Auerbakhite, MnTl₂As₂S₅, a new thallium sulfosalt from the Vorontsovskoe gold deposit, Northern Urals, Russia

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Auerbakhite (IMA 2020–047), MnTl₂As₂S₅, is a new sulfosalt from the Vorontsovskoe gold deposit, Sverdlovsk Oblast’, Northern Urals, Russia. The new mineral occurs in limestone breccias composed of calcite, dolomite, baryte, clinochlore, fluorapatite and quartz, and cemented by major realgar, orpiment and pyrite. Other minerals directly associating with auerbakhite include alabandite, bernardite, christite, cinnabar, coloradoite, dalmegroite, gillulite, gold, hutchinsonite, imhofite, lorándite, metacinnabar, philrothite, rebulite, routhierite, sphalerite, and vrbaite. Auerbakhite forms rare and very small short-prismatic crystals and irregular grains which do not exceed 15 × 5 µm. It is transparent, has a bright red color and adamantine luster. Auerbakhite is brittle, with an uneven fracture. Cleavage is not observed. The calculated density is 5.245 g/cm³. In reflected light, auerbakhite is light gray, weakly bireflectant. In crossed polars, it is distinctly anisotropic, in light gray and brown tones, with abundant bright red internal reflections. The empirical formula of auerbakhite is 

\[
\text{Mn}_{1.94(5)}\text{Tl}_{1.97(3)}\text{Pb}_{0.02(2)}\text{As}_{2.60(2)}\text{S}_{5.62(2)} \quad \text{(based on 10 atoms pfu)}.
\]

Prominent features in the Raman spectrum include bands of Mn–S and As–S stretching vibrations and numerous low-frequency bands related to mixed soft modes involving bending and Ti–S stretching vibrations. Auerbakhite is orthorhombic, space group Cmce, \(a = 15.3280(15)\) Å, \(b = 7.662(7)\) Å, \(c = 16.6330(14)\) Å, \(V = 1953.40(18)\) Å³ and \(Z = 8\). The crystal structure of auerbakhite was refined from the single-crystal X-ray diffraction data to \(R = 0.0723\) for 307 observed reflections with \(I_{\text{obs}} > 3\sigma(I)\). Auerbakhite is isostructural to the synthetic phase \(\text{TiMnAsS}_5\). Its crystal structure consists of complex (001) layers based on a set of \(\text{MnS}_2\) columns parallel to \([010]\) and are composed of edge-sharing slightly irregular \(\text{MnS}_2\) octahedra. The columns are connected via \(\text{TlI}\) and are framed by paired \(\text{AsS}_4\) pyramids with lone electron pairs oriented into interlayer space. Highly irregular \(\text{Ti(2)S}_4\) coordination polyhedra are situated in interlayers and share ligands with the layers. The new mineral honors Russian mining engineer, manufacturer and mineralogist Alexander Andreevitch Auerbakh whose activities were closely related to Northern Urals.

Keywords: auerbakhite, new sulfosalt, thallium, crystal structure, Vorontsovskoe gold deposit, Northern Urals

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1. Introduction

The Vorontsovskoe gold deposit at Northern Urals is unique in Russia and in the world concerning the diversity and originality of the Ti–Hg–Mn–As–Sb–S mineralization. Its ores contain more than 70 rare sulfides, tellurides and sulfosalts, including 30 with thallium, 12 with mercury, and 9 with manganese as species-defining elements (Kasatkin et al. 2020b). Among them, eight mineral species were discovered by our team as entirely new for the science: vorontsovite, ferrovorontsovite (Kasatkin et al. 2018b), tsygankoite (Kasatkin et al. 2018a), gladkovskyite (Kasatkin et al. 2019), luboržákite (Kasatkin et al. 2020a), pokhodyashinite (Kasatkin et al. 2020c), gungerite (Kasatkin et al. 2021), and auerbakhite described herein.

Auerbakhite (pronouncing: a ǝ ba khit; Russian Cyrillic ауэрбахит) is named for Alexander Andreevitch Auerbakh (1844–1916), Russian mining engineer, manufacturer and mineralogist. At the end of the 19th century,
his activities were closely related to Northern Urals. In 1884 he founded the Tur’inskii Mining School at the famous Tur’inskie Copper Mines. During 1881–1896 he managed the Bogoslovsksiy mining district, developed and improved the region’s copper smelting production. The Auerbakh intrusion and Auerbakh ore district comprising the Vorontsovske gold deposit are named after him. A.A. Auerbakh is the author of several mineralogical papers — see, e.g., Auerbakh (1869) — and was the first one in Russia who used microscopic techniques to study minerals. We find it symbolic of naming after him a mineral of a tiny size which has been discovered under the scanning electron microscope.

The new mineral and its name have been approved by the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association (IMA 2020–047). The type specimen is deposited in the collections of the Fersman Mineralogical Museum of the Russian Academy of Sciences, Moscow, Russia with the registration number 5579/1.

2. Occurrence

Vorontsovske gold deposit is located in Krasnotur’inskii district of Sverdlovsk Oblast’ (Northern Urals), 0.5 km W of Vorontsovo settlement, 13 km S of the town of Krasnotur’insk and approximately 310 km N of Yekaterinburg. It was discovered in 1985 and since 1999, its exploitation has been performed by the mining company PLC “Polymetal” utilizing two open pits — Northern (240 m deep) and Southern (80 m deep). A detailed description of the Vorontsovske deposit, its genesis, geology and composition of main types of ores can be found elsewhere (Vikentyev et al. 2016; Kasatkin et al. 2019; Kasatkin et al. 2020a and references therein). The most recent summary of the history of the study of the deposit, its geological background, detailed description of the main mineral assemblages were given by Kasatkin et al. (2020b). The last paper also provides an exhaustive list of 209 mineral species identified there.

Geologically, the Vorontsovske deposit lies on the eastern slope of the Northern Urals, in the eastern part of the Tagil volcanic zone, within the volcano-plutonic belt of submeridional strike. This belt was formed due to the collision of the Tagil island arc with the East Ural microcontinent. Auerbakh gabbro–diorite–granodiorite intrusion of the Middle Devonian age is located in the southern part of that volcano–plutonic belt. The Vorontsovske–Peschanskaya ore-magmatic system is situated in the southwestern exocorent of the Auerbakh intrusion. Vorontsovske deposit is located in the southern part of the system, at some distance from the contact with the intrusive rocks of the Auerbakh intrusion. The volcanic–sedimentary beds, which enclose the Vorontsovske deposit, form a monocline that slopes gently to the west and plunges to the north. The base of this structure consists of limestones, often largely converted to marbles, with interlayers of tuffites and siltstones. This stratum is consistently overlain by volcanic–sedimentary and volcanic rocks: tuff aleurolites, tuffites, diorite porphyrites and tuffs. The Northern open pit of the Vorontsovske deposit exposed a wedge-shaped body of volcanogenic–sedimentary rocks dominated by tuffs of intermediate composition and tuffaceous sandstones. Both limestones and volcanic–sedimentary rocks are subject to brecciation. Breccias consist of semi-rounded and angular limestone fragments up to 25 cm in size, cemented by clay–carbonate and volcanic–sedimentary material (Kasatkin et al. 2020b). Our systematic studies of the samples collected at the deposit in 2013–2020 show that the most extraordinary richness and variety of mineral species occur exactly in ore breccias developed over carbonate rocks. They contain various rare minerals (mainly sulfo salts) with species-defining Tl, Hg, Pb and Mn identified in the deposit, including eight new species mentioned above.

Specimens containing auerbakhite were collected in August 2016 at the lowest horizons of the Northern open pit of the deposit, 50 m from its western wall, directly at the bottom of the pit (59°39’12’’N, 60°12’53’’E) (Fig. 1). Auerbakhite occurs in the same mineral assemblage as gladkovskyyite (Kasatkin et al. 2019) and has been found in limestone breccias composed of Mn-rich carbonates (calcite and dolomite), baryte, clinochlore, fluorapatite and quartz, and cemented by major realgar, orpiment and pyrite. Other minerals directly associating with auerbakhite include alabandite, bernardite, christite, cinnabar, coloradoite, dalnegroite, gillulyite, gold, hutchinsonite, imhofite, lorándite, metacinnabar, philrothite, rebulite, routhierite, sphalerite, and v ciałaite.

Fig. 1 Northern open pit of Vorontsovske deposit where samples containing auerbakhite were collected. August 2016. Photo by S. Yu. Stepanov.
Auerbakhite, a new sulfosalt from Russia

3. Physical and optical properties

Auerbakhite forms rare and very small short-prismatic crystals and irregular grains which do not exceed $15 \times 5$ $\mu$m, and, as a rule, are even smaller (Fig. 2). Auerbakhite is transparent, has a bright red color and adamantine luster. It is brittle, with an uneven fracture. Cleavage is not observed. Its hardness and density could not be measured because of the extremely small size of the grains. The density calculated from the empirical formula ($Z = 8$) and the unit-cell volume determined from the single-crystal X-ray diffraction data is 5.245 g/cm$^3$. In reflected light, auerbakhite is light gray, weakly bireflectant. In crossed polars, it is distinctly anisotropic, in light gray and brown tones. Internal reflections are abundant and have a bright red color. They are distinct in air and strong in immersion. In transmitted light, auerbakhite is moderately pleochroic, from orange-red to dark red. Reflectance values for wavelengths recommended by the Commission on Ore Mineralogy of the IMA are ($R_{\text{max}}/R_{\text{min}}$, %): 25.2/27.1 (470 nm), 24.0/25.2 (546 nm), 23.7/24.7 (589 nm), 23.0/24.0 (650 nm). The complete set of reflectance measurements performed in the air relative to a WTiC standard employing a Universal Microspectrophotometer UMSP 50 (Opton-Zeiss, Germany) is given in Tab. 1 and plotted in Fig. 3.

4. Raman spectroscopy

The Raman spectrum of auerbakhite (Fig. 4) was obtained from a polished section employing a Horiba Labram HR Evolution spectrometer. This dispersive, edge-filter-based system is equipped with an Olympus BX 41 optical microscope, a diffraction grating with 600 grooves per millimeter, and a Peltier-cooled, Si-based charge-coupled device (CCD) detector. The 633 nm He-Ne laser with the beam power of 1 mW at the sample surface was selected for spectra acquisition to minimize analytical artifacts. Raman signal was collected in the range of 30–600 cm$^{-1}$ with a 100× objective and the system operated in the confocal mode; the beam diameter was $< 1 \mu$m and the depth resolution $\sim 2 \mu$m. No visual damage was observed on the analyzed surface under these conditions after the excitation. Wavenumber calibration was done using the Rayleigh line and low-pressure Ne-discharge lamp emissions. The wavenumber accuracy was $\sim 0.5$ cm$^{-1}$, and the

| Tab. 1 Reflectance values of auerbakhite (measured in air) |
|----------------------|----------------------|
| $R_{\text{max}}$ | $R_{\text{min}}$ | $\lambda$ (nm) | $R_{\text{max}}$ | $R_{\text{min}}$ | $\lambda$ (nm) |
| 34.8 | 26.8 | 400 | 24.9 | 23.9 | 560 |
| 33.0 | 26.3 | 420 | 24.8 | 23.8 | 580 |
| 31.3 | 25.9 | 440 | 24.7 | 23.7 | 589 (COM) |
| 28.5 | 25.5 | 460 | 24.5 | 23.5 | 600 |
| 27.1 | 25.2 | 470 (COM) | 24.3 | 23.4 | 620 |
| 26.5 | 24.8 | 480 | 24.1 | 23.2 | 640 |
| 25.9 | 24.5 | 500 | 24.0 | 23.0 | 650 (COM) |
| 25.7 | 24.3 | 520 | 23.9 | 22.8 | 660 |
| 25.5 | 24.1 | 540 | 23.8 | 22.7 | 680 |
| 25.2 | 24.0 | 546 (COM) | 23.7 | 22.6 | 700 |

Fig. 2 Two grains of auerbakhite (Arb) in calcite (very dark-grey) and quartz (black) in association with realgar (Rlg) and pyrite (Pyr). These grains were the biggest ever found and have been extracted for structural studies. Polished section. SEM (BSE) image.
spectral resolution was ~2 cm\(^{-1}\). Band fitting was done after appropriate background correction, assuming combined Lorentzian–Gaussian band shapes using the Voigt function (PeakFit; Jandel Scientific Software).

The assignment of the Raman bands of auberbakhite was made by analogy with gladkovskyite (Kasatkin et al. 2019). In both minerals, the most high-force-strength bonds are Mn–S. Bands of \(M\)-S stretching vibrations in the Raman spectra of pyrite–type compounds \(MS_2\) (\(M =\) Mn, Co, Ni, Cu, Zn) with systems of vertex–sharing \(MS_6\) octahedra are observed in the range of 380–500 cm\(^{-1}\) (Anastassakis and Perry 1976). For gladkovskyite and auberbakhite, which contain 1D systems of MnS\(_6\) octahedra, somewhat lower frequencies should be expected. This conclusion is in agreement with the positions of the strong high-frequency bands observed in the Raman spectra of both minerals in the range of 350–400 cm\(^{-1}\).

Raman bands of As–S stretching vibrations in the Raman spectra of orpiment As\(_2\)S\(_3\) and realgar AsS are observed in the range of 290–360 cm\(^{-1}\) (Forneris 1969; Minceva–Sukarova et al. 2003). In these minerals, the As–S distances are in the range of 2.21–2.31 Å (Morimoto 1954; Mullen and Nowacki 1972). The largest bonding distances correspond to the lowest frequencies of As–S stretching vibrations. In auberbakhite, the shortest As–S distances of the AsS\(_4\) and AsS\(_3\) pyramids are in the range of 2.23–2.31 Å. Consequently, the bands in the range of 300–350 cm\(^{-1}\) in the Raman spectrum of auberbakhite are assigned to As–S stretching vibrations.

The assignment of Raman bands with wavenumbers below 260 cm\(^{-1}\) is ambiguous. Presumably, these bands correspond to mixed soft modes involving...
bending vibrations, as well as Tl–S stretching vibrations.

5. Chemical composition

Preliminary semi-quantitative chemical analyses using a scanning electron microscope CamScan 4D (Fersman museum, Moscow) equipped with INCA Energy micro analyzer (EDS mode, 20 kV, 5 nA and beam diameter 1 μm) showed the presence of essential Mn, Tl, As, S, and traces of Pb in auerbakhite. Contents of other elements with atomic numbers higher than that of carbon were below detection limits.

Quantitative chemical analyses were conducted in the wavelength-dispersive (WDS) mode, using a Cameca SX100 electron microprobe (Masaryk University, Brno) operated at 25 kV and 20 nA with the beam size of 1 μm. Peak counting times were 20 s for all elements, with one-half of the peak time for each background. The following standards, X-ray lines, and crystals (in parentheses) were used: Mn: Mn metal, Kα (LIF); Tl: Tl(Br, I), Mα (PET); Pb: PbSe, Mα (PET); As: pararammelsbergite, Lαp (TAP); S: chalcopyrite, Kα (PET). Raw X-ray intensities were corrected for matrix effects with a φ(pz) algorithm of X-PHI routine (Merlet 1994). Analytical data are given in Tab. 2 (mean of 7 analyses). No other elements with atomic numbers higher than 8 were detected.

The empirical formula of auerbakhite (based on the sum of all atoms = 10 pfu) is Mn1.04 Tl1.97 Pb0.02 As1.05 S5.02. The ideal chemical formula is MnTl2As3S5, which requires Mn 7.10, Tl 52.81, As 19.37, S 20.72, total 100 wt. %.

6. X-ray crystallography

Single-crystal X-ray diffraction data were collected on an extremely small, plate-like single-crystal fragment of auerbakhite, of the approximate dimensions 10 × 8 × 5 μm, embedded in a calcite chip and extracted from the polished section used for EPMA investigations. It was mounted on glass fiber and examined with a Rigaku SuperNova single-crystal diffractometer equipped with the Atlas S2 CCD detector and a microfocus MoKα source (Institute of Physics, Prague). Data reduction was performed using CrysAlisPro Version 1.171.39.46 (Rigaku 2019). The data were corrected for Lorentz factor, polarization effect and absorption (multi-scan, ABSPACK scaling algorithm; Rigaku 2019).

The crystal structure of auerbakhite was refined based on single-crystal X-ray data starting from the structure model of the synthetic MnTlAS S (Gostojić et al. 1982) using the software Jana2006 (Petřiček et al. 2014). The structure refinement smoothly converged to R = 0.0723 for 307 reflections with I > 3σ(I). Anisotropic displacement parameters were refined for all atoms. The relatively high residual electron-density of 29.05 eÅ−3 corresponding to a peak in difference-Fourier located 0.1 Å from Tl.
atom is related to the poorly fitted absorption effects. The crystal size, the fact that the grain itself is embedded in a slightly larger matrix (soft-absorbing, but still) of calcite and probably also the quality of the crystal prevent us from fitting the absorption correction better. The crystal data and the experimental details are given in Tab. 3, atom coordinates, atomic displacement parameters and site occupancies in Tab. 4 and selected interatomic distances in Tab. 5. The CIF file is deposited at the Journal’s webpage www.jgeosci.org.

Due to the lack of material for performing a conventional powder diffraction experiment, only the calculated powder pattern is given in Tab. 6. The theoretical $d_{\text{calc}}$ and relative intensities were calculated using the PowderCell program (Kraus and Nolze 1996).

### 7. Description of the crystal structure

The crystal structure of auerbachite (Fig. 5) is identical to the structure of synthetic $\text{Tl}_2\text{MnAs}_2\text{S}_4$ prepared and investigated by Gostojić et al. (1982). The crystal structure consists of complex (001) layers based on a set of $\text{MnS}_3$ columns, which are parallel to [010] and are composed of edge-sharing slightly irregular $\text{MnS}_6$ octahedra (Tab. 5).

### Tab. 4 Atom positions and equivalent displacement parameters (in Å$^2$) for auerbachite

<table>
<thead>
<tr>
<th>Atom</th>
<th>$x/a$</th>
<th>$y/b$</th>
<th>$z/c$</th>
<th>$U_{eq}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn(1)</td>
<td>0.25</td>
<td>0.3564(15)</td>
<td>0.25</td>
<td>0.032(4)</td>
</tr>
<tr>
<td>Tl(1)</td>
<td>0</td>
<td>0.4126(4)</td>
<td>0.17455(19)</td>
<td>0.0398(12)</td>
</tr>
<tr>
<td>Tl(2)</td>
<td>0.6431(2)</td>
<td>0</td>
<td>0</td>
<td>0.0490(14)</td>
</tr>
<tr>
<td>As(1)</td>
<td>0.1161(3)</td>
<td>0.0348(8)</td>
<td>0.1040(3)</td>
<td>0.030(2)</td>
</tr>
<tr>
<td>S(1)</td>
<td>0</td>
<td>0.845(2)</td>
<td>0.1157(13)</td>
<td>0.038(8)</td>
</tr>
<tr>
<td>S(2)</td>
<td>0.1331(9)</td>
<td>0.1097(18)</td>
<td>0.2336(7)</td>
<td>0.033(5)</td>
</tr>
<tr>
<td>S(3)</td>
<td>0.2807(9)</td>
<td>0.3304(19)</td>
<td>0.0986(7)</td>
<td>0.031(5)</td>
</tr>
</tbody>
</table>

The columns are framed by paired As$_2$S$_3$ pyramids with lone electron pairs oriented into interlayer space. Highly irregular TlS$_2$ coordination polyhedra are situated in interlayers and share ligands with the layers. Tl1 is a part of the complex (001) layer, interconnecting the Mn octahedral rods within this particular layer.

### Tab. 5 Selected interatomic distances (Å) in auerbachite

<table>
<thead>
<tr>
<th>Mn1–S3</th>
<th>2.570(12)</th>
<th>As1–S3v</th>
<th>2.230(16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn1–S3u</td>
<td>2.570(12)</td>
<td>As1–S2</td>
<td>2.246(13)</td>
</tr>
<tr>
<td>Mn1–S2</td>
<td>2.615(16)</td>
<td>As1–S1uv</td>
<td>2.307(11)</td>
</tr>
<tr>
<td>Mn1–S2u</td>
<td>2.616(15)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn1–S2v</td>
<td>2.659(16)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn1–S2v</td>
<td>2.659(16)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tl1–S2</td>
<td>3.241(15)</td>
<td>Tl2–S2v</td>
<td>2.972(14)</td>
</tr>
<tr>
<td>Tl1–S2u</td>
<td>2.964(14)</td>
<td>Tl2–S2uv</td>
<td>2.972(14)</td>
</tr>
<tr>
<td>Tl1–S2v</td>
<td>2.964(14)</td>
<td>Tl2–S2u</td>
<td>3.232(15)</td>
</tr>
<tr>
<td>Tl1–S2v</td>
<td>3.241(15)</td>
<td>Tl2–S2v</td>
<td>3.232(15)</td>
</tr>
<tr>
<td>Tl1–S1</td>
<td>3.453(17)</td>
<td>Tl2–S1u</td>
<td>3.940(14)</td>
</tr>
<tr>
<td>Tl1–S1v</td>
<td>3.523(17)</td>
<td>Tl2–S1v</td>
<td>3.940(14)</td>
</tr>
</tbody>
</table>

Symmetry codes: (i) $x$, $y-1/2$, $-z+1/2$; (ii) $x$, $y+1/2$, $-z+1/2$; (iii) $-x$, $y$, $z$; (iv) $x$, $y+1/2$, $-z+1/2$; (v) $-x+y+1/2$, $y$, $z$; (vi) $-x+y+1/2$, $-y+1/2$, $z$; (vii) $x$, $y-1/2$, $z$; (viii) $-x+y+1/2$, $-y+1/2$, $z$; (ix) $x+y+1/2$, $y+1/2$, $z$; (x) $x+y+1/2$, $y+1/2$, $z$; (xi) $x+y+1/2$, $y+1/2$, $z$; (xii) $x+y+1/2$, $y+1/2$, $z$; (xiii) $x+y+1/2$, $y+1/2$, $z$; (xiv) $x+y+1/2$, $y+1/2$, $z$; (xv) $x+y+1/2$, $y+1/2$, $z$.

In auerbachite, Tl1 and Tl2 are six-coordinated, although they are far from regular polyhedra. Both Tl1 and Tl2 have one-sided coordinations (Tab. 5), which suggest active lone electron pairs, all of which are directed into the interlayer space. Trigonal As pyramids are paired via a common S atom; along the [100] direction, a pyramidal pair matches two Tl2 polyhedra. The basal As–S distances of distorted As$_2$S$_3$ pyramids are 2.307 Å opposed by 3.392...
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Å, and 2.246 Å opposed by 3.863 Å. The vertex distance of 2.228 Å lacks a distant opposing distance within a 4 Å range. The complete $\text{AsS}_5$ pyramids are variously oriented and do not form a simple stacking sequence.

Like another Mn,Tl-sulfarsenite gladkovskyite $\text{MnTlAs}_3\text{S}_6$ (Kasatkin et al. 2019), auerbakhite is characterized by a significant structural role of lone electron pairs of both arsenic and thallium and with a ‘backbone’ formed by relatively small coordination octahedra of divalent manganese. Columnar arrangements of Mn octahedra might play a similar role in the complex structure of tsygankoite (Kasatkin et al. 2018a).

8. Remarks on the origin

The complex mechanisms of hydrothermal-metasomatic processes with successive telescoping of ore mineral assemblages in combination with their superimposition on various volcanic-sedimentary and carbonate rocks became one of the causes of the distribution at Vorontsovskoe gold deposit of several sulfosalts with unique chemical compositions. Manganese does not belong to chalcophile elements, and sulfosalts with Mn are quite rare among minerals. Auerbakhite is one of those sulfosalts: it contains Mn, Tl, As, and S. The only other mineral with the same species-defining elements is gladkovskyite $\text{MnTlAs}_3\text{S}_6$ (Kasatkin et al. 2019). However, it strongly differs from auerbakhite by stoichiometry and crystal structure. Both species were discovered in ore breccias, comprising one of the most interesting mineral assemblages of the deposit. We called it “gladkovskyite mineral assemblage” after the namesake sulfosalt described earlier and found in each of the studied specimens. A detailed description of this assemblage, its minerals and suggested sequence of mineral formation was given by Kasatkin et al. (2019, 2020b). Alternatively, this assemblage can be called “sulfarsenite”: its main features are the arsenic character of ores represented by major orpiment and realgar, and complete absence of stibnite, usually relatively abundant at the deposit, along with general depletion in antimony. Accordingly, the list of minerals belonging to this assemblage includes no single sulfantimonite and, in general, their chemical composition is characterized by the absence of Sb or a strong dominance of As over Sb. Auerbakhite is one of the four sulfarsenites found at the Vorontsovskoe deposit only in this mineral assemblage, along with gladkovskyite, gillulyite and lorándite.

The development of ore breccias with accompanying metasomatic processes in marbled limestones composed of Mn-rich carbonates (calcite and dolomite) led to the formation of this unique mineral assemblage with Mn-Tl-sulfarsenites. The high activity of sulfur and arsenic at the latest stages of the ore-forming process initiated the replacement of early high- and medium-temperature minerals of the base-metal ore association (galena, sphalerite, chalcopyrite, etc.) by rare sulfarsenites. Mechanisms of thallium concentration have not been determined unam-
biguously, but we believe they were related to the interaction between post-magmatic hydrothermal solutions and carbonate rocks. As was suggested in our previous work (Kasatkin et al. 2019), the latter could perform a geochemical trap for ore-bearing solutions and became a place of concentration of thallium and formation of Tl-bearing sulfosalts. Low temperatures could promote the processes of separation of elements between different mineral phases.

To sumarize, auberbahmite, similarly to gladkovskiyite and other sulfarsenites of this mineral assemblage, was formed at the latest stage of low-temperature hydrothermal process due to the development of low-T metasomatic processes in sedimentary carbonate rocks rich in Tl and Mn connected with the saturation of the ore-forming environment by As with simultaneous very low activity of Sb.

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