# Felbertalite, Cu<sub>2</sub>Pb<sub>6</sub>Bi<sub>8</sub>S<sub>19</sub>, a new mineral species from Felbertal, Salzburg Province, Austria

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**Abstract:** Felbertalite, a new copper-lead-bismuth-sulphosalt, has been found in quartz veins, in the scheelite deposit Felbertal, Salzburg Province, Austria. It occurs as rare elongated crystals, up to 0.5 mm long and 0.2 mm in diameter. The mineral is always in contact with Ag-bearing lillianite and a Se-free junoite-like mineral. Associated minerals are: cosalite, galenobismutite, members of the bismuthinite-aikinite series, galena, native Bi and traces of chalcopyrite. Felbertalite is opaque, with metallic lustre and greyish-black streak. In reflected light, it has a white colour with distinct anisotropy and perceptible bireflectance in air and oil and without internal reflections. Reflectance data and colour values are supplied. Mohs hardness is 3.3-3.4, according to a microhardness VHN<sub>25</sub> of 197-216 kg/mm<sup>2</sup>. The mean of 15 electron-microprobe analyses is: Cu 3.56, Ag 1.02, Pb 30.10, Cd 0.38, Bi 48.3, Te 0.23, S 16.76, total 100.36 wt.%, from which a simplified formula Cu<sub>2</sub>Pb<sub>6</sub>Bi<sub>8</sub>S<sub>19</sub> (on the basis of 35 atoms) can be derived. The mineral has a monoclinic unit cell with *a* = 27.637(4), *b* = 4.0499(6), *c* = 20.741(3) Å,  $\beta$  = 131.258(2)°, *V* = 1745.1(7) Å<sup>3</sup>, *a:b:c* = 6.82:1:5.12, *Z* = 2, space group C2/m. The calculated density is D<sub>calc</sub> = 6.948 g/cm<sup>3</sup>. The strongest five lines in the X-ray powder pattern [*d* in Å, (*I*), (*hkl*)] are: 2.904 (100) (510), 3.758 (88) (203, 111, 11-2), 3.379 (77) (40-6, 80-3,112), 3.496 (62) (31-3), 3.432 (45) ( 60-6). Felbertalite is a homologue of junoite. The synthetic AG-phase of Mariolacos (1979) can tentatively be interpreted as synthetic felbertalite. The name is given after the valley of Felbertal where the mine is located.

Key-words: felbertalite, new mineral, Cu-Pb-Bi-sulphosalt, X-ray data, junoite homologous series.

#### 1. Introduction

The first descriptions of the sulphosalts from the Felbertal scheelite-deposit were made by Jahoda (1984) and Thalhammer *et al.* (1989). Galenobismutite, lillianite, cosalite and members of the bismuthinite-aikinite series were mentioned together with a phase having an unusual Ag-Pb-Bi-S composition, described by Paar (1990) and identified by Mumme (1990) and Žák *et al.* (1994) as makovickyite. A systematic investigation of the sulphosalts by means of electron-microprobe (EMP), imaging and X-ray techniques has been started only

recently. Beside other complex (Cu,Ag)-Pb-Bi-sulphosalts which will be described elsewhere, few grains of an unknown mineral, with chemical composition between high-Cu cosalite and the synthetic AG-phase of Mariolacos (1979) drew our attention. X-ray studies on that phase established a new species, felbertalite, which is described herein. The name is given after the valley of Felbertal where the deposit is located. Both the mineral and the name were approved (99-042) by the I.M.A.-Commission on New Minerals and Mineral Names. The holotype material is deposited at the Geological Institute, University of Copenhagen, Denmark, and co-

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Fig. 1. a) Geological sketch map of the central part of the Tauern Window. b) Simplified profile of the Ostfeld and Westfeld scheelite deposit Felbertal. Orebodies K1-K8 are indicated after Höll & Schenk (1987).

type in the reference collection (catalogue no. 14493, 14494) of the Mineralogical Institute, University of Salzburg, Austria and in the Natural History Museum London under catalogue no. BM 1999, 174.

## 2. Occurrence

The Felbertal scheelite deposit (Höll, 1975 and Höll & Schenk, 1987) is the fourth largest producer of tungsten in the world. It is located in the Felbertal, Salzburg Province of Austria, in the north-central part of the Tauern Window. The mineralization is hosted by amphibolites and felsic gneisses of the polymetamorphic volcano-sedimentary Habach formation. The deposit consists of two parts, the Ostfeld open pit, now exhausted, and the Westfeld underground mine, where several ore bodies can be distinguished (Fig. 1). Scheelite is the predominant ore mineral, observed in several generations by Thalhammer et al. (1989). (Cu,Ag)-Pb-Bi-sulphosalts are widespread constituents in laminated discordant quartz veins, associated with scheelite and various sulphides (pyrite, pyrrhotite and chalcopyrite). Locally, significant concentrations of sulphosalts may occur, which are responsible for the silver grade of the scheelite ore.

Felbertalite is a minor to trace constituent in the ore bodies that are indicated as K1, K3 and K6 in Fig. 1. The sulphosalt assemblage associated with felbertalite is composed of:

- galenobismutite, cosalite, members of the bismuthinite-aikinite series, Ag-bearing lillianite in K1 (sample Fe-89/7),
- cosalite and Ag-bearing lillianite (dominant), members of the bismuthinite-aikinite series (krupkaite-lindströmite range) and Se-free junoite in K3 (samples Fe-98/3 and Fe-Wa),
- members of the bismuthinite-aikinite series (gladite-hammarite range), Se-free junoite, Agbearing lillianite and members of the pavonite homologous series in K6 (sample Fe-99/72).

Felbertalite crystals are always intimately intergrown with Ag-bearing lillianite and in rare cases with cannizzarite, Se-free junoite, Se-free proudite, bismuthinite derivatives and cosalite. Felbertalite is of hypogene origin. It was apparently formed either by the reaction of Cu-bearing fluids with lillianite or chemically related phases or by direct recrystallization of Cu-bearing ore material which was present as inclusions in quartz gangue, during the retrograde phase of the Alpine metamorphism.

#### 3. Description

#### 3.1 Appearance and physical properties

Felbertalite occurs as elongated crystals, not exceeding 0.5 mm in size. Its colour is bright white, very similar (almost identical) to the colour(s) of the associated sulphosalts, from which it is indistinguishable. The mineral is opaque, has a metallic lustre, and a greyish black streak. It has a perfect cleavage after (001) but is otherwise brittle with an uneven fracture. The VHN<sub>25</sub> measured from 10 indentations ranges between 197 and 216 (mean 206) kg/mm<sup>2</sup>, which corresponds to a Mohs hardness of 3.3-3.4. The indentations, which were produced with a Leitz Miniload 2 Hardness tester, were all slightly fractured to fractured, with a straight to slightly sigmoidal shape. As felbertalite is always intimately intergrown with other sulphosalts, it was not possible to extract pure fragments to measure the density.

#### **3.2 Optical properties**

In plane-polarized light the specular reflectance of felbertalite is very similar to that of the associated sulphosalts, such as lillianite, junoite, etc. Its bireflectance is perceptible in air, a little more in oil. The sulphosalt is slighly pleochroic in greyish white and creamy white colours. Between crossed polars its anisotropy is distinct (enhanced in oil). The sequence of rotation tints is dominated by brown, pale brown and greyish brown colours. No twinning was observed.

For reflectance studies, the section was polished/buffed with diamond abrasive immediately before measurement. The specular reflectance data were collected in air from five grains of felbertalite, from three grains identified in the EMP study as intermediate members of the lillianite-gustavite series ( ${}^{4}L_{40}$ ) and from two grains identified as bismuthinite derivatives (bd<sub>50</sub> and bd<sub>56</sub> in terms of aikinite mol.%) and one grain of Se-free junoite-like phase. In addition, reflectance spectra were measured in oil (Zeiss,  $N_D = 1.515$ ) for one representative grain of these phases except for junoite. A Zeiss MPM 800 microscope-spectrophotometer, adjusted to collect data at an interval of 10 nm from



Fig. 2. Reflectance spectra (in air and oil) for felbertalite, Ag-bearing lillianite ( ${}^{4}L_{40}$ ) and bismuthinite derivative  $bd_{56}$ .

400 to 700 nm, was used for measurement, with the bandwidth of its grating-monochromator set at 5 nm. The reflectance standard throughout was a Zeiss WTiC (314), and all measurements were made with x50 objectives, the effective numerical apertures of which were reduced (by adjustment of the illuminator aperture diaphragm) to 0.28. Where orientation at extinction positions proved impossible – as in the case of general sections of very weak anisotropy – the orientation of the grains for measurement was found by measurement of reflectance maxima and minima at 550 nm. The complete data sets are filed at the Natural History Museum (London) and at the University of Salzburg.

The air and oil reflectance spectra (Table 1) for the most anisotropic grain of felbertalite are shown in Fig. 2 and confirm the subjective impression of a moderately reflecting, weakly saturated greyish white mineral. These spectra are compared with those of the most bireflectant grains of the associated sulphosalt minerals. In this it is seen that the spectra of the lillianite (lill40) grain are indistinguishable from those of felbertalite, while the spectra for bismuthinite derivative ( $bd_{56}$ ) grain are

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	Felbertalite					ite(40)			bd56						
λnm	<i>R1</i>	R2	imR1	imR2	R1	R2	imR1	imR2	RI	R2	imR1	imR2			
400	42.65	45.85	27.85	30.10	43.05	46.00	28.35	31.70	39.75	43.65	26.50	29.70			
420	42.80	45.80	27.80	30.15	43.10	46.30	28.20	31.65	40.10	43.70	26.05	29.50			
440	42.95	46.15	27.75	30.10	43.00	46.40	27.95	31.65	40.20	43.60	26.05	29.30			
460	42.85	46.15	27.50	29.75	42.65	46.25	27.45	31.30	40.20	43.60	26.05	29.35			
480	42.50	45.90	27.15	29.30	42.20	45.95	27.00	30.90	40.25	43.85	25.95	29.40			
500	41.95	45.45	26.70	28.70	41.50	45.35	26.25	30.20	40.20	44.10	25.80	29.55			
520	41.40	44.90	26.15	28.10	40.90	44.75	25.65	29.60	40.10	44.40	25.70	29.80			
540	40.80	44.30	25.65	27.60	40.35	44.10	25.05	29.00	39.90	44.60	25.50	29.95			
560	40.20	43.80	25.25	27.15	39.75	43.65	24.60	28.50	39.70	44.70	25.40	30.05			
580	39.65	43.30	24.85	26.70	39.30	43.10	24.20	28.05	39.45	44.65	25.20	30.00			
600	39.30	43.10	24.60	26.40	38.90	42.80	23.90	27.90	39.30	44.55	25.00	29.85			
620	39.10	43.00	24.30	26.20	38.65	42.60	23.70	27.70	39.15	44.45	24.75	29.60			
640	38.95	42.95	24.00	25.95	38.40	42.50	23.40	27.40	38.85	44.20	24.45	29.20			
660	38.90	43.15	23.75	25.75	38.25	42.45	23.15	27.20	38.65	43.80	24.10	28.80			
680	38.90	43.10	23.85	25.60	38.10	42.30	23.00	27.10	38.30	43.35	23.80	28.45			
700	39.00	43.15	23.95	25.40	37.85	42.15	22.80	27.05	37.80	42.80	23.55	28.00			
470	42.70	46.10	27.40	29.55	42.50	46.15	27.25	31.00	40.30	43.80	25.85	29.25			
546	40.65	44.30	25.50	27.40	40.15	43.90	24.95	28.90	38.85	44.65	25.45	30.00			
589	39.50	43.20	24.65	26.60	39.10	42.95	24.00	28.00	39.40	44.65	25.05	29.90			
650	38.90	43.10	23.95	25.90	38.50	42.50	23.30	27.35	38.75	44.00	24.30	29.00			

Table 1. Reflectance data (in air and in oil) for felbertalite, Ag-bearing lillianite ( ${}^{4}L_{40}$ ) and bismuthinite derivative bd<sub>56</sub>.

clearly different in their dispersion (but not in their magnitude), and in agreement with its yellowwhite colour when compared with felbertalite. The air reflectance spectrum of Se-free junoite is identical with that of felbertalite and Ag-bearing lillianite and it is not presented in Fig. 2 to avoid overlapping.

The similarity in the reflectance spectra of compositionally similar sulphosalt minerals, at least in the visible spectrum, is well known to the ore microscopist. Comparison with data in the Quantitative Data File for Ore Minerals (Criddle & Stanley, 1993) reveals that felbertalite might also be confused with hammarite (QDF.220, Stanley *et al.*, 1990). The reason for the similarity in the reflectance data of these minerals – at least within the weak energy regime of the visible spectrum – is that these are the product of excitation of outer shell electrons of atoms in broadly similar polyhedra characteristic for all these structures.

#### 3.3 Chemical composition

Chemical analyses were performed at the Mineralogical Institute, University of Salzburg, using a JE-OL JXA-8600 electron microprobe, controlled by LINK-*eXL* system, operated at 25 kV, 30 nA, and 20 s counting time for peaks and 7 s for background. The following natural (n) and synthetic (s) standards and X-ray lines were used: n-CuFeS<sub>2</sub> (CuK $\alpha$ ), s-Bi<sub>2</sub>S<sub>3</sub> (BiL $\alpha$ , SK $\alpha$ ), n-PbS (PbL $\alpha$ ), s-CdTe (CdL $\beta$ , TeL $\alpha$ ), n-Sb<sub>2</sub>S<sub>3</sub> (SbL $\alpha$ ) and pure metal for AgL $\alpha$ . Raw data were corrected with the online ZAF-4 procedure. Standard deviations of analysed elements for felbertalite matrix are: Bi 0.16, Pb 0.13, S and Cd 0.06, Ag, Te and Sb 0.03, Cu 0.02 (all in wt.%)

Felbertalite has Bi, Pb, Cu and S as major constituents; Ag, Cd are present in minor amounts and Sb, Te as trace elements. In some grains Se has been analysed but not detected. Individual grains of felbertalite are chemically homogeneous, whereas a grain to grain variation of Bi and Pb always correlated with Ag is most typical. The mean chemical composition of four selected grains with increasing Ag content is given in Table 2. On the basis of  $\Sigma$ Me + S = 35 atoms, the average empirical formula for grain Fe98/3\* (used for X-ray investigation), is: Cu<sub>2.02</sub>Ag<sub>0.37</sub>(Pb<sub>5.21</sub>,Cd<sub>0.14</sub>)<sub>\Sigma5.35</sub>Bi<sub>8.32</sub>S<sub>18.94</sub>. The simplified formula can be written as:

 $Cu_2Ag_xPb_{6-2x}Bi_{8+x}S_{19}$  with x = 0.37.

On 48 grains of felbertalite from four different locations in the deposit, 240 analyses have been performed. Table 3, deposited at the Editorial Of-

Mineral		felbe	rtalite			XAG <sup>(1)</sup>	AG (2)		junoite		lillianite			
Sample	Fe89/7	Fe-WA	Fe98/3 *	Fe99/72	ideal			Fe88/2	Fe99/68	Fe99/72	ideal	(3)	Fe89/7	Fe98/3
No. of analyses	4	2	7	4				3	3	5				
Cu	3.43(1)	3.39(1)	3.56(4)	3.58(1)	3.48	3.40	4.56	4.36(8)	4.32(1)	4.30(3)	4.33	4.20	-	0.11
Ag	0.18(4)	0.47(1)	1.10(9)	2.38(7)	-	-	-	0.19(4)	0.82(4)	0.49(4)	-	-	0.85	3.64
Cd	0.22(2)	0.28(2)	0.43(5)	0.26(2)	-	-	-	0.9(1)	0.78(4)	0.40(5)	-	-	- 1	0.78
Pb	33.45(9)	32.01(1)	29.9(2)	24.7(3)	34.05	32.60	31.01	19.27(5)	17.9(2)	18.86(9)	21.19	20.30	46.90	35.19
Bi	45.75(8)	47.37(1)	48.3(2)	51.4(2)	45.79	46.50	47.54	57.78(2)	58.6(1)	57.8(2)	56.99	56.50	36.25	43.71
Sb	0.31(4)	0.13(2)	-	-	-	-	- 1	0.15(3)	0.19(3)	0.11(2)	-	-	- 1	-
Te	-	-	0.21(4)	-		-	- 1	-	-	-	-	- 1	-	0.15
Se	-	-	-	-	-	1.10	-	-	-	-	-	7.80	- 1	—
S	16.83(6)	16.8(1)	16.8(2)	16.93(8)	16.69	16.40	16.89	17.81(6)	17.71(5)	17.45(8)	17.49	13.50	15.77	15.99
Total	100.2(2)	100.5(2)	100.4(3)	99.2(1)	100.00	100.10	100.00	100.4(1)	100.3(2)	99.5(2)	100.00	102.30	99.76	99.56
Formula on the	he basis of:		35 atoms, i.	e. ideally C	u2Pb6Bi8S19	)			Pb <sub>3</sub> I	Bi <sub>2</sub> S <sub>6</sub>				
Cu	1.96	1.93	2.02	2.02	2.00	1.95	2.57	1.98	1.96	1.98	2.00	2.01	_	0.02
Ag	0.06	0.16	0.37	0.79	-	-	-	0.05	0.22	0.13	-	-	0.10	0.40
Cd	0.07	0.09	0.14	0.08	-	- 1	- 1	0.23	0.20	0.11	-	-	- 1	-
Pb	5.85	5.59	5.21	4.28	6.00	5.74	5.37	2.68	2.49	2.69	3.00	2.98	2.77	2.11
Bi + Sb	8.03	8.24	8.32	8.84	8.00	8.12	8.16	8.02	8.15	8.14	8.00	8.22	2.12	2.50
S+Te+Se	19.03	18.99	18.94	18.98	19.00	19.18	18.90	16.04	15.97	15.95	16.00	15.80	6.02	5.97
Pb+Cd+2Ag	6.04	6.00	6.08	5.95	6.00	5.74	5.37	3.02	3.13	3.06	3.00	2.98	2.97	2.95
Bi+Sb-Ag	7.97	8.08	7.96	8.05	8.00	8.12	8.16	7.96	7.94	8.00	8.00	8.22	2.02	2.02
Σmetal	15.97	16.01	16.06	16.02	16.00	15.82	16.10	] 12.96	13.03	13.05	13.00	13.20	4.98	5.03
CH (4)	-0.10	0.17	+0.20	0.11	0.00	0.55	0.00	-0.16	0.10	0.21	0.00	1.02	-0.04	0.18
EV (5)	-0.26	+0.45	+0.53	+0.29	0.00	-1.43	0.00	-0.50	+0.31	+0.66	0.00	3.23	-0.33	1.51
x <sup>(6)</sup>	0.06	0.16	0.37	0.79	0.00	0.00	0.00	0.05	0.22	0.13	0.00	0.00	0.11	0.45
(1) Marcoux	et al (1996)		(3) N	(umme (197	(5)	(5) F	V = error r	elative to th	e total of va	lences (Moi	ilo 1989)	•		

Table 2. Representative EMP analyses (in wt.%) and empirical formulae of felbertalite, junoite and Ag-bearing lillianite from the Felbertal deposit compared to selected literature data.

(1) Marcoux *et al.* (1996) (2) Mariolacos (1979) (3) Mumme (1975)(4) CH = charge balance

(5) EV = error relative to the total of valences (Moëlo, 1989)
(6) x = substitution coefficient for Ag.

Felbertalite Cu<sub>2</sub>Pb<sub>6</sub>Bi<sub>8</sub>S<sub>19</sub>

Table 4. X-ray powder data of felbertalite from Felbertal and of the synthetic AG-phase (Mariolacos, 1979).

fel	bertal	lite					AG-ph	ase	felt	erta	ite					AG-ph	ase	felt	perta	ite					AG-ph	ase
h	k	l	d <sub>obs</sub>	I <sub>o</sub>	$d_{\rm calc}$	I <sub>c</sub>	d <sub>obs</sub>	I <sub>o</sub>	h	k	l	d <sub>obs</sub>	$\bar{I}_{o}$	$d_{\text{calc}}$	$I_{\rm c}$	$d_{\rm obs}$	I <sub>o</sub>	h	k	1	$d_{obs}$	-I <sub>o</sub>	$d_{\rm calc}$	I <sub>c</sub>	d <sub>obs</sub>	I <sub>o</sub>
0	0	1			15.60	5			5	1	2			2.385	3			6	2	0			1.7515	1		
2	0	0			10.39	1			9	1	-6			2.380	1			5	1	-10			1.7503	2		
2	0	-2			10.30	1			5	1	-7			2.373	6			8	2	-4			1.7503	2		
0	0	2			7.80	4			1	1	-6	2.320	S	2.314	24	2.310	7	6	2	-6	1.744	S	1.7471	14		
2	0	1			6.81	9	6.758	3	8	0	-9			2.304	1			4	2	-6			1.7403	4		
2	0	-3			6.76	3			9	1	-2			2.285	1			8	2	-3			1.7403	6		
0	0	3			5.20	4			12	0	-7			2.275	1			13	1	-3			1.7397	10	1.736	5
4	0	-4			5.15	2			10	0	-1			2.264	8			8	2	-5			1.7385	1		
2	0	2			4.88	3			3	1	4			2.258	2			0	0	9			1.7324	1		
2	0	-4			4.85	1			6	0	-9			2.254	2			16	0	-8			1.7269	3		
6	0	-3			4.60	4	4.595	3	3	1	7			2.250	1			10	0	-12			1.7269	3		
6	0	-2			4.43	1			0	0	7			2.228	1	2.225	2	16	0	-7			1.7185	7		
6	0	-4			4.41	1			12	0	-8			2.204	4	2.203	4	12	0	-12			1.7161	1		
4	0	-5			4.14	4	4.135	5	2	0	6			2.203	3			8	2	-2			1.7096	1		
1	1	0			3.98	1			2	0	-8			2.196	1			9	1	-11			1.7078	2		
1	1	-1			3.98	2			7	1	-8			2.185	1			8	0	4			1.7043	1		
6	0	- 1			3.98	2			9	1	-1			2.152	6			11	1	-11			1.6996	1		
6	0	-5			3.95	4	3.957	4	5	1	-8			2.137	8			8	0	-12			1.6909	1		
2	0	3	3.78	. S	3.76	72	3.749	100	11	1	-6	2.130	Μ	2.130	13			16	0	-6			1.6897	5		
1	1	1			3.75	9			4	0	5			2.125	1			4	0	7			1.6840	3		
1	1	-2			3.74	7			4	0	-9			2.115	6	2.115	5	7	1	4			1.6806	2		
2	0	-5			3.74	1			12	0	-9			2.099	6			6	2	1			1.6795	1		
3	1	-2			3.69	2			11	1	-4			2.096	1			4	0	-11			1.6766	2		
3	1	0			3.50	4			11	1	-7	2.096	S	2.090	27	2.089	7	15	1	-7			1.6761	1		
3	1	-3	3.51	S	3.50	62	3.485	35	10	0	0			2.078	22	2.075	15	14	0	-2			1.6749	1		
6	0	0			3.46	3			1	1	6			2.061	2			6	2	-7	1.675	Μ	1.6744	10	1.678	2
8	0	-4			3.46	7			10	0	-10			2.059	1			7	1	-11			1.6704	1		
6	0	-6	3.43	W	3.43	45	3.428	80	1	1	-7	2.062	S	2.058	28	2.055	12	1	1	8			1.6693	1		
4	0	-6	3.38	S	3.38	14			0	2	0	2.031	S	2.030	36	2.026	10	1	1	-9			1.6676	1		
8	0	-3			3.38	48	3.374	70	11	1	-3			2.026	1			15	1	-6			1.6582	1		
1	1	2			3.38	15			3	1	5			2.019	7			4	2	3			1.6538	2		
8	0	-5			3.37	3			11	1	-8			2.016	10			4	2	-7			1.6500	1		
5	1	-2			3.26	2			3	1	-8			2.012	4			13	1	-11			1.6489	1		
5	1	-3	3.26	М	3.25	22	3.243	7	7	1	2			2.010	1			16	0	-5			1.6434	2		
3	1	1			3.20	6			9	1	0			2.007	7			6	0	6			1.6263	1		

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felbertalite						AG-ph	ase	felbertalite								AG-phase			lite		AG-ph	ase				
h	k	1	d <sub>obs</sub>	I <sub>o</sub>	$d_{\rm calc}$	I <sub>c</sub>	d <sub>obs</sub>	$\overline{I_{o}}$	h	k	1	$d_{\rm obs}$	I <sub>o</sub>	$d_{\rm calc}$	I <sub>c</sub>	$d_{\rm obs}$	I <sub>o</sub>	h	k	1	d <sub>obs</sub>	$I_{\rm o}$	$d_{\rm calc}$	I <sub>c</sub>	d <sub>obs</sub>	I <sub>o</sub>
3	1	-4	3.19	Μ	3.19	22			7	1	-9			1.9969	2			0	2	6			1.5999	1		
8	0	-2			3.17	2			9	1	-9			1.9935	1			6	2	2			1.5984	1		
8	0	-6			3.15	1			14	0	-7			1.9738	1			5	1	-11			1.5964	1		
5	1	-1	3.13	Μ	3.13	18	3.140	7	14	0	-8			1.9561	4	1.956	3	12	0	-13			1.5939	2		
0	0	5			3.12	1			2	2	1			1.9458	1			6	2	-8	1.593	W	1.5933	3		
5	1	-4			3.12	14	3.112	14	5	1	-9			1.9294	1			2	2	5			1.5903	2		
6	0	1			2.990	2			2	0	-9			1.9271	3			9	1	-12			1.5794	1		
1	1	3			2.986	4			11	1	-9			1.9210	5	1.926	2	14	0	-1			1.5789	1		
6	0	-7	2.964	Μ	2.963	28	2.960	40	14	0	-9			1.9095	4			13	1	-1			1.5745	1		
5	1	0	2.918	S	2.904	100	2.896	60	0	2	3			1.8908	1			15	1	-4			1.5745	1		
5	1	-5			2.892	5			10	0	-11			1.8849	2			4	2	4			1.5604	2		
8	0	-7			2.864	1			13	1	-6			1.8805	6			8	0	5			1.5542	1		
3	1	2			2.859	2			4	0	6	1.881	W	1.8805	8	1.879	20	4	0	8			1.5240	2		
4	0	3			2.852	4			8	0	3			1.8798	1			1	1	9	1.523	W	1.5199	6		
3	1	5			2.848	1			13	1	-7			1.8791	1			4	0	-12			1.5181	1		
4	0	-7			2.833	3			4	0	-10			1.8711	3			15	1	-3			1.5150	1		
7	1	-3			2.820	9			9	1	1			1.8596	2			12	2	-7			1.5145	1		
7	1	-4	2.842	Μ	2.817	13	2.812	9	6	2	-3			1.8575	1			10	2	-1			1.5114	4		
10	0	-5			2.764	1			13	1	-5			1.8560	7			6	2	-9			1.5087	1		
7	1	-5	2.747	Μ	2.727	13			14	0	-4			1.8511	1			17	1	-9			1.5070	1		
5	1	1	2.657	W	2.644	13	2.634	4	13	1	-8			1.8504	1			15	1	-12			1.5052	1		
10	0	-3			2.612	1			9	1	-10	1.851	Μ	1.8469	16	1.847	5	11	1	2			1.4956	1		
0	0	6			2.599	1			1	1	-8			1.8455	1			12	0	2			1.4943	1		
6	0	2			2.593	3			14	0	-10			1.8399	3			12	2	-8			1.4930	2		
7	1	-1			2.583	4			7	1	3			1.8357	16	1.834	3	2	2	6			1.4925	2		
6	0	-8	2.587	W	2.572	6			4	2	-5			1.8220	1			12	0	-14			1.4810	6	1.482	4
7	1	-6			2.572	2			3	1	6			1.8172	2			6	0	7			1.4810	1		
2	0	5			2.559	3			3	1	-9			1.8111	1			4	2	5			1.4680	1		
3	1	-6			2,529	4			13	1	-4			1.8071	3			4	$\overline{2}$	-9			1.4642	4		
9	1	-4			2.443	1			6	2	-5			1.8058	1			5	1	-12			1.4638	1		
9	1	-5			2.440	1			2	2	3	1.791	S	1.7866	19	1.783	3	12	2	-9			1.4589	4		
4	0	4			2.439	5	2.438	3	14	0	-3		-	1.7673	1		-	10	$\overline{2}$	0	1.46	М	1.4520	14		
7	1	0			2.396	4	2.392	3	14	0	-11			1.7546	2	1.756	3		-	_						

Felbertal material: 114.6 mm  $\phi$  Gandolfi camera, Ni-filtered Cu radiation, visually estimated intensities (S = strong, M = medium, W = weak), theoretical pattern calculated with Lazy Pulverix, based on single crystal data: a = 27.6367(40), b = 4.0499(6), c = 20.7409(29) Å,  $\beta = 131.258(2)^\circ$ , SG = C2/m and atomic positions from Topa *et al.* (2000).

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Fig. 3. Correlations of the atomic proportions for Ag *versus* (Pb+Cd) and (Bi+Sb) for felbertalite and Se-free junoite from Felbertal, based on individual analyses. For number of atoms p.f.u. in both minerals see Table 2.

fice of the journal, is available upon request and presents mean values (with standard deviations, compositional ranges and formulae) of felbertalite, grouped according to occurrence and Ag content and shows differences in substitution between locations (K3 and K6 lie deeper than K1). It is worth noting that only one felbertalite grain with Ag over 2 wt.% was found and Ag-free felbertalite grains do not occur in the investigated material from the Felbertal scheelite deposit.

#### 3.4 X-ray diffraction study

A complete single-crystal structure determination (Topa *et al.*, 2000) gave a = 27.637(4) Å, b = 4.0499(6) Å, c = 20.741(3) Å,  $\beta = 131.258(2)^\circ$ , V = 1745.1(7) Å<sup>3</sup>, a:b:c = 6.82:1:5.12, *C2/m* space group and D<sub>calc</sub> = 6.948 g/cm<sup>3</sup> for Z = 2 and structural formula Cu<sub>2</sub>Pb<sub>6</sub>Bi<sub>8</sub>S<sub>19</sub>.

The crystal structure consists of periodically sheared (kinked), two atomic-layer thick  $(100)_{PbS}$  layers (with two Cu atoms in the kink region) which alternate with periodically sheared double-octahedral layers (111)\_{PbS}. Bi atoms have square pyramidal to distorted octahedral coordinations, Pb is octahedral to bicapped trigonal prismatic; Cu is tetrahedrally coordinated. Felbertalite is the second, double-layer homologue to junoite which has single-octahedral kinked (111)\_{PbS} layers.

The crystal structure indicates that the most probable cleavage planes in felbertalite are (001).

Due to the scarcity of the mineral, its minute grain size and the mixture with Ag-bearing lillianite and other minerals, powder data were derived only from diffraction patterns, carried out with Gandolfi technique on single crystals. The observed powder pattern and the theoretical pattern, based on unit-cell parameters obtained from singlecrystal study and calculated with the computer program Lazy Pulverix (Yvon *et al.*, 1977), are listed in Table 4. The poor agreement of some observed intensities and *d*-values with the calculated ones stems from the quality of Gandolfi camera records and strong overlap of some reflections.

### 4. Discussion

An attempt to find an empirical formula from EMP data, through trial and error procedures at the first stage of investigation, failed. The recalculation of the results of felbertalite chemical analysis to a total of 35 atoms (Table 2) is based on the structural formula and shows a good agreement between the structural and chemical data.

The presence of Ag and its variable content is explained by the classic substitution mechanism in Pb-Bi-sulphosalts:  $2Pb^{2+} Ag^+ + Bi^{3+}$ . Atomic proportions of Ag plotted *versus* those of (Pb + Cd) on the one hand, and (Bi + Sb) on the other, display correlations that obey this substitution rule (Fig. 3) for all felbertalite and junoite point analyses. Atomic proportions of Cu *versus* Pb+Cd and Bi+Sb show no dependence of Pb and Bi contents p.f.u. on the Cu value, which is centred at about two atoms. The general formula for felbertalite can therefore be expressed as: Cu<sub>2</sub>Ag<sub>x</sub>Pb<sub>6-2x</sub>Bi<sub>8+x</sub>S<sub>19</sub> where x = substitution factor for Ag, 0.06 < x < 0.79, from which an Ag-free ideal formula can be derived as: Cu<sub>2</sub>Pb<sub>6</sub>Bi<sub>8</sub>S<sub>19</sub>.

The position of felbertalite and junoite in the  $(Cu+Ag)-M^{2+}-M^{3+}$  triangle is shown in Fig. 4a and after conversion of substitutional Ag and Bi into



Fig. 4. Plot of felbertalite and junoite mean compositions from Felbertal in the: a) -(Cu+Ag) - (Pb+Cd) - (Bi+Sb) and b) -Cu - (Pb+Cd+2Ag) - (Bi+Sb-Ag) ternary plot (*i.e.* after conversion of substitutional Ag and (Bi+Sb) into M<sup>2+</sup>). Published empirical and ideal compositions of felbertalite, junoite and the bismuthinite derivatives (bd) kr - krupkaite, li - lindströmite and ha - hammarite, are included for comparison.

 $M^{2+}$  in Fig. 4b. A comparison of Fig. 4a and 4b corroborates the conclusion about the roles of Ag and Cu in the structure reached from the trends observed in Fig. 3. It also shows the trend of the junoite-felbertalite homologous series  $Cu_2Pb_{3N}Bi_8$  $S_{13+3N}$  (Topa *et al.*, 2000) in the  $Cu_2S-Pb_2S_2-Bi_2S_3$ system and its modifications by the silver substitution.

Two phases are known which are close to the felbertalite stoichiometry: the synthetic AG phase reported by Mariolacos (1979) at 440 °C in the Bi<sub>2</sub>S<sub>3</sub>-PbS-CuPbBiS<sub>3</sub> system and the XAG phase from Algare, Portugal reported by Marcoux et al. (1996). The synthetic AG phase is presented by Mariolacos as a limited solid-solution field with the average composition: Pb25Cu12Bi38S88 (not supported by any chemical analysis) but for which an X-ray diffraction pattern (without indexing) is given. The chemistry resulting from that composition is presented in Table 2 and Fig. 4 and its diffraction pattern is compared with felbertalite X-ray data in Table 4. The XAG phase described by Marcoux et al. (1996) has an empirical formula close to the ideal Cu<sub>4</sub>Pb<sub>11</sub>Bi<sub>16</sub>S<sub>37</sub> (Fig. 4) and was interpreted as the natural occurrence of the AG phase. Both phases were recalculated in terms of 35 atoms pfu and compared with ideal felbertalite in Table 2. The ratio ( $\Sigma$ M)/S for XAG is 0.825 compared with 0.842 for ideal felbertalite and indicates a slight overestimation of S and underestimation of metal contents. The ratio  $(\Sigma M)/Cu$  for AG is 6.265 compared with 8.000 for ideal felbertalite and shows a clearly higher Cu content. Although the X-ray powder diffraction pattern of the AG-phase matches moderately well the theoretical powder diffraction pattern of felbertalite, a reinvestigation (in terms of chemical composition and crystal structure) of the synthetic AG-phase is needed to confirm (or infirm) the relationship with felbertalite. The microscopic grain of XAG phase analysed by Marcoux et al. (1996) possibly represents the first detected occurrence of felbertalite in nature.

In the Felbertal deposit, felbertalite is, in most cases, in contact with members of the lillianite-gustavite solid solution series, which have Ag contents ranging from 0.85 to 3.64 wt.% (Table 2), with a calculated homologue order, N<sub>L</sub> in the lillianite homologous series between 3.85-3.95 and molar fractions of the fully substituted end-member (gustavite) in terms of Makovicky & Karup-Møller (1977a), *i.e.*, <sup>N</sup>L<sub>sub</sub>, between 10 and 40 %. Singlecrystal study on a fragment from <sup>4</sup>L<sub>40</sub> gives: a =13.534(2), b = 20.163(3), c = 4.105(1), space group *Bbmm*. The value of the lattice parameter b and the degree of substitution are in accordance with data published by Makovicky & Karup-Møller (1977b). The contents of Ag in felbertalite and in lillianite are correlated: low Ag-felbertalite is associated with <sup>4</sup>L<sub>10</sub> and high Ag-felbertalite with <sup>4</sup>L<sub>40</sub> (samples Fe-89/7 and Fe-98/3 in Table 2 and Fig. 5a, b, c, and e).

The other phases intergrown with felbertalite are (tentatively) identified only on the basis of chemical composition obtained by means of EMP analyses:

- Se-free junoite with variable Ag contents (Table 2 and Fig. 3) which has an empirical formula very close to theoretical junoite, if Ag is assumed to be substitutional;

- makovickyite: Cu 0.15, Ag 7.08, Fe 0.41, Pb 6.13, Cd 0.98, Bi 66.49, S 17.82, total 99.05 (wt.%) with empirical formula  $Cu_{0.04}Ag_{1.06}(Fe_{0.12} Cd_{0.14}Pb_{0.48})_{\Sigma0,74}Bi_{5.16}S_{9.00}$  based on 16 atoms pfu; the calculated order of pavonite homologous series is N<sub>p</sub>= 3.84, CH = 0.04, EV = 0.22; (for CH and EV definitions see footnote of Table 2); with Cu considered substituting for Ag, the formula is  $Ag_{1.10}Pb_{0.74}Bi_{5.16}S_9$  or  $Ag_{1.47}Bi_{5.53}S_9$  after Pb subtraction. The results are close to an ideal Pb-substituted makovickyite  $Ag_{1.5-x}Pb_{2x}Bi_{5.5-x}S_9$  with x = 0.37;

- presumed cannizzarite: Cu 0.2, Ag 1.1, Pb 31.6, Cd 1.0, Bi 48.5, Te 0.2, S 17.8, total 100.4 (wt.%) with empirical formula  $(Ag_{2.44}Cu_{0.73})_{\Sigma3,17}$  $(Pb_{37.54}Cd_{2.17})_{\Sigma39.72}Bi_{57.09}$  (S<sub>126.64</sub>Te<sub>0.38</sub>)<sub> $\Sigma127.03$ </sub> based on 227 atoms pfu, CH = 0.17, EV = 0.07 and x = 3.17 (substitutional factor for Ag) which gives Pb<sub>46.05</sub> Bi<sub>53.92</sub> S<sub>127.03</sub> after Ag and Bi subtraction, indicating an ideal Ag-substituted cannizzarite Ag<sub>x</sub>Pb<sub>46-2x</sub>Bi<sub>54-x</sub>S<sub>127</sub> with x = 3.17;

- presumed Se-free proudite: Cu 1.66, Ag 1.03, Pb 31.10, Cd 0.63, Bi 47.88, Sb 0.15, Te 0.22, S 16.50, total 99.16 (wt.%) with empirical formula  $Cu_{1.12}Ag_{0.41}Cd_{0.24}Pb_{6.40}Bi_{9.81}S_{22}$  based on 22 S atoms (Sb grouped with Bi and Te with S) and CH = 0.24, EV = 0.55, rewritten as  $Cu_{1.12}Pb_{7.44}Bi_{9.40}S_{22}$  after Ag and Bi subtraction, close to general proudite formula  $Cu_xPb_{7.5}Bi_{9.67-0.33x}S_{22}$  with x = 1.12. - cosalite: Cu 0.44, Ag 1.14, Fe 0.05, Pb 37.55, Cd 0.52, Bi 43.48, Sb 0.1, S 16.22, total 99.49 (wt.%) with empirical formula  $Cu_{0.27}Ag_{0.41}(Cd_{0.18}Pb_{7.13})_{\Sigma 7.31}Bi_{8.18}S_{19.82}$  based on 36 atoms pfu; - bismuthinite derivatives in the krupkaite-lind-

- bismuthinite derivatives in the krupkaite-lindströmite range: Cu 5.83, Pb 19.49, Bi 56.91, Sb 0.1, S 17.77, total 100.1 (wt.%) with empirical formula  $Cu_{2.02}Pb_{2.03}Bi_{5.97}S_{12.08}$  and  $n_a = 50.64$  close to krupkaite ( $n_a = 50$ ); Cu 6.85, Pb 22.83, Bi 52.8, Sb 0.1, S 17.49, 100.06 (wt.%) with empirical for-



Fig. 5. Backscattered electron images of typical associations of felbertalite (fe) with Ag-bearing lillianite ( ${}^{4}L_{10.44}$ ), junoite (ju), galena (ga), cannizzarite (ca), proudite (pr), makovickyite ( ${}^{4}P_{0.37}$ ), cosalite (co), bismuthinite derivates (bd) and native bismuth (bi) examples of intergrowths and replacements.

mula  $Cu_{2.38}Pb_{2.43}Bi_{5.59}S_{12.04}$  and  $n_a = 60.14$  close to lindströmite ( $n_a = 60$ ), where  $n_a$  is aikinite mol.%.

Texturally, the sulphosalts aggregates containing felbertalite are subhedral intergrowths of two to four sulphosalts isolated in the quartz matrix. In several of them (e.g. Fig. 5a) felbertalite might have been co-crystallizing with other sulphosalts as a result of retrograde metamorphism of preexisting, more or less isolated ore aggregates. In other cases, e.g. in Fig. 5b and e, felbertalite apparently originated by replacement of cannizzarite and/or lillianite; ubiquitous galena might have originated from this process. This mode of formation suggests metasomatism of sulphosalt inclusions by Cu-bearing ore solutions during the retrograde metamorphism of the ore-bearing suites. Other illustrated sections can be explained by either process or by their combination. The observed heterogeneity of ore mineral associations already on a centimetre scale suggests however, that no extensive hydrothermal migration of ore elements has taken place at this stage of deposit formation. Formation of omnipresent native bismuth postdates formation of felbertalite and is connected with its partial decomposition. In this process, felbertalite is corroded and replaced by porous Bi aggregates faster than the associated lillianite.

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