

**COMPOSITION AND SPECTRAL REFLECTANCE OF FAHLORES  
FROM RAMPURA AGUCHA, INDIA, AND KLAMM ALM, AUSTRIA**

by

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**Zusammenfassung**

Die Ergebnisse der spektralen Reflexionsmessungen und Berechnungen der Chromatizitäts-Koordinaten ( $x$ ,  $y$ ) und des Normfarbwertes ( $Y$ ) von Fahlerzen aus der schichtgebundenen Zn-Pb-(Ag) Lagerstätte Rampura Agucha (Indien) und der polymetallischen Sulfid-Mineralisation Klamm Alm, Tirol (Österreich) werden dargestellt.

Weiters wird versucht, diese Parameter mit dem Chemismus der Fahlerze und wichtigen Substitutionsvektoren (z.B.  $SbAs_{-1}$  and  $CuAg_{-1}$ ) zu korrelieren. Diese Arbeit bestätigt, daß die Veränderungen der spektralen Reflexion und des Normfarbwertes ( $Y$ ) von der chemischen Zusammensetzung der Fahlerze abhängen.

Die dominierende Substitution in Fahlerzen von der Klamm Alm ist  $SbAs_{-1}$ , wobei höhere Sb/As-Verhältnisse in höherer Reflexion über den gesamten, insbesondere aber im langwellig roten Spektralbereich, resultieren. Die geringe Substitution von Fe bzw. Zn für Cu zeigt in den untersuchten Proben keinen deutlich erkennbaren Einfluß auf die Reflexionswerte.

Fahlerze von Rampura Agucha sind als Ag-reiche Freibergite (30.8 bis 32.8 Gew.% Ag) charakterisiert, wobei die  $AgCu_{-1}$ -Substitution vorherrscht. Das Reflexionsvermögen dieser Fahlerze steigt mit dem Ag/Cu-Verhältnis systematisch an. Der Normfarbwert ( $Y$ ) ist ebenfalls positiv mit dem Ag-Gehalt korreliert.

Wir schlußfolgern, daß, zumindest für natürliche Fahlerze mit einer eingeschränkten Substitution, die Änderungen des absoluten Reflexionsvermögens und der Form der Spektralkurven diagnostisch sind und für eine erste Identifizierung bzw., im Falle der Freibergite, für eine erste Abschätzung des Ag/Cu-Verhältnisses verwendet werden können.

## Abstract

Results of spectral reflectance measurements and the calculation of chromaticity co-ordinates (x,y) and the luminous reflectance (Y) of fahlores from the stratabound Zn-Pb-(Ag) deposit Rampura Agucha (India) and the polymetallic sulfide mineralization Klamm Alm, Tyrol (Austria) are presented.

It is tried to correlate these parameters with major substitution schemes in this mineral group; i.e.  $SbAs_{-1}$  and  $CuAg_{-1}$ . This study confirms that changes in spectral reflectance and chromaticity of fahlores are a function of their chemical composition.

The dominant substitution in fahlores from Klamm Alm is  $SbAs_{-1}$ . Higher Sb/As results in higher reflectance over the whole spectral range which is, however, especially pronounced in the red part of the spectrum. Minor substitution of Fe and Zn for Cu in these fahlores has no detectable influence on the reflectance values.

Fahlores from Rampura Agucha are characterised as Ag-rich freibergites (30.8 to 32.8 wt.% Ag) the dominant substitution being  $AgCu_{-1}$ . The absolute spectral reflectance of these fahlores increases systematically with increase of Ag/Cu.

The luminous reflectance (Y) is positively correlated with the Ag content. It is concluded that the spectral reflectance values and curves show diagnostic changes with mineral chemical composition, at least for fahlores exhibiting a restricted range of substitutions. They can be used for a preliminary identification and, for freibergites, a first estimation of Ag/Cu ratios.

## Introduction

Fahlores represent a complex group of sulfosalts. Their general formula can be written as  $M(1)_6^{4+}M(2)_6^{3+}(X^3+Y_3^{4+})_{\Sigma 4}Z_{13}^{4+}$  (JOHNSON et al., 1986). The M(1) site is occupied by Cu,  $Fe^{2+}$ ,  $Fe^{3+}$ , Zn, Mn, Hg and Cd, the M(2) site by Cu and Ag, X by Sb, As, Bi and Te and Y and Z by S and Se (HALL, 1972; HALL et al., 1974; PATRICK & HALL, 1983; JOHNSON et al., 1986). Other elements which can be incorporated in the structure are Co, Ni, Mn, and to a minor amount Pb (MAKOVICKY & MÖLLER, 1994). Mössbauer spectroscopy and EXAFS studies of Fe-bearing tetrahedrites suggest the presence of  $Fe^{2+}$  and  $Fe^{3+}$ , the former occupying trigonal planar and the latter tetrahedral sites in synthetic tetrahedrite (CHARNOCK et al., 1989; MAKOVICKY et al., 1990). Several previous studies tried to correlate mineral chemical composition with changes in spectral reflectance (HALL et al., 1974; CHARLAT & LÉVY, 1976; ARAYA et al., 1977) or color (CHIKHAOUI & LÉVY, 1982) but came, due to the complex mineral chemistry and manifold substitutions possible, to quite pessimistic conclusions; i.e. the variation of these parameters is difficult to relate to specific substitution schemes.

In this study we present first results of spectral reflectance and chromaticity measurements on fahlores from two localities: 1) the Rampura Agucha Zn-Pb-(Ag) deposit, India, and 2) the Klamm Alm mineralization in the Navis Valley, northern Tyrol, Austria. This note is a contribution to the understanding of the interrelationship between chemical composition and optical parameters of fahlores. In contrast to previous studies these first results are encouraging and suggest that, at least for fahlores close to end member compositions, significant correlation between chemical composition and spectral reflectance and for chromaticity exist and may be used for a quick optical distinction of fahlores.

## Geological background

Rampura Agucha, located about 220 km south-west of Jaipur, Rajasthan, India is a stratabound sediment-hosted Zn-Pb-(Ag) deposit (DEB, 1992; HÖLLER et al., 1995). It is the most important base metal deposit in India. Sulfide ores occur predominantly in high-grade metamorphic graphite-sillimanite-mica schists and contain sphalerite, galena, pyrite, pyrrotite, arsenopyrite, chalcopyrite, freibergite and other rare sulfides and sulfosalts (HÖLLER & GANDHI, 1995; HÖLLER et al., 1995).

The second locality studied, Klamm Alm, is an epigenetic polymetallic sulfide mineralization occurring in graphitic schists and scheelite-bearing ferroan dolomites which are intercalated in low-grade metamorphic quartz phyllites of Lower Palaeozoic age. Pyrite, arsenopyrite, chalcopyrite, sphalerite and tetrahedrite-tennantite are the main sulfides (RAITH, 1990).

## Mineral chemical composition of fahlores

Composition of fahlores was determined by electron microprobe techniques (ARL SEMQ 30; 15 kV; 15 nA; correction after BENCE & ALBEE, 1968; natural mineral standards).

Mineral formulae were calculated according to JOHNSON et al. (1986) on the basis of 29 atoms per formula unit. All iron has been calculated as divalent. Microprobe analyses are listed in Table 1. For some of the analyses the reader is referred to HÖLLER et al. (1995) and RAITH (1990). Low totals of some analyses may reflect minor analytical problems which are known to occur when analyzing Cu- and Ag-rich members of this group (MAKOVICKY & MÖLLER, 1994).

All fahlores from Rampura Agucha are classified as freibergite (argentian tetrahedrite). They are chemically rather homogeneous (HÖLLER et al., 1995) with ca. 31-33 wt.% Ag and 13.6-15.3 wt.% Cu (Table 1). Iron contents range between 4.6 to 5.5 wt.%; Zn and As contents are less than 1 wt.%.

Fahlores from Klamm Alm are classified as tetrahedrite-tennantite solid solutions. They exhibit a marked variation in Sb/As (0.09-0.51; Fig. 1a), combined with minor variations of cations in the M(1) position (e.g. Zn 1.1 to 3.6 wt.%, and Fe 3.2 to 4.8 wt.%). They are very low in Ag, the M(2) position thus being mainly filled with Cu.

The chemical composition of fahlores from Klamm Alm is related to different host rock lithologies. Fahlores from graphitic schists are As-rich, those from ferroan dolomites show intermediate compositions.

## Spectral reflectance and its relation to chemical composition

Reflectance measurements were performed on Rehwald polished (diamond compound <1  $\mu\text{m}$ ) sections in air between 400 to 700 nm using a Carl Zeiss reflectance polarizing microscope Axio-plan MPM 400 with an attached photomultiplier Hamamatsu type R 928. Silicon carbide No. 157 ( $R_{\text{air}}$ , 546nm = 20.2 $\pm$ 1.5 %; Carl Zeiss Jena, Oberkochen) was used as standard. For the computer-supported calculation (Zeiss Lambda Scan software, vs. 1.45) of chromaticity co-ordinates (x,y) and the related luminous reflectance (Y) the standard CIE (1931) scheme was used.

Measurements at a fixed wavelength of 546 nm were made with the Zeiss Photan software, vs. 5.4. A tungsten halogen lamp (12 V/100 W; 3200 K at 11.5 V) and a blue filter were used. Results are listed in Table 2.

	<b>B 14-2</b>	<b>B 25-2</b>	<b>B 25-6</b>	<b>RA-3a</b>	<b>RA-60</b>	<b>RA-86</b>	<b>RA-93</b>
<i>wt%</i>							
S	24.89	25.91	27.20	20.91	20.95	20.73	20.58
Fe	3.19	3.52	4.82	5.50	4.62	4.73	4.93
Cu	40.05	41.40	43.93	13.62	15.31	13.84	14.82
Zn	3.60	2.09	1.12	0.92	0.95	0.94	0.63
As	9.98	11.81	19.18	0.81	0.90	0.28	0.85
Ag	0.20	0.10	0.03	32.43	30.82	32.87	31.33
Sb	16.64	14.18	3.03	24.74	24.41	24.88	24.65
Hg	0.54	0.58	0.21	0.00	0.00	0.00	0.00
$\Sigma$	99.09	99.59	99.52	98.93	97.96	98.27	97.79
Ag	0.030	0.015	0.005	5.837	5.562	5.986	5.702
Cu	5.970	5.985	5.995	0.163	0.438	0.014	0.298
M(2)	6.000	6.000	6.000	6.000	6.000	6.000	6.000
Cu	4.017	4.120	4.211	3.999	4.252	4.264	4.280
Fe	0.933	1.007	1.316	1.912	1.610	1.665	1.733
Zn	0.900	0.512	0.260	0.273	0.283	0.284	0.189
Hg	0.044	0.047	0.016	0.000	0.000	0.000	0.000
M(1)	5.894	5.686	5.803	6.184	6.145	6.213	6.203
Sb	2.235	1.864	0.380	3.945	3.903	4.017	3.975
As	2.176	2.521	3.898	0.210	0.234	0.073	0.223
X	4.411	4.385	4.278	4.155	4.137	4.090	4.197
S	12.689	12.928	12.918	12.661	12.718	12.699	12.600
<i>mole% (tet)</i>	0.51	0.43	0.09	0.95	0.94	0.98	0.95

Table 1

Mineral chemistry of tetraedrite-tennantite from Klamm Alm, Austria and freibergite from Rampura Agucha, India. Formulae were calculated on the basis of 29 atoms p.f.u. according to the general formula of JOHNSON et al. (1986).

The spectral reflectance measurements of seven representative samples show significant differences in both reflectance (R%) and shape of the reflectance curves (Table 2, Fig. 1).

Freibergite generally exhibits higher reflectance (intensity) than tetraedrite-tennantite (Figures. 1a, b). The reflectance curves of tetraedrite-tennantite from the Klamm Alm show minor differences in the blue spectral range (between 400-450 nm). They become, however, diagnostic in the green and red part of the spectrum (ca. 500-700 nm) where they change systematically with the Sb/As ratio.

The reflectance increases with increasing Sb/As ratio, being highest in Ag-tetraedrite. Increase of Zn- and Cu-contents in the M(1) position results in small variations (ca.  $\pm 1\%$ ) of reflectance in the 400-450 nm range.

$\lambda$	B 14-2		B 25-2		B 25-6		RA-3a		RA-60		RA-86		RA-93	
	mean	$\sigma$	mean	$\sigma$	mean	$\sigma$	mean	$\sigma$	mean	$\sigma$	mean	$\sigma$	mean	$\sigma$
400 nm	33.15	0.51	32.85	0.43	31.59	0.31	34.72	0.74	32.74	0.33	35.51	0.3	35.00	0.23
420 nm	32.36	0.27	31.13	0.25	31.65	0.21	34.51	0.44	32.42	0.14	34.72	0.22	33.63	0.08
440 nm	31.16	0.04	30.82	0.05	30.49	0.08	34.09	0.26	32.24	0.07	34.39	0.13	32.77	0.07
460 nm	30.74	0.04	30.56	0.05	30.21	0.06	33.37	0.22	32.07	0.09	34.21	0.11	32.68	0.06
480 nm	30.72	0.03	30.44	0.05	29.96	0.04	33.24	0.19	32.18	0.09	33.87	0.10	32.40	0.04
500 nm	30.78	0.04	30.39	0.05	30.01	0.05	32.72	0.16	31.88	0.06	33.56	0.10	32.20	0.05
520 nm	30.69	0.04	30.29	0.03	29.71	0.06	32.25	0.11	31.76	0.08	33.11	0.09	32.14	0.07
540 nm	30.82	0.04	30.14	0.02	29.35	0.07	31.83	0.13	31.43	0.07	32.64	0.08	31.74	0.09
560 nm	30.61	0.04	30.12	0.04	29.21	0.07	31.82	0.07	31.33	0.07	32.09	0.07	31.44	0.06
580 nm	30.39	0.03	29.72	0.02	28.74	0.06	31.41	0.06	30.97	0.07	31.91	0.07	31.21	0.07
600 nm	30.21	0.06	29.35	0.08	28.18	0.06	30.97	0.04	30.71	0.06	31.51	0.07	30.96	0.05
620 nm	29.66	0.05	28.68	0.04	27.42	0.06	30.58	0.03	30.42	0.08	30.99	0.07	30.63	0.04
640 nm	29.31	0.05	28.34	0.07	27.14	0.05	30.21	0.05	30.19	0.07	30.39	0.05	30.17	0.06
660 nm	28.84	0.07	27.68	0.05	26.83	0.06	29.76	0.03	29.71	0.06	30.21	0.05	29.81	0.05
680 nm	28.05	0.07	27.28	0.02	26.44	0.04	29.61	0.05	29.48	0.05	29.74	0.06	29.56	0.05
700 nm	27.74	0.09	26.97	0.05	26.21	0.04	29.09	0.07	28.91	0.06	29.25	0.05	29.04	0.05
<b>Chromaticity</b>														
x	0.309		0.308		0.305		0.305		0.308		0.305		0.307	
y	0.327		0.327		0.325		0.322		0.326		0.322		0.325	
Y	30.48		29.87		29.02		31.72		31.25		32.30		31.51	

Table 2

Spectral reflectance and chromaticity data of tetrahedrite-tennantite from Klamm Alm, Austria, and freibergite from Rampura Agucha, India, measured between 400 and 700 nm. The results are means of 30-40 spectral measurements on each sample. The large error in the spectral range between 400-460 nm are due to the low luminat signal (about 10% of intensity); errors in the spectral range betwwen 480-700 nm are generally less than 0.1%.

Freibergites from Rampura Agucha show a systematic negative correlation between reflectance and wavelength (Fig. 1b) and differences in reflectance are more pronounced between ca. 400–500 nm. These marked differences in the blue spectral range predominantly reflect substi-tutions in the M(2) position; i.e. AgCu<sub>-1</sub> substitution. There is a significant increase in spectral reflectance with Ag-contents of freibergite. Differences of ca. 2 wt.% Ag result in ca. 2% higher spectral reflectance (at 450 nm; RA-60 vs. RA-86; Fig. 1b). Complementary higher Cu-contents lower reflectance values.

Fahlores from both localities were also measured at a fixed wavelength of 546 nm (Fig. 2). Tetrahedrite-tennantite samples from Klamm Alm show lower mean reflectance (absolute frequency maxima ( $R_{\text{mean}}$ ) 29-31%) in contrast to freibergite which show higher relative frequen-cy (absolute frequency maxima ( $R_{\text{mean}}$ ) between 31 and 32%). However these data show considerable overlap and are therefore less diagnostic than spectral reflectance curves.

There is also a systematic relation between luminous reflectance (Y) and chemistry. The Ag- and Zn-contents and Sb/As ratio show positive, Cu-contents negative correlation with luminous reflectance (Table 1 and 2).

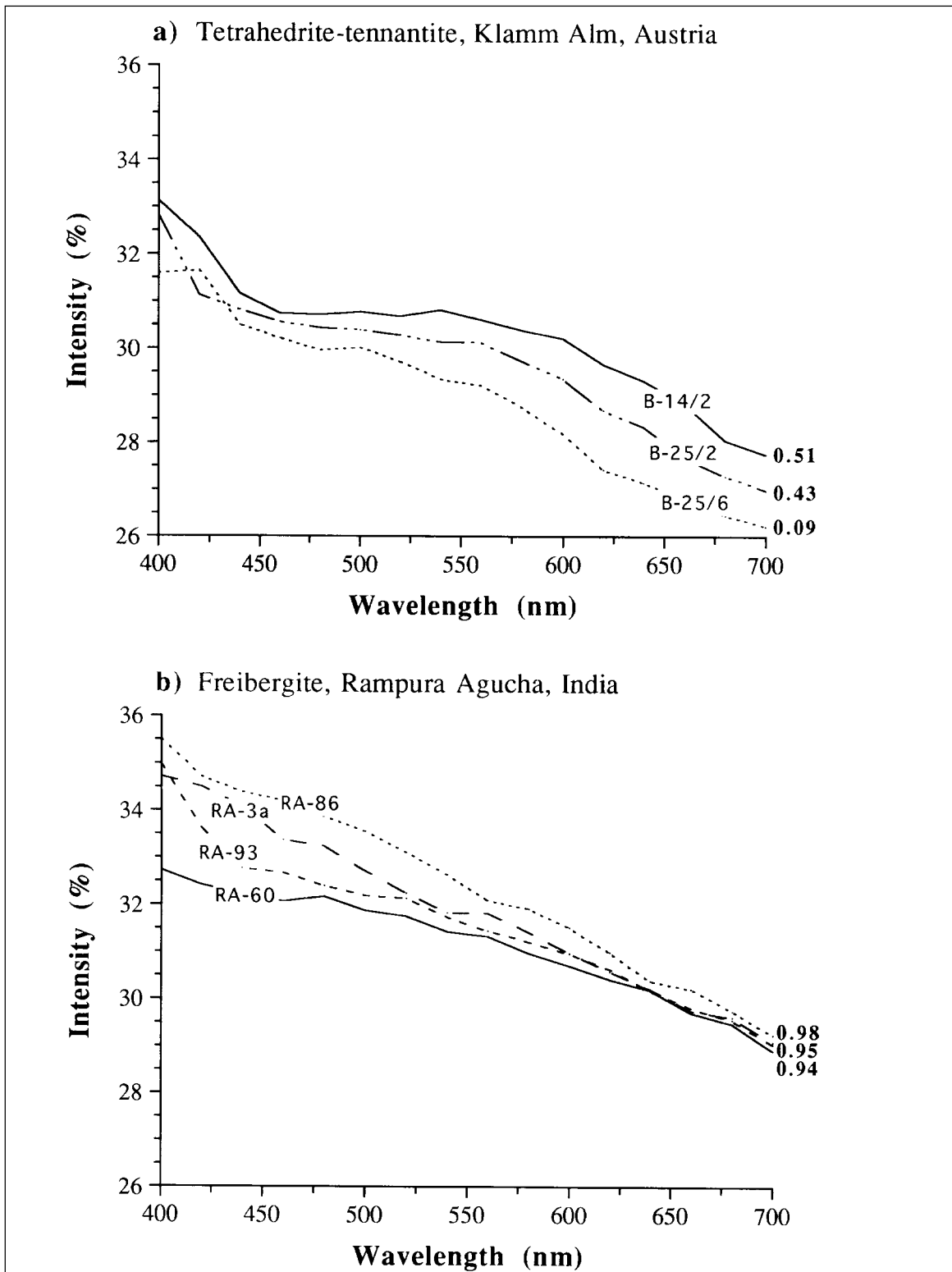


Figure 1  
Spectral reflectance curves (means of ca. 20 measurements) of fahlores measured between 400 and 700 nm; (a) Tetrahedrite-tennantite from Klammsalm, Navis, Austria. (b) Freibergite from Rampura Agucha, India. Numbers (bold) give mean Sb/As ratios of each sample.

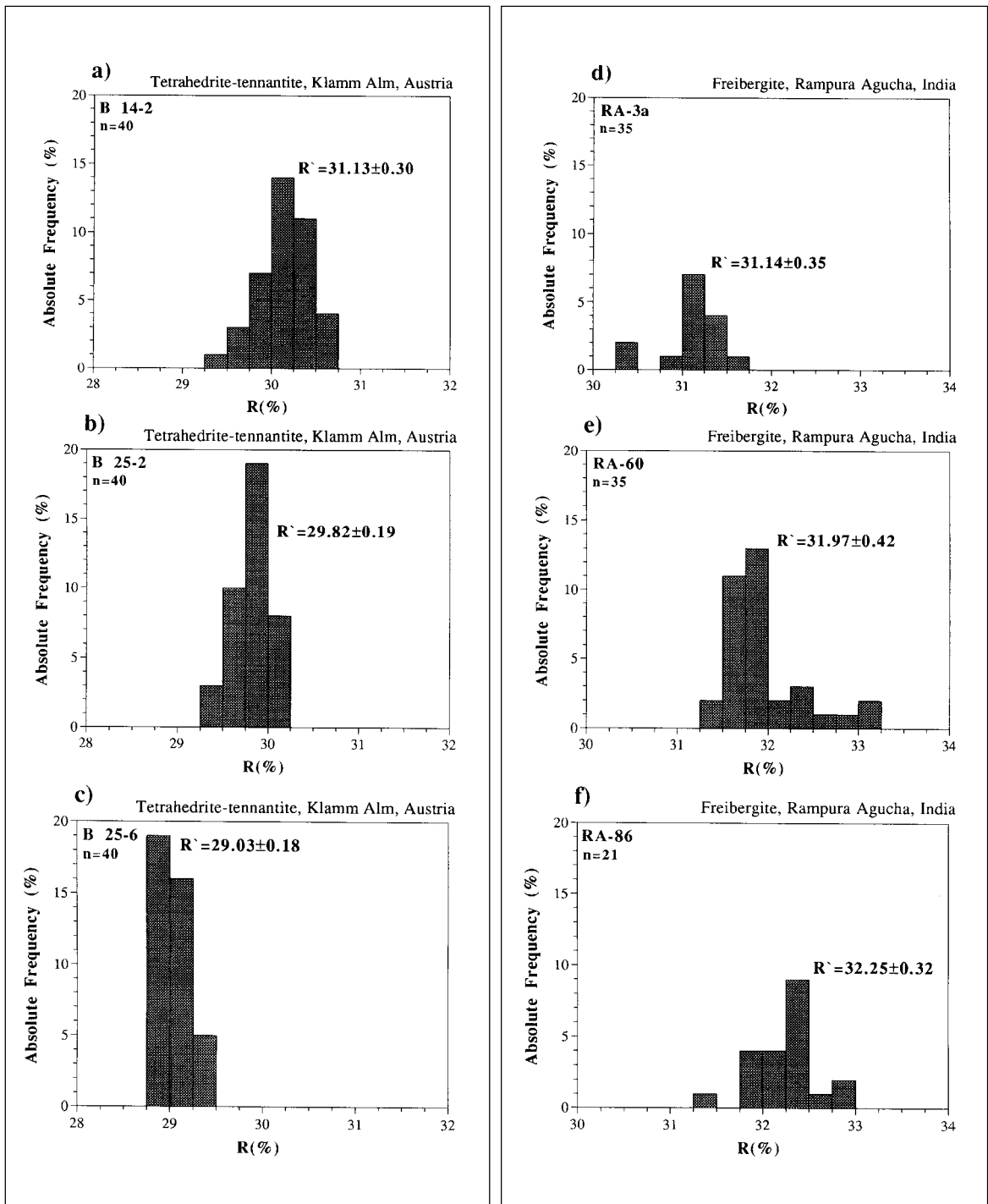


Figure 2

Histogramms showing the reflectance (absolute frequency maxima ( $R' = R_{\text{mean}}$ )) and standard deviation at a fixed wavelength of 546 nm of n measurements; (a)-(c) Tetrahedrite-tennantite from Klamm Alm, Navis, Austria. (d)-(f) Freibergite from Rampura Agucha, India.



## Discussion and conclusion

Although our data largely confirm previous results documenting differences in the spectral reflectance of fahlores in relation to their chemistry (e.g. HALL et al., 1974; CHARLAT & LÉVY, 1976; ARAYA et al., 1977; PICOT & JOHAN, 1982; CRIDDLE & STANLEY, 1986) this study revealed additional details which are discussed below.

Most previous studies on natural tetrahedrite-tennantite solid solutions (e.g. CHARLAT & LÉVY, 1976; ARAYA et al., 1977) concluded that tetrahedrites are distinguished from tennantites by generally higher reflectance over the whole spectral range. For example ARAYA et al. (1977) studied tennantite-tetrahedrite from the El Teniente deposit in Chile and explained differences in the spectral reflectance mainly with variations of the Sb/As ratio. With reference to our data from Klamm Alm we could demonstrate that  $\text{SbAs}_{-1}$  substitution mainly affects the red part of the spectrum. This observation is in general agreement with the curves given by CHARLAT & LÉVY (1976), although none of our samples from Klamm Alm showed the marked reflectance maximum (at ca. 540-580 nm) which is typical for Cu-Fe- and Cu-Zn-rich tetrahedrites.

Substitution of Fe and/or Zn for Cu in the M(1) site is rather limited in the Klamm Alm samples (e.g. 0.9-1.3 Fe and 0.3-0.9 Zn cations per formula unit; Table 1) and has, for the samples studied, a negligible effect. Significant  $\text{FeCu}_{-1}$  substitution would strongly increase the reflectance in the red spectral range (CHARLAT & LÉVY, 1976), a feature which is not confirmed by the Klamm Alm samples (Fig. 1a); even the Fe-richest sample from Klamm Alm still shows the lowest reflectance values over the whole measured spectral range.

Freibergites from Rampura Agucha allow some general conclusions mainly about  $\text{AgCu}_{-1}$  substitution in the M(2) site. Our results indicate that diagnostic changes in the shape of the spectral reflectance curves and absolute reflectance are mainly expressed in the blue-green spectral range; i.e. higher Ag contents increase, higher Cu contents decrease reflectance values especially in the 400 to 550 nm range (Fig.1b). Such a systematic positive correlation between Ag contents and reflectance has not been documented in previous papers (e.g. CHARLAT & LÉVY, 1976; HALL et al., 1974); probably because most of the fahlores studied contained less Ag and  $\text{AgCu}_{-1}$  substitution was masked by other substitutions.

PICOT & JOHAN (1982) report a qualitative relationship between Sb and Ag substitution in fahlores. Their data also indicate that argentian tetrahedrites show slightly higher spectral reflectance than Cu-rich varieties. This trend is also documented in our data where differences in the Ag content (ca. 30.8-32.9 wt.% Ag) result in significant changes in reflectance values, especially at short wavelengths. This may also explain why reflectance values of freibergite from Rampura Agucha are slightly lower (ca. 1%) compared to those given in the IMA/COM Quantitative Data File (CRIDDLE & STANLEY, 1986). Incorporation of As may have a similar effect, although it should affect reflectance especially in the red spectral range.

It is concluded that: (a) These data confirm that optical parameters strongly reflect Sb/As ratios of fahlores and are thus well suitable to discriminate between tetrahedrite and tennantite-rich



end members, if other substitutions are not too complex. (b) For freibergites with a restricted substitutional range the Cu/Ag ratios may be estimated in a semiquantitative manner from spectral reflectance and chromaticity data. This could prove to be a quick and cheap method in mining and exploration industry where sophisticated microanalytical techniques are often not available routinely. (c) Reflectance measurements at a fixed wavelength (e.g. 546 nm) do not discriminate between different fahlore compositions. This can only be obtained by measuring spectral reflectance over the whole range of wavelengths (400-700 nm).

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### References

- ARAYA, R.A., BOWLES, J.F.W. & SIMPSON, P.R. (1977): Relationships between composition and reflectance in the tennantite-tetrahedrite series of the El Teniente ore deposit, Chile. - *N. Jb. Miner. Mh.*, 10, 467-482.
- BENCE, A.E. & ALBEE, A.L. (1968): Empirical correction factors of the electron microanalysis of silicates and oxides. - *J. Geol.*, 76, 382-403.
- CHARLAT, M. & LÉVY, C. (1976): Influence des principales substitutions sur les propriétés optiques de la série tennantite-tétraédrite. - *Bull. Soc. fr. Minéral. Cristallogr.*, 99, 29-37.
- CHARNOCK, J.M., GARNER, C.D., PATTRICK, R.A.D. & VAUGHAN, D.J. (1989): EXAFS and Mössbauer spectroscopic study of Fe-bearing tetrahedrites. - *Min. Mag.*, 53, 193-199.
- CHIKHAOUI, S. & LÉVY, C. (1982): Expression quantitative de la couleur dans la série tennantite-tétraédrite: Influence des substitutions. - *Can. Mineral.*, 20, 101-109.
- CRIDDLE, J.R. & STANLEY, C.J. (1986): The quantitative data file for ore minerals. - British Museum (Natural History), London.
- DEB, M. (1992): Litho-geochemistry of rocks around Rampura Agucha massive zinc sulfide ore-body, NW India - implications for the evolution of a Proterozoic 'Aulakogen'. - In: SARKAR, S.C. (Ed.) *Metallogeny related to tectonics of the Proterozoic mobile belts*, A.A. Balkema, Rotterdam, Brookfield.
- HALL, A.J. (1972): Substitution of Cu by Zn, Fe and Ag in synthetic tetrahedrite,  $\text{Cu}_{12}\text{Sb}_4\text{S}_{13}$ . - *Bull. Soc. fr. Minéral. Cristallogr.*, 95, 583-594.
- HALL, A.J., CERVELLE, B. & LÉVY, C. (1974): The effect of substitution of Cu by Zn, Fe and Ag on the optical properties of synthetic tetrahedrite,  $\text{Cu}_{12}\text{Sb}_4\text{S}_{13}$ . - *Bull. Soc. fr. Minéral. Cristallogr.*, 7, 18-26.
- HÖLLER, W., GANDHI, S.M. (1995): Silver-bearing sulfosalts from the metamorphosed Rampura Agucha Zn-Pb-(Ag) deposit, Rajasthan, India. - *Can. Mineral.*, 33, 1047-1057.
- HÖLLER, W., STUMPFL, E.F. & GANDHI, S.M. (1995): Rare oxide minerals and Ag-Pb-Sb sulfosalts from the metamorphosed Rampura Agucha Zn-Pb-(Ag) deposit, Rajasthan, India. - In: PASAVA, J., KRÍBEK, B., ZÁK, K. (Eds.) *Mineral Deposits: From their origin to their environmental impacts*, A.A. Balkema, Rotterdam, Brookfield, pp 869-872.

- JOHNSON, N.E., CRAIG, J.R.& RIMSTIDT, J.D. (1986): Compositional trends in tetrahedrite. - *Can. Mineral.*, 24, 385-397.
- MAKOVICKY, E., FORCHER, K., LOTTERMOSER, W.& AMTHAUER, G. (1990): The role of Fe<sup>2+</sup> and Fe<sup>3+</sup> in synthetic Fe-substituted tetrahedrite. - *Mineral. Petrol.*, 43, 73-81.
- MAKOVICKY, E.& MÖLLER, S.K. (1994): Exploratory studies on substitutions of minor elements in synthetic tetrahedrite. 1. Substitution by Fe, Zn, Co, Ni, Mn, Cr, V and Pb - unit-cell parameter changes on substitution and the structural role of Cu<sup>2+</sup>. - *N. Jb. Mineral. Abh.*, 167, 89-123.
- PATTRICK, R.A.D.& HALL, A.J. (1983): Silver substitution into synthetic zinc, cadmium, and iron tetrahedrites. - *Min. Mag.*, 47, 441-451.
- PICOT, P.& JOHAN, Z. (1982): *Atlas of ore minerals*. - Elsevier, Amsterdam.
- RAITH, J.G. (1990): Strata-bound scheelite in metacarbonate rocks - example from Lower Austroalpine Klamm Alm mineralization, Navis, Tyrol, Austria. - *Trans. Instn. Min. Metall. (Sect. B: Appl. earth sci.)*, 99, 81-90.