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JONASSONITE, $Au(Bi,Pb)_5S_4$, A NEW MINERAL SPECIES FROM NAGYBÖRZSÖNY, HUNGARY

WERNER H. PAAR[§], HUBERT PUTZ AND DAN TOPA

Department of Material Science, Division of Applied Mineralogy, University of Salzburg,
Hellbrunnerstr. 34, A-5020 Salzburg, Austria

ANDREW C. ROBERTS

Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario KlA OE8, Canada

CHRIS J. STANLEY

Department of Mineralogy, The Natural History Museum, Cromwell Road, London SW7 5BD, U.K.

FRANZ J. CULETTO

KELAG - Kärntner Elektrizitäts-Aktiengesellschaft, Arnulfpl. 2, A-9020 Klagenfurt, Austria

ABSTRACT

Jonassonite, ideally $Au(Bi,Pb)_5S_4$, was detected in old mining dumps of the abandoned Nagybörzsöny deposit at Alsó–Rózsa, on the western margin of the Börzsöny Mountains, northern Hungary. The mineralization is hosted by Miocene calc-alkaline volcanic rocks and occurs as a stockwork in a propylitized dacite breccia pipe. The assemblage of metallic minerals with which jonassonite is associated consists of arsenopyrite, pyrite, marcasite, pyrrhotite, sphalerite, chalcopyrite, native gold, native bismuth, bismuthinite, ikunolite, cosalite, lillianite and possibly cannizzarite. Jonassonite occurs as anhedral grains of up to 500 × 150 μm, and contains inclusions of native bismuth, ikunolite and bismuthinite. It is megascopically tin-white with a metallic luster and a black streak. The mineral is brittle, with no obvious cleavage. Twinning is present. VHN_5 ranges between 125 and 153 (mean 134.5) kg/mm^2 (Mohs hardness of about 2½ to 3). In plane-polarized reflected light, jonassonite is opaque, pale grey with a bluish tint, has weak bireflectance and pleochroism, and is distinctly anisotropic. Internal reflections are absent. The reflectances in air and oil, respectively, are 48.6–50.1, 35.0–36.7 (470 nm), 46.6–49.4, 32.7–35.7 (546 nm), 46.6–48.9, 32.9–35.2 (589 nm) and 48.0–48.8, 34.2–35.0 (650 nm). The chemical composition based on four analyses is: Au 14.95, Ag 0.09, Bi 69.06, Pb 6.12, Cd 0.06, Sb 0.08 S 9.76, Se 0.41, total 100.53 wt.%. This leads to the empirical formula $(Au_{1.02}Ag_{0.01})_{\Sigma 1.03}(Bi_{4.42}Pb_{0.39}Cd_{0.01}Sb_{0.01})_{\Sigma 4.83}(S_{4.07}Se_{0.07})_{\Sigma 4.14}$. The ideal formula, $AuBi_5S_4$, requires Au 14.38, Bi 76.26, S 9.36, total 100 wt.%. Jonassonite is monoclinic with unit-cell parameters, refined from powder data: *a* 18.329(29), *b* 4.108(4), *c* 13.974(16) Å, β 100.90(10)°, *V* 1033(2) $Å^3$, space-group choices *F*2/*m*, *F*2 or *Fm*, and *Z* = 4. The density could not be measured because suitable material was not available. It was calculated using the empirical formula: 8.64 g/cm^3. The strongest seven lines of the X-ray powder-diffraction pattern [*d* in Å(*I*)(*hkl*)] are: 9.002(40)(200), 6.876(30)(002), 3.460(30)($402,\bar{2}04$), 3.382(40)($\bar{3}11$), 2.959(100)($\bar{6}02,113$), 2.101(50)(711) and 2.086(50)($\bar{5}15$). The relationship to other species is unknown, and the mineral appears to have a unique prototype structure. The mineral name honors Dr. Ian Roy Jonasson, an economic geologist at the Geological Survey of Canada, Ottawa, for his outstanding contributions to global ore-deposit research. Both the mineral and the name have been approved by the Commission on New Minerals and Mineral Names, IMA (2004–031).

Keywords: jonassonite, new mineral species, gold bismuth sulfide, electron-microprobe analyses, X-ray data, reflectance data, Nagybörzsöny, Hungary.

SOMMAIRE

Nous avons découvert la jonassonite, de composition idéale $Au(Bi,Pb)_5S_4$, dans des haldes minières du gisement abandonné de Nagybörzsöny à Alsó–Rózsa, le long de la bordure occidentale des montagnes Börzsöny, dans le nord de la Hongrie. Les roches-hôtes de la minéralisation en stockwerk sont dacitiques, calco-alcalines, d'âge miocène, et montrent les effets d'une

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[§] *E-mail address*: werner.paar@sbg.ac.at

altération propylitique dans une colonne de minerai bréchique. L'assemblage de minéraux métalliques associés à la jonassonite comprend arsénopyrite, pyrite, marcasite, pyrrhotite, sphalérite, chalcopyrite, or natif, bismuth natif, bismuthinite, ikunolite, cosalite, lillianite, et possiblement cannizzarite. La jonassonite se présente en grains xénomorphes atteignant 500 × 150 μm, et contient des inclusions de bismuth natif, d'ikunolite et de bismuthinite. Il s'agit d'un minéral blanc-étain avec un éclat métallique et une rayure noire. Il est cassant, sans clivage apparent. Les cristaux sont maclés. La dureté VHN_5 va de 125 à 153 (en moyenne, 134.5) kg/mm^2, équivalant une dureté de Mohs entre 2½ et 3. En lumière réfléchie polarisée, la jonassonite est opaque, gris pâle avec une teinte bleuâtre, et elle possède une faible biréflectance et un faible pléochroïsme; elle est nettement anisotrope. Il n'y a pas de réflexions internes. Les valeurs de réflectances, dans l'air et dans l'huile, respectivement, sont 48.6–50.1, 35.0–36.7 (470 nm), 46.6–49.4, 32.7–35.7 (546 nm), 46.6–48.9, 32.9–35.2 (589 nm) et 48.0–48.8, 34.2–35.0 (650 nm). La composition chimique, établie suite à quatre analyses, est: Au 14.95, Ag 0.09, Bi 69.06, Pb 6.12, Cd 0.06, Sb 0.08 S 9.76, Se 0.41, pour un total de 100.53% (poids), ce qui mène à la formula empirique $(Au_{1.02}Ag_{0.01})_{\Sigma 1.03}(Bi_{4.42}Pb_{0.39}Cd_{0.01}Sb_{0.01})_{\Sigma 4.83}(S_{4.07}Se_{0.07})_{\Sigma 4.14}$. La formule idéale, $AuBi_5S_4$, requiert Au 14.38, Bi 76.26, S 9.36, total 100%. La jonassonite est monoclinique, avec les paramètres réticulaires suivants, affinés à partir de données sur poudre: *a* 18.329(29), *b* 4.108(4), *c* 13.974(16) Å, β 100.90(10)°, *V* 1033(2) Å^3, groupes d'espace possibles *F*2/*m*, *F*2 ou *Fm*, et *Z* = 4. Nous n'avons pas pu mesurer la densité faute de matériau. La densité calculée à partir de la formule empirique est 8.64 g/cm^3. Les sept raies les plus intenses du spectre de diffraction, méthode des poudres [*d* en Å(*I*)(*hkl*)] sont: 9.002(40)(200), 6.876(30)(002), 3.460(30)(402,$\bar{2}$04), 3.382(40)($\bar{3}$11), 2.959(100)($\bar{6}$02,113), 2.101(50)(711) et 2.086(50)($\bar{5}$15). Il ne semble y avoir aucune relation avec une autre espèce; le minéral présenterait une structure prototype unique. Le nom choisi honore Ian Roy Jonasson, géologue à la Commission géologique du Canada, pour ses nombreuses contributions importantes à la recherche en gîtologie à l'échelle du globe. La nouvelle espèce minérale et son nom ont été approuvés par la Commission sur les nouveaux Minéraux et les Noms de Minéraux (IMA2004–031).

(Traduit par la Rédaction)

Mots-clés: jonassonite, nouvelle espèce minérale, sulfure d'or et de bismuth, analyses de microsonde électronique, données en diffraction X, données de réflectance, Nagybörzsöny, Hongrie.

INTRODUCTION

The new mineral species *jonassonite*, of ideal composition $AuBi_5S_4$, is a rare constituent of various genetic types of gold mineralization. The first report of a natural Au–Bi sulfide mineral, from the Tsugahira mine, southwestern Japan, was by Hamasaki *et al*. (1986). The chemical composition of this mineral corresponds almost exactly to the ideal composition of jonassonite. A characterization of the interesting compound failed because the small grain-size did not permit extraction for a study using single-crystal X-ray methods. Compositionally related Au–Bi-sulfide phases have since been identified and reported from at least ten occurrences (Table 1); Nagybörzsöny is one of these, and is taken as the type locality. Only three small grains were observed by Dobosi & Nagy (1989) in specimens from this Hungarian locality, and they were not suitable for X-ray study.

Recently, an additional occurrence of a Au–Bi sulfide from the Viceroy mine at Zimbabwe, closely corresponding to Pb-free jonassonite compositionally, was brought to the attention of the authors (Thomas Oberthür, priv. comm.).

The grain size of this new species, as well as the complex intergrowth with associated metallic phases at all occurrences, explain why this mineral has not yet been completely characterized.

During an excursion by Austrian mineral collectors to the Nagybörzsöny deposit in 2002, several specimens were collected from dumps of the abandoned mine. The only piece that contains jonassonite was split up into several fragments, which were then distributed amongst the collecting team. One of the authors (HP) eventually acquired a large fragment, measuring approximately 5 × 4 × 3 cm. It consists of massive arsenopyrite and contains visible crystals of needle-shaped bismuth sulfosalts and anhedral grains of native bismuth with which jonassonite is associated. This large fragment was then cut into eight thin slices, from which eight polished sections were prepared. All polished sections contain jonassonite in varying amounts and grain sizes.

The name *jonassonite* honors Dr. Ian Roy Jonasson (b. 1939), an economic geologist, geochemist and mineralogist at the Geological Survey of Canada, Ottawa, in recognition of his outstanding contributions to research on ore deposits, both on land and the sea floor. It is particularly fitting that the new species is abundant in mineral deposits of Australia (Stegman 2000, 2001), since Dr. Jonasson is a native Australian who emigrated to Canada in 1969.

The mineral and the name have been approved by the Commission on New Minerals and Mineral Names, IMA (2004–031). Holotype material (two polished sections) is deposited under catalogue numbers 14941, 14942 in the Systematic Mineralogical Collection of the Department of Material Sciences, Division of Applied Mineralogy, University of Salzburg, Austria.

LOCATION AND GEOLOGY

The new mineral was detected in a single specimen collected from old mining dumps of the abandoned Nagybörzsöny mine at Alsó-Rózsa, on the western margin of the Börzsöny Mountains, northern Hungary. This is the same location from which a mineral with

TABLE 1. LOCATIONS AND PARAGENESIS OF JONASSONITE IN CHRONOLOGICAL ORDER OF DESCRIPTION

Location	Size of grain(s) (μm)	Paragenesis[1]	Quant. data[2]	Type of mineralization	Reference
Tsugahira mine, southern Kyushu, Japan	15 × 40 (1 grain)	Wo, Apy, Py → Po, Cp, Au-Ag, Bi, Bmt, Js, Pb-Bi-Te-S, Mld, Jo	EPMA,R	Au-Bi-W-tourmaline-quartz veins within metamorphosed mudstone and sandstone	Hamasaki *et al.* (1986)
northeastern Yakutia, Russia (2 locations)	15–20 (rims) ≤50 (grains)	Au, Scl, Td, Tsm → Au, Mld, Bi, Hdl, Js → Gn, Cls, Jo	EPMA	vein fillings, crush zones, associated with tourmalinized siltstone	Nekrasov *et al.* (1988)
northwestern Kazakhstan (Koostanay)	≤30 × 50 (3 grains)	Au, Bi, Mld, Js, Cos, Bmt, Apy, Cp, Py, Po, Mrc, Sp, Gn, Jo	EPMA, R, XRD	unknown	Pavlova & Kotelnikov (1988)
Nagybörzsöny, Hungary	10–20 (3 grains)	Ga, Sp, Cp, Po → Apy, Bi, Bmt, Ik, Pb-Bi-SS, Au, Jo	EPMA	stockwork impregnation in altered dacite breccia pipe (+ tourmaline)	Dobosi & Nagy (1989)
Unterlangau, Bavaria, Germany	≤40	Au → Lol, Mld → Apy, Jo → Au, Bi	EPMA	stratiform disseminations in cordierite-sillimanite gneiss	Lehrberger *et al.* (1990)
Kašperské Hory, Czech Republic	unknown	Au, Bi, Bi-tellurides, Bi-sulfotellurides	EPMA	quartz veins and lenses in sillimanite-biotite paragneisses, migmatites	Scharmová & Pertoldová (1990, 1993), Litochleb *et al.*(1994)
Petráčkova hora, Czech Republic	unknown	Mld, Ast, Apy, Mrc, Gdf, Jo	EPMA		
Oukilal, Morocco	up to100	Po, Lol, Apy, Au → Po, Py, Au → Apy, Cp, Sp, Gn, Jo, Js, Grü, Pek, Mld, Au, Bi, Bmt, Tb	EPMA	quartz veins in a ductile shear zone within volcanic rocks	Jouhari *et al.* (1999)
New Occidental (Peak) mine, Australia	up to50	Mgt, Scl, Cst, Wo → Au, Mld, Bi, Ik, Cls, Ast → Ik, Gn, Po, Qtz → Au, Bmt, Jo,Cp, Qtz, → Asp → Cp, Po, Au, Au-Ag, Py → Sp, Gn, Po → Py	EPMA	multiple lenses with sulfide mineralization within zones of quartz veining, hosted by Devonian sediments	Stegman (2000, 2001)
Highis, Romania	1–30	Bmt, Cos, Lil, Bi, Ing, Ik, Ltk, Au, Jo	EPMA	vein-type, within basaltic hornfels	Damian *et al.* (2004)

[1] Crystallization sequence where described in the respective publications: Au: gold, Au-Ag: Au–Ag alloy, Ast: aurostibite, Apy: arsenopyrite, Bi: bismuth, Bmt: bismuthinite, Cst: cassiterite, Cls: clausthalite, Cos: cosalite, Cp: chalcopyrite, Cbn: cubanite, Fbr: ferberite, Gn: galena, Gdf: gersdorffite, Grü: "grünlingite", Hdl: hedleyite, Ik: ikunolite, Ing: ingodite, Jo: jonassonite, Js: joseite, Ltk: laitakarite, Lil: lillianite, Lol: löllingite, Mgt: magnetite, Mld: maldonite, Mrc: marcasite, Mlb: molybdenite, Pek: pekoite, Py: pyrite, Po: pyrrhotite, Qtz: quartz, Scl: scheelite, Sp: sphalerite, Td: tetradymite, Tb: tellurobismuthite, Tsm: tsumoite.

[2] EPMA (Electron-probe microanalysis), R (Reflectance data), XRD (X-ray diffraction).

almost the same chemical composition was observed in a drill core of borehole Nb–10 at 148.8 m (Dobosi & Nagy 1989).

The gold mineralization at Nagybörzsöny consists of a stockwork impregnation in a dacite breccia pipe hosted within Miocene calc-alkaline volcanic rocks and affected by propylitic alteration. Two different stages of mineralization have been distinguished (Koch & Grasselly 1953, Pantó & Mikó 1964).

Galena, sphalerite, chalcopyrite and pyrrhotite were formed during the first stage. Arsenopyrite, native bismuth, bismuthinite, Pb–Bi sulfosalts and native gold formed during the second stage. The unnamed Au–Bi sulfide of Dobosi & Nagy (1989) was assumed by these authors to have formed during this second stage. In our specimen, the second-stage mineralization predominates and includes jonassonite, arsenopyrite, pyrite–marcasite associated with native bismuth, bismuthinite, ikunolite, cosalite, lillianite, a cannizzarite-type phase and native gold. Sulfides of the first-stage assemblage, such as pyrrhotite, sphalerite and chalcopyrite, are present in minor amounts (Figs. 1a–c).

APPEARANCE AND PHYSICAL PROPERTIES

Jonassonite occurs as opaque anhedral grains, up to 500 × 150 μm, with inclusions of native bismuth, ikunolite and bismuthinite (Figs. 1a–c). The color is assumed to be similar to that of bismuthinite or ikunolite, which are tin-white. The mineral has a metallic luster with a black streak. It is brittle, with an irregular fracture, and no observable cleavage. The density could not be measured because suitable material was not available. A value of 8.64 g/cm^3 was calculated on the basis of the empirical formula. Microhardness measurements were made with a Leica Miniload VMHT MOT tester and a load of 5 g. This comparatively low load was dictated by the small size of the available homogeneous grains. The Vickers hardness ranges between 125 and 153, mean 134.5 kg/mm^2. Most of the twenty indentations were perfect to slightly fractured with concave to distinctly sigmoidal outlines. The calculated Mohs hardness (Young & Millman 1964) is between 2½ and 3. Twinning is evident in a single grain.

TABLE 2. REFLECTANCE DATA FOR JONASSONITE FROM UNTERLANGAU, GERMANY AND NAGYBÖRZSÖNY, HUNGARY

	Unterlangau				Nagybörzsöny			
λ nm	R_1	R_2	$^{im}R_1$	$^{im}R_2$	R_1	R_2	$^{im}R_1$	$^{im}R_2$
400	51.4	52.2	39.6	40.4	48.8	49.8	35.8	36.6
420	51.5	52.1	39.1	39.8	49.1	50.1	35.8	36.8
440	51.5	52.0	38.3	38.9	49.1	50.2	35.8	36.8
460	51.3	51.6	37.5	37.8	48.8	50.1	35.3	36.8
480	50.9	51.1	36.6	36.9	48.4	50.0	34.7	36.6
500	50.4	50.6	36.0	36.1	47.6	49.7	33.7	36.3
520	49.8	50.0	35.3	35.6	47.1	49.4	33.1	35.9
540	49.2	49.5	34.7	35.1	46.7	49.2	32.7	35.7
560	48.7	49.0	34.1	34.6	46.5	49.0	32.6	35.5
580	48.3	48.7	33.6	34.3	46.5	48.9	32.7	35.3
600	48.0	48.6	33.4	34.1	46.7	48.8	33.1	35.1
620	47.8	48.6	33.2	34.2	47.2	48.8	33.5	35.0
640	47.8	48.8	33.1	34.4	47.7	48.8	34.0	35.0
660	47.9	49.3	33.1	35.0	48.2	48.9	34.4	35.0
680	47.9	49.8	33.3	35.7	48.4	49.0	34.6	35.1
700	48.1	50.5	33.5	36.5	48.6	49.0	34.8	35.1
COM wavelengths								
470	51.1	51.3	37.0	37.3	48.6	50.1	35.0	36.7
546	49.1	49.3	34.6	35.0	46.6	49.4	32.7	35.7
589	48.1	48.6	33.5	34.2	46.6	48.9	32.9	35.2
650	47.8	49.0	33.1	34.7	48.0	48.8	34.2	35.0
Color Values, C illuminant								
x	0.305	0.305	0.300	0.302	0.307	0.308	0.306	0.306
y	0.311	0.311	0.306	0.306	0.311	0.315	0.308	0.313
Y%	48.9	49.3	34.4	34.9	46.9	49.1	33.1	35.6
λ_d	480	476	477	473	455	479	433	480
P_e%	2.6	2.3	4.9	4.3	1.7	0.9	2.8	1.7

OPTICAL PROPERTIES

In reflected light, jonassonite is pale grey in color with weak bireflectance and weak pleochroism from pale, slightly bluish grey to pale grey. In slightly uncrossed polars, it has a distinct anisotropy in shades of green and purple.

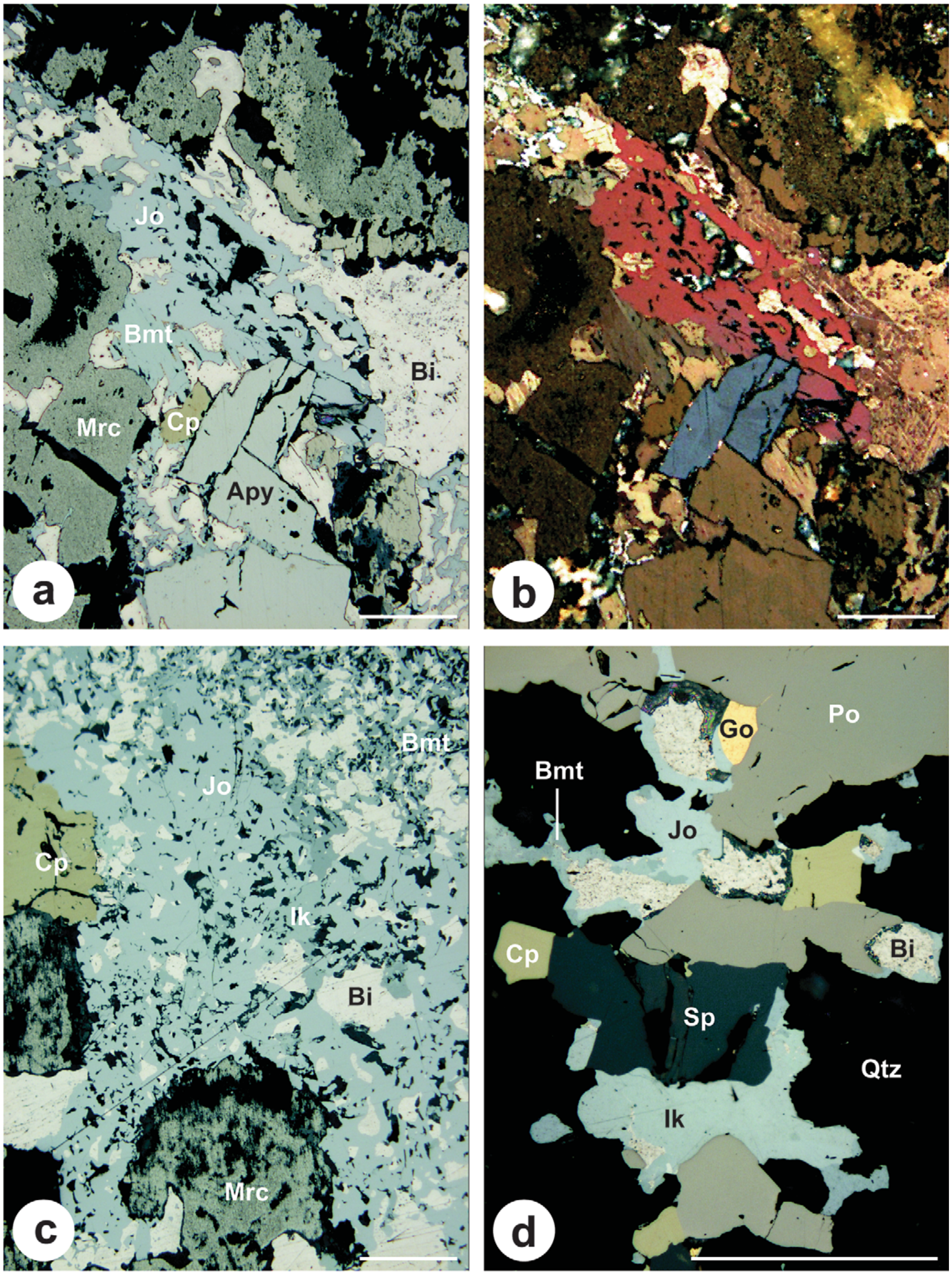
The section containing jonassonite from Nagybörzsöny was cleaned and buffed before measurement using 0.25 μm diamond paste, as were sections from Unterlangau, Bavaria, Germany, containing the same but chemically slightly different species (Lehrberger *et al.* 1990). Optical data on the latter were obtained in 1988 using equipment and techniques outlined in Criddle *et al.* (1989), whereas the optical data for jonassonite from Nagybörzsöny were obtained using similar techniques but more modern equipment in 2004, as outlined in Stanley *et al.* (2002). The results are given in Table 2 and Figure 2.

It is unclear whether the differences in dispersion between the two samples (Fig. 2) are due to measurement of the monoclinic mineral in different orientations or to the real difference in composition between jonassonite grains from these two localities.

CHEMICAL COMPOSITION

Jonassonite was analyzed in one polished section (P02/01) with a JEOL Superprobe JXA–8600, equipped with an ELX–Link system, and utilizing an operating voltage of 25 kV and a beam current of 25 nA. We used a beam diameter of 4 μm. The following standards were used: Au and Ag metal (Au*L*α, Ag*L*α), natural bismuthinite, galena and stibnite (Bi*L*α, S*K*α, Pb*L*α, Sb*L*α), synthetic CdTe and Bi_2Se_3 (Cd*L*α, Se*K*α). The counting time was 15 s (peak) and 7 s (background); the raw data were corrected with the LINK ZAF–4 program.

FIG. 1. a) Jonassonite (Jo) with inclusions of native bismuth (Bi) is intergrown with native bismuth (Bi) and bismuthinite (Bmt). Jonassonite replaces euhedral arsenopyrite (Apy) and an intimate mixture of pyrite and marcasite (Mrc); a grain of chalcopyrite (Cp) also is present. Air, uncrossed polars. b) Same as a) but with crossed polars to demonstrate the characteristic orange-red color of jonassonite in one position. c) Jonassonite (Jo) grain with small inclusions of native bismuth (Bi) and ikunolite (Ik) that is almost visually indistinguishable from jonassonite. Other associated phases are native bismuth (Bi), bismuthinite (Bmt), marcasite (Mrc) and chalcopyrite (Cp). d) Jonassonite (Jo) intergrown with native bismuth (Bi), bismuthinite (Bmt) and native gold (Go). Pyrrhotite (Po), sphalerite (Sp) and chalcopyrite (Cp) represent an earlier stage of mineralization. Ikunolite (Ik) with traces of native bismuth (Bi) is assumed to be cogenetic with jonassonite. Air, uncrossed polars, RTTD 13920. a) – c) Nagybörzsöny, d) New Occidental (Peak) mine. Length of bar in all figures is 100 μm.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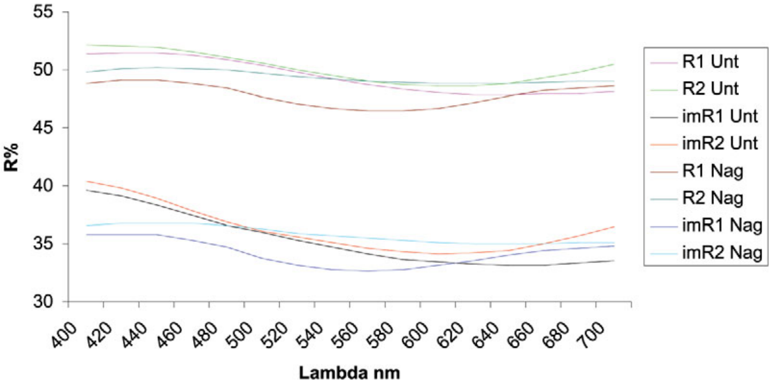

FIG. 2. Reflectance curves for jonassonite from Unterlangau, Germany (Unt) and Nagybörzsöny, Hungary (Nag) in air (R) and in oil (^{im}R).

The results of four analyses of two grains are included in Table 3 and are compared with previously acquired chemical data from the same locality (Dobosi & Nagy 1989) and from other occurrences. The empirical formula (based on 10 atoms) is $(Au_{1.02}Ag_{0.01})_{\Sigma 1.03}(Bi_{4.42}Pb_{0.39}Cd_{0.01}Sb_{0.01})_{\Sigma 4.83}(S_{4.07}Se_{0.07})_{\Sigma 4.14}$. The ideal formula, $AuBi_5S_4$, requires Au 14.38, Bi 76.26, S 9.36, total 100 wt.%.

Two distinct chemical groups can be distinguished in Table 3: one group is represented by a composition very close to the ideal formula and with only minor deviation from the Au:Bi:S proportions of 1:5:4; the other group, including jonassonite from the type locality, is typified by a significant Pb content, which probably substitutes for Bi in the structure. Minor elements in the Pb-containing jonassonite are Ag, Cd, Sb, Se and Te.

On the basis of the available analytical data (Table 3, Nos. 1–11), there exists a narrow range of chemical compositions of both Pb-free and Pb-substituted jonassonite. It is doubtful, however, whether the Au–Bi–S phase from Yakutia, Russia (Table 3, No. 12) represents this mineral. Nekrasov *et al.* (1988) described it to be optically isotropic, whereas jonassonite is anisotropic. The proportion of Au:Bi:S is significantly different from that of jonassonite, and in one sample the proportion is almost 1:4:4. Therefore, the mineral from Yakutia may represent yet another phase in the ternary system Au–Bi–S.

The chemical compositions of various Bi-bearing phases that are associated with jonassonite from the type locality are summarized in Table 4.

X-RAY CRYSTALLOGRAPHY

A small fragment, dug out of the type polished section, was mounted and studied by X-ray single-crystal precession methods employing unfiltered Mo radiation. The fragment was oriented with a^* parallel to the dial axis. The reciprocal lattice levels collected were: $h0l$, $h1l$, $hk0 \rightarrow hk3$, $a^* \wedge 011^*$, $a^* \wedge 012^*$, $a^* \wedge 013^*$ and $a^* \wedge 015^*$. On the basis of a visual inspection of reciprocal-lattice nodes, this fragment is composed of two nearly overlapping individual crystals and is probably not suitable for crystal-structure analysis. Jonassonite is monoclinic, space-group choices $F2/m$, $F2$ or Fm (diffraction aspect $F*/*$), with the following systematic absences: hkl with $h + k = 2n$ and $k + l = 2n$; $h0l$ with $h = 2n$ and $l = 2n$; $0k0$ with $k = 2n$. The preliminary unit-cell parameters derived from zero-level precession photographs are: a 18.50, b 4.155, c 14.12 Å, β 100.91°. The refined unit-cell parameters: a 18.329(29), b 4.108(4), c 13.974(16) Å, β 100.90(10)°, V 1033(2) Å^3, $a:b:c$ 4.4618:1:3.4017, Z = 4, are based on 15 reflections between a d value of 3.382 and 1.474 Å in the X-ray powder pattern for which unambiguous indexing, based on visual inspection of single-crystal precession photos, was possible. All reflections down to 1.40 Å were visually observed on the single-crystal precession films. This F-lattice cell is not in its reduced crystallographic form; the correct space-group choices are $I2/m$, $I2$ or Im (diffraction aspect $I*/*$), and the refined reduced unit-cell parameters are: a 12.531, b 4.108, c 10.421 Å, β 105.62°, V 516.6 Å^3, $a:b:c$: 3.0504:1:2.5368, Z = 2. The PSC (Pearson Symbol Code) is $mC20$, and the mineral appears to have a unique prototype structure.

X-ray powder data were obtained from an area adjacent to that from which the "single-crystal" fragment was dug out; however, owing to the small grain-size, it was not possible to extract jonassonite powder without admixed native bismuth and bismuthinite. Fully indexed 114.6 mm Debye–Scherrer camera X-ray powder data are presented in Table 5. Diffraction lines that are solely ascribable to admixed native bismuth and bismuthinite have been omitted. Six other reflections (clearly designated in Table 5) have reduced intensities because of

TABLE 3. CHEMICAL COMPOSITION OF JONASSONITE FROM DIFFERENT LOCATIONS

No.	Location	n	Au	Ag	Bi	Sb	Pb	Cd	S	Se	Te	Total	Reference
1	Nagybörzsöny, Hungary	4	14.95	0.09	69.06	0.08	6.12	0.06	9.76	0.41		100.53	this study
2	Nagybörzsöny, Hungary	2	14.84	0.20	69.75		5.13		9.78			99.70	Dobosi & Nagy (1989)
3	Highis, Romania		14.67		68.84		7.11		9.37			99.99	Damian *et al.* (2004)
4	Oukilal, Morocco	1	13.91	0.02	68.21		7.58		9.90	0.03	0.02	99.67	Jouhari *et al.* (1999)
5	Tsugahira, Japan	2	15.42		75.26				9.40			100.08	Hamasaki *et al.* (1986)
6	Güttingwald, Germany	1	15.10		75.63				9.06			99.79	Lehrberger *et al.* (1990)
7	Kašperské Hory, Czech Republic	21	13.40		77.60				8.90			99.90	Scharmová & Pertoldová (1990)
8	Kašperské Hory, Czech Republic	3	14.52		77.80				9.25			101.57	Scharmová & Pertoldová (1993)
9	Petráčkova hora, Czech Republic	2	14.13		76.16				8.93			99.22	Scharmová & Pertoldová (1993)
10	New Occidental, Australia (#12 at 665.2 m)	8	14.14		76.34				9.40			99.88	Chris Blake, personal commun.
11	Kazakhstan	1	12.46		77.49				9.18			99.13	Pavlova & Kotelnikov (1988)
12	Yakutia, Russia	4	14.91		76.01				9.83			100.75	Nekrasov *et al.* (1988)

n: number of spot analyses.
Empirical formulae: 1) $(Au_{1.02}Ag_{0.01})_{\Sigma 1.03}(Bi_{4.42}Pb_{0.39}Cd_{0.01}Sb_{0.01})_{\Sigma 4.83}(S_{4.07}Se_{0.07})_{\Sigma 4.14}$, 2) $(Au_{1.02}Ag_{0.025})_{\Sigma 1.045}(Bi_{4.505}Pb_{0.335})_{\Sigma 4.84}S_{4.115}$, 3) $Au_{1.02}(Bi_{4.51}Pb_{0.47})_{\Sigma 4.98}S_4$, 4) $(Au_{0.95}Ag_{0.002})_{\Sigma 0.952}(Bi_{4.39}Pb_{0.49})_{\Sigma 4.88}(S_{4.16}Se_{0.005}Te_{0.002})_{\Sigma 4.167}$, 5) $Au_{1.07}Bi_{4.92}S_{4.01}$, 6) $Au_{1.06}Bi_{5.02}S_{3.92}$, 7) $Au_{0.99}Bi_{5.06}S_{3.95}$, 8) $Au_{1.00}Bi_{5.07}S_{3.93}$, 9) $Au_{1.00}Bi_{5.099}S_{3.897}$, 10) $Au_{0.983}Bi_{5.002}S_{4.015}$, 11) $Au_{0.88}Bi_{5.15}S_{3.97}$, 12) $Au_{1.01}Bi_{4.88}S_{4.01}$.

TABLE 4. CHEMICAL COMPOSITION OF Bi-BEARING SULFOSALTS AND IKUNOLITE IN ASSOCIATION WITH JONASSONITE FROM NAGYBÖRZSÖNY, HUNGARY

No.	Mineral	Cu	Ag	Fe	Pb	Cd	Bi	Sb	Se	Te	S	Total	N
1	bismuthinite	0.25			0.92		79.79				18.70	99.67	8*
2	bismuthinite	0.26			0.78		80.50	0.10			18.84	100.47	8*
3	bismuthinite	0.55			1.75		76.42	1.84			19.01	99.57	8*
4	bismuthinite	0.10			0.24		80.24	0.40			18.77	99.75	8*
5	cosalite	0.19	0.71	0.17	38.29		43.09	0.16			16.07	98.68	36
6	cosalite	0.20	0.66	0.18	39.02		42.82	0.13		0.11	16.14	99.26	36
7	lillianite		1.01		45.64		36.80	0.12			15.53	99.11	11
8	lillianite		1.00	0.10	46.30	0.22	36.95	0.40			15.60	100.27	11
9	"cannizzarite"	0.49			35.82	0.21	46.52	0.10			16.21	99.34	227
10	ikunolite				6.29	0.18	79.31		1.97	1.76	9.10	98.61	7
11	ikunolite				5.81	0.18	79.77		1.82	1.48	9.02	98.08	7
12	ikunolite				6.79		80.03		0.44	1.46	10.01	98.82	7

Compositions are quoted in wt.%. N: number of atoms per formula unit (*apfu*) used for formula calculations; * Bi – (Cu + Pb) / 2 = 8 *apfu*. Empirical formulae: 1) $Cu_{0.08}Pb_{0.09}Bi_{7.91}S_{12.09}$, 2) $Cu_{0.08}Pb_{0.08}Bi_{7.92}S_{12.05}$, 3) $Cu_{0.18}Pb_{0.17}Bi_{7.82}S_{12.18}$, 4) $Cu_{0.03}Pb_{0.02}Bi_{7.97}S_{12.05}$, 5) $Cu_{0.12}Ag_{0.26}Pb_{7.46}Bi_{8.24}S_{19.91}$, 6) $Cu_{0.12}Ag_{0.24}Pb_{7.57}Bi_{8.14}(S_{19.89}Te_{0.03})_{\Sigma 19.92}$, 7) $Ag_{0.12}Pb_{2.72}Bi_{2.19}S_{5.98}$, 8) $Ag_{0.11}Pb_{2.77}Bi_{2.19}S_{5.93}$, 9) $Cu_{1.92}Pb_{43.52}Bi_{55.65}S_{125.90}$, 10) $(Pb_{0.3}Bi_{3.62})_{\Sigma 3.92}(Se_{0.24}Te_{0.13}S_{2.71})_{\Sigma 3.08}$, 11) $(Pb_{0.29}Bi_{3.67})_{\Sigma 3.96}(Se_{0.22}Te_{0.11}S_{2.71})_{\Sigma 3.04}$, 12) $(Pb_{0.31}Bi_{3.60})_{\Sigma 3.91}(Se_{0.05}Te_{0.11}S_{2.93})_{\Sigma 3.09}$.

overlap with the aforementioned contaminants. The powder data are unique and do not bear resemblance to any mineral or inorganic compound listed in the PDF file up to and including Set 53.

CONDITIONS OF FORMATION

In nature, jonassonite is typically associated with a mineral assemblage that contains Au, Bi, Pb, Te and S. This is documented from all occurrences listed in Table 1. In many cases, jonassonite is accompanied by native bismuth, native gold, bismuthinite, ikunolite, cosalite and tellurides belonging to the system Bi–Te–S (joséite-type phases). Less common associated phases are Bi-bearing sulfosalts such as pekoite, lillianite, "cannizzarite", ingodite, as well as laitakarite. Jonassonite in a paragenesis with galena, clausthalite and intermediate members of the PbS–PbSe series has been reported twice in the literature. Four hypotheses have been proposed to explain the formation of a compound chemically closely related to jonassonite:

(1) coprecipitation with native bismuth and bismuthinite near the native bismuth – bismuthinite univariant curve (Hamasaki *et al.* 1986, Dobosi & Nagy 1989);

(2) cocrystallization with cosalite from a Pb–Bi–S melt which scavenged 7–10 wt.% Au at a binary eutectic point in the quaternary system Au–Bi–Pb–S (Damian *et al.* 2004);

(3) replacement of earlier-formed maldonite, native gold and native bismuth by solutions with a very high fugacity of sulfur (Lehrberger *et al.* 1990, Scharmová & Pertoldová 1990, 1993, Jouhari *et al.* 1999, Stegman 2000, 2001);

(4) reaction of Au-bearing solutions with sulfotellurides according to the equation (Nekrasov *et al.* 1988):

$$\underset{\text{joséite-B}}{4\,Bi_4Te_2S} + \underset{\text{gold}}{Au} = \underset{\text{jonassonite}}{Bi_5AuS_4} + \underset{\text{hedleyite}}{3\,Bi_2Te} + \underset{\text{tsumoite}}{5\,BiTe}$$

There are a number of controversial estimates of the temperature and pressure at which jonassonite crystallized. Hamasaki *et al.* (1986) and Dobosi & Nagy (1989) argued for a "high" temperature and pressure and supported this assumption by the presence of tourmaline. In contrast, temperatures around 200°C (Jouhari *et a*l. 1999) and between 200 and 350°C (at a pressure of 2–3 kbar) (Stegman 2000, 2001) were determined from fluid-inclusion studies.

Unfortunately, very few experimental studies have been undertaken in the system Au–Pb–Bi–Te–S (Nekrasov 1996), and no thermodynamic data are available to calculate the equilibria involved. Nekrasov (1985) and Konyushok & Nekrasov (1987) succeeded in determining the stability ranges of maldonite and Pb-free $AuBi_5S_4$ using the method of univariant equilibria with a pyrrhotite indicator and sulfide buffers. They concluded that the formation of the Au–Bi sulfide is possible only under conditions of high $f(S_2)$, close to 10^{-1} Pa. They compared the conditions of deposition of jonassonite [T, $f(S_2)$] with those of the Au–Ag sulfides. Uytenbogaardite is stable at temperatures below 200°C (Barton 1980), and petrovskaite is stable below 270°C (Nekrasov *et al.* 1988).

TABLE 5. X-RAY POWDER-DIFFRACTION DATA FOR JONASSONITE

I_{est}	d_{meas} Å	d_{calc} Å	*hkl*	I_{est}	d_{meas} Å	d_{calc} Å	*hkl*
40	9.002	8.999	200	+3	1.942	1.944	$\bar{2}22$
30	6.876	6.861	002	+3	1.865	1.869	420
20	6.046	6.034	$\bar{2}02$	* 5	1.852	1.858	$\bar{7}15$
20	5.004	5.018	202	3	1.828	1.828	$\overline{10}02$
5	4.489	4.500	400			1.823	$\bar{9}11$
+5b	3.921	3.889	$\bar{1}11$	* 10	1.800	1.803	515
30	3.460	3.473	402			1.791	$\bar{1}17$
		3.429	$\bar{2}04$	5	1.785	1.781	$\bar{8}06$
* 40	3.382	3.376	$\bar{3}11$			1.780	$\bar{9}13$
3	3.206	3.212	311	* 10	1.764	1.762	$\bar{2}24$
++5b	3.100	3.078	$\bar{1}13$	* 15	1.739	1.737	804
* 100	2.959	2.962	$\bar{6}02$	* 5	1.715	1.714	$\bar{4}08$
		2.952	113	* 20	1.690	1.688	$\bar{6}22$
* 5	2.314	2.310	$\bar{1}15$	+5	1.636	1.629	208
+10	2.268	2.269	$\bar{8}02$	3	1.595	1.590	$\bar{7}17$
3	2.225	2.221	115	3	1.581	1.584	913
3	2.190	2.197	513	3	1.526	1.527	$\overline{12}02$
* 20	2.127	2.123	206			1.517	820
* 50	2.101	2.101	711	3	1.509	1.511	408
* 50	2.086	2.081	$\bar{5}15$	* 15	1.474	1.476	226
* 10	2.053	2.054	020				

114.6 mm Debye–Scherrer powder camera employing Ni-filtered Cu radiation (λ Cu*K*α = 1.54178 Å). Intensities estimated visually. Not corrected for shrinkage, and no internal standard. b: Broad line; *: lines used for unit-cell refinement. Diffraction lines solely ascribable to admixed native bismuth and bismuthinite have been deleted from the powder data. +: diffraction line overlaps with lines of native bismuth. ++: diffraction line overlaps with those of bismuthinite. Indexed with *a* 18.329, *b* 4.108, *c* 13.974 Å, β 100.90°.

SYNTHESIS

The hydrothermal synthesis of $AuBi_5S_4$, initially reported as $AuBi_2S_4$, seems to have been successful (Nekrasov 1985, 1996, Konyushok & Nekrasov 1987). Unfortunately, these results could not be reproduced (Culetto 2005, unpubl. data), probably because of missing vital details. Fractional crystallization using liquids of the Au – Bi – S, Au – (Bi,Pb) – (S,Se), Au – Bi – S – Te, Ag – Au – Bi – S, Au – Pb – Bi – S – Te, Au – Cu – Pb – Bi – S, Ag – Au – Pb – Bi – S – Te, Ag – Au – Cu – Bi – S – Se and Ag – Au – Pb – Bi – As – S systems, *i.e.,* covering a temperature range from 940°C down to below the melting point of Bi, all turned out to be failures. The reported cocrystallization of a Au–Bi sulfide and cosalite (Damian *et al.* 2004) from a melt could not be reproduced. Upon cooling of a melt phase, compositionally $\Sigma Au_2Pb_{0.1}BiS_{0.5}Se_{0.05}$, from 940°C, a minor amount of selenian cosalite, chemically $Pb_{1.93}Bi_{2.15}(S_{4.64}Se_{0.28})_{\Sigma 4.92}$, was produced, but without detectable traces of jonassonite. The total failure of synthesis from a melt was then attributed to possible incongruent melting accompanied by the formation of the Au–Bi sulfide. Solid-state reactions in precursor mixtures from the Au – Bi – S – Te system (covering temperature levels of 465°, 480°, 570° and 600°C, ±5°C each), all turned out to be failures, probably also having missed other essential (non-thermal) conditions.

Recently, some progress was achieved after allowing for quite complex (and still poorly understood) synergetic action, running in larger systems with fractional crystallization and vapor-phase reaction and transport as degrees of freedom. A very minor amount of Pb-free jonassonite was observed microscopically and confirmed by the electron microprobe. The grain size, however, is still insufficient for an X-ray examination. Synthesis efforts are continuing with the focus to produce suitable crystals for a crystal-structure analysis and to disentangle the complex genesis of jonassonite.

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