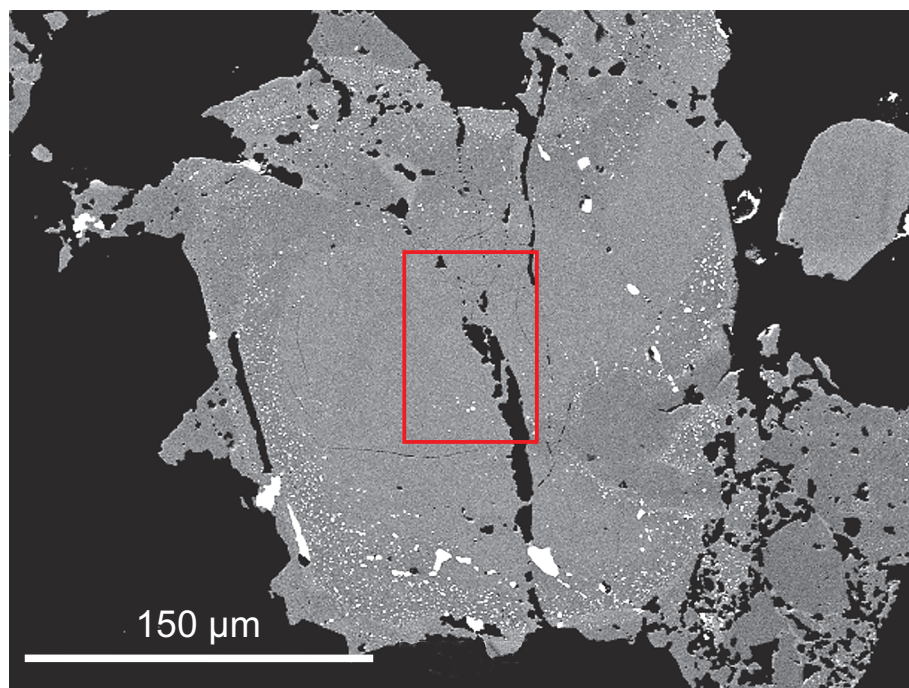
Fig. 1 Backscattered electron image of arsenogoldfieldite from the North Star mine, USA. The crystal shows a distinct zoning, but in all domains $\text{As} > \text{Sb}$. The red box shows the zone where the grain used for single-crystal X-ray diffraction study was extracted. Holotype specimen.

Thrace, Greece (cotype locality) was characterized. The Pefka epithermal ore deposit is hosted by andesitic lavas and rhyodacitic pyroclastics of Oligocene age. This deposit is characterized by several tellurides, sulfostannates, and sulfosalts (Dimou et al. 1994; Voudouris 2006; Repstock et al. 2015; Voudouris et al. 2022). Associated ore minerals are enargite/luzonite, colusite, “arsenosulvanite”, stibiofieldite, members of the tetrahedrite series with different ratios of formally divalent Cu, Zn, and Fe, native gold, native tellurium, and tellurobismuthite. Gangue minerals are quartz, baryte, and white mica. The crystallization of arsenogoldfieldite is related to the high-sulfidation stage of mineralization at Pefka.

2.2. Physical and optical properties

Arsenogoldfieldite occurs at the North Star mine as anhedral grains up to $200 \times 300 \mu\text{m}$ in size (Fig. 1); at Pefka forms anhedral grains up to $200 \mu\text{m}$ in size in intergrowths with tetrahedrite-(Fe/Zn) with inclusions of native tellurium and tellurobismuthite (Fig. 2). Arsenogoldfieldite is black in color and opaque in transmitted light; it has a metallic luster. The Mohs hardness is close to $3\frac{1}{2}$ –4, in agreement with other members of the tetrahedrite group. Arsenogoldfieldite is brittle, with an indistinct cleavage and a conchoidal fracture. Density was not measured, owing to the small amount of available material and absence of heavy liquids with suitable density; on the basis of the empirical formula ($Z=2$) and the single-crystal unit-cell parameters, the calculated density is $4.954 \text{ g}\cdot\text{cm}^{-3}$. In reflected light, arsenogoldfieldite is isotropic, grey with a brownish shade. Internal reflections were not observed. Reflectance spectra were measured in air with a TIDAS MSP400 spectrophotometer attached to a Leica microscope ($50\times$ objective) using a WTiC (Zeiss no. 370) standard, with a square sample measurement field of ca. $10 \times 10 \mu\text{m}$. The results for the 400–700 nm range are given in Tab. 1 and plotted in Fig. 3 in comparison with data for members of the goldfieldite series.

Fig. 2 Backscattered electron image of arsenogoldfieldite (core) and other tetrahedrite-group minerals (margin of aggregate) in a quartz gangue from the Pefka mine, Greece. White grains are native tellurium and tellurobismuthite. The red box shows the zone where the grain used for single-crystal X-ray diffraction study was extracted. Cotype specimen.



Tab. 1 Reflectance values (%) for arsenogoldfieldite from the North Star mine*

λ (nm)	R (%)	λ (nm)	R (%)
400	29.7	560	29.9
420	30.2	580	29.9
440	30.3	589	29.9
460	30.2	600	30.0
470	30.2	620	30.2
480	30.1	640	30.3
500	30.0	650	30.4
520	29.9	660	30.4
540	29.8	680	30.6
546	29.9	700	30.6

*The reference wavelengths required by the Commission on Ore Mineralogy (COM) are given in bold

2.3. Chemical composition

Chemical analyses were performed using a Cameca SX100 electron microprobe (National Museum, Prague) operating in wavelength-dispersive mode (25 kV, 20 nA and $1 \mu\text{m}$ wide beam). The following standards and X-ray lines were used to minimize line overlap: Ag (AgLa), Bi_2Se_3 (BiM β), chalcopyrite (CuK α , SK α), InAs (InL α), pyrite (FeK α), Mn (MnK α), NiAs (AsL β), PbSe (SeL β), PbTe (TeL α), Sb_2S_3 (SbL α) and ZnS (ZnK α). Peak counting times were 20 s for all elements and one half of the peak time for each background. Other elements, such as Au, Cd, Cl, Co, Cr, Ga, Ge, Hg, Ni, Pb, Sn and Tl were found to be below the detection limits (0.02–0.10 wt. %). Raw intensities were converted to the concentrations of elements using the automatic “PAP” matrix-correction software (Pouchou and Pichoir 1985).

Tab. 2 Chemical data (in wt. %) for arsenogoldfieldite from the North Star mine (grain used for single crystal study) and the Pefka mine

Element	North Star mine			Pefka mine		
	Mean	Range (n = 17)	(σ)	Mean	Range (n = 5)	(σ)
Cu	46.10	45.55–46.45	0.27	46.30	45.20–46.95	0.61
Fe	0.07	0.00–0.16	0.07	0.06	0.00–0.29	0.12
Zn	0.13	0.00–0.31	0.12	0.45	0.27–0.62	0.13
Mn	0.00			0.13	0.07–0.20	0.05
In	0.00			0.08	0.00–0.16	0.06
As	6.67	6.11–7.11	0.31	6.34	5.62–6.92	0.58
Sb	3.22	2.13–4.42	0.75	7.11	5.68–8.77	1.26
Te	15.74	14.55–17.89	1.07	13.71	12.89–14.17	0.52
Bi	1.70	0.83–2.45	0.54	0.19	0.00–0.51	0.19
S	25.94	25.69–26.29	0.18	25.54	25.17–25.72	0.20
Se	0.00			0.13	0.00–0.28	0.12
Total	99.57	99.18–100.01	0.24	100.04	99.11–100.65	0.53

(σ) – estimated standard deviation; n = number of spot analyses.

Analytical data for arsenogoldfieldite from the North Star mine (grain used for single crystal study, average of 17 spot analyses) are given in Tab. 2. On the basis of $(\text{As} + \text{Sb} + \text{Te} + \text{Bi}) = 4$ atoms per formula unit (*apfu*), the empirical chemical formula is $\text{Cu}_{11.75}\text{Zn}_{0.03}\text{Fe}_{0.02}[(\text{As}_{1.44}\text{Sb}_{0.43}\text{Bi}_{0.13})_{\Sigma 2.00}\text{Te}_{2.00}]_{\text{S}_{13.11}}$. The ideal formula is $\text{Cu}_{12}(\text{As}_2\text{Te}_2)\text{S}_{13}$, which requires (in wt. %) Cu 48.13, As 9.46, Te 16.11, S 26.30, total of 100.00. Two EDS spot analyses of the arsenogoldfieldite grain from Pefka used for single crystal study results in the chemical formula $\text{Cu}_{12.4}[(\text{As}_{1.3}\text{Sb}_{1.0}\text{Te}_{1.7})_{\Sigma 4.0}\text{S}_{13.0}]$. The chemical composition of corresponding material from Pefka is given in Tab.2 and its empirical formula is $\text{Cu}_{11.59}\text{Zn}_{0.11}\text{Mn}_{0.04}\text{Fe}_{0.02}\text{In}_{0.01}[(\text{As}_{1.35}\text{Sb}_{0.93}\text{Bi}_{0.01})_{\Sigma 2.29}\text{Te}_{1.71}\text{S}_{12.67}\text{Se}_{0.03}]$.

Chemical data (all spot analyses) of the samples from the North Star mine and Pefka mine are deposited as Supplementary Material (ESM1) of this paper. Chemical composition of all studied arsenogoldfieldite grains from

the North Star mine is relatively uniform (Fig. 4) with contents in the range 1.81–2.51 *apfu* Te, 1.08–1.59 *apfu* As, 0.21–0.63 *apfu* Sb and minor Bi (up to 0.24 *apfu*). The composition of the studied sample from the Pefka mine is more variable, ranging from tennantite-(Fe) and -(Zn), stibiofieldite to arsenogoldfieldite (Fig. 4), some with minor Mn, Hg and In contents. Arsenogoldfieldite from the Pefka mine is in general more Te-poorer with Te contents in the range 1.13–2.25 *apfu* and 1.05–1.77 *apfu* As.

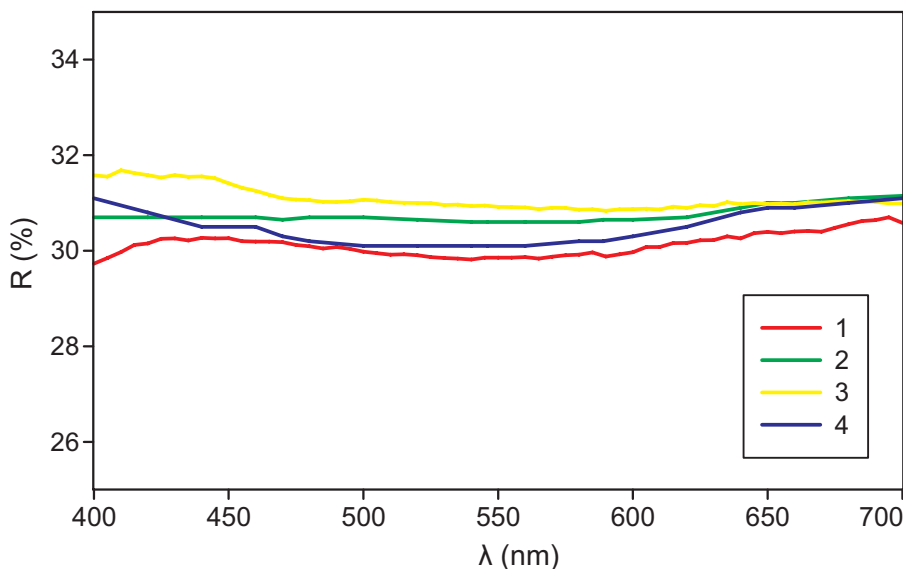
2.4. X-ray powder diffraction data

X-ray powder diffraction data of arsenogoldfieldite from the North Star mine (Tab. 3) were collected at room temperature using a Bruker D8 Advance diffractometer equipped with solid-state LynxEye detector and secondary monochromator producing $\text{CuK}\alpha$ radiation housed at the Department of Mineralogy and Petrology, National Museum, Prague, Czech Republic. The instrument was operating at 40 kV and 40 mA. In order to minimize the background, the powder samples were placed on the surface of a flat silicon wafer. The powder pattern was collected in the Bragg–Brentano geometry in the range $3\text{--}65^\circ 2\theta$, step 0.01° and counting time of 20 s per step (total duration of experiment was c. 30 hours). The positions and intensities of diffraction lines were found and refined using the Pearson VII profile-shape function of the ZDS program package (Ondruš 1993). The unit-cell parameters were refined by the least-squares program of Burnham (1962) as follows: $a = 10.285(2) \text{ \AA}$ and $V = 1087.9(7) \text{ \AA}^3$.

2.5. X-ray single-crystal diffraction data

Grains of arsenogoldfieldite from both occurrences were extracted from the polished sections previ-

Fig. 3 Reflectivity curve for arsenogoldfieldite (1) from the North Star mine (holotype sample). The curves for arsenogoldfieldite (2) from the Tramway mine (Criddle and Stanley 1993, p. 209, described as *goldfieldite*), stibiofieldite (3) from the Mohawk mine (Biagioni *et al.*, 2022) and stibiofieldite (4) from Goldfield (Criddle and Stanley 1993, p. 208, described as *goldfieldite*) are shown for the sake of comparison.

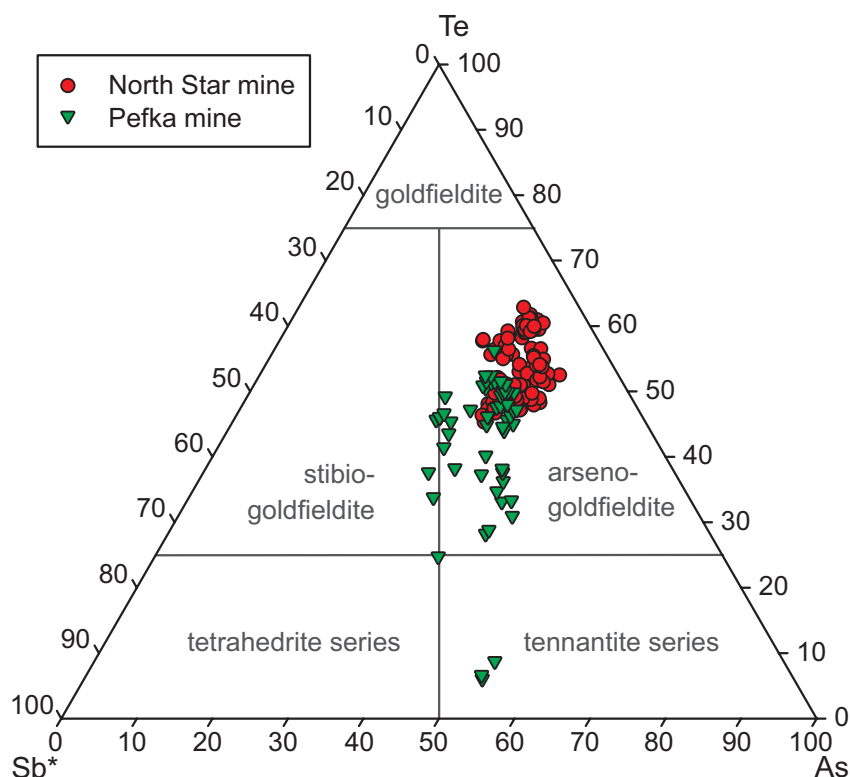


Tab. 3 X-ray powder diffraction data (d in Å) for arsenogoldfieldite from the North Star mine. The five strongest reflections are given in bold

I_{obs}	d_{obs}	d_{calc}	I_{calc}^1	d_{calc}^1	hkl
5	7.251	7.273	1	7.274	1 1 0
1	5.153	5.142	3	5.143	2 0 0
1	4.195	4.199	3	4.200	2 1 1
8	3.638	3.636	8	3.637	2 2 0
3	3.246	3.252	1	3.253	3 1 0
100	2.969	2.969	100	2.970	2 2 2
2	2.751	2.749	5	2.749	3 2 1
9	2.573	2.571	21	2.572	4 0 0
5	2.4259	2.4242	2	2.425	3 3 0
5	2.4259	2.4242	4	2.425	4 1 1
			2	2.300	4 2 0
			1	2.193	3 3 2
2	2.0930	2.0994	2	2.100	4 2 2
1	2.0189	2.0170	2	2.017	5 1 0
1	2.0189	2.0170	4	2.017	4 3 1
3	1.8784	1.8778	7	1.878	5 2 1
21	1.8187	1.8181	43	1.818	4 4 0
2	1.7620	1.7639	2	1.764	4 3 3
			1	1.714	4 4 2
2	1.6691	1.6684	1	1.669	5 3 2
2	1.6691	1.6684	4	1.669	6 1 1
			2	1.626	6 2 0
9	1.5504	1.5505	23	1.551	6 2 2
			1	1.517	6 3 1
7	1.4840	1.4845	3	1.485	4 4 4

I_{calc}^1 and d_{calc}^1 were calculated using the software *PowderCell2.3* (Kraus and Nolze 1996) on the basis of the structural model given in Tabs 4 and 5. Only reflections with $I_{\text{calc}} > 1$ are listed.

ously studied through electron microprobe analysis (Figs 1 and 2), mounted on a carbon fiber and examined with single-crystal X-ray diffraction techniques. Intensity data for the sample from the North Star mine were collected using a Bruker D8 Venture single-crystal X-ray diffractometer equipped with an air-cooled Photon III area detector and microfocus MoK α radiation (Centro per l'Integrazione della Strumentazione Scientifica dell'Università di Pisa, University of Pisa). The detector-to-crystal distance was set to 38 mm and data were collected using ϕ scan modes in 0.5° slices, with an exposure time of 5 s per frame. Unit-cell parameters, refined on the basis of the XYZ centroids of 2212 reflections above $20\sigma I$ with $5.60 < 2\theta < 65.02^\circ$, are $a = 10.2868(4)$, $V = 1088.53(13) \text{ Å}^3$.

Fig. 4 Ternary Te–Sb–As diagram (at. %) for studied samples from the North Star mine and Pefka mine; $\text{Sb}^* = \text{Sb} + \text{Bi}$.

Data for the sample from the Pefka mine were collected using a Bruker Smart Breeze single-crystal X-ray diffractometer equipped with an air-cooled Photon II CCD detector and graphite-monochromatized MoK α radiation (Dipartimento di Scienze della Terra, University of Pisa). The detector-to-crystal distance was set at 50 mm and data were collected using ϕ scan modes in 0.5° slices, with an exposure time of 25 s per frame. Unit-cell parameters, refined on the basis of the XYZ centroids of 1089 reflections above $20\sigma I$ with $5.59 < 2\theta < 56.80^\circ$, are $a = 10.2991(14)$, $V = 1092.4(4) \text{ Å}^3$.

In both cases, data were integrated with the Bruker *SAINT* software package using a narrow-frame algorithm and they were corrected for Lorentz-polarization, absorption, and background. The crystal structure of both samples was refined using *Shelxl-2018* (Sheldrick 2015), starting from the atomic coordinates of stibio-goldfieldite given by Biagioni et al. (2022). The occurrence of racemic twin was modelled and the structure of the sample from Pefka should be inverted. The $M(2)$ site was found to be split into two sub-positions, $M(2a)$ and $M(2b)$. The following neutral scattering curves, taken from the *International Tables for Crystallography* (Wilson 1992) were used: Cu vs $\square$ (vacancy) at $M(2a)$, Cu vs $\square$ at $M(2b)$, Cu vs $\square$ at $M(1)$, As vs Te at $X(3)$, S at $S(1)$ and $S(2)$ sites. Further details on data collection and refinement are given in Tab. 4. Fractional atom coordinates and equivalent

Tab. 4 Crystal and experimental data for arsenogoldfieldite

Crystal data	North Star mine	Pefka mine
Crystal size (mm)	0.110 × 0.100 × 0.080	0.080 × 0.075 × 0.050
Cell setting, space group	Cubic, <i>I</i> -43 <i>m</i>	Cubic, <i>I</i> -43 <i>m</i>
<i>a</i> (Å)	10.2868(4)	10.2991(14)
<i>V</i> (Å ³)	1088.53(13)	1092.4(4)
<i>Z</i>	2	2
Data collection and refinement		
Radiation, wavelength (Å)	Mo Kα, λ = 0.71073	
Temperature (K)	293(2)	
2θ _{max} (°)	65.01	56.80
Measured reflections	2617	1618
Unique reflections	390	279
Reflections with <i>F</i> _o > 4σ(<i>F</i> _o)	380	271
<i>R</i> _{int}	0.0348	0.0503
<i>R</i> σ	0.0231	0.0438
Range of <i>h</i> , <i>k</i> , <i>l</i>	−13 ≤ <i>h</i> ≤ 15, −10 ≤ <i>k</i> ≤ 15, −11 ≤ <i>l</i> ≤ 12	−12 ≤ <i>h</i> ≤ 12, −12 ≤ <i>k</i> ≤ 9, −13 ≤ <i>l</i> ≤ 7
<i>R</i> [<i>F</i> _o > 4σ(<i>F</i> _o)]	0.0221	0.0257
<i>R</i> (all data)	0.0230	0.0269
<i>wR</i> (on <i>F</i> _o ²)	0.0456	0.0614
Goof	1.117	1.105
Absolute structure parameter	−0.01(4)	0.02(7)
Number of least-squares parameters	22	22
Maximum and minimum residual peak (<i>e</i> Å ^{−3})	0.56 [at 0.68 Å from <i>X</i> (3)] −0.55 [at 0.64 Å from <i>M</i> (2a)]	0.49 [at 2.23 Å from <i>X</i> (3)] −0.78 [at 0.50 Å from <i>M</i> (2a)]

isotropic displacement parameters are reported in Tab. 5, whereas Tab. 6 shows selected bond distances. Weighted bond-valence sums, calculated using the bond-parameters of Brese and O’Keeffe (1991), are given in Tab. 7. For both arsenogoldfieldite samples, Crystallographic Information Files (CIF) have been deposited as Supplementary Materials (ESM2 and 3).

Tab. 5 Atoms, atom coordinates, equivalent isotropic displacement parameters (Å²), and refined (obs) and calculated (calc) site scattering for arsenogoldfieldite

North Star mine						
Site	<i>x/a</i>	<i>y/b</i>	<i>z/c</i>	<i>U</i> _{eq}	SREF _{obs}	SREF _{calc}
<i>M</i> (2a)	0.2166(2)	0	0	0.0346(18)	23.5	29.0
<i>M</i> (2b)	0.2185(11)	−0.044(2)	0.044(2)	0.0346(18)	5.5	
<i>M</i> (1)	¼	½	0	0.0235(4)	29.0	29.0
<i>X</i> (3)	0.26210(4)	0.26210(4)	0.26210(4)	0.0150(2)	46.6	46.0
<i>S</i> (1)	0.11571(12)	0.11571(12)	0.36032(14)	0.0159(3)	16.0	16.0
<i>S</i> (2)	0	0	0	0.0190(9)	16.0	16.0
Pefka mine						
Site	<i>x/a</i>	<i>y/b</i>	<i>z/c</i>	<i>U</i> _{eq}	SREF _{obs}	SREF _{calc}
<i>M</i> (2a)	0.7837(4)	0	0	0.037(4)	21.8	29.3
<i>M</i> (2b)	0.7811(14)	−0.961(2)	0.961(2)	0.037(4)	7.5	
<i>M</i> (1)	¾	½	0	0.0243(6)	29.0	29.0
<i>X</i> (3)	0.73750(6)	0.73750(6)	0.73750(6)	0.0171(4)	43.7	45.3
<i>S</i> (1)	0.88374(16)	0.88374(16)	0.6399(2)	0.0178(6)	16.0	16.0
<i>S</i> (2)	0	0	0	0.0221(15)	16.0	16.0

3. Results and discussion

3.1. Crystal structure of arsenogoldfieldite

The crystal structures of arsenogoldfieldite from both occurrences agree with the general features of the members of the tetrahedrite isotypic group (Biagioni et al. 2020), i.e., a three-dimensional framework formed by corner-sharing *M*(1)-centered tetrahedra with cages hosting *S*(2)-centered *M*(2)₆-octahedra, encircled by four *X*(3)*S*(1)₃ trigonal pyramids. As observed in some of other tetrahedrite-group isotypes (e.g., Andreasen et al. 2008; Welch et al. 2018; Musetti et al. 2024), the *M*(2) site is split into two sub-positions, namely *M*(2a) and *M*(2b).

The *M*(2) site is split into two sub-positions *M*(2a) and *M*(2b). The former has a triangular planar coordination, whereas the latter has a flat trigonal pyramidal coordination. Average bond distances for the *M*(2a) and *M*(2b) sites are 2.236 and 2.324 Å for the sample from the North Star mine and 2.242 and 2.310 Å for the Greek sample, respectively. Copper was hosted at both sub-positions; minor vacancies, suggested by electron microprobe analysis (ca. 0.20 *apfu* in both samples, corresponding to the site occupancy Cu_{0.967}□_{0.033}), are probably within the experimental uncertainty. Bond-valence sums at the *M*(2a) + *M*(2b) sites are 1.06 and 1.04 valence units (v.u.) for holotype and cotype material, respectively.

The tetrahedrally coordinated *M*(1) site has an average bond distance of 2.322 and 2.326 Å from the North Star mine and Pefka samples, respectively, shorter than that observed in mixed (Cu, Zn, Fe) tetrahedral sites in tetrahedrite-group minerals (e.g., Wuensch 1964; Wuensch et al. 1966) and similar to that observed in stibio-goldfieldite (2.329 Å). This

Tab. 6 Selected bond distances (in Å) for arsenogoldfieldite

		North Star mine	Pefka mine
<i>M</i> (1)	– S(1) ×4	2.3215(9)	2.3256(14)
<i>M</i> (2a)	– S(2)	2.228(2)	2.228(4)
	– S(1) ×2	2.2404(19)	2.249(3)
<i>M</i> (2b)	– S(2)	2.337(15)	2.324(18)
	– S(1) ×2	2.318(10)	2.303(10)
<i>X</i> (3)	– S(1) ×3	2.3571(16)	2.355(2)

bond distance is also in agreement with other Cu-centered tetrahedral sites, e.g., in chalcopyrite (2.302–2.33 Å; Hall 1975). On the basis of electron microprobe data, this site could be modelled as a pure Cu site, neglecting very minor Zn and Fe (probably occurring as Fe^{3+} , in agreement with, for instance, Makovicky et al. 2003). Bond-valence sums in the North Star and Pefka samples are 1.16 and 1.12 v.u., respectively, in accordance with the almost pure Cu occupancy at *M*(1).

The *X*(3) site has average bond distance of 2.357 Å for the sample from the North Star mine, whereas the bond distance observed in the specimen from Pefka is 2.355 Å. The refined site occupancy in holotype specimen corresponds to a mean atomic number of 46.6 electrons; on the basis of electron microprobe data, the site occupancy is $(\text{Te}_{0.50}\text{As}_{0.36}\text{Sb}_{0.11}\text{Bi}_{0.03})$, corresponding to a calculated mean atomic number of 46.0 electrons. The bond-valence sum at the *X*(3) site of the North Star mine sample is 3.33 v.u., to be compared to a theoretical one of 3.50 v.u. The refined mean atomic number of the sample from Pefka is 43.7 electrons. This value has to be compared to that calculated on the basis of the site occupancy proposed in accordance with electron microprobe data, i.e., $(\text{As}_{0.34}\text{Sb}_{0.23}\text{Te}_{0.43})$, corresponding to 45.3 electrons. Bond-valence sum at this site is 3.36 v.u., in agreement with a calculated value of 3.43 v.u.

The S(1) and S(2) sites are both fully occupied by S. No evidence for the occurrence of minor vacancy (0.30 *apfu*) suggested by the electron microprobe analysis of the sample from Pefka was observed. Bond-valence sums at S(1) and S(2) are 2.03 and 2.10 v.u. for holotype material and 2.02 and 2.16 v.u. for the Greek one.

3.2. Crystal chemistry of arsenogoldfieldite

Arsenogoldfieldite and its Sb-isotype stibiogoldfieldite (Biagioni et al. 2022) are new additions to the tellurium-bearing minerals belonging to the tetrahedrite group, along with goldfieldite and isotypic selenides arsenoustalečite and stibioústalečite (Tab. 8).

Tellurium-bearing tetrahedrite-group minerals have several crystal-chemical features deciphered since the end of the 1960s. Kato and Sakurai (1970) and Kalbskopf (1974) realized that Te does not substitute for S (as initially hypothesized) but behaves like As and Sb, as proposed by Lévy (1967). This agrees with our results, showing a full S occupancy at the S(1) and S(2) sites of arsenogoldfieldite and a site scattering at the *X*(3) site in accord with a mixed (As, Te, Sb, Bi) occupancy.

Kalbskopf (1974) also reported the occurrence of vacancies at the trigonally-coordinated *M*(2) sites in Te-rich tetrahedrite-group minerals. Similar results were then obtained by Dmitrieva et al. (1987) and Pohl et al. (1996). At the end of the 1970s and during the 1980s, several authors (e.g., Novgorodova et al. 1978; Kase 1986; Knittel 1989) proposed that the accommodation of Te^{4+} (up to 2 Te *apfu*) in the crystal structure of tetrahedrite-group minerals is possible through an increase of the $(\text{Cu,Ag})^+$ content from 10 to 12 *apfu*, according to the substitution (i) $^{M(1)}\text{Me}^{2+} + ^{X(3)}(\text{Sb/As})^{3+} = ^{M(1)}\text{Cu}^+ + ^{X(3)}\text{Te}^{4+}$, where $\text{Me} = \text{Fe, Zn, Hg, Mn} \dots$ For Te contents between 2 and 4 *apfu*, the charge balance is maintained through the creation of vacancies at the *M*(2) site, according to the substitution mechanism (ii) $^{M(2)}\text{Cu}^+ + ^{X(3)}(\text{Sb/As})^{3+} = ^{M(2)}\square + ^{X(3)}\text{Te}^{4+}$ (e.g., Shimizu and Stanley 1991). Summarizing, the general chemical formula can be written as $\text{Cu}_{10+x}\text{Me}_{2-x}[(\text{Sb/As})_{4-x}\text{Te}_x]\text{S}_{13}$ for $0 \leq \text{Te} \leq 2$ *apfu* and $(\text{Cu}_{12-y}\square_y)[\text{Te}_{2+y}(\text{Sb/As})_{2-y}]\text{S}_{13}$ for $2 < \text{Te} \leq 4$ *apfu*. Data collected on the specimens from the North Star mine and the Pefka mine agree with these substitution mechanisms, the same as in the case of stibiogoldfieldite (Biagioni et al. 2022; Musetti et al. 2024). Figure 5a shows the relations between formally monovalent cations (Cu+Ag) and Te. There is a positive relation up to about 2 Te *apfu* and 12 (Cu+Ag) *apfu*. Then, a negative correlation between the Te and (Cu+Ag) can be observed. This is likely related to the transition from substitution (i) to (ii). Figure 5b is in keeping with this hypothesis. Indeed, the content of (Zn+Fe+Cd...), i.e., formally divalent cations (Fe could

Tab. 7 Weighted bond-valence sums (in valence unit) in arsenogoldfieldite

North Star mine						
Site	<i>M</i> (1)	<i>M</i> (2a)	<i>M</i> (2b)	<i>X</i> (3)	Σ anions	Theor.
S(1)	$2 \times \rightarrow 0.29 \times 4$	0.29×2	$2 \times \rightarrow 0.03 \times 2$	1.11×3	2.03	2.00
S(2)		$6 \times \rightarrow 0.30$	$12 \times \rightarrow 0.03$		2.10	2.00
Σ cations	1.16	0.88	0.09	3.33		
Theor.	1.00	0.81	0.09	3.50		
Pefka mine						
Site	<i>M</i> (1)	<i>M</i> (2a)	<i>M</i> (2b)	<i>X</i> (3)	Σ anions	Theor.
S(1)	$2 \times \rightarrow 0.28 \times 4$	0.26×2	$2 \times \rightarrow 0.04 \times 2$	1.12×3	2.02	2.00
S(2)		$6 \times \rightarrow 0.28$	$12 \times \rightarrow 0.04$		2.16	2.00
Σ cations	1.12	0.80	0.12	3.36		
Theor.	1.00	0.75	0.13	3.43		

Tab. 8 Comparison of Te-members of the tetrahedrite-group

	arsenogoldfieldite North Star mine	arsenogoldfieldite Pefka mine	stibiogoldfieldite Mohawk mine
ideal	$\text{Cu}_6\text{Cu}_6(\text{As}_2\text{Te}_2)\text{S}_{13}$	$\text{Cu}_6\text{Cu}_6(\text{As}_2\text{Te}_2)\text{S}_{13}$	$\text{Cu}_6\text{Cu}_6(\text{Sb}_2\text{Te}_2)\text{S}_{13}$
$M(2)$	$\text{Cu}_{5.80}$	$\text{Cu}_{5.77}$	$(\text{Cu}_{6.09}\text{Ag}_{0.04})_{\Sigma 6.13}$
$M(1)$	$(\text{Cu}_{5.95}\text{Zn}_{0.03}\text{Fe}_{0.02})_{\Sigma 6.00}$	$(\text{Cu}_{5.82}\text{Zn}_{0.11}\text{Mn}_{0.04}\text{Fe}_{0.02}\text{In}_{0.01})_{\Sigma 6.00}$	$(\text{Cu}_{5.96}\text{Zn}_{0.03}\text{Fe}_{0.01})_{\Sigma 6.00}$
$X(3)$	$(\text{As}_{1.44}\text{Sb}_{0.43}\text{Bi}_{0.13}\text{Te}_{2.00})_{\Sigma 4.00}$	$(\text{As}_{1.35}\text{Sb}_{0.93}\text{Bi}_{0.01}\text{Te}_{1.71})_{\Sigma 4.00}$	$(\text{Sb}_{1.12}\text{As}_{0.63}\text{Bi}_{0.23}\text{Te}_{2.02})_{\Sigma 4.00}$
$S(1)+S(2)$	$\text{S}_{13.11}$	$(\text{S}_{12.67}\text{Se}_{0.03})_{\Sigma 12.70}$	$(\text{S}_{12.99}\text{Se}_{0.11})_{\Sigma 13.10}$
a [Å]	10.2868(4)	10.2991(14)	10.3466(17)
V [Å ³]	1088.53(13)	1092.4(4)	1107.6(5)
Ref.	[1]	[1]	[2]

	stibiogoldfieldite Mohawk mine	goldfieldite synth.	arsenostalečite Ústaleč	stibiostalečite Ústaleč
ideal	$\text{Cu}_6\text{Cu}_6(\text{Sb}_2\text{Te}_2)\text{S}_{13}$	$(\text{Cu}_4\text{□})\text{Cu}_6\text{Te}_4\text{S}_{13}$	$\text{Cu}_6\text{Cu}_6(\text{As}_2\text{Te}_2)\text{Se}_{13}$	$\text{Cu}_6\text{Cu}_6(\text{Sb}_2\text{Te}_2)\text{Se}_{13}$
$M(2)$	$(\text{Cu}_{5.30}\text{Ag}_{0.03})_{\Sigma 5.33}$	$\text{Cu}_{3.57}$	$(\text{Cu}_{5.81}\text{Ag}_{0.17})_{\Sigma 5.98}$	$(\text{Cu}_{5.69}\text{Ag}_{0.07})_{\Sigma 5.76}$
$M(1)$	$\text{Cu}_{6.00}$	$\text{Cu}_{6.00}$	$(\text{Cu}_{5.95}\text{Fe}_{0.02}\text{Zn}_{0.02}\text{Hg}_{0.01})_{\Sigma 6.00}$	$(\text{Cu}_{5.80}\text{Zn}_{0.13}\text{Fe}_{0.06}\text{Hg}_{0.01})_{\Sigma 6.00}$
$X(3)$	$(\text{Sb}_{0.80}\text{As}_{0.57}\text{Bi}_{0.06}\text{Te}_{2.57})_{\Sigma 4.00}$	$\text{Te}_{4.00}$	$(\text{As}_{1.40}\text{Sb}_{0.87}\text{Te}_{1.73})_{\Sigma 4.00}$	$(\text{Sb}_{1.82}\text{As}_{0.42}\text{Te}_{1.76})_{\Sigma 4.00}$
$S(1)+S(2)$	$(\text{S}_{12.83}\text{Se}_{0.20})_{\Sigma 13.03}$	$\text{S}_{12.73}$	$(\text{Se}_{10.30}\text{S}_{2.32})_{\Sigma 12.61}$	$(\text{Se}_{9.52}\text{S}_{3.10})_{\Sigma 12.62}$
a [Å]	10.2947(3)	10.266(4)	10.6580(19)	10.6975(16)
V [Å ³]	1091.04(10)	1081.9	1210.7(6)	1224.2(5)
Ref.	[3]	[4]	[5]	[5]

[1] this paper; [2] Biagioni et al. (2022); [3] Musetti et al. (2024); [4] Makovicky and Karup-Møller (2017); [5] Sejkora et al. (2024).

also occurs as ferric iron when occurring in low amounts – e.g., Makovicky and Karup-Møller 2017), decreases up to 2 Te *apfu*, when the sum of transition metals approaches zero. In the studied samples, the content of Te then increases up to about 2.5 *apfu*.

Taking the general formula discussed above, the holotype material has $x=2$, corresponding ideally to $\text{Cu}_{12}[(\text{As,Sb})_2\text{Te}_2]\text{S}_{13}$. Indeed, the amount of Zn and Fe is

very low, close to the detection limit, i.e., 0.03 and 0.02 *apfu*, respectively, and the sum of the formally monovalent cations Cu and Ag is close to 12 *apfu*. Trivalent cations are represented by As (1.44 *apfu*), Sb (0.43 *apfu*), and minor Bi (0.13 *apfu*). The arsenogoldfieldite grain from the Pefka mine studied by SCXRD is distinctly Te-poorer with $x=1.7$ and 1.35 *apfu* As, 0.93 *apfu* Sb and only traces of Bi (0.01 *apfu*).

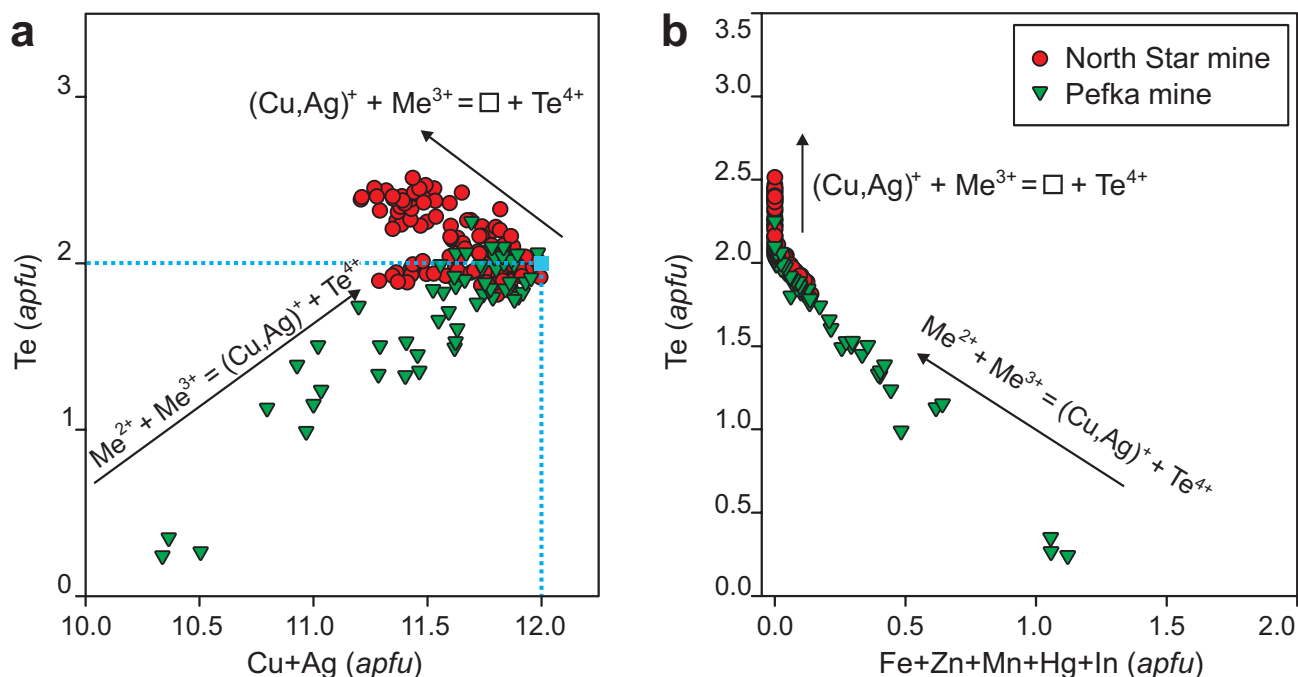


Fig. 5 Relationships between Te vs (Cu+Ag) (a) and Te vs (Zn+Fe+Cd) (b) in *apfu* in arsenogoldfieldite. Blue square indicates the position of the ideal arsenogoldfieldite, i.e., (Cu+Ag)=12 *apfu* and Te=2 *apfu*.

3.3. Other known arsenogoldfieldite occurrences

Members of the goldfieldite series with chemical composition corresponding to arsenogoldfieldite are known from several other localities. For instance, Biagioni et al. (2022) reported the occurrence of arsenogoldfieldite coexisting with stibio-goldfieldite at the Mohawk mine, Nevada, USA. Other findings were reported from the Ozerovskoye deposit, Kamchatka, Russia (Spiridonov and Okrugin 1985), the Ikazadu deposit, Japan (Kase 1986), the Marian Au mine, Philippines (Knittel 1989), the Iriki and Kawazu mines, Japan (Shimizu and Stanley 1991), the Tramway mine, Butte mining district, Montana (Criddle and Stanley 1993), Mina Capillitas, Argentina (Márquez-Zavalía and Craig 2004), the Rhodope area, Greece (Repstock et al. 2016) and the Maletoyvayam deposit, Kamchatka (Tolstykh et al. 2025).

4. Conclusions

Arsenogoldfieldite is a new member of the tetrahedrite group and, along with stibio-goldfieldite and goldfieldite, forms the goldfieldite series. The discovery of these species and the refinement of their crystal structures agree with previous investigations and hypotheses about the role of Te in these sulfosalts as well as the mechanisms favouring its incorporation in their crystal structures (e.g., Makovicky and Karup-Møller 2017).

Original goldfieldite of Ransome (1909) corresponds to stibio-goldfieldite; consequently, notwithstanding goldfieldite is still a valid mineral species, a study on natural specimens is mandatory, coupled with a definition of neotype material. Since some occurrences of goldfieldite, with up to 3.77 Te *apfu* are known (i.e. Perama Hill and Mavrokoryfi, NE Greece; Voudouris et al. 2011; Voudouris 2011), their crystal-chemical study should be performed, improving our knowledge on this important sulfosalt group.

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