Sulfosalt systematics: a review.
Report of the sulfosalt sub-committee of the IMA Commission on Ore Mineralogy

YVES MOËLO¹,*, Secretary, EMIL MAKOVICKY²,**, Associate Secretary, NADEJDA N. MOZGOVA³, past President of the Sulfosalt Sub-Committee, JOHN L. JAMBOR⁴, NIGEL COOK⁵, ALLAN PRING⁶, WERNER PAAR⁷, ERNEST H. NICKEL⁸, STEPHAN GRAESER⁹, SVEN KARUP-MØLLER¹⁰, TONČI BALIĆ-ŽUNIC², WILLIAM G. MUMME⁸, FILIPPO VURRO¹¹, DAN TOPA⁷, LUCA BINDI¹², KLAUS BENTE¹³ and MASAKI SHIMIZU¹⁴

¹ Institut des Matériaux Jean Rouxel, UMR 6502 CNRS-Université de Nantes, 2, rue de la Houssinière, 44 322 Nantes Cedex 3, France
*Corresponding author, e-mail: Yves.Moelo@cnrs-imn.fr
² Department of Geography and Geology, University of Copenhagen, Østervoldgade 10, 1350 Copenhagen, Denmark
**Corresponding author, e-mail: emilm@ged.ku.dk
³ IGEM, Russian Academy of Sciences, Staromonetny per. 35, Moscow 109017, Russia
⁴ Leslie Research and Consulting, 316 Rosehill Wynd, Tsawwassen, B.C. V4M 3L9, Canada
⁵ Natural History Museum (Geology), University of Oslo, Postboks 1172 Blindern, 0318 Oslo, Norway
⁶ South Australian Museum, Department of Mineralogy, North Terrace, Adelaide, South Australia 5000, Australia
⁷ Department of Materials Engineering and Physics, University of Salzburg, Hellbrunnerstraße 34, 5020 Salzburg, Austria
⁸ CSIRO-Exploration & Mining, PO Box 5, Wembley, Western Australia 6913, Australia
⁹ Naturhistorisches Museum, Augustinerstraße 2, 4001 Basel, Switzerland
¹⁰ Institute of Mineral Industry, Danish Technical University, 2800 Lyngby, Denmark
¹¹ Dipartimento Geomineralogico, Università degli Studi di Bari, via E. Orabona 4, 70125 Bari, Italy
¹² Museo di Storia Naturale, Sezione di Mineralogia, Università degli Studi di Firenze, via La Pira 4, 50121 Firenze, Italy
¹³ Institute of Mineralogy, Crystallography and Material Science, University of Leipzig, Scharnhorststraße 20, 04275 Leipzig, Germany
¹⁴ Department of Earth Sciences, Faculty of Sciences, University of Toyama, Toyama 9308555, Japan

Abstract: This report deals with a general reexamination of the systematics of sulfosalts. It represents an update of the activity of the Sulfosalt Sub-Committee within the Commission on Ore Mineralogy of the International Mineralogical Association, in connection with the Commission on New Minerals, Nomenclature and Classification (CNMNC-IMA). Part I presents generalities of sulfosalt definition and nomenclature. After an extended chemical definition of sulfosalts, attention is focused on “classic” sulfosalts with As³⁺, Sb³⁺, Bi³⁺ or Te⁴⁺ as cations, corresponding to the general formula \((\text{Me}^+, \text{Me}''^+, \text{etc.})_x [\text{Bi, Sb, As}]^{3+}, \text{Te}^{4+}]_y [(\text{S, Se, Te})^{2−}]_z (\text{Me}, \text{Me}'': \text{various metals})\). General aspects of their chemistry and classification principles are summarized, especially with regard to chemical substitutions and modular analysis of complex crystal structures. On this basis, Part II presents a review of sulfosalt systematics. Six main crystal-chemical sub-groups are distinguished (plus some unclassified species), concerning more than 220 valid mineral species. Among others whose status is questioned are those considered to be varieties of well-defined species; minerals with ill-defined X-ray data; those that are possibly identical species; and those that represent the potential revalidation of old species. More than 50 crystal structures still remain unsolved, among which about a half probably corresponds to new structure types.

Key-words: sulfosalt, nomenclature, crystal chemistry, systematics.
Preamble

Y. MOËLO and E. MAKOVICKY

The International Mineralogical Association (IMA) was founded in 1958. To coordinate its regular activity between general meetings (held every two years initially, and every four years since 1982), the IMA organized different specialized commissions, the best known being the Commission on New Minerals and Mineral Names (CNMMN – now Commission on New Minerals, Nomenclature and Classification, CNMNC). The Commission on Ore Microscopy (COM), since renamed the Commission on Ore Mineralogy, was originally created to establish quantitative data on the optical properties of opaque minerals. The data were subsequently published as *Quantitative Data File* volumes (see the Web-site of the IMA-COM). Within this Commission, the aim of the Sulfosalts Sub-Committee, under the direction of late Dr Roy Phillips, Chairman, was primarily to collect data for a complex group of ore minerals which, at the time, were poorly characterised. During the 13th General Meeting of IMA at Varna, Bulgaria (1982), Dr N. Mozgova succeeded R. Phillips as the new chair, with Dr. Y. Moëlo as secretary and the active collaboration of D.C. Harris (CANMET, Ottawa). Since the 15th IMA meeting at Beijing, China (1990), the activity of the Sulfosalts Sub-Committee has been carried on by us (Moëlo & Makovicky), primarily by compiling the internal reports and disseminating these among the committee members and specialists.

During the last four decades there has been a tremendous evolution of knowledge in the field of mineral systematics. More than 60% of the mineral species known today were described since the foundation of the IMA-CNMMN. The percentage is even higher in the field of ore minerals, especially the complex groups of sulfosalts and the minerals of the platinum-group elements (Cabri, 1981, 2002). Together with the classic procedures to define the ore minerals, the increasing number of crystal-structure studies has permitted a general deciphering of the crystal chemistry of sulfosalts, which is the basis for a precise definition of mineral species and an understanding of their limits of validity.

This report is an update of the systematics of sulfosalts, reflecting a fruitful collaboration, past and present, of many specialists of sulfosalts mineralogy. Part I presents generalities concerning the definition and chemistry of sulfosalts, as well as some basic principles relevant to sulfosalts crystal-chemical classification. Part II is a detailed presentation of all known sulfosalts species, with selected references about their definition (if recent) and crystal structure (if solved). Problems concerning the definition and nomenclature of some species are discussed on the basis of published data.

The choice of the crystal-chemical scheme used for the classification in Part II is a development of the modular approach to crystal structures. This choice does not necessarily reflect that of all the contributors and committee members, who may have adopted other points of view; above all, the choice is intended to promote the use of crystal-structure analysis as a basis for understanding the complex chemistry of sulfosalts in nature.

A draft version of this report was presented by E. Makovicky during the 19th General Meeting of the IMA at Kobe, Japan (July 23–28, 2006). A copy of this internal report was sent to the national representatives of the COM and CNMNC, for information and critical reading. This circulation led to significant improvements in the preparation of the final manuscript. The report has been approved as a whole by the CNMNC, through the direction of its Secretary, W.D. Birch. Nevertheless, due to the complexity of the sulfosalt group, this final version may contain errors and imperfections, for which we (Y.M. & E.M.) accept sole responsibility. Above all, this report must be considered as a guide for specialists interested in the field of ore mineralogy, and as help for the discovery and description of new mineral species. Without any excessive pretention, we hope that the report will be considered as the “state of the art” in sulfosalts systematics; however, the details of the classification of these species are considered as a basis for further work rather than a definitive scheme. The review of sulfosalts systematics may also be useful in the field of solid-state chemistry and material sciences, as sulfosalts today have aroused increasing attention in the search for new materials with interesting physical properties, such as in thermoelectricity, photovoltaic conversions, and magnetism.

All participating members are sincerely thanked for their contribution. We mention especially Dr N. Mozgova, past President of the Sulfosalt Sub-Committee, as well as Drs J.L. Jambor, N. Cook (Chairman of the IMA-COM) and E.H. Nickel (former Vice-Chairman of the CNMNC), for their careful reading of the text. We also thank E.A.J. Burke and W.D. Birch (Chairman and Secretary of the CNMNC, respectively), and anonymous members of this commission, as well as Prof. Y. Takéuchi (University of Tokyo) and Dr. Y. Matsushita (National Institute for Materials Science), for their useful comments and corrections.
Part I. Revision of sulfosalt definition and nomenclature: generalities

Y. MOËLO and E. MAKOVICKY

1. Definition and general formula

1.1. What is a sulfosalt?

The term “sulfosalt” (or “thiosalt”) was created by chemists during the XIXth century, by analogy to complex salts of oxygen, such as sulfate, phosphate, arsenate, antimonate, arsenite and antimonite. Oxysalts generally correspond to the combination of a simple cation with a complex anion (MeO₆)²⁺; this has been confirmed by crystal-structure studies and bond-valence calculations. In sulfosalts, S is considered to play the role of oxygen to similarly form complex anions. Although the configurations found in most modern studies of sulfosalts are more complicated than those encountered in similar oxysalts (e.g., oxyarsenites), the term “sulfosalt” has been preserved as a practical, working category in the field of ore mineralogy. The main reason is that sulfosalt minerals form a genetically well-defined group encountered in specific conditions of ore formation, usually referred to as hydrothermal processes.

1.2. Chemical nomenclature: an extended definition

In the literature, the definition of sulfosalts takes either formal chemistry or structural considerations as the starting point. According to the chemical definition, most sulfosalts are thioarsenites, thioantimonites, thiobismuthites and their combinations, i.e., sulfosalts in which As, Sb and Bi have the same oxidation state +3. Goldfieldite is the only natural example of a thiotellurite (i.e., with Te⁴⁺).

Remark: In the chemical literature, elements of group 15 of the periodic system, P, As, Sb and Bi (but not N, chemically very different) are designated as “pnictogens” (like “chalcosogens” for S, Se and Te). Compounds in which pnictogens act as anions correspond to pnictides (see “sulfosalts-pnictides” below).

If the bond-valence concept is accepted as a basis for classification, the sulfosalts of both the lower- or higher valence elements [with groups such as (As³⁺S³⁻)²⁻ or (As⁵⁺S²⁻)³⁻] represent classification categories equally well justified as those of oxyarsenites (As⁵⁺O³⁻)³⁻ or oxyarsenates (As³⁺O₂⁻)²⁻. This aspect was first considered by Nowacki (1968, 1969). Any problem encountered for some sulfosalts using this concept will have a near-mirror image in the oxy-realms as well, with somewhat diminished covariance.

A very limited number of natural sulfosalts correspond to thioarsenates (As³⁺ – enargite, luzonite) or thioantimonates (Sb³⁺ – famatinite). There are about 15 thioantinates (Sn³⁺), mainly related to the ZnS archetypes (sphalerite and wurtzite), and a few thiogermanates (Ge⁴⁺). Similarly, sulvanite could be considered as a thiovanadate (V⁴⁺), whereas thio tungstates (W⁶⁺), and thio molybdates (Mo⁶⁺) are exceptional. Thiophosphates (P⁵⁺) are as yet unknown in nature. Minerals corresponding to selenio- and telluro-salts, with trivalent As, Sb or Bi, or, exceptionally, Sb³⁺ (permingeate) are uncommon.

Table 1 enumerates these different types of chalcogeno-salts. The present report deals only with the definition and nomenclature of chalcogeno-salts with As³⁺, Sb³⁺, Bi³⁺ and Te⁴⁺, having lone-pair electrons with generally a strong stereochemical activity, that enhances the complexity of crystal structures. However, Table 2 summarizes all mineral species corresponding to other chemical types of chalcogeno-salts.

Table 1. Different chemical types of thiosalts/sulfosalts and related chalcogenides.

<table>
<thead>
<tr>
<th>Anion Cation</th>
<th>Chemical name</th>
<th>Example</th>
<th>Frequency in nature</th>
</tr>
</thead>
<tbody>
<tr>
<td>S²⁻ As³⁺</td>
<td>thioarsenite</td>
<td>tenenite</td>
<td>numerous species</td>
</tr>
<tr>
<td>Sb³⁺</td>
<td>thioantimonite</td>
<td>boulangerite</td>
<td>numerous species</td>
</tr>
<tr>
<td>Bi³⁺</td>
<td>thiobismuthite</td>
<td>cosalite</td>
<td>numerous species</td>
</tr>
<tr>
<td>Te⁴⁺</td>
<td>thiotellurite</td>
<td>goldfieldite</td>
<td>exceptional</td>
</tr>
<tr>
<td>(P³⁺)</td>
<td>thioorthophosphate</td>
<td>none</td>
<td>unknown in nature</td>
</tr>
<tr>
<td>As⁵⁺</td>
<td>thioarsenate</td>
<td>enargite</td>
<td>rare</td>
</tr>
<tr>
<td>Sb⁵⁺</td>
<td>thioantimonate</td>
<td>famatinite</td>
<td>very rare</td>
</tr>
<tr>
<td>(Bi⁵⁺)</td>
<td>unknown with S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sn⁴⁺</td>
<td>thioantanasite</td>
<td>stannite</td>
<td>a few</td>
</tr>
<tr>
<td>Ge⁴⁺</td>
<td>thiogermainate</td>
<td>briartite</td>
<td>very rare</td>
</tr>
<tr>
<td>V⁵⁺</td>
<td>thiovanadate</td>
<td>sulvanite</td>
<td>very rare</td>
</tr>
<tr>
<td>Mo⁶⁺</td>
<td>thiomolybdate</td>
<td>hensmite</td>
<td>exceptional</td>
</tr>
<tr>
<td>W⁶⁺</td>
<td>thiotungstate</td>
<td>kiddercreekite</td>
<td>exceptional</td>
</tr>
<tr>
<td>Se²⁻ As³⁺</td>
<td>selenio-arsenite</td>
<td>giraudite</td>
<td>exceptional</td>
</tr>
<tr>
<td>Sb³⁺</td>
<td>selenio-antimonite</td>
<td>hakite</td>
<td>exceptional</td>
</tr>
<tr>
<td>Bi³⁺</td>
<td>selenio-bismuthite</td>
<td>bokhodanovcizite</td>
<td>exceptional</td>
</tr>
<tr>
<td>Sh³⁺</td>
<td>selenio-antimonate</td>
<td>permingeate</td>
<td>exceptional</td>
</tr>
<tr>
<td>Te²⁻ Bi³⁺</td>
<td>telluro-bismuthite</td>
<td>volynskite</td>
<td>exceptional</td>
</tr>
</tbody>
</table>

In bold type: chalcogeno-salts dealt with in the detailed report (Part II).
general formula (Cu₆−, V₄)(Pb₁₋ₓBiₓ)Se₄ (with x close to 0.4), with identical coordinates for Pb and Bi. This species ought to be considered as a Bi-rich selenide of Pb, whereas the Bi-dominant derivative (x > 0.5), if it exists, would be a selenio-salt.

1.3. General formula of the principal sulfosalts category with As³⁺, Sb³⁺, Bi³⁺ or Te⁴⁺

1.3.1. Basic structural formula

As the bulk of natural thioarsenites, thioantimonites, etc. correspond structurally to homeotypes of simple sulfides, the term “sulfosalts” is usually limited to the vast group of chalcogeno-salts containing trivalent As, Sb, or Bi, as well as (exceptionally) Te⁴⁺. They correspond to simple sulfides (more generally chalcogenides) wherein one or more of the cations As³⁺, Sb³⁺, Bi³⁺ or Te⁴⁺ is associated with one or more metallic cation(s), Me, as essential (intrinsic) constituents. The S²⁻ anion may be replaced by Se²⁻ or Te²⁻ (chalcogeno-salts). Thus, the general chemical formula can be given as:

\[(Me^+, Me'^{2+}, etc.)_1 \{[Bi, Sb, As]^{3+}, Te^{4+}\}_y \times \{(S, Se, Te)^{2-}\}_z.\]  \hspace{1cm} (1)

From a structural point of view, atoms of the metals and atoms of the metalloids are not bonded to one another, and are bonded only to anions. Thus, compounds such as arsenopyrite, FeAsS, löllingite, FeAsS₂, or gudmundite, FeSbS, are not sulfosalts, as As or Sb are directly bonded to Fe, and act as anions relative to the metal. In sulfosalts, it is the lone-electron-pair activity of As³⁺, etc. and, as a consequence, a nearly universally present asymmetric coordination of these metalloids, that causes the structural complexity and specificity of these compounds, setting them apart from nearly all other chalcogenides.

1.3.2. Boundary compounds

Several mineral species combine the structural properties of sulfides (chalcogenides) with those of the other chemical groups, and can be considered as boundary cases.

Sulfur-excess compounds

Sulfur (chalcogen) excess corresponds to S–S bonds in the crystal structure. These occur alongside the metal–sulfur bonds. Such compounds may be qualified as “persulfides” (“perchalcogenides” – the words “polysulfides” and “polychalcogenides” are also convenient). A well-known example among sulfosalts is livingstonite, HgSb₂S₆(S₂) (Sririshan & Nowacki, 1975). It is also the case for moëloïte, Pb₆Sb₂S₆(S₄) (Orlandi et al., 2002), and of the synthetic sulfosalts Cu₄Bi₂X₆ (X = S, Se – Bente & Kupčík, 1984; Makovicky et al., 2002). Another possible example is that of museumite, Pb₂(Pb, Sb)₂S₆[Te, Au]₂ (Bindi & Cipriani, 2004a).

Subsulfides/subchalcogenides

In this case, the compounds have a sulfur (chalcogen) deficiency relative to those with ‘normal’ valences. Cations in their crystal structure display metal–metal or metalloid–metalloid bonding alongside the metal–chalcogen bonding. The name of “subsulfides” (“subchalcogenides”) has been used for such cases.

As the first example, within the tetradymite homologous series of layered structures, all compounds having a chalcogen deficit display pairs of Bi atomic layers, implying Bi–Bi bonding. Such is the case for the thiobismitite bakñinite, Pb₂Bi₁(S, Se)₃.

In gabrielite, Cu₃Ag₂Tl₂As₂S₇, the valence balance is respected. Nevertheless, examination of the crystal structure (Balić-Žunić et al., 2006) showed that Tl atoms form Tl–Tl pairs with a short distance (3.09 Å) corresponding to the sum of covalent radii, that indicates a metal–metal interaction. This is similar to the interaction in the Hg₁⁻₁Hg pairs (2.535 Å) in deansmite, (Hg)₂Hg₃CrO₃S₂ (Szymański & Grota, 1997). In stalerite, Cu₂(Zn, Fe, Hg)₂TlAs₂S₆ (Graeser et al., 1995),

Table 2. List of minerals of the chalcogeno-salt types not considered in Part II.

<table>
<thead>
<tr>
<th>Type</th>
<th>Species</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thioarsenites (As³⁺)</td>
<td>Billingslyte</td>
<td>Ag₃AsS₄</td>
</tr>
<tr>
<td></td>
<td>Enargite</td>
<td>Cu₁AsS₄</td>
</tr>
<tr>
<td></td>
<td>Fangite</td>
<td>Ti₁AsS₄</td>
</tr>
<tr>
<td></td>
<td>Luzonite</td>
<td>Cu₁AsS₄</td>
</tr>
<tr>
<td>Thioantimonites (Sb³⁺)</td>
<td>Famatinité</td>
<td>Cu₁SbS₄</td>
</tr>
<tr>
<td></td>
<td>Canfieldite</td>
<td>Ag₃SbS₄</td>
</tr>
<tr>
<td></td>
<td>Cerérite</td>
<td>Cu₂CdSbS₄</td>
</tr>
<tr>
<td></td>
<td>Chakalitique</td>
<td>Cu₂FeSnS₄</td>
</tr>
<tr>
<td></td>
<td>Ferroesterite</td>
<td>Cu₂(Fe, Zn)SnS₄</td>
</tr>
<tr>
<td></td>
<td>Hocaritite</td>
<td>Ag₂FeSnS₄</td>
</tr>
<tr>
<td></td>
<td>Kesterite</td>
<td>Cu₂(Zn, Fe)SnS₄</td>
</tr>
<tr>
<td></td>
<td>Kuramite</td>
<td>Cu₃SnS₄</td>
</tr>
<tr>
<td></td>
<td>Massovitine</td>
<td>Cu₂Fe₂SnS₄</td>
</tr>
<tr>
<td></td>
<td>Mohite</td>
<td>Cu₂SnS₄</td>
</tr>
<tr>
<td></td>
<td>Petukhite</td>
<td>(Cu, Ag)Z₃(Fe, Zn)Sn₂S₄</td>
</tr>
<tr>
<td></td>
<td>Pir quartzite</td>
<td>Ag₂ZnSnS₄</td>
</tr>
<tr>
<td></td>
<td>Staninite</td>
<td>Cu₂FeSnS₄</td>
</tr>
<tr>
<td></td>
<td>Stannoidite</td>
<td>Cu₂(Fe, Zn)SnS₄</td>
</tr>
<tr>
<td></td>
<td>Velikite</td>
<td>Cu₂HgSnS₄</td>
</tr>
<tr>
<td>Thioindates (In³⁺)</td>
<td>Cadmoindite</td>
<td>CdIn₂S₄</td>
</tr>
<tr>
<td></td>
<td>Indite</td>
<td>Fe₃InS₄</td>
</tr>
<tr>
<td>Thioberinganites (Ge⁴⁺)</td>
<td>Argyroïdite</td>
<td>Ag₃GeS₄</td>
</tr>
<tr>
<td></td>
<td>Barquillite</td>
<td>Cu₃(Cd,Zn)GeS₄</td>
</tr>
<tr>
<td></td>
<td>Briaritite</td>
<td>Cu₂(Fe,Zn)GeS₄</td>
</tr>
<tr>
<td></td>
<td>Calvertite</td>
<td>Cu₂Ge₂S₄</td>
</tr>
<tr>
<td></td>
<td>Germanite</td>
<td>Cu₃(Fe,Ge)₂S₄</td>
</tr>
<tr>
<td></td>
<td>Putzite</td>
<td>(Cu₁Ag₃)₂(Fe, Ge)S₆</td>
</tr>
<tr>
<td>Thiovandates (V⁶⁺)</td>
<td>Sulvanite</td>
<td>Cu₃VS₄</td>
</tr>
<tr>
<td></td>
<td>Thio-molybdate/stannate</td>
<td>Hesseite</td>
</tr>
<tr>
<td></td>
<td>Thio-tungstate/stannate</td>
<td>Kiddreckite</td>
</tr>
<tr>
<td></td>
<td>Thio-molybdate/germanate</td>
<td>Maikainite</td>
</tr>
<tr>
<td></td>
<td>Thio-tungstate/germanate</td>
<td>Catamarancite</td>
</tr>
<tr>
<td></td>
<td>Other mixed types</td>
<td>Ovamboite</td>
</tr>
<tr>
<td></td>
<td>Colusite</td>
<td>(Cu₂₁V₁₂₁₃₁₄₁₈₁₄₁₈₁₄₁₆)</td>
</tr>
<tr>
<td></td>
<td>Germanoculsite</td>
<td>Cu₁₁V₁₄Ge₁₈As₁₁₈₁₆</td>
</tr>
<tr>
<td></td>
<td>Nebrasovite</td>
<td>Cu₁₁V₁₄Sn₁₈As₁₁₈₁₆</td>
</tr>
<tr>
<td></td>
<td>Renierite</td>
<td>Cu₁₁(Zn₁₂₁₃₁₈₁₄₁₈₁₄₁₆)</td>
</tr>
<tr>
<td></td>
<td>Stiboculosite</td>
<td>Cu₁₁V₁₄As₁₁₈₁₄₁₈₁₄₁₆</td>
</tr>
<tr>
<td></td>
<td>Vinccentite</td>
<td>Cu₁₁FeSnS₉As₉₁₈₁₄₁₈₁₄₁₆</td>
</tr>
<tr>
<td>Seleno-antimonite</td>
<td>Permanganite</td>
<td>Cu₂₁₁₈₁₄Sn₅₁₈₁₄₁₈₁₄₁₆</td>
</tr>
</tbody>
</table>

Y. Moëlo et al.
and its isotype routhierite, CuHg_{2}Ta_{2}S_{6}, Ti–Ti pairs, with a somewhat longer bond, are also present.

Dervillite, Ag_{2}As_{2}, vaughanite, HgTiS_{2}S_{7}, and fetetlite, Ag_{24}Hg_{8}As_{5}S_{20}, all with unknown crystal structures, apparently have a small excess of positive charges with respect to the charge balance, thus probably indicating some cation–cation bonding. The “excess” of positive charges is more pronounced in criddleite, Ag_{2}Au_{5}TiSb_{10}S_{10}, and tvalchrelidzeite, Hg_{2}SbAs_{3}S_{3} (Yang et al., accepted). In all of these structures either metalloid–metalloid or metal–metalloid bonds are probably present, or even entire antimonide portions exist. Analogies to these situations are pääkkonenite Sb_{2}As_{2}S_{2} (Bonazzi et al., 1980) and chalcocathalite (a sulfide–antimonide of Ti and Cu) (Makovicky et al., 1980).

The same situation is encountered in two PGE (Platinum Group Elements)-bearing chalcogenides, borovskite, Pd_{3}SbTe_{4}, and cererarite, (Pt,Pb)Bi_{3}(S,Se)_{4–x}, for which the valence state of the metalloid is unknown.

Sulfosalt-pnictides

In the crystal structure of hauchecornite, Ni_{8}Bi(Bi,Sb)S_{8}, the pure Bi atom position is preferentially bound to four S atoms (together with two Ni atoms) and acts partly as a cation, whereas the mixed (Bi,Sb) atom is exclusively bound to Ni atoms, and acts as an anion (Kocman & Nuffield, 1974). The same duality can be observed in other species isotypic with hauchecornite: arsenohauchecornite, bismutohauchecornite, tellurohauchecornite and tucekite. All these minerals are transition compounds between sulfosalts and pnictides.

Halide-sulfides (or halogeno-sulfides)

Ardaite, Pb_{7}Sb_{15}S_{36}Cl_{9}, damsonite, Pb_{32}Sb_{25}S_{6}Cl, and playfairite, Pb_{16}(Sb,As)_{10}S_{4}Cl, are three examples of natural chloro-sulfosalts. Only the crystal structure of damsonite is known (Makovicky et al., 2006b), but here, despite the very low Cl/S ratio, the Cl atom is fixed in a specific atomic position. Consequently Cl is essential for the formation of the mineral species.

Oxide (hydroxide)-sulfides

In scainite, Pb_{14}Sb_{29}S_{44}O_{3} (Moïlo et al., 2000), the O atoms are bound preferentially to Sb atoms, in a way analogous to that in kermesite Sb_{2}S_{2}O. Scainite can be considered as an oxy-sulfosalts.

In cetineite, ~NaK_{5}Sb_{14}S_{18}(H_{2}O)_{6}, both the SbS_{4} and SbO_{3} groups are present, and K is bound almost exclusively, and Na completely, to O atoms (Sabello et al., 1988; Wang & Liebau, 1999), with additional H_{2}O molecules bound only to Na. This compound is thus a hydrated thiosoxy salt, like its Na-pure end-member, attensite (Sejkor & Hyrl, 2007).

In sarabauite, (Sb_{2}Sb)(CaSb_{2}O_{10}), Sb atoms again bind both to S and O atoms, whereas Ca atoms are exclusively bound to O atoms (Nakai et al., 1978). This compound could be considered to be a “thio-oxy salt”.

Apuanite and versilaitie are two Sb-containing oxy sulfides, derived from the oxide schafarzikite (Mellini & Merlino, 1979). In apuanite, ideally Fe^{2+}Fe^{3+}Sb^{3+}O_{12}S, the Sb is bound only to O; thus the mineral cannot be considered to be an oxy-sulfosalts. In versilaitie, Fe^{2+}^{2+}(Fe_{6}^{3+}Sb_{6}^{3+}Zn_{3}^{2+})_{2}=O_{16}S, the situation is more complicated, as some Sb partly replaces Fe in a tetrahedral site, coordinated by 1 S and 3 O atoms. The Sb should correspond to Sb^{5+}, which suggests that versilaitie is a combination of antimonite-antimonite with thio-antimonite.

Hydrated sulfosalts

In gerstleyite, Na_{2}(Sb,As)_{3}S_{15}2H_{2}O (Nakai & Appleman, 1981), Sb is bound only to S atoms, whereas Na is bound to S atoms and H_{2}O molecules; the mineral corresponds to a hydrated sulfosalts. Numerous synthetic hydrated sulfosalts have been synthesized.

Oxy-chloro-sulfides

Minor contents of O and Cl have been recently discovered in two new Pb–Sb sulfosalts, pillaite, Pb_{9}Sb_{10}S_{23}ClO_{5}, and pellouxite, (Cu,Ag)_{2}Pb_{21}Sb_{23}S_{33}ClO. Crystal-structure studies proved the O and Cl to be intrinsic components (Meerschaut et al., 2001; Palvadeau et al., 2004). These two minerals correspond to oxy-chloro-sulfosalts.

1.4. Conclusion

Taking into account the mineral species listed in Table 2 (more than 40 compounds) and those corresponding to the general formula [1] above (see the alphabetical index), as well as the borderline compounds, more than 260 mineral species belong to the “sulfosalts group” (sulfosalts and other chalcogeno-salts). There are also about 200 incompletely defined minerals (so-called “UM” – unnamed minerals) in the literature related to this vast group (Smith & Nickel, 2007), mainly because the chemical composition alone was determined by EPMA, which is generally easier to obtain than crystallographic data.

The “sulfosalts group” is as heterogeneous from a crystal-chemical point of view as, e.g., the silicate group. Consequently, a rigorous classification and nomenclature of sulfosalts is much more complicated than that of more restricted mineral groups which have been reexamined in the past by specific committees of the IMA (amphiboles, micas, zeolites...). As already mentioned, some sulfosalts fit perfectly in specific sulfide groups; for instance, most of the sulfostannates belong structurally within the sphalerite group. Only the vast group of sulfosalts with As\(^{3+}\), Sb\(^{3+}\), Bi\(^{3+}\) or Te\(^{4+}\) stands structurally as an almost separate family – this group is the topic of the present report. At the present stage of research, some groups of these sulfosalts can already be neatly classified on a crystal-chemical basis, whereas others await further discoveries for achieving the same depth of classification. The latter are grouped on purely chemical principles. The intention of the report is to assist further development of mineralogical studies in the field of complex sulfides.
Table 3. Classification hierarchy within the present sulfosalts report.

<table>
<thead>
<tr>
<th>Level of classification</th>
<th>Class</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chemical sub-type</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Large structural family (plesiotypic and merotypic series, other groups)</td>
<td>Chalcogenides</td>
</tr>
<tr>
<td></td>
<td>Homologous series</td>
<td>Sulfosalts</td>
</tr>
<tr>
<td></td>
<td>Iso- and homeotypic series</td>
<td>Boulangerite plesiotypic family</td>
</tr>
<tr>
<td></td>
<td>Species</td>
<td>Lillianite homologous series</td>
</tr>
<tr>
<td></td>
<td>Sub-species: Polyleptides</td>
<td>Plagonite homologous series</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tetrahedrite isotypic series; aikinite homeotypic series</td>
</tr>
</tbody>
</table>

2. Sulfosalts with \(\text{As}^{3+}, \text{Sb}^{3+}, \text{Bi}^{3+}, \text{Te}^{4+}\): chemistry and classification principles

2.1. General outline

There are various ways of classifying minerals. Some classifications are extrinsic (i.e., a paragenetic classification), but intrinsic ones are the best for development of the scientific field of mineralogy. Today, the deeper level of knowledge about minerals is that of their crystal structure (their “genetic code”); thus, the best classification ought to be a crystal-chemical classification. The first general crystal-chemical approach for sulfide minerals and related species was presented by Hellner (1958). Since the end of the 1960s, several mineralogical crystallographers have paid special attention to the sulfosalts group: Makovicky (1967), Nowacki (1969), Takéuchi & Sadanaga (1969), Povarennykh (1971), Wuensch (1974) and Edenharter (1976). In the following decade, some important aspects of the systematics of sulfosalts were emphasized: polymerization of complex anions and comparison with the classification of silicates (Ramdohr & Strunz, 1978; Kostov & Mincheva-Stefanova, 1981; Nakai & Nagashima, 1983), problems of non-stoichiometry (Mozgova, 1984), modular analysis of the crystal structures (Makovicky, 1981, 1985a, 1989). Noteworthy is also the more recent work of Takéuchi (1997) on tropochemical cell-twinning (Remark: ‘cell-twinning’, defined by Takéuchi et al. (1979), differs from ordinary twinning – see Nespolo et al., 2004).

Table 3 presents the hierarchical structure of the system chosen for this review. Whenever possible, the system is based on the level of structural relationships among mineral species. Thus, for a large number of species the system is essentially a modular classification. The general definition of isotypic, homeotypic, and homologous series is given in “Nomenclature of Inorganic Structure Types” (Lima-de-Faria et al., 1990). The best known example of homeotypic series is certainly the aikinite–bismuthinite series (Topa et al., 2002a). A clear example of homologous series is that of the plagonite series, \(\text{Pb}_{3n+1}\text{SbS}_{3n+1}\) (with \(n = 0, 1, 2, 3\)). The lillianite series is more complex, with numerous homeotypic and homologous phases. Dimorphism has been recognized in several, relatively rare cases, *e.g.* for proustite *versus* xanoconite, \(\text{Ag}_2\text{AsS}_3\), for pyrargyrite *versus* pyrostilpnite, \(\text{Ag}_2\text{SbS}_3\), or for clerite *versus* synthetic monoclinic \(\text{MnSb}_2\text{S}_4\).

The notion of family is less rigorous and corresponds to the “plesiotypic” and “merotypic” series of Makovicky (1997), or to more complex groups which may include such series. As detailed in Ferraris *et al.* (2004), within “plesiotypic” and “merotypic” series are grouped complex crystal structures showing a lower degree of topologic similarities than homologous series. For instance, in the zinkenite family, crystal structures consist of rods with simpler internal structure that are organized in different ways around pseudo-trigonal columns with \(\text{Pb}\) atoms in mono- or bi-capped prismatic coordination. This zinkenite family belongs to the supergroup of \(\text{Pb}\) sulfosalts with rod-type building blocks.

Definition of many of these series is fortified by data for a number of synthetic sulfosalts that do not have natural equivalents (*e.g.*, especially in Makovicky 1989, 1997, and Ferraris *et al.*, 2004). The current presentation, which in many aspects is distinct from the general classification of Strunz & Nickel (2001), is not intended to be an overall crystal-chemical classification; rather, the presentation is a review of sulfosalts species, organized on the basis of chemistry and, where possible, on the basis of crystal chemistry. In the future, discovery of new sulfosalts species, as well as the resolution of up to now unknown crystal structures, will permit the development and improvement of this sulfosalts systematization.

2.2. Chemistry

The formula indicated is the ideal formula derived from a crystal-structure study or, if the species is poorly characterised, it is the simplified formula given for the type sample. For non-commensurate composite structures (for instance cylindrite), a reduced formula is given, which is always an approximation of the true formula.

Many sulfosalts have a complex chemistry, and frequently a minor chemical component appears to be essential for the stabilization of a mineral species (*e.g.*, \(\text{Cu}\) in natural meneghinite, \(\text{Cl}\) in dadsonite). For a given species, the choice of the structural formula must indicate such minor components, whereas other elements, which are verifiably not essential (solid solution), can be excluded from the ideal formula as much as possible.

For the derivation of simplified formulae, it is important to know the principal substitution rules encountered among sulfosalts. For instance, if there is minor \(\text{As}\) together with
major Sb, in many cases As can be totally substituted by Sb, and thus will disappear from the final structural formula. On the contrary, Cl even in low concentration (some tenths of a percent – see dadsonite), is expected to play a specific role and therefore, generally, must be retained in the formula. The avoidance or retention of a minor component necessitates a precise knowledge of the crystal structure, particularly of the specific atomic positions at which this minor component is located. Experimental studies are often the only way to obtain the compound without the minor component, and to verify that this pure compound has the same crystallographic characteristics. For instance, natural geocronite always contains minor amounts of As, but synthetic As-free geocronite is known (Jambor, 1968).

Table 4 presents a non-exhaustive list of various substitution rules encountered in sulfosalts. It represents a first step in the examination of new EPMA data, in order to correlate them more or less precisely with a chemical group of sulfosalts or a definite mineral species.

Remark: A one-for-one atom substitution does not necessarily imply that one element substitutes another on the same position in the crystal structure. Sometimes, it may imply distinct sub-sites within a polyhedron, or quite distinct sites. The mechanism may be more complex for heterovalent substitution rules.

The role of temperature can be important in controlling the substitution. Extended solid solutions at high temperature (in hydrothermal conditions: 300 to 400 °C) may be drastically restricted at low temperature (epithetical conditions). For instance this aspect is particularly important in the aikinite–bismuthinite series (Topa et al., 2002a). The substitution rules in Table 4 generally correspond to solid solutions, but the rules may also describe the homeotypic derivation of a species of complex chemistry, from another species that has a very close structure but a simpler composition (e.g., all Pb- and Cu-containing derivatives of bismuthinite in the aikinite–bismuthinite homeotypic series).

Careful EPMA of sulfosalts in routine conditions (for instance, 20 kV, 20 nA, counting time 10 s, compositionally close secondary standards) permits a very good mineral identification, if no minor element is omitted (down to 0.1 wt.%). When such minor elements are present, and are not essential constituents (contrary to the 0.4 wt.% Cl in dadsonite, Pb$_2$Sb$_2$S$_6$Cl), their subtraction using the substitution rules from Table 4 gives a simplified chemical formula that generally results in only one mineral species.

Remark: Exceptionally, some sulfosalts have a very low content of oxygen (0.1 wt.%), which is nevertheless essential for their stability, as their crystal structure reveals a specific position for oxygen atoms (pillaite, pellouxite). EPMA would not be sufficient to prove the presence of oxygen within the structure, due to the easy formation of an oxidation film at the polished surface of the sample.

The search for minor elements is important both for mineral identification and for ore geochemistry and regional metallogeny, as is well known especially for the tetrahedrite series. Another example is the andorite series, which contains small amounts of Sn, Cd, and In in the Potosi district (Bolivia), whereas in Romania the characteristic minor elements are Mn and Fe.

### 2.3. Crystal structure and modular analysis

Knowledge of the crystal structure is not necessary for the validation of a new mineral species by the CNMNC of the IMA. Nevertheless, for sulfosalts having a large unit cell (e.g., most of the Pb sulfosalts), a solution of the crystal structure is today strongly recommended in order to prove the uniqueness of a new mineral species, and to reveal the role of minor components in the structure and composition. For these large structures it is also the only way to obtain a precise structural formula, and in some cases to decide whether a solid solution exceeds the 50 % limit in a characteristic site of the crystal structure, thereby giving a new isotypic mineral species.

Differences between the bonding strength and character of the metalloids (As, Sb, Bi) and metals, especially Pb, are less pronounced in sulfosalts than those between the bonding character in tetrahedral/triangular coordinations of Si, B, P, etc. and the associated cations in the relevant oxysalts. This difference, together with the variable types of coordination polyhedra of As, Sb and Bi and other crystal-chemical phenomena connected with the covalent character of bonding in the majority of sulfosalts, makes a polyhedral classification ineffective for most sulfosalts families. The approach at a higher level of organization in accordance with the principles of modular analysis seems to be the most efficient way to obtain a crystal-chemical classification of sulfosalts. Modular analysis of a crystal structure is based on the discrimination of sub-units called building blocks. This does not signify that interatomic bonding between constitutive building blocks is weaker than inside these blocks (they can be as strong, indeed stronger).

Typical for the combined arrays of metalloids and Pb and some other metals (e.g., Ag), as well as for some fairly pure Bi or Sb arrays, are extensive building blocks. The blocks approximate the topology of the PbS structure (cases with low activity of lone electron pairs) or of the SnS structure (TlI, TlSbS$_2$; are also approximations) for arrays that have well-expressed activity of lone electron pairs. Lone electron pairs of metalloids are accommodated by the archetypal motif (often congregating in common spaces, so-called “lone electron pair micelles”) whereas the contact between blocks takes place via mutually non-commensurate surfaces or by means of unit-cell twinning (details in Makovicky 1989, 1997). Structures with low contents of metalloids tend to follow the topologies dictated by the principal metals, eventually modified to satisfy the metalloid requirements as well.

The structural principles outlined in the preceding paragraph commonly lead to the presence of homologous series differing in the size of blocks but not in the principles of their recombination into one structure, or to more general families of related structures when the simple homologous expansion is hindered on structural grounds. Increase in the block size alters the Pb/Sn/metalloid ratio in favour of divalent metals; the same may happen in favour of combined AgBi or, rarely, even CuBi arrays. More extensive arrays and less expressed lone-electron-pair character may be favoured by elevated temperatures and by the substitution of S by Se or even Te.
Table 4. Principal chemical substitution rules observed in natural sulfosalts.

<table>
<thead>
<tr>
<th>Anions</th>
<th>Comments/Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>S(^{2-}) \leftrightarrow Se(^{2-})</td>
<td>cannizzarite ↔ wittite (e – see abbreviations at the bottom of the table)</td>
</tr>
<tr>
<td>(Se, S(^{2-})) \rightarrow Te(^{2+})</td>
<td>watkinsonite (I)</td>
</tr>
<tr>
<td>Cl(^{-}) \leftrightarrow S(^{2-})</td>
<td>pellouxite, dadsonite (I), coupled with cation substitutions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cations</th>
<th>Comments/Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi(^{3+}) ↔ Sb(^{3+})</td>
<td>easy and frequent</td>
</tr>
<tr>
<td>Sb(^{3+}) ↔ As(^{3+})</td>
<td>easy and frequent (especially: tetrahedrite–tennantite isoseries)</td>
</tr>
<tr>
<td>As(^{3+}) \rightarrow Bi(^{3+})</td>
<td>jordanite (I); tennantite (e – but rare)</td>
</tr>
<tr>
<td>Pb(^{2+}) \rightarrow Sn(^{2+})</td>
<td>cylindrite, franckeite (e)</td>
</tr>
<tr>
<td>Pb(^{2+}) \rightarrow (Mn, Fe, Cd(^{2+}))</td>
<td>andorite series (I)</td>
</tr>
<tr>
<td>Cd(^{2+}) \rightarrow Pb(^{2+})</td>
<td>kudriavite (I)</td>
</tr>
<tr>
<td>3 Pb(^{2+}) \rightarrow 2 Bi(^{3+}) + V</td>
<td>easy in galena, but difficult to prove in Pb sulfosalts (Ag-free lillianite – I)</td>
</tr>
<tr>
<td>3 Pb(^{2+}) \rightarrow 2 Sb(^{3+}) + V</td>
<td>limited in galena, possible but not proved in Pb sulfosalts</td>
</tr>
<tr>
<td>2 Pb(^{2+}) ↔ Ag(^{+}) + Bi(^{3+})</td>
<td>lillianite series (e)</td>
</tr>
<tr>
<td>2 Pb(^{2+}) ↔ Ag(^{+}) + Sb(^{3+})</td>
<td>andorite series (e)</td>
</tr>
<tr>
<td>2 Pb(^{2+}) \rightarrow (Ag, Ti(^{3+}) + As(^{3+})</td>
<td>sartorite series</td>
</tr>
<tr>
<td>Bi(^{3+}) + V ↔ Pb(^{2+}) + Cu(^{+})</td>
<td>bismuthinite–aiakinite series (e – ordered compounds (homeotypes) with decreasing T); cosalite, nuffieldite (I)</td>
</tr>
<tr>
<td>Sb(^{3+}) + V ↔ Pb(^{2+}) + Cu(^{+})</td>
<td>rare (zinkenite – I; meneghinite)</td>
</tr>
<tr>
<td>Fe(^{3+}) + Pb(^{2+}) \rightarrow Cu(^{+}) + Bi(^{3+})</td>
<td>kobellite homologous series (I)</td>
</tr>
<tr>
<td>Bi(^{3+}) \rightarrow 3 Cu(^{+}) (distinct sites)</td>
<td>pavonite series (I). In this series and in some other sulfosalts, Cu may enter various interstitial sites, and the exact substitution rule needs accurate studies (first of all, precise crystal-structure data)</td>
</tr>
<tr>
<td>2 Bi(^{3+}) \rightarrow 2 Ag(^{+}) + 4 Cu(^{+}) (distinct sites)</td>
<td>angelaite</td>
</tr>
<tr>
<td>Bi(^{3+}) \rightarrow In(^{3+})</td>
<td>kudriavite</td>
</tr>
<tr>
<td>Sb(^{3+}) + Ag(^{+}) ↔ Pb(^{2+}) + Mn(^{3+})</td>
<td>at high temperature; ordering at low T: uchuchacuaita</td>
</tr>
<tr>
<td>Ti(^{4+}) ↔ Ag(^{+})</td>
<td>never in the same atomic position! Limited at low T (rathite?); in the sartorite homologous series, Ti and Ag are apparently distributed in distinct sites, or in distinct sulfosalts (Lengenbach deposit)</td>
</tr>
<tr>
<td>Fe(^{2+}) ↔ Mn(^{2+})</td>
<td>jamesonite–beavidesite (e)</td>
</tr>
<tr>
<td>Hg(^{2+}) ↔ Zn(^{2+}), (Fe(^{2+}))</td>
<td>routhierite–stalderite (e)</td>
</tr>
</tbody>
</table>

Mutual substitution among Fe\(^{3+}\) ↔ Zn\(^{2+}\) ↔ Mn\(^{2+}\) ↔ Cd\(^{2+}\) ↔ Hg\(^{2+}\) 

Ag\(^{+}\) ↔ Cu\(^{+}\) tetrahedrite series (e); lengenbachite (I); pearceite–polysalts series (I) 
2 Fe\(^{2+}\) ↔ Fe\(^{3+}\) + Cu\(^{+}\) tetrahedrite series (up to 1 atom in the structural formula) 
Fe\(^{3+}\) + Cu\(^{+}\) ↔ 2 Cu\(^{+}\) tetrahedrite series (remark: the presence of divalent Cu in sulfides etc. may be a purely formal expression of the true situation; this is discussed by the specialists of chalcogene solid chemistry) 

(Fe\(^{2+}\), Zn\(^{2+}\))… + (As, Sb\(^{3+}\)) ↔ Cu\(^{+}\) + Te\(^{+}\) tetrahedrite–goldfieldite series (up to 2 atoms in the structural formula) 
Cu\(^{+}\) + (Sb, As\(^{3+}\)) ↔ V + Te\(^{+}\) tetrahedrite–goldfieldite series (when Te > 2 atoms in the structural formula) 

Fe\(^{3+}\) ↔ 2 Cu\(^{+}\) cylindrite–lèvyclaudite (e) 
Cu\(^{+}\) ↔ Ti\(^{3+}\) exceptional (galkhaite – e) 
Cu\(^{+}\) (Ag\(^{+}\)) → Au\(^{+}\) exceptional (goldfieldite – I; needs crystal-structure study) 
Ag\(^{+}\) → Au\(^{+}\) exceptional (polybasite) 

Solid solutions with unknown substitution rules

S\(^{2-}\) ↔ V\(^{0}\) with increasing Ag content in freibergite (and decreasing unit cell) 
In\(^{3+}\) in ramdothrite (I) 
Ti\(^{3+}\) in owyheeite (I) 

*Abbreviations: e = easy/extended substitution; I = limited; V = vacancy; ↔ = reciprocal; → = unidirectional.*
Blocks of these archetypal structures can be, according to the general vocabulary:
- 0-dimensional (0D): fragments; clusters; molecules
- 1D: chains, rods, ribbons, columns (= complex rods)
- 2D: layers (generally plane, sometimes undulated); sheets (= layers with weaker interlayer bonding); slabs (= thick, complex layers)
- 3D: cases where the entire structure approximates an archetype (= 3-dimensional; no blocks distinguished) are rarer.

Numerous Pb sulfosalts, among them the boulangerite pleisiotypic series, have been described using an intermediate category between 2D- and 1D blocks. The intermediate category is the “rod-layer” type, which results from the connection of rods along one direction (Makovicky, 1993).

The description of the general organization of a crystal structure involves the discrimination of the constitutive building blocks, and how they are interconnected. The description thus permits definition of the type of architecture of the crystal structure. The main part of the architectural types is based on a single type of building block. A significant part results in the combination of two types of blocks, as in some homologous series. The most complex architectural type is the boxwork type, a combination of three distinct blocks, as exemplified by the crystal structure of neyite (Makovicky et al., 2001a).

2.4. Non-stoichiometry in sulfosalts

The concept of non-stoichiometry in sulfosalts has been promoted especially by Mozgova (1984, 2000), and is discussed briefly here by using both a general approach and specific examples. The most common case of non-stoichiometry corresponds to various solid solutions, as presented in Table 4. Some substitution rules, isovalent or heterovalent, do not change the total number of atoms in the structural formula (= in the unit cell); other substitutions imply filling, or creating vacancies, which changes the total number of atoms present.

At the opposite end of the scale, syntactic intergrowths correspond to a mixture, at the (pseudo-)crystal level, of 3D domains of (at least) two species with similar crystal structures. Such intergrowths have various origins and present various textures (exsolution process, myrmekites by decomposition or substitution, simultaneous precipitation...). When the size of domains decreases to a micrometer scale, it becomes difficult to recognize the domains even at the highest magnification with a metallographic microscope, and microprobe analysis typically shows analytical dispersion around theoretical stoichiometric formulae; examples are the plagonite (Mozgova & Borodaev, 1972) and andorite–fizélyite (Moëlo et al., 1989) homologous series.

Intergrowths of the aforementioned type may be present even at a nanometric scale, and are visible with high-resolution techniques such as electron microscopy. SEM may give good images, which generally reveal a strong geometrical anisotropy of intergrowths, towards 2D domains with more or less pronounced stacking disorder. One of the best approaches is HRTEM, which permits a precise crystallographic characterisation of associated sulfosalts. These species correspond to two closely related members of a homologous series (Pring et al., 1999), exceptionally even to more distinct species (Pring & Etschmann, 2002; Ciobanu et al., 2004).

The most complex cases encountered in the sulfosalt group are exsolution aggregates of the bismuthinite series, wherein some samples correspond to a nanometric association of two or three members, some of them with their own deviations from a simple stoichiometry, which are related to a solid-solution mechanism (Topa et al., 2002b).

Of course, these various types of non-stoichiometric members will give different X-ray signatures in powder diagrams or by single-crystal study.

A special example of non-stoichiometry is that of sulfosalts with layered composite non-commensurate structure (cylindrite and related compounds – Makovicky & Hyde, 1981, 1992). In these sulfosalts, each of the two constituent layers may have a stoichiometric formula, but the non-commensurate (non-integer) ratio between one or two pairs of in-plane parameters results in a “non-stoichiometric” (i.e., complex) structural formula.
Part II. Review of sulfosalt systematics

INTRODUCTION: GENERAL PRESENTATION OF SULFOSALT SPECIES

This general presentation takes into account the sulfosalt species given by “Fleischer’s Glossary of Mineral Species” (Mandarino & Back, 2004) (see also Blackburn & Dennen, 1997; Martin & Blackburn, 1999, 2001; Martin, 2003), plus the new species published or approved recently by the CNMNC-IMA (see its website). The presentation is concerned with more than 220 sulfosalt species, for which an alphabetical list is given at the end of the text, together with an appendix that lists discredited species.

As the crystal-chemical classification of sulfosalts is incomplete at present, the following general presentation of sulfosalt mineral species is subdivided into large chemical groups. Within each group, subdivisions are generally based on well-defined structure types.

Sulfosalt species whose specific crystal structure does not have a close relationship to those of other species are indicated separately as “Single type”. If the crystal structure of a species is not known, this species is classified, as much as possible, with sulfosalts that have a similar chemistry.

ABOUT THE REFERENCES

To reduce as much as possible the number of references cited in this review, only the following have been included:

- systematically, the studies presenting the crystal structures of the sulfosalt species (noted “STR” afterwards), but also taking into account data obtained on synthetic compounds (“synth.” afterwards);
- recent papers that define sulfosalt species (since 1990, or older, when necessary);
- all references needed for the presentation and discussion of problems of definition and nomenclature.

Crystallographic data (unit-cell parameters, symmetry, space group) have been avoided, except when a change in symmetry or space group appears crucial for the distinction between two very close species (e.g., giessenite versus izoklakeite).

All other references and basic data are available in fundamental books on systematic mineralogy (e.g., Strunz & Nickel, 2001; Mandarino & Back, 2004), as well as in PDF (JCPDF) or ICSD (FIZ – Karlsruhe) databases. Concerning the crystal structures, especially noteworthy is the extensive work of Dr Y. Matsushita, who has compiled systematically all chalcogenide and related structures, both of natural and synthetic phases. Access to the data-library is free at http://www.crystalmaker.co.uk/library/chalcogenides.html.

Where problems are present regarding the definition of a species, relevant comments are given after the presentation of each species or group. The aim is to present the current status of sulfosalts definition, nomenclature and classification for all specialists interested in this field of research, thereby pointing out various unsolved questions and facilitating the discovery of new mineral species.

1. SULFOSALTS WITH ATOM RATIO OF CATION/CHALCOGEN = 1

1.1. Binary sulfosalts (MPnCh2), where M = univalent cation (Cu, Ag, Tl); Pn = pnictogen (As, Sb, Bi); Ch = chalcogen

These sulfosalts are presented according to the organisation of pnictogen polyhedra.

1. Matildite isotypic series (trigonal derivatives of PbS, according to (PbS)111 slices)

Matildite, AgBiS2

Bohdanowiczite, AgBiSe2

Volynskite, AgBiTe2
STR (synth.): Pinsker & Imamov (1964).

All these structures could also be considered as derivatives of the CdI2 archetype (single layer of BiCh6 octahedra), with Ag atoms intercalated between the layers (so-called “intercalation compounds”). However, these old structure determinations appear to be (pseudo)cubic approximations, as it is unrealistic to consider regular BiCh6 octahedra because of the lone-electron-pair of Bi3+.

2. Aramayoite isotypes

Aramayoite, Ag3Sb2(Bi, Sb)S6
Definition of baumstarkite and STR of aramayoite and baumstarkite are given by Effenerger et al. (2002).

3. (Single type)

Smithite, AgAsS2
STR: Hellner & Burzlaff (1964). In the structure, As in triangular pyramidal coordination forms As3S6 trimers arranged in columns parallel to b.

Cuboargyrite, AgSbS2

STR: Smith et al. (1997).

4. (Single type) (sheared derivative of SnS archetype)

Miargyrite, AgSbS2
STR: Smith et al. (1997).

5. (Single type)
6. (Single type) Cyclic trigonal

Trechmannite, AgAsS₂
STR: Matsumoto & Nowacki (1969). Arsenic in triangular pyramidal coordination forms As₅S₆ trimers that have trigonal symmetry.

7. Emplectite isotypic series

Emplectite, CuBiS₂
Chalcostibite, CuSbS₂
STR: Razmara et al. (1997).

8. Weissbergite homeotypic pair

Weissbergite, TiSbS₂
STR: Rey et al. (1983).
Lorandite, TiAsS₂
Weissbergite is a direct substitution derivative of the SnS archetype, whereas lorandite is a stacking variant related to this archetype with a double-layer periodicity.

1.2. Ternary sulfosalts (M₁⁺M₂⁺PnS₃)

1. Freieslebenite family (3-dimensional PbS-like arrays)

Freieslebenite (isotypic) series

Freieslebenite, AgPbSbS₃
Marrite, AgPbAsS₃
Related

Diaphorite, Ag₃Pb₂Sb₂S₈
STR: Armbruster et al. (2003).
Quadratite, Ag(Cd, Pb)(As, Sb)S₃
STR: Berlepsch et al. (1999).
Schapbachite, Ag₀.₄₄Pb₀.₄₂Bi₀.₄₄S
Schirmerite (Type 1), Ag₁PbBi₁Sₙ₉

Schirmerite and schirmerite (Type 1): the same compound?
Schirmerite, initially defined as the cubic form of AgBiS₂, was subsequently discredited because it is a high-temperature form that always decomposes at low T to its trigonal dimorph, maitlidite. Schirmerite, was recently redefined by Walenta et al. (2004) through the study of a sample containing a significant amount of Pb (~ 20 % of the cation sum). This Pb content seems necessary for the stabilization of schirmerite, and ought to appear in the chemical formula.

Previously, Bortnikov et al. (1987) discovered a mineral (“Phase I”) that has the composition originally assigned to schirmerite (Type 1), Ag₁PbBi₁S₉ (that is, strictly in the AgBiS₂–PbS pseudo-binary system), but without X-ray data. This schirmerite is very close to the stable form of schapbachite (Ag₀.₄₄Pb₀.₄₂Bi₀.₄₄S); however, in the absence of crystallographic data, it is not possible to conclude whether schirmerite is equivalent to schapbachite or corresponds to an ordered dimorph.

2. Bournonite isotypic series

Bournonite, CuPbSbS₃
STR: Edenharter et al. (1970).
Seligmanite, CuPbAsS₃
STR: Edenharter et al. (1970).
Součekite, CuPbBi(S, Se)₃

3. Mückeite isotypic series

Mückeite, CuNiBiS₃
Lapieite, CuNiSbS₃
Malyshevite, CuPdBiS₃
Def.: Chernikov et al. (2006).
IMA 2007-003, CuPtBiS₃

4. (Single type)

Christite, HgTlAsS₃
STR: Brown & Dickson (1976). It is a layered structure where a HgS mono-atomic layer alternates with a di-atomic layer (TlAsS₂) of the SnS archetype.

1.3. Quaternary sulfosalts (M₁⁺M₂⁺M₃⁺PnS₅)

Hatchite isotypes

Hatchite, AgTlPbAs₂S₅
Wallisite, CuTlPbAs₂S₅
STR: Takéuchi et al. (1968); Boiocchi & Callegari (2003).

2. Lead sulfosalts with a pronounced 2D architecture, their derivatives with a composite structure, and related compounds

2.1. Layered sulfosalts related to the tetradyminite archetype

Tetradymite is the archetype of a complex group of chalcogenides, composed of numerous natural and synthetic compounds, of a great interest in the field of thermoelectrics. All crystal structures are derivatives of a NaCl distorted close packing, generally with trigonal symmetry. Within this group, minerals can be classified according to two complementary homologous series:

– the first homologous series results from the combination of (Bi₂) layers with tetradymite-type layers (Bi₂Ch₃) (Ch = Te, Se, S), giving the general formula nBi₂₃mBi₅Ch₃;
– the second homologous series (“aleksite series”) corresponds to an expansion of the tetradyminite layer, related to an incorporation of Pb in specific atom sheets, according to the general formula Pbₙ₋₁Bi₅Ch₃(₀+₂);
– an unique case (bakinrite) results apparently from the combination of these two trends (see below).
Details concerning the crystal chemistry of minerals of this group, especially complex Pb–Te derivatives, are presented by Cook et al. (2007a, 2007b). These Pb derivatives relate to the chemical definition of sulfosalts; but one must point that, in all this group, Bi\(^{3+}\) ought to present a fairly its octahedral coordination, indicating a weak stereochemical activity of lone electron pair. Within this group are six Pb-Bi sulfosalts, among which five belong to the aleksite homologous series.

**Aleksite homologous series, \(Pb_{(n-1)}Bi_2Ch_{(n+2)}\)**

**Kochkarite**, \(PbBi_2Te_7\) (\(c = 72.09\) Å) \((n = 1, 2)\)  
STR (synth. – \(c = 23.6\) Å); Petrov & Imamov (1970); Shelimova et al. (2004). The structure has a regular alternation, along \(c\), of two layers, the first of which is five atoms thick (Te-Bi-Te-Bi-Te), and the second seven atoms thick (Te-Bi-Te-Pb-Te-Bi-Te). It can thus be modelled as a 1/1 intergrowth of tellurobismuthite \(Bi_2Te_3\) with rucklidgeite.

**Poubaite isotypic pair \((n = 2)\)**  
In this series, the \(c\) periodicity corresponds to three seven-atom-thick layers \(Ch\)-Me-\(Ch\)-Me-\(Ch\)-Me-\(Ch\), with the central \(Me\) atom probably corresponding to \(Pb\), and the two marginal ones to \(Bi\).

**Poubaite**, \(PbBi_2(Se,Te,S)_{14}\) (\(c = 40.09\) Å)  
STR (synth. – \(c = 39.20\) Å); Agaev & Semiletov (1963). Only a simplified structural model, based on an electron-diffraction study, is available.

**Rucklidgeite**, \(PbBi_2Te_4\) (\(c = 41.49\) Å)  
STR (synth. – \(c = 41.531\) Å); Zhubova & Zaslavskii (1972). The structural model was proposed on the basis of X-ray powder diagrams (especially 00l reflections).

**Aleksite**, \(PbBi_2S_2Te_2\) (\(c = 79.76\) Å) \((n = 2)\)  
STR: unknown. The \(c\) periodicity corresponds to \((14 \times 3)\) atom layers, and may correspond ideally to the stacking sequence (Te-Bi-S-Pb-S-Bi-Te) \((Z = 6)\).

**Saddlebackite**, \(PbBi_2Te_2S_3\) (\(c = 33.43\) Å) \((n = 3)\)  
Def.: Clarke (1997). \(c\) would correspond to an 18-atom sequence.

**Complex derivative**

**Babkinite**, \(PbBi_2(S,Se)_{13}\) (\(c = 39.60\) Å)  
Def.: Bryzgalov et al. (1996). STR: unknown. The \(Me/Ch\) ratio is > 1, and the formula is unbalanced, indicating a transitional compound of the subchalcogenide type. It can be modeled as \(2Bi_2BiCh_3.6PbCh\), and may be the chief-member of a complex homologous series, \(nBi_2.mBiCh_3.PbCh\) (Cook et al., 2007b).

**Remarks**: 1. Higher or combined members of the aleksite series require detailed X-ray structure determinations. 2. Cannizzarite (see 2.3) is a composite structure with one of the two layers of the tetradymite type. 3. “Platynite”, commonly given as \(PbBi_2(Se, S)_{12}\) in the literature, has been discredited (Holstam & Söderhielm, 1999).

### 2.2. Composite structures from alternating pseudohexagonal and PbS/SnS-like tetragonal layers

#### 1. Commensurate structures

**Nagyágite homologous series**

**Buckhornite**, \(Pb_2BiS_3(AuTe_2)\) \((N = 1)\)  
STR: Effenberger et al. (2000).

**Nagyágtite**, \([Pb_3(Pb, Sb)S_3]1(Te, Au)_{3}\) \((N = 2)\)  
STR: Effenberger et al. (1999).

**Related**

**Museumite**, \([Pb_2(Pb, Sb)S_3][Te, Au]_2\)  
Def.: Bindi & Cipriani (2004a).

**Berryite**, \(Cu_3Ag_2Pb_3Bi_2S_{16}\)  
STR: Topa et al. (2006a).

**Tentative assignment to this series**

**Watkinsonite**, \(Cu_3PbBi_4(Se, S)_8\)  
Def.: Johan et al. (1987).

STR: unknown. A structure model was recently proposed by Topa et al. (2006a), on the basis of crystallographic similarities with berryite.

#### 2. Non-commensurate structures

**Type 1: Cylindrite homologous series**

**Cylindrite**

\(~FePb_3Sn_4Sb_2S_{14}\)  

**Lévyclaudite**, \(~Cu_3Pb_3Sn_7(Bi, Sb)_2S_{28}\)  
Def.: Moëlo et al. (1990).

STR: Evain et al. (2006a), for the synthetic Sb-pure iso-type (“lévyclaudite-(Sb)”).

**IMA 2006-016**, \(Pb_2SnInBiS_7\)

**Franckeite type**

**Franckeite**, \(~Fe(Pb, Sn^{2+})_3Sn^{3+}Sb_2S_{14}\)  

“Potosinite”, \(~FePb_6Sn^{2+}Sb_2S_{14}\)

“Incaite”, \(~FePb_4Sn^{2+}Sn^{3+}Sb_2S_{14}\)  
Isotype

**IMA 2005-024**, \((Pb, Sn)_{12.5}As_5Sn_5FeS_{28}\)
Potosite and incaite: two varieties of franckeite

Franckeite has a composite layered structure, with in-plane non-commensurability (Makovicky & Hyde, 1981). One layer “H” is of the CdI₂ type, (Sn, Fe, Sb)S₂, like in cylindrite (Makovicky, 1974); the second one “Q” is of the SnS/TeI₂ type, four atoms thick (twice that of cylindrite): (Pb, Sn, Sb, Fe?)₄S₄. Sn is tetravalent in H, divalent in Q, where it substitutes for divalent Pb. The synthetic composite compound ([Pb, Sb]S₁₂₋₂₃Nb₁₂ (Lafond et al., 1997)) has the same Q layer as franckeite; here Sb is exclusively in the two central atomic planes of this layer. Wolf et al. (1981 – definition of poto-
siite) and Mozgova et al. (1976) pointed out that franckeite is crystallographically similar to potosiite and incaite (defined by Makovicky, 1974 and 1976). On the basis of the crystal-
chemical model, potosiite is Sn⁴⁺-poor franckeite (Makovicky
& Hyde, 1992), and incaite is Sn⁴⁺⁺-rich franckeite, always with Pb > Sn⁴⁺ in natural samples. Thus, potosiite and incaite corre-
respond to varietal compositions in the franckeite solid-solution
field (Mozgova et al., 1976) and should be taken off the list of mineral species.

In synthetic samples, Sn/Pb can surpass 1 (up to Pb-free franckeite and cylindrite – Moh, 1987). The discovery of such samples in nature would permit redefinition of incaite as a new mineral species.

Type 2

Lengenbachite, ~ Cu₂Ag₄Pb₁₈As₁₂S₃₉
Crystal chemistry revised by Makovicky et al. (1994).

Type 3: Cannizzarite isotypic pair

Cannizzarite, ~ Pb₈Bi₁₀S₂₃
Wittite, ~ Pb₁₈Bi₁₀(S, Se)₂₃

Remark: “Wittite B” of Large & Mumme (1975) corre-
sponds to proudite (Mumme, 1976).

Wittite: original species, or Se-rich cannizzarite?

Wittite and cannizzarite obey the same crystal-chemical model of composite, non-commensurate structure: a (Pb, Bi)₂(S, Se)₂ layer “Q” alternating with a (Bi, Pb)₂(S, Se)₁ layer of the tetradymite type (i.e., a double-octahedral layer). The main difference in the structural formula is the high Se/S ratio of wittite (Mumme, 1980a). This Se/S atomic ratio never exceeds 1, but the tetradymite-type layer is very probably enriched in Se relative to the Q layer (Mozgova et al., 1992). Precise knowledge of the Se partitioning between the two layers is necessary to validate wittite as a species, if Se/S > 1 in the tetradymite-type layer.

On the contrary, if in natural compounds the Se/S atomic ratio is always below 1 in the tetradymite-type layer, wittite would correspond to a Se-rich variety of cannizzarite. The pure Se derivative of cannizzarite has been synthesized recently, and its structure solved (Zhang et al., 2005). This complete Se-for-
S substitution enhances the possibility of validating wittite.

2.3. Commensurate composite derivatives of cannizzarite

In this group, all structures show an alternation of two types of ribbons or stepped layers resulting from the fragmenta-
tion of the two layers comprising the cannizzarite-like structure (one pseudo-quadratic, of the PbS archetype, the other pseudo-hexagonal, of the CdI₂ archetype). Three factors govern structural variations: 1) the thickness of each layer/ribbon; 2) the widths between consecutive planes of slip/shear and the width of their interface (according to a mQ/nH ratio); and 3) the spatial offset of ribbons of each type around planes of step (relative to the original layer).

1. Cannizzarite plesiotypic derivatives

This sub-group is described by Makovicky (1997).

(a) Stepped layers

Homologous pair

Junôite, 3Q₂/₅H – Cu₃Pb₃Bi₆(S, Se)₁₆
Def./STR: Mumme (1975a); Large & Mumme (1975).
Felbertalite, 3Q₂/₅H – Cu₃Pb₃Bi₆S₁₉
Defined by Topa et al. (2001).
STR: Topa et al. (2000a).
Nordströmite, 4Q₂/₅H – CuPb₂Bi₇(S, Se)₁₄
STR: Mumme (1980b).
Proudite, 8Q₂/₅H – CuPb₁₆Bi₃(S, Se)₁₇
Def./STR: Mumme (1976, and unpublished new revi-

(b) Sheared layers (chessboard type)

Galenobismutite, 1/₂Q₁/₂H – PbBi₂S₄
Angelaite, Cu₂AgPbBiS₄
(Remark: The Me/S ratio is > 1)
Def.: Brodkorb & Paar (2004); (Topa et al., in prep.).
STR: Topa et al. (2004 – abstract). It is a homeotype of galenobismutite.
Nufieldite, 1Q₂/₅H – Cu₁₄Pb₄Bi₂₂Sb₂O₂S₇
STR: Moëlo et al. (1997). The general structural formula is
Cu₁₄⁺,Pb₂₊ₓBi₃₋ₓSb₂S₇.
Weibullite, 6Q₂/₅H – Ag₀₃₃Pb₅₃₃Bi₈₃(S, Se)₁₈
STR: Mumme (1980c).

2. Boxwork derivatives of cannizzarite

This boxwork type results from a combination of three
types of building blocks. There are two types of ribbons (slab fragments) alternating to form complex slabs. These slabs are separated by a layer or ribbon-layer (here three atoms in thickness), giving the final boxwork architecture. One type of ribbons in the complex slabs and the latter layer (both with surfaces of pseudotetragonal character) form a boxwork system of partitions; the remaining type of fragments fills the boxes.

Neyite, 7Q₂/₅H – Cu₆Ag₃Pb₂₃Bi₂₁S₆₈
STR: Makovicky et al. (2001a).
Rouxelite, 5Q₂/₅H – Cu₂HgPb₂₂Sb₂₇S₆₄(O, S)₂
Def./STR: Orlandi et al. (2005).

Remark: Complex Pb/Sb oxy-(chloro)-sulfosalts (scainite, pillaita and pellowyite) belonging to the zinkenlite pleiostyptic series can also be described by a similar boxwork architecture.

3. Lead sulfosalts based on large 2D fragments of PbS/SnS archetype

3.1. Lillianite homologous series (PbS archetype)

The definition and crystal chemistry of this homologous series were presented by Makovicky (1977), and Makovicky & Karup-Møller (1977a, 1977b). Additional data were given in Makovicky & Balić-Žunić (1993). All structures are based on PbS-like slabs of various thickness (number N of octahedra). Each homologue type is symbolized as N_L, or as N1N2_L (when there are two slabs of distinct thickness).

1. Lillianite homeotypic series (4_L)

Bi-rich members

Lillianite, Ag,Pb3−xBi2+xS6
STR: Takagi & Takéuchi (1972); Ohsumi et al. (1984).

Gustavite, Ag,Pb3,S6
STR (synth.): Bente et al. (1993).

Sh-rich members

General formula: Ag,Pb3−x,Sn2+xS6 (Andn; n = 100 x)

Andorite VI*, Ag,Pb3,S6 (And100)
*Named “senandorite” by Moëlo et al. (1984a).

Nakashite, ~ (Ag0.93Cu0.07)2−1.06Pb0.08Sb3.06S6
(~ And100).

Andorite IV*, Ag,Pb11Sb27S96 (And93.75)
*Named “quatandorite” by Moëlo et al. (1984a).

Ramdohrite, (Cd,Mn,Fe)Ag5.5Pb12Sb21.5S48 (And68.75)

Fizélyite, Ag5Pb14Sb21S48 (And62.5)

Uchucchauaitite, MnAgPb5Sb3S12 (And90)

Rosichenite, (Ag,Cu)10Pb10Sb5S96 (And118.75)
Def.: Spiridonov et al. (1990).
STR: Petrova et al. (1986).

Lillianite dimorph (4,4L)

Xilingolite, Pb3Bi2S6
STR: Berlepsch et al. (2001a). In comparison with lillianite, the cations in the crystal structure are ordered in a monoclinic fashion.

Doubtful

“Bursaite”, Pb3−3xBi2+2xS6 (?)

Andorites IV and VI: two distinct species

These two minerals have distinct symmetry, with very close but distinct chemistry, without solid solution, as they are frequently observed in close epitactic intergrowth (Moëlo et al., 1984a, 1989). Thus they correspond to two homeotypic species, with distinct superstructures (4c and 6c, respectively) and not to two polytypic forms of the same species. The study of Sawada et al. (1987) solved the true (6c) crystal structure of andorite VI (or “senandorite”).

Nakashite: a variety of andorite VI

Nakashite, defined by Ito & Muraoka (1960) as a Cu-rich derivative of andorite with a superstructure of (c × 24), was considered by Fleischer (1960) to be a polytypic variety of andorite (andorite XXIV). A later detailed examination of minerals of the andorite–fizélyite series (Moëlo et al., 1989) confirmed that nakaséite is an oversubstituted, Cu-rich (~ 1 wt.%) variety of andorite VI, with a formula close to (Ag0.93Cu0.07)2−1.06Pb0.08Sb3.06S6.

Ramdohrite: species, or variety of fizélyite?

Ramdohrite from the type deposit has a significant Cd content (Moëlo et al., 1989) and is compositionally close to fizélyite (ideally And68.75 and And62.5, respectively), but it is not known if there is a solid solution (ramdohrite = Cd-rich variety of fizélyite?) or an immiscibility gap (ramdohrite = specific species?). Fizélyite from Kiszénáya (Romania) shows exsolutions of a (Mn, Fe)-rich variety of ramdohrite; such exsolutions correspond to a specific species (same study). A crystal-structure study of fizélyite from the type deposit is necessary to confirm the distinction between these two species.

“Bursaite”

Bursaite from the type deposit corresponds to Ag-poor lillianite (Makovicky & Karup-Møller, 1977b). A new occurrence (Shumilovskoe, West Transbaikal) studied by Mozgova et al. (1988) was found by X-ray powder and electron-microdiffraction data to be an intergrowth of two lillianite-related phases, each with a distinct unit cell. The electron-microprobe composition, which represents a composite from the two phases, indicates a Pb deficit (N ~ 3.83). Bursaite would correspond to the Pb-poor phase, with cation vacancies.

(4,4L) homologue

Vikingite, Ag3Pb8Bi3S30

(4,4L) homologue

Treasurite, Ag7Pb6Bi13S30

Remark: Borodaevite (see 3.2) may correspond to a homeotypic derivative of treasurite (Ilínca & Makovicky, 1997).

2. Heyrovskýite homeotypic series (7_L)

Orthorhombic, disordered (with minor Ag)

Heyrovskýite, Pb5Bi2S9
STR: Otto & Strunz (1968 – synth.); Takéuchi & Takagi (1974). The structure of an (Ag, Bi)-rich derivative was solved by Makovicky et al. (1991). Its structural formula is Pb3.38Ag1.32Bi1.32S9, and one of the cation sites has major Ag (s.o.f. ~ 0.657), that could justify (Ag, Bi)-rich heyrovskýite as a specific mineral species.

Homeotype (monoclinic, ordered)

Aschamalinite, Pb3−3xBi2+3xS9
STR: Mumme et al. (1983).
3.2. Pavonite homologous series

The pavonite homologous series was defined by Makovicky et al. (1977) (P = homologue number), and additional structural data were presented by Mumme (1990).

Grumiplucite, HgBi₂S₄ (4P)
Def.: Orlandi et al. (1998).
STR (synth.): Mumme & Watts (1980).

Kudriavite, (Cd, Pb)Bi₂S₄ (4P)
Def.: Chaplygin et al. (2005).
STR: Balić-Žunić & Makovicky (2007). About 1/10 Bi is substituted by In.

Makovickyite, Cu₈AgPb₂Bi₁₀S₃₈ (4P)
Def.: Žák et al. (1994).
STR: Mumme (1990); Topa et al. (2007).

Homeotype
Cupromakovickyite, Cu₄AgPb₂Bi₆S₁₈ (4P)
Def.: (Topa & Paar, accept.). The name of this new species was first given in the definition paper of kupčíkite (Topa et al., 2003a).
STR: Topa et al. (2007).

Pavonite, AgBi₃S₅ (5P)
STR (synth.): Makovicky et al. (1977).

Homeotype
Cupropanovite, Cu₀₋₉Ag₀₋₅Pb₀₋₅Bi₂₋₄S₅ (5P)
Benjaminite, Ag₃Bi₇S₁₂ (7P)

Mummeite, Cu₀₋₈Ag₃₋₁₁Pb₁₀₋₁₁Bi₆₋₆₅S₁₃ (8P)

Borodaevite, Ag₄₋₈Fe₀₋₂₁Pb₀₋₄₅Bi₀₋₈₈S₁₆ (11P)
Def.: Nenasheva et al. (1992), who considered this species as 12P. Borodaevite is questionable as a pavonite homologue (see treasurite (3.1.1) – Ilinca & Makovicky, 1997).

IMA 2005-036, Cu₈Ag₃Bi₄Pb₁₀S₃₈

Derivatives
Mozgovaita, PbBi₄(S, Se)₇
Def.: Vuorro et al. (1999). According to the unit-cell parameter (with b = 37.4 Å, derived from powder data), this mineral probably corresponds to synthetic Phase V (Takéuchi, 1997), giving the ideal formula Pb₃₋₉V₅₋₂₇Bi₁₂₋₅₄S₂₂ (V = cationic vacancy). The structure would be a composite of lillianite- and pavonite-type layers (m²P + n²L).

Livingstonite, HgSb₄S₆(S₂)
STR: Srikrishman & Nowacki (1975). It is a composite structure formed of two rod-layers, one of which is equivalent to a component of the rod-layer structure of grumiplucite. Homeotype of 2P.

3.3. Cuprobrismutite homologous series

A general review of this series is given by Topa et al. (2003b).

Kupčíkite, Cu₃₋₄Fe₀₋₄Bi₅S₁₀ (Type 1,1,1)
Definition and STR: Topa et al. (2003a).

Hodrushite, Cu₆Bi₁₀S₂₂ (Type 1, 2, 1, 2)
STR: Topa et al. (2003b). It explains chemical shifts relative to the ideal formula given here, analogous to those in kupčíkite and cuprobrismutite.

Cuprobrismutite, Cu₈AgBi₁₃S₂₄ (Type 2, 2, 2)
STR: Topa et al. (2003b).

Related:

Pizgrischite, (Cu, Fe)Cu₁₂PbBi₁₇S₃₄
Definition and STR: Meisser et al. (2007). It is further twinning of a kupčíkite-like structure.
Related (unit-cell-intergrowth derivative of kupčíkite)

Paděraïte, Cu$_7$[(Cu, Ag)$_{0.33}$Pb$_{1.33}$Bi$_{1.33}$]$_2$S$_{22}$
STR: Mumme (1986); Topa & Makovicky (2006).

3.4. Meneghinite homologous series (SnS archetype)

This series, defined by Makovicky (1985a), was reexamined by Berlepsch et al. (2001b). It also includes the aikinite–bismuthinite homeotypic series ($N = 2$), placed in section 4.5 of the present report.

**Meneghinite**, CuPb$_{11}$Sb$_7$S$_{24}$ ($N = 5$)

**Jaskolskiïte**, Cu$_x$Pb$_2$$_x$Sb$_2$$_x$Bi$_{2-x}$$_x$S$_5$ ($x$ close to 0.2) ($N = 4$)

3.5. Jordanite homologous series

1. **Jordanite**, Pb$_{14}$(As, Sb)$_6$S$_{23}$

**Geocrinite**, Pb$_{14}$(Sb, As)$_6$S$_{23}$
STR: Birnie & Burnham (1976). There is a continuous solid solution between jordanite and geocrinite. In nature, geocrinite always contains some As, but the pure Sb member has been synthesized (Jambor, 1968).

2. **Kirkite homologue** ($N = 3$)

**Kirkite**, Pb$_{10}$Bi$_3$As$_3$S$_{19}$
STR: Makovicky et al. (2006a).

3. Related?

**Tsugaruite**, Pb$_4$As$_2$S$_7$
Def.: Shimizu et al. (1998).

The crystal structure of tsugaruite is unknown, but is probably complex as is indicated by the large unit cell ($V = 4678 \, \text{Å}^3$).

3.6. (Single type) PbS hexagonal derivative

**Gratonite**, Pb$_{9}$As$_3$S$_{15}$

3.7. Plagionite homologous series

The crystal chemistry of this homologous series was characterised by Kohatsu & Wuenesch (1974), and was reexamined by Takéuchi (1997). General formula: Pb(Pb$_{2/3}$Sb$_{1/3}$)$_2$Si$_{13}$)$_{2-2N}$ ($N = 1$ to 4).

**Füllöppite**, Pb$_3$Sb$_8$S$_{15}$ ($N = 1$)
STR: Nuffield (1975), and Edenharter & Nowacki (1975).

**Plagionite**, Pb$_3$Sb$_8$S$_{17}$ ($N = 2$)

**Heteromorphite**, Pb$_7$Sb$_8$S$_{19}$ ($N = 3$)
STR: Edenharter (1980).

**Senseyye isotypic pair** ($N = 4$)

**Senseyye**, Pb$_3$Sb$_8$S$_{23}$
STR: Kohatsu & Wuenesch (1974); Matsushita et al. (1997).

**Rayite**, (Ag, Tl)$_2$Pb$_3$Sb$_8$S$_{21}$

**Rayite**: true unit cell?

Rayite (Basu et al., 1983) was related to senseyye on the basis of the powder diagram, but this choice was disputed by Roy Choudury et al. (1989), who could only synthesize (Ag, Tl)-rich boulangerite with a composition close to that of rayite. This result was confirmed by Bente & Meier-Salimi (1991). Rayite needs a single-crystal study (X-ray or electron diffraction) of the type sample to confirm the unit cell and the relationship of rayite to the plagionite series.

3.8. Sartorite homologous series

General building principles for structures of this series were described by Le Bihan (1962); the homologous series was defined by Makovicky (1985a) and was completed by Berlepsch et al. (2001c). Only two types of homologous slabs are known ($N = 3$ or 4), and each homologue type corresponds to a regular stacking of these slabs.

1. **Sartorite homeotypes** ($N = 3$)

**Sartorite**, Pb$_8$As$_2$S$_4$ (or Pb$_1$$_{12}$, As$_2$$_{2-2}$S$_4$$_{4}$, ?)

**Sartorite-9c**, Ti$_{1,3}$Pb$_8$As$_{17,5}$S$_{35}$
STR: Berlepsch et al. (2003).

**Twininite**, Pb(Sb$_{0,63}$As$_{0,37}$)$_2$S$_4$

**Guettardite**, Pb$_6$(Sb$_{0,56}$As$_{0,44}$)$_{16}$S$_{32}$

2. **Baumhauerite homeotypes** ($N = 3$, 4, 3, 4)

**Baumhauerite**, Pb$_{12}$As$_{16}$S$_{36}$

**Baumhauerite-2a**, ~ Ag$_{1,5}$Pb$_{22}$As$_{33,5}$S$_{72}$
Def.: Pring et al. (1990). Remark: The proposed chemical formula, which with a 2a periodicity is Ag$_{1,5}$Pb$_{22}$(As, Sb)$_{33,5}$S$_{72}$, is not charge balanced. A simplified formula is proposed above on the basis of EPMA by Laroussi et al. (1989).

STR: according to Laroussi et al. (1989), the crystal structure of “baumhauerite” published by Engel & Nowacki (1969) corresponds to baumhauerite-2a, and not to baumhauerite.

**Baumhauerite-ψ/O3ahc**, Ag$_3$Pb$_{38,1}$(As, Sb)$_{52,8}$S$_{96}$
Def.: Pring & Graeser (1994).

3. **Homologue** $N = 4$, 3, 4

**Livingeïte**, Pb$_{20}$As$_{24}$S$_{56}$
4. Dufrénoysite homeotypes (N = 4)

**Dufrénoysite**, Pb$_2$As$_2$S$_5$


**Veenite**, Pb$_2$(Sb, As)$_2$S$_5$

**Rathite**, Ag$_2$Pb$_2$–Tl$_1$/2As$_{18+u}$/2S$_{40}$

STR: Marumo & Nowacki (1965); Berlepsch et al. (2002). The developed structural formula is Pb$_8$Pb$_4$–(Tl$_2$As$_2$)$_1$(Ag$_2$As$_2$)$_2$As$_{16}$S$_{40}$.

5. Homologues with long-range periodicity

**Marumoite** (IMA 1998-004), Pb$_{32}$As$_{40}$S$_{92}$

This mineral species was approved by the CNMNC, but the description has not as yet been published. Preliminary data were given by Ozawa & Takéuchi (1983). The composition and unit-cell parameters indicate that the mineral belongs to the sartorite series. The long periodicity (115 Å) corresponds to 2 × (4, 3, 4, 3, 4) stacking sequences. Recently, the name marumoite was used in the study of another occurrence of the mineral (Shimizu et al., 2005).

**Rathite-IV** (unknown formula)

This rathite-IV (Ozawa & Nowacki, 1974) is the renamed rathite-V of Nowacki et al. (1964); its periodicity of 138 Å corresponds to the stacking sequence (4, 3, 4, 3, 4, 3, 4, 3, 4, 3, 4, 3, 4) (see Berlepsch et al., 2003). The mineral is an insufficiently described homologue, more complicated and quantitatively different from liveingite. The chemical composition is unknown; without additional cations, the stacking sequence would give the formula Pb$_{19}$As$_{24}$S$_{55}$.

6. Unit-cell-intergrowth derivative of dufrénoysite

**Chabournéite**, Tl$_5$(Sb, As)$_2$S$_{34}$

Def.: Mantienne (1974); Johan et al. (1981).


The structural formula proposed by Nagl (1979) for a b/2 subcell is Tl$_8$Pb$_2$Sb$_2$As$_{10}$S$_{68}$. This formula is questioned by Johan et al. (1981), who proposed the formula Tl$_2$(Sb, As)$_2$S$_{47}$ for the unit cell of the Pb-free member, but this formula shows clearly a S excess, incompatible with the modular organisation of the crystal structure. According to the substitution Tl$^+$ + (Sb, As)$^{3+}$ → 2 Pb$^{2+}$, demonstrated by Johan et al. (1981), the general simplified formula is Tl$_{5-}$.Pb$_2$(Sb, As)$_{21-}$S$_{34}$. The Pb-free pole (x = 0) corresponds to Tl$_5$(Sb, As)$_{21}$S$_{34}$, while the Pb-rich composition studied by Nagl (x ~ 1) is close to Tl$_4$Pb$_2$(Sb, As)$_{20}$S$_{34}$.

7. Pierrotite homeotypic pair (N = 3, 3)

**Pierrotite**, Tl$_2$(Sb, As)$_{10}$S$_{16}$ (ortho.)

STR: Engel et al. (1983).

**Parapierrotite**, TlSb$_5$S$_8$ (monocl.)

STR (synth.): Engel (1980).

**Sartorite**: chemical formula?

The crystal chemistry of sartorite is very complex, and has been recently reviewed by Berlepsch et al. (2003). Various supercells and non-commensurate superstructures seem common (Pring et al., 1993). According to Berlepsch et al. (2003) different chemical and crystallographic varieties of sartorite ought to be considered as polytypoids, and not as distinct mineral species.

The classic stoichiometric formula, Pb$\delta$_As$_\delta$S$_5$, is doubtful, and has never been encountered in modern EPMA. There is always some Tl, which is up to 6.4 wt.% in sartorite-9c, whose structural formula is Tl$_{1.5}$Pb$_{4.0}$As$_{17.4}$S$_{35}$. A Tl-poor variety ("Mineral A" of Laroussi et al., 1989) is close to Tl$_{0.02}$Pb$_{1.11}$As$_{1.87}$S$_{3.96}$ (Σ$cations = 3$ at.), but its crystal structure is unknown. Tentatively, Tl-free sartorite may correspond to the formula Pb$_{1+2x}$As$_{2-2x}$S$_{4-x}$, with x close to 0.07.

**Twinnite and guettardite: one or two species?**

Twinnite and guettardite, defined by Jambor (1967b), and re-analyzed by Jambor et al. (1982), are very close, chemically and structurally. Original twinnite has a slightly higher Sb/As ratio than guettardite (~ 1.7 against ~ 1.3, respectively), but this ratio may reach 3.1 (Moëlo et al., 1983). Guettardite is defined as a monoclinic dimorph of twinnite, but Z. Johan (unpublished – see Mantienne, 1974), on the basis of the examination of twinnite from another deposit, considered twinnite and guettardite as identical. Reexamination of the type samples, including structure data, would be necessary to understand the exact structural relationships.

**Baumhauerite varieties: polytypes or homeotypes?**

Baumhauerite-2a and baumhauerite-ϕO3abc were considered by Pring & Graeser (1994) as polytypes of baumhauerite, but they differ chemically because of the presence of Ag. Thus, it seems better to consider them as homeotypes. Whereas baumhauerite-2a is a well-defined species, approved by the IMA-CNMNC, the validation of baumhauerite-ϕO3abc would need a crystal-structure study.

Baumhauerite II of Rösch & Hellner (1959) was first obtained by hydrothermal synthesis, and was subsequently recognized by those authors in a natural sample. Pring & Graeser (1994) considered baumhauerite II as identical to baumhauerite-2a. However, baumhauerite II does not contain Ag. See also Pring (2001).

**Rathite varieties**

Numerous rathite varieties from the deposit of Lengenbach, Switzerland, have been described. A critical review of these rathites has been given by Makovicky (1985a), and, more recently, by Berlepsch et al. (2002), through the reexamination of the crystal structure of rathite. According to these authors and some previous works, the following is concluded:

- "a-Rathite" = rathite;
- "Rathite-I" = rathite or dufrénoysite;
- "Rathite-1a" = dufrénoysite;
- "Rathite II" is liveingite (Nowacki, 1967);
- "Rathite III" is most probably a misidentified compound;
- "Rathite-IV" (of Nowacki et al., 1964) = sartorite.
3.9. Unclassified

Mutnovskite, Pb₃AsS₂(I, Cl, Br)
Def./STR: Zelenksi et al. (2006).
The crystal structure of this halogeno-sulfosalts is very specific, with a layered organisation, but there is no clear relationship with any other Pb sulfosalts.

4. Sulfosalts based on 1D derivatives of PbS/SnS archetype, i.e., on rod-type building blocks

A general review of this vast group of Pb sulfosalts and related synthetic compounds has been presented by Makovicky (1993). The main geometric factors that are used for the description and comparison of the various crystal structures and their hierarchy are:

- the size of the rod component(s);
- the number of different rod-types coexisting in a structure (generally only one; exceptionally up to four);
- their general organisation, giving principally the “rod-layer”, “cyclic” and “chessboard” sub-types.

4.1. Rod-layer sub-type (boulangerite plesiotypic family)

Cosalite, Pb₂Bi₂S₅
Falkmanite, Pb₂Sb₂S₆ (or Pb₅S₄S₃₆S₁₀₈ ?)
Redefinition: Mozgova et al. (1983).
Boulangerite, Pb₅Sb₁₁Si₁
Plumosite, Pb₂Sb₂S₅
Moëloite, Pb₂Sb₁₄₁Si₁
Definition & STR: Orlandi et al. (2002).
Dadsonite, Pb₂Sb₂S₆₀Cl₁
Robinsonite, Pb₂Sb₆Si₁₃

Jamesonite isotypic series

Jamesonite, FePb₂Sb₂S₁₄
STR: Niiyuki & Buerger (1957); Léone et al. (2003); Matsushita & Ueda (2003 – synth.)
Benavidesite, MnPb₂Sb₂S₁₄
STR: Léone et al. (2003 – synth.).
Saharovaite, FePb₂Bi₁₄₁₄
Def.: Kostov (1959).

Saharovaite: species, or jamesonite variety?
In saharovaite, the Bi-for-Sb substitution is close to the 50 % at. limit, but does not clearly exceed it (Saharova, 1955; Kostov, 1959; Borodae & Mozgova, 1975). Thus, unless there is strong partitioning in the substitution of Bi among the three Sb positions in the jamesonite crystal structure (see below for the example of garavellite), saharovaite is a Bi-rich variety of jamesonite. Confirmation of saharovaite needs a crystal-structure study.

Parajamesonite: reexamination of a specimen from the type deposit (Herja, Romania)
Parajamesonite was defined by Zsviny & Naray-Szabo (1947) as a dimorph of jamesonite, with a distinct X-ray powder diagram. The unit cell was not determined, but the elongate crystals were reported to be up to 8 mm long and 2.8 mm wide, and would have easily permitted a single-crystal study. It was thought that the type sample was destroyed by fire during the conflict in Budapest in 1956, but rediscovery of the original samples studied by Zsviny permitted the discreditation (Papp, 2004; Papp et al., 2007).

Falkmanite: crystal structure relative to that of boulangerite?
The validity of falkmanite was questioned for a long time. Re-examination of falkmanite from the type locality led Mozgova et al. (1983) to suggest its close relationship with boulangerite but with a higher Pb/Sb ratio and a different degree of structural ordering. McQueen (1987) studied a second occurrence of falkmanite, with a chemical composition very close to the ideal one, Pb₂Sb₂S₆, and with crystal data (X-ray powder pattern; unit cell) almost identical to those of boulangerite. Without cation excess, its formula could be Pb₅S₄S₃₆S₁₀₈. A solution of the crystal structure of falkmanite is necessary for its definitive classification.

Plumosite: a specific, but incompletely defined mineral species
Many old museum samples labelled “plumosite”, Pb₂Sb₂S₅, correspond to various Pb–Sb sulfosalts with a hair-like habit. Mozgova & Bortnikov (1980) identified a plumosite-type phase, ~ Pb₁₂Sb₁₂S₆, in symplectite association with boulangerite. Later, Mozgova et al. (1984) and Vrublevskaya et al. (1985) described another occurrence of plumosite as lamellar exsolutions in boulangerite, with the same sub-cell, but with a distinct true unit cell. Like falkmanite, plumosite is considered as a homologous derivative of boulangerite (the term “homeotype” seems more appropriate). Mumme (1989) pointed out similarities between plumosite and jaskolskiite. Crystal-structure data are needed to classify this species.

Berthierite isotypic series

Berthierite, FeSb₂S₄
STR: Lemoine et al. (2019).
Garavellite, FeSb₈S₄
Def.: Gregorio et al. (2005).
Clerite, MnSb₂S₄
Def.: Kurowski (2000).

Remark: A synthetic monoclinic dimorph of clerite is known; its crystal structure (Pfitzner & Kurowski, 2000) is isotypic with that of grumiplucite (Part III, § 3.2). Unnamed MnSb₂S₄ described by Harris (1989) in the Hemlo
gold deposit (Ontario) may correspond to this monoclinic dimorph.

Garavellite: a definite species
The recent study by Bindi & Menchetti (2005) of a new occurrence of garavellite has proved that Sb and Bi atoms, despite their close crystal-chemical affinity, are positioned on distinct sites in the crystal structure. As a consequence, garavellite is clearly a definite mineral species, and not a Bi-rich variety of berthierite. This aspect is considered for the discussion of the validity of sakharovaite.

4.2. “Cyclic” sub-type and chessboard derivatives (zinkenite family)
The fundamentals of the crystal chemistry of this family have been defined by Makovicky (1985b).

1. Zinkenite plesiotypic series (cyclic rod-type)

Zinkenite, Pb_Sb2S4
Pillait, Pb_Sb3ClO6.5
Def.: Orlandi et al. (2001).
STR: Meerschaut et al. (2001).

Remark: An iodine derivative of pillait was recently synthesized (Kryukowa et al., 2005).

Scaininite, Pb14Sb30S54O5
Def.: Orlandi et al. (1999).
STR: Moëlo et al. (2000).
Marrucite, Hg2Pb16Sb18S46
Definition and STR: Orlandi et al. (2007); STR: Laufek et al. (2007).

Pellouxite, (Cu, Ag)3Pb21Sb23S55ClO
Def.: Orlandi et al. (2004).
STR: Palvadeau et al. (2004).
Vurroite, Sn2Pb50(Bi, As)22S54Cl6
Def.: Garavelli et al. (2005).
STR: Pinto et al. (2004 – abstract; accept.).

Owyheeite, Ag3Pb10Sb11S28
The chemistry of owyheeite was reexamined by Moëlo et al. (1984b), giving the general structural formula: Ag3+, Pb10–2, Sb11+, S28 (~–0.13 < x < + 0.20).
STR: Laufek et al. (2007). The proposed structural formula, Ag13Pb43Sb60.7S14, is outside the compositional field established by Moëlo et al. (1984b).

Remark: Pillait, scaininite and pellouxite can also be described according to a “boxwork” principle (see neyite and rouxelite in Sect. 2.3).

2. Chessboard derivatives (kobellite plesiotypic series)

Kobellite homologous series
The crystal chemistry of this series has been defined by Zakrzewski & Makovicky (1986) and Makovicky & Mumme (1986), and a general chemical formula was proposed by Moëlo et al. (1995).

Kobellite isotypic pair
Kobellite, (Cu, Fe)2Pb11(Bi, Sb)15S35
STR: Miehe (1971).

Tintinaita, Cu2Pb16Sb35
The composition was redefined by Moëlo et al. (1984c).

GIessenite homeotypic pair
GIessenite, (Cu, Fe)2Pb26,4(Bi, Sb)19,6S57
IZoklakite, (Cu, Fe)2Pb26,4(Sb, Bi)19,6S57
STR: Makovicky & Mumme (1986); Armbruster & Hummel (1987), for a Bi-rich variety.

GIessenite and izoklakite: from monoclinic to orthorhombic symmetry with increasing Sb content
There is apparently a quasi-continuous solid solution from gessenite to izoklakite with increasing Sb/Bi ratio, which is nevertheless always < 1 except for izoklakite of the type locality (~ 1.04). The main difference is that the monoclinic symmetry of gessenite (Bi-rich) changes to orthorhombic in izoklakite (Sb-rich) (Makovicky & Karup-Møller, 1986).

The exact Sb/Bi ratio at which the symmetry changes is unknown.

Related
Eclarite, (Cu, Fe)Pb12S28
Def.: Paar et al. (1983).

3. Related?
Zoubekite, AgPb4Sb14S10
Zoubekite: needs single-crystal study
Zoubekite, defined by Megaskaya et al. (1986), was approved by the IMA-CNMC, although the unit cell was calculated solely on the basis of a powder diagram with only six lines above 2.00 Å. Zoubekite is compositionally close to owyheeite; X-ray single-crystal study is needed to prove that the two are distinct species.

4.3. Aikinite–bismuthinite homeotypic series
This family constitutes the most complex and didactic series of homeotypes among the sulfosalts. The first sulfosalts member, aikinite, was defined by Chapman (1843), and the fundamental work of Johansson (1924) permitted definition of the series on the basis of the new descriptions of gladite, lindströmite and hammarite. Since the end of the 1960s, numerous papers have brought new chemical, crystallographic and crystal-structure data, and very recent works have presented a relatively advanced overview of this series.

Besides the end-member bismuthinite, there are ten homeotypic sulfosalt species. Three members, the two end-members bismuthinite (Bi2S6 = b) and aikinite ((Cu,Pb)2Bi2S6 = a), and the median one krupkaite (CuPbBi2S6 = k), permit definition of structural formulae of the eight other members by a simple combination of b or a with k. This also leads to the idealized classical formulae given below.
Nevertheless, careful examination of various samples indicates that chemical shifts from the ideal compositions (Mozgova et al., 1990) are common because of Cu over- or undersubstitution (Topa et al., 2002b), or because of the presence of very fine exsolution or intergrowth textures (Topa et al., 2002a) that extend to the nanometer scale (Pring & Hyde, 1987). As a consequence, it is dangerous to assign specific mineral names (the end-members excepted) on the basis of EPMA data alone, and the best way is to use a chemical notation, as proposed by Makovicky & Makovicky (1978), indicating the “aikinite substitution percentage”, $n_{aik}$, equal to $[2Pb/(Pb + Bi)] \times 100$. For instance, ideal hammarite, $Cu_2Pb_2Bi_3S_9$, corresponds to $n_{aik} = 67$.

Remark: This homeotypic series is also the lowest known homologue of the meneghinite homologous series (see Part 3, Sect. 4).

In the following list, the idealized substitution percentage is followed by the observed analytical values (in italics), when different. All species probably have narrow solid-solution fields (see for instance krupkaite and gladite – Topa et al., 2002b), but the fields are difficult to delimit, all the more because they may vary with crystallization temperature.

**Aikinite.** $CuPbBiS_3$ ($a = Cu_2Pb_2Bi_3S_6 - n_{aik} : 100$) STR: Ohnaka & Nowacki (1970).

**Friedrichite.** $Cu_3Pb_2Bi_2S_{18}$ ($2a + k - n_{aik}: 83; 80$) Def.: Chen et al. (1978).

**Hammarite.** $Cu_2Pb_2Bi_3S_9$ ($a + 2k - n_{aik}: 67; 68$) STR: Horiuichi & Wuensch (1976).

**Emilite.** $Cu_{10.7}Pb_{10.7}Bi_{21.3}S_{48}$ ($a + 3k - n_{aik}: 63; 67$) Def.: Topa et al. (2006b).

**Lindströmite.** $Cu_9Pb_2Bi_7S_{15}$ ($a + 4k - n_{aik}: 60$) STR: Balic-Žunić et al. (2002).

**Krupkaite.** $CuPbBi_1S_6$ ($k - n_{aik}: 50; 49$ to $50$ ?) STR: Mumme (1975b), and Syneček & Hybler (1975).

**Paarite.** $Cu_{1.2}Pb_{1.2}Bi_{6.3}S_{15}$ ($b + 4k - n_{aik}: 40; 42$) Def.: Topa et al. (2005).

**Salzburgite.** $Cu_{1.6}Pb_{1.6}Bi_{2.4}S_{12}$ ($b + 3k - n_{aik}: 38; 41$) Def.: Topa et al. (2005).

**Gladite.** $CuPbBi_2S_5$ ($b + 2k - n_{aik}: 33; below 33$, up to 38) STR: Syneček & Hybler (1975), Kohatsu & Wuensch (1976), Topa et al. (2002b).

**Pekoite.** $CuPbBi_{1.6}S_{18}$ ($2b + k - n_{aik}: 17$) STR: Mumme & Watts (1976).

**Bismuthinite.** $Bi_2S_3$ ($b = Bi_4S_6 - n_{aik} : 0$) Ciobanu & Cook (2000) detected by ore microscopy and EPMA two new Bi-rich minerals, “Phase 70”, close to $CuPbBi_2S_{12}$ ($n_{aik} = 25$), and “Phase 88.6”, close to $Cu_{0.33}Pb_{0.33}Bi_2S_{12}$ ($n_{aik} = 8$), which could correspond to new homeotypes between gladite and pekoite (type “$b + k$”?), and between pekoite and bismuthinite (type “$5b + k$”?), respectively. Similar suggestions, with $n_{aik} \sim 22$ and 27, appear in Topa et al. (2002b). All of these possible minerals need further study.

### 4.4. Related sulfosalts?

The crystal structures of following species are unknown, which does not permit their classification among the groups within Sect. 4 (or in Sects. 2 or 3).

**Ardaitie.** $Pb_{17}Sb_{15}S_3Cl_0$ Def.: Breskovska et al. (1982).

**Launayite.** $CuPb_{10}(Sb,As)_{13}S_{30}$

**Madocite.** $Pb_{19}(Sb,As)_{16}S_{43}$

**Playfairite.** $Pb_{16}(Sb,As)_{19}S_{44}Cl$

**Sorbyite.** $CuPb_6(Sb,As)_{11}S_{26}$

**Sterryite.** $(Ag,Cu)_2Pb_{10}(Sb,As)_{12}S_{29}$ These five species have been defined in the same deposit of Madoc, Ontario (Jambor, 1967a, 1967b).

**IMA 2007-010.** PbHgAs$_2$S$_6$

Considering As only at the trivalent state would indicate a S excess (“persulfosalt?”).

### 5. Specific Tl(Pb) and Hg sulfosalts: structures with SnS layers (with or without additional layers)

A first overview of the systematics of Tl sulfosalts has been presented by Babić-Žunić (1989).

### 5.1. Hutchinsonite merotypic series

The general outline of this series is given in Makovicky (1997 – Table 5). The series consists principally of Tl sulfosalts and related compounds (natural or synthetic) with large monovalent cations (Na$^+$, NH$_4^+$, Cs$^+$). All structures are based on the combination of two types of layers, one of which corresponds to an (010)$_{SnS}$ slab of variable width (with the exception of gerstleyite, derived from the PbS archetype).

1. **Hutchinsonite–bernardite homologous pair**

**Hutchinsonite.** TlPbAs$_2$S$_6$

STR: Takéuchi et al. (1965); Matsushita & Takéuchi (1994).

**Bernardite.** TlAs$_2$S$_6$

Definition and STR: Pasava et al. (1989).

2. **Edenharterite–jentschite pair**

A detailed structural comparison of edenharterite and jentschite was given by Berlesch et al. (2000).

**Edenharterite.** TlPbAs$_2$S$_6$


**Jentschite.** TlPb$_2$Sb$_6$S$_6$

Def.: Graeser & Edenharter (1997).

**Berlesch.** TlPb$_2$Sb$_6$S$_6$

Def.: Graeser & Edenharter (1997).
3. Other members

**Imhofite**, Tl₅₃As₁₅₄S₄₂₆
Def.: Divjakovic & Nowacki (1976); Balić-Žunić & Makovicky (1993).

**Gillulyte**, Tl₂As₅Sb₁₂S₁₃

4. PbS archetype

**Gerstleyite**, Na₂(Sb₃As₁₃)·2H₂O

5.2. Rebulite plesiotypic pair

A comparative modular analysis of the crystal structures of rebulite and jankovićite has been presented by Makovicky & Balić-Žunić (1998).

**Rebulite**, Tl₃Sb₃S₂₂
Def.: a complete description required for a definition is lacking.
STR: Balić-Žunić et al. (1982).

**Jankovićite**, Tl₂Sb₃(As, Sb)₃S₂₂
Def.: Cvetkovic et al. (1995).

5.3. Single type: sicherite

**Sicherite**, Ag₂½Tl(As, Sb)₁₂S₆
Definition and STR: Graeser et al. (2001).

5.4. Unclassified

**Ernigglite**, SnTl₂As₂S₆
Definition and STR: Graeser et al. (1992).

**Vrbaite**, Hg₃Tl₄As₄Sb₅S₂₀

**Simonite**, Hg₁Tl₁As₅S₆
Def.: a complete description required for a definition is lacking.
STR: Engel et al. (1982).

**Vaughanite**, Hg₁Tl₁Sb₁S₇
Def.: Harris et al. (1989).

**Gabriellite**, Cu₂AgTl₂As₁₃S₇
Def.: Graeser et al. (2006).
STR: Balić-Žunić et al. (2006). A 3-slab structure, with one of the layers related to cyclic sulfosalts.

**Rebulite: needs a mineralogical description**

Rebulite was defined on the basis of its crystal-structure study (Balić-Žunić et al., 1982), but without a proposal submitted to the IMA-CNMC. A complete mineralogical description is needed.

**Simonite: needs a mineralogical description**

Like rebulite, simonite is known only by its crystal-structure study (Engel et al., 1982). It has been approved by the IMA-CNMC, but a mineralogical description is lacking.

6. Sulfosalts with an excess of small (univalent) cations (Ag, Cu) relative to (As, Sb, Bi)

In the majority of these sulfosalts the ratio (ΣMe)/S is 1; however, in the presence of divalent metals (Zn, Hg, Fe), the ratio may equal 1 (galkhaite, laffittite, routhierite and staldlerite).

6.1. Cu(Ag)-rich sulfosalts

1. Wittichenite homeotypic pair

**Wittichenite**, Cu₃Bi₅S₃

**Skinnerite**, Cu₃Sb₃S₇

2. Tetrahedrite isotypic series

Among sulfosalts, this is the most complex isotypic series, because of the multiplicity of iso- and heterovalent substitutions. Numerous crystal-structure studies have been performed since the early ones of Machatschki (1928) and Pauling & Neuman (1934). The simplified general formula is A₄(B, C)₄X₄Y₄Z₄, where A is Cu or Ag in triangular coordination, B is Cu or Ag in tetrahedral coordination, C is generally a divalent metal (typically Fe or Zn, but also Hg, Mn, Cd...) in the same tetrahedral coordination, X is Sb, As, Bi or Te in trigonal pyramidal coordination, Y is S or Se in tetrahedral coordination, and Z is S or Se in a special octahedral coordination. The presence of vacancies or interstitial atoms (e.g., Cu), or heterovalent substitutions due to the incorporation of Fe³⁺ or Te⁴⁺, have been confirmed by structural studies.

In tetrahedrite–tennantite, the amount of divalent metals is limited to 2 a.p.f.u. but, especially in synthetic samples, it may vary between 0 and 2, indicating the variable presence of (formal) Cu²⁺.

There are seven well-defined species, but various data (EPMA, experimental studies, Mössbauer spectroscopy, X-ray) indicate that the crystal chemistry of this series is complex, and individual problems can require highly specialized research methods. As a consequence, limits between mineral species (for instance freibergite or goldfieldite relative to tetrahedrite) are still questionable.

Structural formulae presented below are simplified to ideal ones as much as possible (for instance, the B/C ratio is equal to 4/2, and C is restricted generally to Fe and Zn). In other cases, the formula of the type sample is also given (for very rare species).

**Tetrahedrite**, Cu₆[Cu₄(Fe, Zn)₂]Sb₅S₁₃
STR: Wuenisch (1964); Peterson & Miller (1986); Makovicky & Skinner (1979) and Pützner et al. (1997) for Cu-pure synthetic varieties, Cu₁₂₅Sb₅S₁₃.

**Tennantite**, Cu₆[Cu₄(Fe, Zn)₂]As₅S₁₃
STR: Wuenisch et al. (1966); Makovicky et al. (2005) for a Cu-rich unsubstituted composition, Cu₁₂₅As₅S₁₃.

**Freibergite**, Ag₆[Ag₁₂Fe₂]Sb₅S₁₃
STR: Rozhdestvenskaya et al. (1993).

**Argentotennantite**, Ag₆[Ag₁₂Fe₂]As₅S₁₃
Type sample (Spiridonov et al., 1986a):
Argentotetrahedrite, \( \text{Ag}_{10}(\text{Fe}, \text{Zn})_2 \text{Sb}_4 \text{S}_13 \)

Formula according to Zhdanov et al. (1992): 
\( \text{Ag}_{10.9}(\text{Fe}, \text{Zn}, \text{Hg})_{1.9}(\text{Sb}_{3.9}\text{As}_{0.1})_{4.0}\text{S}_{12.2} \).

Goldfieldite, \( \text{Cu}_{10}\text{Te}_2 \text{S}_3 \)

Relative to this ideal end-member, charge-balanced with Cu⁺ and Te⁶⁺, natural compositions of goldfieldite with decreasing Te content agree with the two complementary formulae (see comments below):

1. \( \text{Cu}_{12-x}(\text{Te}_{2+x}(\text{Sb}, \text{As}, \text{Bi}))_{2-x}\text{S}_3 (2 > x > 0) \), and
2. \( \text{Cu}_{10+x}(\text{Fe}, \text{Zn})_{2-y}(\text{Sb}, \text{As}, \text{Bi})_{4-y}\text{S}_3 (y < 2, \text{ and } \text{Te} > \text{Sb}, \text{As}, \text{Bi}) \).

Numerous EPMA data are given by Kovalenker & Rusinov (1986).

**Related**

Galkhaite, \( (\text{Cs}, \text{Ti}, \text{Y})(\text{Hg}, \text{Cu}, \text{Zn}, \text{Te})_9(\text{As}, \text{Sb})_4 \text{S}_{12} \)

This mineral species was initially defined as \( \text{HgAsS}_2 \) by Gruzdev et al. (1972). The structural role of Ti was determined by Divjakovic & Nowacki (1975), but Chen & Szmyński (1981, 1982) subsequently proved that Cs always exceeds Ti.

**Freibergite**

The status of freibergite as a valid species is still discussed. The Ag-for-Cu substitution induces a regular increase of the parameter \( a \), as exemplified by the tennantite–argentotennantite complete solid solution; this solid solution has been also observed to occur between tetrahedrite and its pure Ag derivative, argentotetrahedrite. However, when the Ag content is more than about 23 wt.% (~ 4 a.p.f.u.), an abnormal trend of decreasing \( a \) has been observed (Riley, 1974; Samusikov et al., 1988; Balitskaya et al., 1989). The decrease has been explained by Rozhdestvenskaya et al. (1993) as follows. In the metal site with planar triangular coordination, Cu is mainly or completely substituted by Ag. At the same time, the special S position (Z) with octahedral coordination is progressively emptied, thereby permitting the formation of \( \text{Ag}_x \text{octahedral metallic clusters} \).

For the highest Ag content, the crystal structural formula is: 
\[ \text{[Ag}^{\text{I}}\text{Cu}^{\text{II}}\text{]}_4\text{Cu}_{44}(\text{Fe}, \text{Zn})_{30}\text{Sb}_{30}\text{S}_20.89 \]

Thus, this abnormal trend may be considered as belonging to a specific species, freibergite, which is distinct from Ag-rich tetrahedrite (improperly called “freibergite”). For the time being, the structural formula of this freibergite trend may be idealised as: 
\[ (\text{Ag}_{4+x}, \text{Cu}_{2-x})_4(\text{Cu}, \text{Ag})_4(\text{Fe}, \text{Zn})_{2x}\text{Sb}_4 \text{S}_{13-x} (0 < x < 1) \]
Varieties with Ag below 4 a.p.f.u. should be called Ag-rich tetrahedrite. The problem definitely needs further study.

**Goldfieldite nomenclature**

In goldfieldite Te⁴⁺ substitutes for Sb³⁺ in the tetrahedrite structure. For compositions with up to 2 Te a.p.f.u., the valence balance is maintained by an equivalent substitution of the divalent metals (Fe, Zn...) by monovalent Cu, as in structural formula (2) above. When \( \text{Te} > 2 \) a.p.f.u., there are no more divalent metals; hence, the excess of Te above 2 at. is balanced by an equal number of vacancies among Cu sites that have three-fold coordination (structural formula (1) above). In these two consecutive solid-solution fields, the name goldfieldite is to be used when Te is predominant over each of Sb, As and Bi. Conversely, if for instance Te is minor together with major Sb, one has Te-rich tetrahedrite, and not goldfieldite.

**“Annivite”: potential revalidation**

“Annivite” from the type deposit of Einfisch or Anniversary valley (Wallis, Switzerland) corresponds to a Bi-rich (~ 5 wt.%) variety of tennantite, according to the original analysis of Fellenberg (1854). On the basis of a total of 16 cations, its structural formula is: 
\[ \text{Cu}_{93}\text{Fe}_{122}\text{Zn}_{0.55}\text{S}_{11.06}\text{As}_{5.06}\text{Sb}_{2.82}\text{Bi}_{0.42}\] 
Since this time, microprobe analyses have revealed in some deposits compositions in which the Bi atom concentration exceeds those of Sb or As (Kieft & Eriksson, 1984; Bortnikov et al., 1979; Spiridonov et al., 1986a). X-ray data from one of these occurrences could permit the validation of annivite as the Bi pole relatively to tetrahedrite and tennantite.
4. Routhierite isotypic pair

Routhierite, CuHg$_2$TlAs$_2$S$_6$
Stalderite, Cu(Zn, Fe, Hg)$_2$TlAs$_2$S$_6$
Definition and STR: Graesser et al. (1995).

| Routhierite: new structural formula |
The formula of routhierite (Johan et al., 1974) was revised by Graesser et al. (1995), together with the definition of stalderite: routhierite is the Hg isotype of stalderite (Zn-rich end-member).

| 5. Unclassified Cu sulfosalts |

| Miharaite, Cu$_4$FePbBiS$_6$ |
| STR: Petrova et al. (1988). |
| Petrovicite, Cu$_3$HgPbBiSe$_6$ |
| Mazzettiite, Ag$_3$HgPbSbTe$_5$ |
| Def.: Bindi & Cipriani (2004b). |
| Chaméanite, (Cu, Fe)$_4$As(Se, S)$_4$ |
| Def.: Johan et al. (1982). |
| Mgrite, (Cu, Fe)$_3$AsSe$_3$ |
| Def.: Dymkov et al. (1982). |
| Larosite, (Cu, Ag)$_2$PbBiS$_3$ |
| Arcubisite, CuAg$_6$BiS$_4$ |

| Chaméanite and mgrite: the same species? |
Chaméanite (Johan et al., 1982) and mgrite (Dymkov et al., 1982) have very similar chemical compositions and X-ray powder diagrams; the $a$ parameter of chaméanite is twice that of mgrite. They probably are the same species; in this case, chaméanite (IMA 1980-088) would have priority relatively to mgrite (IMA 1980-100), but reexamination of the type samples is needed.

In the Cu–As–Se ternary system (Cohen et al., 1995), there are only two ternary phases, CuAsSe$_2$ and Cu$_3$AsSe$_4$. According to Golovej et al. (1985), Cu$_3$AsSe$_4$ has the same unit cell as mgrite (5.530 Å; chaméanite: 5.519 × 2), and its crystal structure is given. Thus, the discrepancy between Cu/As/Se ratios of these three close compounds is difficult to explain.

6.2. Ag–rich sulfosalts

1. (Single type)

Samsonite, MnAg$_3$Sb$_2$S$_6$

2. Pyrargyrite family

Pyrargyrite isotypic pair

| Pyrargyrite, Ag$_3$Sb$_3$ |
| Prousite, Ag$_3$AsS$_3$ |
| STR: the two structures were refined by Engel & Nowacki (1966). |

| Related |

Ellisite, Tl$_3$AsS$_3$
STR: Gostojic (1980 – synth.).

3. Pyrostilpnite isotypic pair

| Pyrostilpnite, Ag$_3$SbS$_3$ |
| STR: Kutoglu (1968). |
| Xanthoconite, Ag$_3$AsS$_3$ |

4. Polybasite isotypic series

The nomenclature of this series has now been clarified through the resolution of the crystal structures of various polytypes. Details are given by Bindi et al. (2007a).

| Polybasite, Cu(Ag, Cu)$_6$Ag$_9$Sb$_2$S$_{11}$ |
| STR: Evain et al. (2006b). |
| Pearceite, Cu(Ag, Cu)$_6$Ag$_9$As$_2$S$_{11}$ |
| STR: Bindi et al. (2006). |

| Correspondence between old mineral names and related unit-cell types and new polytype nomenclature is given in Table 5. |

5. Unclassified sulfosalts

| Stephanite, Ag$_3$Sb$_4$ |
| Selenostephanite, Ag$_3$Sb(Se, S)$_4$ |
| Related? |

| Pettelite, Ag$_{24}$HgAs$_8$S$_{20}$ |
| STR: abstract by Pérez-Priede et al. (2005), who indicate similarities with laffittite although in this species the (Ag, Hg)/Pn/S ratio is quite distinct, and is identical to that of stephanite (5/1/4). |

6. Unclassified Ag sulfosalts

| Benleonardite, Ag$_3$(Sb, As)Te$_2$S$_3$ |
| Tsnigriite, Ag$_9$Sb(S, Se)$_3$Te$_3$ |
| Def.: Sandomirskaya et al. (1992). May be related to the argyrodate group. |
| Dervillite, Ag$_2$AsS$_3$ |
| Redefinition: Bari et al. (1983). |

| Dervillite: As–As bonding? (subulfosalt) |
As in tvalchrelidzeite (see below), the redefinition of dervillite (Bari et al., 1983) indicates a sulfur deficit that may correspond to As–As bonding, as in realgar. A crystal-structure determination is needed.

7. Unclassified sulfosalts

| Sarabauite, Sb$_4$S$_6$CaSb$_6$O$_{10}$ |
Table 5. Polytype nomenclature in the polybasite-pearceite series (Bindi et al., 2007a).

<table>
<thead>
<tr>
<th>Name</th>
<th>As/Sb ratio</th>
<th>Unit-cell</th>
<th>Old name</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearceite-Tac</td>
<td>As &gt; Sb</td>
<td>Type 111</td>
<td>Pearceite</td>
<td>Bindi et al. (2006)</td>
</tr>
<tr>
<td>Pearceite-T2ac</td>
<td>As &gt; Sb</td>
<td>Type 221</td>
<td>Arsenopolybasite</td>
<td>Bindi et al. (2007b)</td>
</tr>
<tr>
<td>Pearceite-M2a2b2c</td>
<td>As &gt; Sb</td>
<td>Type 222</td>
<td>Arsenopolybasite</td>
<td>– – –</td>
</tr>
<tr>
<td>Polybasite-Tac</td>
<td>Sb &gt; As</td>
<td>Type 111</td>
<td>Antimonopolybasite</td>
<td>– – –</td>
</tr>
<tr>
<td>Polybasite-T2ac</td>
<td>Sb &gt; As</td>
<td>Type 221</td>
<td>Polybasite</td>
<td>Evain et al. (2006b)</td>
</tr>
<tr>
<td>Polybasite-M2a2b2c</td>
<td>Sb &gt; As</td>
<td>Type 222</td>
<td>Polybasite</td>
<td>– – –</td>
</tr>
</tbody>
</table>

In addition to the sulfosalt minerals listed in this report, the published literature contains reports of about 200 unnamed minerals that can probably be regarded as sulfosalts, with compositions significantly different from those of known sulfosalts. Data on these minerals are included in a report by the Sub-Committee for Unnamed Minerals of the IMA Commission on New Minerals, Nomenclature and Classification (Smith & Nickel, 2007).

The still outstanding questions of systematics encountered in this report are summarized below. The questions mainly concern the status of about twenty species. As a complement, the final appendix is an extract of discredited names of sulfosalt species.

1. Valid minerals without specific published definitions
   - Approved by the IMA-CNMNC, but unpublished: marumoite (IMA 1998-004);
   - approved by the IMA-CNMNC, but only the crystal structure has been published: simonite (IMA 1982-052) (Engel et al., 1982);
   - without approval of the IMA-CNMNC, with publication of only the crystal structure: rebulite (Balić-Zumić et al., 1982).

2. Identical, or distinct species?
   - Fizélyite – ramdohrite pair;
   - twinnite – guettardite pair;
   - chaméanite – mgriite pair.

3. “Sulfosalt limbo”

3.1. Ill-defined or still questionable mineral species
   - Falkmanite (Pb2Sb2S6) and plumosite (Pb2Sb2S5): relationship with boulangerite?
   - Sakharovaité [FePb4(Sb, Bi)6S14]: species, or Bi-rich jamesonite?
   - Ustarasite [Pb(Bi, Sb)6S10]: no unit-cell determination.
   - Wittite [Pb3Bi10(S, Se)23]: species, or Se-rich variety of cannizzarite?
   - Zoubekite (AgPb2Sb4S10): doubtful unit-cell data.

3.2. Possible definition or redefinition as valid species
   - Annivite [Cu6(Cu4(Fe, Zn)2)[Bi, Sb, As]4S13]: possible revaluation for Bi > Sb, As (unit-cell data lacking);
   - Baumhauerite-ψO3abc [Ag3Pb38.1(As, Sb)52.8S96]: homeotype of baumhauerite andbaumhauerite-2a?
   - Bursaite [Pb3–3, Bi2+2, S6(?)]: needs crystal-structure data;

7.2. “Subsulfosalts”

Tvalchrelidzieite, Hg3SbAsS3
STR: Yang et al. (2007).

Criddleite, Ag2Au3T13S6S10

Jonassonite, Au(Bi, P b)2S4
Def.: Paar et al. (2006). There are two varieties of jonassonite. One variety, including that from the type deposit (Nagybörzsöny, Hungary) is Pb-rich (between 5 and 8 wt. %); the second one, which is more common, is Pb-free. Without crystal-structure data, one cannot say if the incorporation of Pb just corresponds to a solid solution, or if it induces structural changes.

In addition to the sulfosalts listed in this report, the published literature contains reports of about 200 unnamed minerals that can probably be regarded as sulfosalts, with compositions significantly different from those of known sulfosalts. Data on these minerals are included in a report by the Sub-Committee for Unnamed Minerals of the IMA Commission on New Minerals, Nomenclature and Classification (Smith & Nickel, 2007).

The still outstanding questions of systematics encountered in this report are summarized below. The questions mainly concern the status of about twenty species. As a complement, the final appendix is an extract of discredited names of sulfosalts.

1. Valid minerals without specific published definitions
   - Approved by the IMA-CNMNC, but unpublished: marumoite (IMA 1998-004);
   - approved by the IMA-CNMNC, but only the crystal structure has been published: simonite (IMA 1982-052) (Engel et al., 1982);
   - without approval of the IMA-CNMNC, with publication of only the crystal structure: rebulite (Balić-Zumić et al., 1982).

2. Identical, or distinct species?
   - Fizélyite – ramdohrite pair;
   - twinnite – guettardite pair;
   - chaméanite – mgriite pair.

3. “Sulfosalt limbo”

3.1. Ill-defined or still questionable mineral species
   - Falkmanite (Pb2Sb2S6) and plumosite (Pb2Sb2S5): relationship with boulangerite?
   - Sakharovaité [FePb4(Sb, Bi)6S14]: species, or Bi-rich jamesonite?
   - Ustarasite [Pb(Bi, Sb)6S10]: no unit-cell determination.
   - Wittite [Pb3Bi10(S, Se)23]: species, or Se-rich variety of cannizzarite?
   - Zoubekite (AgPb2Sb4S10): doubtful unit-cell data.

3.2. Possible definition or redefinition as valid species
   - Annivite [Cu6(Cu4(Fe, Zn)2)[Bi, Sb, As]4S13]: possible revaluation for Bi > Sb, As (unit-cell data lacking);
   - Baumhauerite-ψO3abc [Ag3Pb38.1(As, Sb)52.8S96]: homeotype of baumhauerite andbaumhauerite-2a?
   - Bursaite [Pb3–3, Bi2+2, S6(?)]: needs crystal-structure data;

7.2. “Subsulfosalts”

Tvalchrelidzieite, Hg3SbAsS3
STR: Yang et al. (2007).

Criddleite, Ag2Au3T13S6S10

Jonassonite, Au(Bi, P b)2S4
Def.: Paar et al. (2006). There are two varieties of jonassonite. One variety, including that from the type deposit (Nagybörzsöny, Hungary) is Pb-rich (between 5 and 8 wt. %); the second one, which is more common, is Pb-free. Without crystal-structure data, one cannot say if the incorporation of Pb just corresponds to a solid solution, or if it induces structural changes.

Sulfosalts, or not?
All these three minerals show a strong sulfur deficiency (“subsulfides”), indicating that As, Sb or Bi may also act as an anion (see also dervillite). Crystal-structure studies are necessary to answer this question and to confirm that these minerals conform to the extended definition of a sulfosalt.

7.3. PGE sulfosalts?

Borovskite, Pd3SbTe4
Crerarite, (Pt, Pb)Bi3(S, Se)4–x
Def.: Cook et al. (1994).
Crystal-structure data are necessary to ascertain whether these minerals are sulfosalts.

8. Conclusion
This re-examination of sulfosalts systematics indicates that today there are more than 220 valid mineral species (see the alphabetical index). Together with the regular discovery of new species, as exemplified by the annual reports of the IMA-CNMNC and previous CNMMN, the progress in crystal-structure study will play a critical role for the resolution of some questions of systematics still in abeyance. More than 50 crystal structures remain unsolved, among which about half probably correspond to new structure types.
- **Incaite** (~ FePb$_4$Sn$_2$Sb$_2$S$_{14}$): possible revalidation if Sn$^{2+}$ > Pb$^{2+}$ in a natural sample;
- **Ourayite-P** (~ Ag$_{3.6}$Pb$_{2.8}$Bi$_{6}$S$_{13}$): empirical formula;
- **Rathite-IV**: chemical formula unknown;
- **Schirmerite** (Type 1 – Ag$_4$Pb$_4$S$_9$): identical with schapbachite, or a dimorph?

Beyond, and complementary to the definition of each individual mineral species, is the question of relative limits of neighbouring sulfosalts in complex crystal-chemical systems. Four examples have been presented in this report:

- the aikinite–bismuthinite homeotypic series. Here numerous intermediate homeotypes have been defined, but the narrow solid-solution fields of all species have to be defined;
- the sartorite homologous series. In this group complex superstructures are present, especially for As-rich members, together with the presence of minor Tl or Ag. New resolutions of true structures in this system are necessary to understand the role of these chemical factors;
- tetrahedrite isotypic series. Contrary to the aikinite–bismuthinite series, in this series there are extended solid solutions, and the transitions between different poles must be defined (e.g., the limits between tetrahedrite, freibergite and argentotetrahedrite);
- the lillianite–andorite homologous series. Here there are extended (but not complete) solid solutions on the one hand (e.g., Bi$^{3+}$ ↔ Sb$^{3+}$, or 2 Pb$^{2+}$ ↔ Ag$^+$ + Bi$^{3+}$), and, on the other hand, stabilization of discrete compounds by metals with minor content (Mn, Cd, Fe).

In the years to come, progress in the field of the systematics of sulfosalts will be more and more dependent on crystal structure studies, that requires the availability of well-ordered natural or synthetic crystals, as well as a combination of various methods, taking into account modern approaches (e.g., single crystal and powder synchrotron X-ray diffraction; application of non-harmonic approach to atomic displacement parameters for Cu- and Ag-rich sulfosalts; *ab initio* structure determinations).

---

**Alphabetical index of accepted species of sulfosalts with As$^{3+}$, Sb$^{3+}$, Bi$^{3+}$ or Te$^{4+}$**

<table>
<thead>
<tr>
<th>Species</th>
<th>Chapter</th>
<th>Formula</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aikinite</td>
<td>4.3</td>
<td>CuPbBiS$_3$</td>
<td>CSU</td>
</tr>
<tr>
<td>Aktashite</td>
<td>6.1.3</td>
<td>Cu$_9$H$_2$As$<em>3$S$</em>{12}$</td>
<td></td>
</tr>
<tr>
<td>Aleksite</td>
<td>2.1</td>
<td>PbBi$_2$S$_2$Te$_2$</td>
<td></td>
</tr>
<tr>
<td>Andorite IV</td>
<td>3.1.1</td>
<td>Ag$<em>{11}$Pb$</em>{12}$Sb$<em>2$S$</em>{66}$</td>
<td>CSU – also named “quatrandorite”</td>
</tr>
<tr>
<td>Andorite VI</td>
<td>3.1.1</td>
<td>AgPbSb$_3$S$_6$</td>
<td>Also named “senandorite”</td>
</tr>
<tr>
<td>Angelaita</td>
<td>2.3.1</td>
<td>Cu$_3$AgPbBiS$_4$</td>
<td></td>
</tr>
<tr>
<td>Aramaoyite</td>
<td>1.1.2</td>
<td>Ag$_2$Sb$_2$(Bi, Sb)S$_6$</td>
<td></td>
</tr>
<tr>
<td>Arcubisite</td>
<td>1.5</td>
<td>CuAg$_2$BiS$_4$</td>
<td>CSU</td>
</tr>
<tr>
<td>Ardaite</td>
<td>4.4</td>
<td>Pb$<em>{7}$Sb$</em>{13}$S$_{25}$Cl$_9$</td>
<td>CSU</td>
</tr>
<tr>
<td>Argentotennantite</td>
<td>6.1.2</td>
<td>Ag$_{10}$[Cu$_4$(Fe, Zn)$_2$]As$<em>3$S$</em>{13}$</td>
<td>CSU</td>
</tr>
<tr>
<td>Argentotetrahedrite</td>
<td>6.1.2</td>
<td>Ag$_{10}$(Fe, Zn)$_2$Sb$<em>2$S$</em>{13}$</td>
<td>CSU. Published without CNMNC approval</td>
</tr>
<tr>
<td>Aschamalinite</td>
<td>3.2</td>
<td>Pb$<em>{6-3}$,Bi$</em>{2+1}$S$_9$</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Babkinite</td>
<td>2.1</td>
<td>Pb$_2$Bi$_2$(S, Se)$_3$</td>
<td>CSU</td>
</tr>
<tr>
<td>Baumhauerite</td>
<td>3.8.2</td>
<td>Pb$<em>{13}$As$</em>{16}$S$_{56}$</td>
<td>CSU</td>
</tr>
<tr>
<td>Baumhauerite-2a</td>
<td>3.8.2</td>
<td>~ Ag$<em>{11}$Pb$</em>{22}$As$<em>{15.5}$S$</em>{72}$</td>
<td></td>
</tr>
<tr>
<td>Baumstarkite</td>
<td>1.1.2</td>
<td>Ag$_2$Sb$_2$S$_6$</td>
<td></td>
</tr>
<tr>
<td>Benavidesite</td>
<td>4.1</td>
<td>MnPb$_2$Sb$<em>2$S$</em>{14}$</td>
<td></td>
</tr>
<tr>
<td>Benjamineite</td>
<td>3.2</td>
<td>Ag$_3$Bi$<em>2$S$</em>{12}$</td>
<td></td>
</tr>
<tr>
<td>Benlemardite</td>
<td>6.2.6</td>
<td>Ag$_2$(Sb, As)$_2$Te$_2$S$_5$</td>
<td>CSU</td>
</tr>
<tr>
<td>Bernardite</td>
<td>5.1.1</td>
<td>TiAs$_2$S$_8$</td>
<td></td>
</tr>
<tr>
<td>Berryite</td>
<td>2.2.1</td>
<td>Cu$_3$Ag$_2$Pb$_2$Bi$<em>4$S$</em>{16}$</td>
<td></td>
</tr>
<tr>
<td>Bertherite</td>
<td>4.1</td>
<td>FeSb$_2$S$_4$</td>
<td></td>
</tr>
<tr>
<td>Bohdanoviczite</td>
<td>1.1.1</td>
<td>AgBiS$_2$</td>
<td>True crystal-structure unknown</td>
</tr>
<tr>
<td>Borodavite</td>
<td>3.2</td>
<td>Ag$<em>{2-8}$Fe$</em>{0-21}$Pb$<em>{0.45}$(Bi, Sb)$</em>{8.84}$S$_{16}$</td>
<td>CSU</td>
</tr>
<tr>
<td>Borovskite</td>
<td>7.3</td>
<td>Pb$_3$SbTe$_2$</td>
<td>CSU</td>
</tr>
<tr>
<td>Boulangerite</td>
<td>4.1</td>
<td>Pb$_2$Sb$_2$S$_9$</td>
<td></td>
</tr>
<tr>
<td>Bournonite</td>
<td>1.2.2</td>
<td>CuPbSb$_3$S$_9$</td>
<td></td>
</tr>
<tr>
<td>Buckhornite</td>
<td>2.2.1</td>
<td>(Pb$_2$Bi$_3$)(AuTe$_2$)</td>
<td></td>
</tr>
</tbody>
</table>

CSU: Crystal structure unsolved. Φ: vacancy. Q: Validity questionable (see Sect. 3.1 of the final conclusion)
<table>
<thead>
<tr>
<th>Species</th>
<th>Chapter</th>
<th>Formula</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cannizzarite</td>
<td>2.2.2</td>
<td>~ Pb$<em>3$Bi$</em>{16}$S$_{23}$</td>
<td></td>
</tr>
<tr>
<td>Cetineite</td>
<td>7.1</td>
<td>Na$_2$Sb$_2$O$_3$(H$_2$O)$_6$</td>
<td></td>
</tr>
<tr>
<td>Chabournéite</td>
<td>3.8.5</td>
<td>Tl$<em>x$(Sb, As)$</em>{2-x}$S$_4$</td>
<td></td>
</tr>
<tr>
<td>Chalcobmite</td>
<td>1.1.7</td>
<td>CuSbS$_2$</td>
<td></td>
</tr>
<tr>
<td>Chahénaire</td>
<td>6.1.5</td>
<td>(Cu, Fe)$_3$As(Se, S)$_4$</td>
<td>CSU – probably identical with mgriite</td>
</tr>
<tr>
<td>Christite</td>
<td>1.2.4</td>
<td>HgTlAsS$_3$</td>
<td></td>
</tr>
<tr>
<td>Clerite</td>
<td>4.1</td>
<td>MnSbS$_4$</td>
<td></td>
</tr>
<tr>
<td>Cosalite</td>
<td>4.1</td>
<td>Pb$<em>3$Bi$</em>{16}$S$_{23}$</td>
<td></td>
</tr>
<tr>
<td>Cersarite</td>
<td>7.3</td>
<td>(Pt, Pb)Bi$<em>4$(S, Se)$</em>{4-x}$</td>
<td>CSU</td>
</tr>
<tr>
<td>Criddleite</td>
<td>7.2</td>
<td>Ag$<em>2$Au$<em>2$Tl$</em>{10}$S$</em>{16}$</td>
<td>CSU</td>
</tr>
<tr>
<td>Cuboargyrite</td>
<td>1.1.3</td>
<td>AgSbS$_2$</td>
<td></td>
</tr>
<tr>
<td>Cuprobismutite</td>
<td>3.3</td>
<td>Cu$<em>4$AgBi$</em>{12}$S$_{23}$</td>
<td></td>
</tr>
<tr>
<td>Cupromakovickyite</td>
<td>3.2</td>
<td>Cu$_4$AgPb$<em>2$Bi$</em>{18}$</td>
<td>CSU</td>
</tr>
<tr>
<td>Cupropavonite</td>
<td>3.2</td>
<td>Cu$<em>{0.9}$Ag$</em>{0.5}$Pb$<em>{0.6}$Bi$</em>{2.5}$S$_5$</td>
<td></td>
</tr>
<tr>
<td>Cylindrite</td>
<td>2.2.2</td>
<td>~ FePb$_3$Sn$_2$Sb$<em>2$S$</em>{14}$</td>
<td>(mean structure only)</td>
</tr>
<tr>
<td>Dadsonite</td>
<td>4.1</td>
<td>Pb$<em>3$Sb$</em>{16}$S$_{20}$Cl</td>
<td></td>
</tr>
<tr>
<td>Dervillite</td>
<td>6.2.6</td>
<td>Ag$_3$AsS$_2$</td>
<td>CSU</td>
</tr>
<tr>
<td>Diaphorite</td>
<td>1.2.1</td>
<td>Ag$_3$Pb$_2$Sb$_6$</td>
<td></td>
</tr>
<tr>
<td>Dufrénoysite</td>
<td>3.8.6</td>
<td>Pb$_3$As$_2$S$_5$</td>
<td></td>
</tr>
<tr>
<td>Edenharterite</td>
<td>5.1.2</td>
<td>TIPb$_3$As$_3$S$_8$</td>
<td></td>
</tr>
<tr>
<td>Ellisite</td>
<td>6.2.2</td>
<td>Tl$_3$AsS$_3$</td>
<td></td>
</tr>
<tr>
<td>Emilite</td>
<td>4.3</td>
<td>Cu$<em>{10.7}$Pb$</em>{10.7}$Bi$<em>{21.1}$S$</em>{48}$</td>
<td></td>
</tr>
<tr>
<td>Eclarite</td>
<td>4.2.2</td>
<td>(Cu, Fe)Pb$<em>3$Bi$</em>{12}$S$_{28}$</td>
<td></td>
</tr>
<tr>
<td>Empelcit</td>
<td>1.1.7</td>
<td>CuBiS$_2$</td>
<td></td>
</tr>
<tr>
<td>Erniggliite</td>
<td>5.4</td>
<td>SnTl$_2$As$_2$S$_6$</td>
<td></td>
</tr>
<tr>
<td>Eskimoite</td>
<td>3.1.2</td>
<td>Ag$<em>3$Pb$<em>2$Bi$</em>{15}$S$</em>{16}$</td>
<td>(CSU – structure model only)</td>
</tr>
<tr>
<td>Falkmanite</td>
<td>4.1</td>
<td>Pb$<em>3$Sb$</em>{16}$S$_{20}$Cl</td>
<td>Q – CSU. Relationship with boulangerite?</td>
</tr>
<tr>
<td>Felbertalite</td>
<td>2.3.1</td>
<td>Cu$_3$Pb$_2$Sb$_6$</td>
<td></td>
</tr>
<tr>
<td>Fetetelite</td>
<td>6.2.5</td>
<td>Ag$<em>{24}$HgAs$</em>{33}$S$_{20}$</td>
<td>Crystal structure: abstract only</td>
</tr>
<tr>
<td>Fizélyite</td>
<td>3.1.1</td>
<td>Ag$_3$Pb$_2$Sb$<em>6$S$</em>{18}$</td>
<td>CSU</td>
</tr>
<tr>
<td>Frankeite</td>
<td>2.2.2</td>
<td>Fe(Pb, Sn)$_3$S$_2$Bi$_2$Sb$<em>2$S$</em>{14}$</td>
<td>(mean structure only)</td>
</tr>
<tr>
<td>Freibergite</td>
<td>6.1.2</td>
<td>Ag$_{([Cu}<em>4$Fe$</em>{2}]$Sb$<em>3$S$</em>{13-15}$)?</td>
<td>Limit with Ag-rich tetrahedrite?</td>
</tr>
<tr>
<td>Freieslebenite</td>
<td>1.2.1</td>
<td>AgPbSbS$_3$</td>
<td></td>
</tr>
<tr>
<td>Friedrichte</td>
<td>4.3</td>
<td>Cu$<em>3$Pb$<em>2$Bi$</em>{18}$S$</em>{18}$</td>
<td>CSU</td>
</tr>
<tr>
<td>Fülöppite</td>
<td>3.7</td>
<td>Pb$<em>3$Sb$</em>{16}$S$_{15}$</td>
<td></td>
</tr>
<tr>
<td>Gabrielite</td>
<td>5.4</td>
<td>Cu$_3$AgTl$_2$As$_3$S$_7$</td>
<td></td>
</tr>
<tr>
<td>Galenobismutite</td>
<td>2.3.1</td>
<td>PbBi$_2$S$_3$</td>
<td></td>
</tr>
<tr>
<td>Galkhaite</td>
<td>6.1.2</td>
<td>(Cs, Tl, Y)(Hg, Cu, Zn, Tl)$_6$ (As, Sb)$<em>4$S$</em>{12}$</td>
<td></td>
</tr>
<tr>
<td>Garavellite</td>
<td>4.1</td>
<td>FeSbBiS$_4$</td>
<td></td>
</tr>
<tr>
<td>Geocronite</td>
<td>3.5.1</td>
<td>Pb$_{14}$Sb$_3$Sb$_2$Sb$<em>2$S$</em>{23}$</td>
<td></td>
</tr>
<tr>
<td>Geslyeite</td>
<td>5.1.4</td>
<td>Na$_x$(Sb, As)$_3$S$_7$2H$_2$O</td>
<td></td>
</tr>
<tr>
<td>Giessenite</td>
<td>4.2.2</td>
<td>(Cu, Fe)$<em>2$Pb$</em>{25.4}$Bi$<em>{19.6}$S$</em>{57}$</td>
<td>CSU</td>
</tr>
<tr>
<td>Gillulyite</td>
<td>5.1.3</td>
<td>Tl$_3$As$_7$Sb$_2$Sb$<em>3$S$</em>{13}$</td>
<td></td>
</tr>
<tr>
<td>Giraudite</td>
<td>6.1.2</td>
<td>Cu$_{4([Cu}<em>3$Fe$</em>{2}]$Sb$<em>3$S$</em>{13}$?</td>
<td>CSU</td>
</tr>
<tr>
<td>Gladite</td>
<td>4.3</td>
<td>CuPbBi$_2$S$_3$</td>
<td></td>
</tr>
<tr>
<td>Goldfieldite</td>
<td>6.1.2</td>
<td>Cu$_{19}$Te$<em>2$S$</em>{13}$</td>
<td></td>
</tr>
<tr>
<td>Gratonite</td>
<td>3.6</td>
<td>Pb$_3$As$_2$S$_5$</td>
<td></td>
</tr>
<tr>
<td>Grumiplucite</td>
<td>3.2</td>
<td>HgBi$_2$S$_4$</td>
<td></td>
</tr>
<tr>
<td>Gruzdevite</td>
<td>6.1.3</td>
<td>Cu$<em>{6}$Hg$</em>{3}$Sb$_{12}$</td>
<td>CSU</td>
</tr>
<tr>
<td>Guettardite</td>
<td>3.8.1</td>
<td>Pb$<em>3$(Sb$</em>{36}$As$_{9.41}$)$<em>6$S$</em>{32}$</td>
<td>CSU – difference with twinnite?</td>
</tr>
<tr>
<td>Gustavite</td>
<td>3.1.1</td>
<td>AgPbBi$_2$S$_3$</td>
<td></td>
</tr>
<tr>
<td>Species</td>
<td>Chapter</td>
<td>Formula</td>
<td>Remark</td>
</tr>
<tr>
<td>------------------</td>
<td>---------</td>
<td>-------------------------------------------------------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>Hakite</td>
<td>6.1.2</td>
<td>Cu₂[(Cu, Hg)₂]Sb₂Se₁₃</td>
<td>CSU</td>
</tr>
<tr>
<td>Hammarite</td>
<td>4.3</td>
<td>Cu₃Pb₂Bi₄S₉</td>
<td></td>
</tr>
<tr>
<td>Hatchite</td>
<td>1.3</td>
<td>AgTlPbAs₂S₅</td>
<td></td>
</tr>
<tr>
<td>Heteromorphite</td>
<td>3.7</td>
<td>Pb₃Sb₂S₁₉</td>
<td></td>
</tr>
<tr>
<td>Heyrovskýite</td>
<td>3.1.2</td>
<td>Pb₆Bi₂S₉</td>
<td></td>
</tr>
<tr>
<td>Hodrushite</td>
<td>3.3</td>
<td>Cu₃Bi₂S₂₂</td>
<td></td>
</tr>
<tr>
<td>Hutchinsonite</td>
<td>5.1.1</td>
<td>TlPbAs₅S₉</td>
<td></td>
</tr>
<tr>
<td>Imhotite</td>
<td>5.1.3</td>
<td>Tl₃,₅As₁₂,₂S₂₆</td>
<td></td>
</tr>
<tr>
<td>Izoklakeite</td>
<td>4.2.2</td>
<td>(Cu, Fe)₂Pb₂₆₋₄(Sb, Bi)₁₀₋₉S₇₁</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jamesonite</td>
<td>4.1</td>
<td>FePb₃Sb₆S₁₄</td>
<td></td>
</tr>
<tr>
<td>Jankovičite</td>
<td>5.2</td>
<td>Tl₆Sb₆(As, Sb)₄S₂₂</td>
<td></td>
</tr>
<tr>
<td>Jaskólskiite</td>
<td>3.4</td>
<td>Cu₃Pb₂₋₂(Sb, Bi)₂₋₁S₅</td>
<td></td>
</tr>
<tr>
<td>Jentschite</td>
<td>5.1.2</td>
<td>TlPbAs₂Sb₆</td>
<td></td>
</tr>
<tr>
<td>Jonassonite</td>
<td>7.2</td>
<td>Au(Bi, Pb)₂S₄</td>
<td>CSU</td>
</tr>
<tr>
<td>Jordanite</td>
<td>3.5.1</td>
<td>Pb₄₋₂(As, Sb)₂S₂₃</td>
<td></td>
</tr>
<tr>
<td>Junoite</td>
<td>2.3.1</td>
<td>Cu₃Pb₆Bi₆(S, Se)₁₆</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kirkrite</td>
<td>3.5.2</td>
<td>Pb₁₀Bi₁₆As₁₃S₉₁</td>
<td></td>
</tr>
<tr>
<td>Kobellite</td>
<td>4.2.2</td>
<td>(Cu, Fe)₂Pb₁₁(Bi, Sb)₁₁S₅</td>
<td></td>
</tr>
<tr>
<td>Kochkarite</td>
<td>2.1</td>
<td>PbBi₄Te₇</td>
<td></td>
</tr>
<tr>
<td>Krupkaite</td>
<td>4.3</td>
<td>CuPb₂S₆</td>
<td></td>
</tr>
<tr>
<td>Kudriavite</td>
<td>3.2</td>
<td>(Cd, Pb)Bi₂S₃</td>
<td></td>
</tr>
<tr>
<td>Kupčíkite</td>
<td>3.3</td>
<td>Cu₁₃,₄Fe₀₋₉Bi₆S₁₀</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laffitte</td>
<td>6.1.3</td>
<td>AgHgAsS₃</td>
<td></td>
</tr>
<tr>
<td>Lapiite</td>
<td>1.2.3</td>
<td>CuNiSb₃</td>
<td>CSU</td>
</tr>
<tr>
<td>Larosite</td>
<td>6.1.5</td>
<td>(Cu, Ag)₁₂PbBiS₁₃</td>
<td>CSU</td>
</tr>
<tr>
<td>Launayite</td>
<td>4.4</td>
<td>CuPb₁₀(Sb, As)₁₁S₃₀</td>
<td>CSU</td>
</tr>
<tr>
<td>Lengenbachite</td>
<td>2.2.2</td>
<td>~ Cu₃Ag₃Pb₁₈As₁₂S₉₉</td>
<td>CSU - structural model</td>
</tr>
<tr>
<td>Lévyieldingtide</td>
<td>2.2.2</td>
<td>~ Cu₁₉Pb₁₈S₁₉(Bi, Sb)₁₈S₂₈</td>
<td></td>
</tr>
<tr>
<td>Lilianite</td>
<td>3.1.1</td>
<td>Ag₁₅Pb₂₋₂Bi₂₋₁S₅</td>
<td></td>
</tr>
<tr>
<td>Lindströmite</td>
<td>4.3</td>
<td>Cu₃Pb₂Bi₂S₅</td>
<td></td>
</tr>
<tr>
<td>Liveingite</td>
<td>3.8.3</td>
<td>Pb₂₀As₁₂S₃₆</td>
<td></td>
</tr>
<tr>
<td>Livingstonite</td>
<td>3.2</td>
<td>HgSb₄S₈₂(S₂)</td>
<td></td>
</tr>
<tr>
<td>Lorandite</td>
<td>1.1.7</td>
<td>Ti₂As₅S₂</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Madocite</td>
<td>4.4</td>
<td>Pb₁₀(Sb, As)₁₆S₄₃</td>
<td>CSU</td>
</tr>
<tr>
<td>Makovickyite</td>
<td>3.2</td>
<td>Cu₁₁₂Ag₃₁₃Pb₂₇Bi₅₃S₅</td>
<td>CSU</td>
</tr>
<tr>
<td>Malyshhevite</td>
<td></td>
<td>CuPb₂BiS₃</td>
<td></td>
</tr>
<tr>
<td>Marrite</td>
<td>1.2.1</td>
<td>AgPbAsS₅</td>
<td></td>
</tr>
<tr>
<td>Marumoite</td>
<td>3.8.5</td>
<td>Pb₃As₆₀S₉₂</td>
<td>CSU - no mineral description (IMA 1998-004)</td>
</tr>
<tr>
<td>Marruccite</td>
<td>4.2.1</td>
<td>Hg₈Pb₁₆Sb₁₆S₆₆</td>
<td></td>
</tr>
<tr>
<td>Matildite</td>
<td>1.1.1</td>
<td>Ag₂BiS₂</td>
<td>True crystal-structure unknown</td>
</tr>
<tr>
<td>Mazzettiite</td>
<td>6.1.5</td>
<td>Ag₁₅HgPb₂BiS₃₅</td>
<td>CSU</td>
</tr>
<tr>
<td>Meneghinite</td>
<td>3.4</td>
<td>Cu₃Pb₂Sb₂S₂₄</td>
<td></td>
</tr>
<tr>
<td>Mgrite</td>
<td>6.1.5</td>
<td>(Cu, Fe)₂As₆S₃</td>
<td>CSU - probably identical with chamanéite</td>
</tr>
<tr>
<td>Miargyrite</td>
<td>1.1.4</td>
<td>Ag₂Sb₂S₅</td>
<td></td>
</tr>
<tr>
<td>Miharaite</td>
<td>6.1.5</td>
<td>Cu₃FePb₂BiS₆</td>
<td></td>
</tr>
<tr>
<td>Moëloite</td>
<td>4.1</td>
<td>Pb₂Sb₂S₁₄(S₁₃)</td>
<td></td>
</tr>
<tr>
<td>Mozgovite</td>
<td>3.2</td>
<td>Pb₂Bi₄(S, Se)₇</td>
<td>CSU</td>
</tr>
<tr>
<td>Mückeite</td>
<td>1.2.3</td>
<td>CuNiBi₃S₅</td>
<td></td>
</tr>
<tr>
<td>Mummeite</td>
<td>3.2</td>
<td>Cu₆₅₈₅Ag₁₁₁₁Pb₁₀₀₈₁₈₆S₁₃</td>
<td></td>
</tr>
<tr>
<td>Musemumite</td>
<td>2.2.1</td>
<td>Pb₂(Pb, Sb)₂S₈(Te, Au)₂</td>
<td>CSU</td>
</tr>
<tr>
<td>Mutnovskite</td>
<td>3.9</td>
<td>Pb₂As₃₅(L, Cl, Br)</td>
<td></td>
</tr>
<tr>
<td>Species</td>
<td>Chapter</td>
<td>Formula</td>
<td>Remark</td>
</tr>
<tr>
<td>------------------</td>
<td>---------</td>
<td>----------------------------------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>Nagyágite</td>
<td>2.2.1</td>
<td>[Pb₃(Pb, Sb)₃S₉]₄[Te, Au]₃</td>
<td></td>
</tr>
<tr>
<td>Neyite</td>
<td>2.3.2</td>
<td>Cu₆Ag₃Pb₂Bi₃S₈</td>
<td></td>
</tr>
<tr>
<td>Nordströmîte</td>
<td>2.3.1</td>
<td>CuPbBi₇(S, Se)₁₄</td>
<td></td>
</tr>
<tr>
<td>Nowackiite</td>
<td>6.1.3</td>
<td>Cu₆Zn₁As₃S₁₂</td>
<td></td>
</tr>
<tr>
<td>Nuffixite</td>
<td>2.3.1</td>
<td>Cu₁₁Pb₂Bi₃S₈</td>
<td></td>
</tr>
<tr>
<td>Ottensite</td>
<td>7.1</td>
<td>Na₆(Sb₂O₃)₇(SbS₄)₃·H₂O</td>
<td>CSU</td>
</tr>
<tr>
<td>Ourayite</td>
<td>3.1.3</td>
<td>Ag₃Pb₃Bi₃S₁₃</td>
<td>CSU</td>
</tr>
<tr>
<td>Owyheeite</td>
<td>4.2.1</td>
<td>Ag₃Pb₉Sb₁₁S₂₈</td>
<td></td>
</tr>
<tr>
<td>Paarite</td>
<td>4.3</td>
<td>Cu₁₁Pb₁₇Bi₆₃S₁₂</td>
<td></td>
</tr>
<tr>
<td>Padérite</td>
<td>3.3</td>
<td>Cu₆[(Cu, Ag)₆₃Pb₁₁₃Bi₁₁₃]₂₁₃S₂₂</td>
<td></td>
</tr>
<tr>
<td>Parapierrotite</td>
<td>3.8.7</td>
<td>Tl₇Sb₈S₉</td>
<td></td>
</tr>
<tr>
<td>Pavonite</td>
<td>3.2</td>
<td>AgBi₃S₉</td>
<td></td>
</tr>
<tr>
<td>Pearceite</td>
<td>6.2.4</td>
<td>Cu₆Ag₃Cu₆Ag₃As₃S₁₁</td>
<td></td>
</tr>
<tr>
<td>Pekoite</td>
<td>4.3</td>
<td>CuPbBi₁₇S₈</td>
<td></td>
</tr>
<tr>
<td>Pellouxite</td>
<td>4.2.1</td>
<td>(Cu, Ag)₆₃Pb₃Sb₃₅S₅ClO</td>
<td>CSU</td>
</tr>
<tr>
<td>Petroviciite</td>
<td>6.1.5</td>
<td>Cu₉HgPbBi₃S₉</td>
<td></td>
</tr>
<tr>
<td>Pierrotite</td>
<td>3.8.7</td>
<td>Tl₇(Sb, As)₁₀S₁₆</td>
<td></td>
</tr>
<tr>
<td>Pillâite</td>
<td>4.2.1</td>
<td>Pb₂Sb₉S₅ClO₅</td>
<td></td>
</tr>
<tr>
<td>Pizgrischite</td>
<td>3.3</td>
<td>(Cu, Fe₆₃PbBi₁₇S₄₄</td>
<td></td>
</tr>
<tr>
<td>Plagiornitie</td>
<td>3.7</td>
<td>Pb₂Sb₇S₁₇</td>
<td></td>
</tr>
<tr>
<td>Playfairite</td>
<td>4.4</td>
<td>Pb₁₆(Sb, As)₁₀S₄₄Cl</td>
<td>CSU</td>
</tr>
<tr>
<td>Plutusite</td>
<td>4.1</td>
<td>Pb₂Sb₅S₉</td>
<td>Q – CSU. Relationship with boulangerîte?</td>
</tr>
<tr>
<td>Polybasite</td>
<td>6.2.4</td>
<td>Cu₆Ag₃Cu₆Ag₃Sb₅S₁₁</td>
<td></td>
</tr>
<tr>
<td>Poubaite</td>
<td>2.1</td>
<td>PbBi₁₇(Se, Te, S)₄</td>
<td></td>
</tr>
<tr>
<td>Proudite</td>
<td>2.3.1</td>
<td>Cu₆PbBi₁₇(Se, Te, S)₄₀</td>
<td></td>
</tr>
<tr>
<td>Proustite</td>
<td>6.2.2</td>
<td>Ag₃As₃S₉</td>
<td></td>
</tr>
<tr>
<td>Pyrargyrite</td>
<td>6.2.2</td>
<td>Ag₃Sb₃S₉</td>
<td></td>
</tr>
<tr>
<td>Pyrostîlpnite</td>
<td>6.2.3</td>
<td>Ag₃Sb₃S₉</td>
<td></td>
</tr>
<tr>
<td>Quadratîte</td>
<td>1.2.1</td>
<td>Ag₃(Cd, Pb)(As, Sb)₃S₉</td>
<td></td>
</tr>
<tr>
<td>Rambôîrite</td>
<td>3.1.1</td>
<td>(Cd, Mn, Fe)₆₃Pb₃Sb₂₁₃S₄₈</td>
<td>Distinction from ûzélyîte?</td>
</tr>
<tr>
<td>Ratîte</td>
<td>3.8.4</td>
<td>Ag₆Pb₁₂·Ti(1/2)As₁₆₃/₄S₄₀</td>
<td></td>
</tr>
<tr>
<td>Rayîte</td>
<td>3.7</td>
<td>(Ag, Ti)₆₃Pb₃Sb₇S₄₃</td>
<td>CSU – needs an unit-cell redetermination</td>
</tr>
<tr>
<td>Rebulite</td>
<td>5.2</td>
<td>Ti₇As₃Sb₇S₂₂</td>
<td>No mineral description, nor CNMNC approval</td>
</tr>
<tr>
<td>Robinsonite</td>
<td>4.1</td>
<td>Pb₂Sb₉S₁₃</td>
<td></td>
</tr>
<tr>
<td>Rokshîmite</td>
<td>3.1.1</td>
<td>(Ag, Cu)₆₃Pb₉Sb₁₁S₆₆</td>
<td></td>
</tr>
<tr>
<td>Rouhierîte</td>
<td>6.1.4</td>
<td>CuHg₆TlAs₃S₉</td>
<td>CSU</td>
</tr>
<tr>
<td>Rouxelite</td>
<td>2.3.2</td>
<td>Cu₆HgPbBi₂₁₇Sb₂₃S₆₄(O, S)₂</td>
<td></td>
</tr>
<tr>
<td>Rucklîdgeîte</td>
<td>2.1</td>
<td>PbBi₁₇Te₄</td>
<td></td>
</tr>
<tr>
<td>Saddlebackîte</td>
<td>2.1</td>
<td>Pb₂Bi₁₇Te₅</td>
<td>CSU</td>
</tr>
<tr>
<td>Salzbergîte</td>
<td>4.3</td>
<td>Cu₆Pb₆Bi₆₃S₁ₒ</td>
<td></td>
</tr>
<tr>
<td>Sakharovîte</td>
<td>4.1</td>
<td>Fe₆₃Pb₆(Sb, Bi)₆₃S₁₄</td>
<td>Q – CSU. unit cell not given</td>
</tr>
<tr>
<td>Samsonite</td>
<td>6.2.1</td>
<td>Mn₆₃Pb₆Sb₉S₉</td>
<td></td>
</tr>
<tr>
<td>Sarabauîte</td>
<td>7.1</td>
<td>Sb₉S₉·CuSb₉O₁₀</td>
<td></td>
</tr>
<tr>
<td>Sartorîte</td>
<td>3.8.1</td>
<td>Pb₈Sb₉S₉</td>
<td></td>
</tr>
<tr>
<td>Scâinîte</td>
<td>4.2.1</td>
<td>Pb₆Sb₉S₆O₄</td>
<td></td>
</tr>
<tr>
<td>Schapbachîte</td>
<td>1.2.1</td>
<td>Ag₆Pb₁₂Bi₆₃S₆</td>
<td>Redefinition</td>
</tr>
<tr>
<td>Selenopolybasite</td>
<td>6.2.4</td>
<td>Cu₆Ag₃Cu₆Ag₃Sb₂₁₇S₆₃S₆₄(S, Se)₆₄</td>
<td></td>
</tr>
<tr>
<td>Selenostîpheîte</td>
<td>6.2.5</td>
<td>Ag₃Sb₉(Se, S)₆₄</td>
<td>CSU</td>
</tr>
<tr>
<td>Seïlgmînîte</td>
<td>1.2.2</td>
<td>CuPb₆Sb₉S₉</td>
<td></td>
</tr>
<tr>
<td>Species</td>
<td>Chapter</td>
<td>Formula</td>
<td>Remark</td>
</tr>
<tr>
<td>-----------------------</td>
<td>---------</td>
<td>----------------------------------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>Semseyite</td>
<td>3.7</td>
<td>Pb$_3$Sb$<em>5$S$</em>{11}$</td>
<td></td>
</tr>
<tr>
<td>Sicherite</td>
<td>5.3</td>
<td>Ag$_2$Tl(As, Sb)$_3$S$_6$</td>
<td></td>
</tr>
<tr>
<td>Simonite</td>
<td>5.4</td>
<td>HgTlAs$_3$S$_6$</td>
<td></td>
</tr>
<tr>
<td>Sinnerite</td>
<td>6.1.3</td>
<td>Cu$_6$As$_3$S$_9$</td>
<td>No mineral description</td>
</tr>
<tr>
<td>Skinnerite</td>
<td>6.1.1</td>
<td>Cu$_3$SbS$_3$</td>
<td></td>
</tr>
<tr>
<td>Smithite</td>
<td>1.1.5</td>
<td>Ag$_5$As$_2$</td>
<td></td>
</tr>
<tr>
<td>Sorbyite</td>
<td>4.4</td>
<td>CuPb$<em>3$(Sb, As)$</em>{11}$S$_{26}$</td>
<td></td>
</tr>
<tr>
<td>Součekite</td>
<td>1.2.2</td>
<td>CuPbBi(S, Se)$_3$</td>
<td></td>
</tr>
<tr>
<td>Stalderite</td>
<td>6.1.4</td>
<td>Cu(Zn, Fe, Hg)$_2$TlAs$_2$S$_6$</td>
<td></td>
</tr>
<tr>
<td>Stephanite</td>
<td>6.2.5</td>
<td>Ag$_5$SbS$_4$</td>
<td></td>
</tr>
<tr>
<td>Sterryite</td>
<td>4.4</td>
<td>(Ag, Cu)$<em>2$Pb$</em>{10}$(Sb, As)$<em>3$S$</em>{29}$</td>
<td></td>
</tr>
<tr>
<td>Tennantite</td>
<td>6.1.2</td>
<td>Cu$_6$[Cu$_4$(Fe, Zn)$_2$]As$<em>3$S$</em>{13}$</td>
<td></td>
</tr>
<tr>
<td>Tetrahedrite</td>
<td>6.1.2</td>
<td>Cu$_4$[Cu$_4$(Fe, Zn)$_2$]Sb$<em>3$S$</em>{13}$</td>
<td></td>
</tr>
<tr>
<td>Tintinaite</td>
<td>4.2.2</td>
<td>Cu$<em>3$Pb$<em>3$Sb$</em>{10}$S$</em>{15}$</td>
<td>CSU</td>
</tr>
<tr>
<td>Treasurite</td>
<td>3.1.1</td>
<td>Ag$<em>7$Pb$<em>3$Bi$</em>{11}$S$</em>{30}$</td>
<td>CSU</td>
</tr>
<tr>
<td>Trechmannite</td>
<td>1.1.6</td>
<td>Ag$_5$As$_2$</td>
<td></td>
</tr>
<tr>
<td>Tsingirite</td>
<td>6.2.6</td>
<td>Ag$_9$Sb(S, Se)$_3$Te$_3$</td>
<td>CSU</td>
</tr>
<tr>
<td>Tsugarite</td>
<td>3.5.3</td>
<td>Pb$_3$As$_3$S$_7$</td>
<td>CSU</td>
</tr>
<tr>
<td>Tvalchrelidzeite</td>
<td>7.2</td>
<td>Hg$_5$Sb$_3$S$_3$</td>
<td></td>
</tr>
<tr>
<td>Twinnite</td>
<td>3.8.1</td>
<td>Pb(Sb$<em>{0.63}$As$</em>{0.37}$)$_2$S$_4$</td>
<td>CSU – difference with guettardite?</td>
</tr>
<tr>
<td>Treasurite</td>
<td>3.1.1</td>
<td>MnAgPb$_3$Sb$<em>5$S$</em>{12}$</td>
<td>CSU</td>
</tr>
<tr>
<td>Ustarasite</td>
<td>3.1.5</td>
<td>Pb(Bi, Sb)$<em>6$S$</em>{10}$</td>
<td>Q – CSU. No unit-cell data</td>
</tr>
<tr>
<td>Vaughanite</td>
<td>5.4</td>
<td>HgTlSb$_3$S$_7$</td>
<td>CSU</td>
</tr>
<tr>
<td>Veenite</td>
<td>3.8.4</td>
<td>Pb$_2$(Sb, As)$_2$S$_3$</td>
<td>CSU</td>
</tr>
<tr>
<td>Vikingite</td>
<td>3.1.1</td>
<td>Ag$<em>5$Pb$<em>3$Bi$</em>{11}$S$</em>{30}$</td>
<td>CSU</td>
</tr>
<tr>
<td>Volynskite</td>
<td>1.1.1</td>
<td>Ag$_5$BiTe$_2$</td>
<td>True crystal structure unknown</td>
</tr>
<tr>
<td>Vrbaitse</td>
<td>5.4</td>
<td>Hg$_5$Tl$_4$As$<em>3$Sb$</em>{20}$</td>
<td></td>
</tr>
<tr>
<td>Vurroite</td>
<td>4.2.1</td>
<td>Sn$<em>2$Pb$</em>{20}$(Bi, As)$<em>2$S$</em>{25}$Cl$_6$</td>
<td></td>
</tr>
<tr>
<td>Wallisite</td>
<td>1.3</td>
<td>CuTlPbAs$_3$S$_5$</td>
<td></td>
</tr>
<tr>
<td>Watanabeite</td>
<td>6.1.3</td>
<td>Cu$_4$(As, Sb)$_2$S$_3$</td>
<td>CSU</td>
</tr>
<tr>
<td>Watkinsite</td>
<td>2.2.1</td>
<td>Cu$_2$Pb$<em>3$Bi$</em>{12}$(Se, S)$_8$</td>
<td>CSU</td>
</tr>
<tr>
<td>Weibullite</td>
<td>2.3.1</td>
<td>Ag$<em>{0.33}$Pb$</em>{0.67}$Bi$<em>{33}$(S, Se)$</em>{18}$</td>
<td></td>
</tr>
<tr>
<td>Weissbergite</td>
<td>1.1.7</td>
<td>TlSb$_3$S$_5$</td>
<td></td>
</tr>
<tr>
<td>Wittichenite</td>
<td>6.1.1</td>
<td>Cu$_5$Bi$_3$S$_7$</td>
<td></td>
</tr>
<tr>
<td>Wittite</td>
<td>2.2.2</td>
<td>Pb$<em>3$Bi$</em>{12}$(S, Se)$_{23}$</td>
<td>Q</td>
</tr>
<tr>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xanthoconite</td>
<td>6.2.3</td>
<td>Ag$_5$As$_3$S$_1$</td>
<td></td>
</tr>
<tr>
<td>Xilingolite</td>
<td>3.1.1</td>
<td>Pb$_3$Bi$_2$S$_8$</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinkenite</td>
<td>4.2.1</td>
<td>Pb$_9$Sb$<em>2$S$</em>{42}$</td>
<td>Q</td>
</tr>
<tr>
<td>Zoubekite</td>
<td>4.2.3</td>
<td>AgPb$_3$Sb$<em>4$S$</em>{10}$</td>
<td>Q</td>
</tr>
<tr>
<td><strong>IMA approved</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IMA 2005-024</td>
<td>2.2.2</td>
<td>(Pb, Sn)$_{12}$As$_3$Sn$<em>3$Fe$</em>{28}$</td>
<td>As-derivative of franckeite</td>
</tr>
<tr>
<td>IMA 2005-036</td>
<td>3.2</td>
<td>Cu$_2$Ag$_3$Pb$_3$Bi$<em>3$S$</em>{38}$</td>
<td>Pavonite series</td>
</tr>
<tr>
<td>IMA 2006-016</td>
<td>2.2.2</td>
<td>Pb$_2$SnInBi$_5$S$_7$</td>
<td>In-derivative of cylindrite</td>
</tr>
<tr>
<td>IMA 2007-003</td>
<td>1.2.3</td>
<td>Cu$_7$Pb$_3$S$_7$</td>
<td>Pt-isotype of lapieite</td>
</tr>
<tr>
<td>IMA 2007-010</td>
<td>4.4</td>
<td>PbHgAs$_3$S$_6$</td>
<td></td>
</tr>
</tbody>
</table>

Appendix: Additional list of discredited species

This list represents a selection of abandoned names, which are found in modern publications. The great majority of these discredited names (noted *) is compiled in the recent report on “Mass discreditation of GQN minerals” by E.A.J. Burke (2006), Chairman of the CNMNC-IMA. This report is of free access on the Net, at the CNMNC-IMA site.

***: Possible revalidation (see 3.1 in the final conclusion).
Alaskaitié = a mixture of various Bi sulfo-salts (Karup-Møller, 1972).
Annivite* = Bi-rich tennantite.
Beegerite* = a mixture of “schirmerite” and matildite (Karup-Møller, 1973).
Bonchevite*, PbBiSs, defined by Kostov (1958), was formally discredited by the CNMNC (IMA 67-2a; Franz et al., 1967; 1969), as a mixture of galenobismutite with a sulfo-salt of the lillianite type. Through reexamination of new material from the type deposit, Birch & Mumme (1985) identified pekoite, and considered bonchevite as a mixture of pekoite and galenobismutite.
Bursaitié = an intergrowth of two phases (Mozgova et al., 1988).
Eichbergite = a mixture of jaskolskiite and Bi-bearing meneghinite (Paar et al., in prep.)
Goongarritte*, PbBi2S5 = a symplectic mixture of galena and cosalite, from the decomposition of metastable heyrovskýite (Klominsky et al., 1971). See also Rüder (1963).
Gelnícite/Gelnicate* = identical with marrucuite (Orlandi et al., 2007).
Incaite*; Sn2+-rich frankeite (Mozgova et al., 1976).
Kitaïbelie* = Pb-containing pavonite (Weisburg et al., 1992).
Nakaséite, Ag2CuPbS12S24 (Flesicher, 1960) = a disordered precursor of andorites IV and VI (Moëlo et al., 1989).
Parajamesonite*, FePb5Sb2S9 = a mixture of jamesonite and other sulfo-salts (Papp, 2004; Papp et al., 2007).
Potosiite = Sn2+-poor frankeite (Makovicy & Hyde, 1992).
Rathite varieties: see details in this report.
Rézbianite = a mixture of aikinite derivatives, padérite and other sulfo-salts (Zák et al., 1992).
Schirmerite (Type I)*, AgPbBi4S = schachichte.?
Schirmerite (Type II), Ag3PbBi6S9 to Ag3PbBi3,5S9 = a disordered member of the lillianite homologous series (Makovicy & Karup-Møller, 1977b).
Schulzite, Pb1,4Sb3S12 (As-free geocronite).
Scleroclase, PbAs3S4 (old name for sartorite).
Teremkovite, Pb7Ag2Sb8S30 (CNMMN-IMA, 1971) (probable Ag-poor variety of owyheeite – Moëlo et al., 1984b).
Wittite B = proustite (Mumme, 1976).

References


Bindi, L., Evain, M., Menchetti, S.: Selenopolybasite, [(Ag,Cu₉)(Sb,As)₆(S,Se)₆][Ag₃Cu(S,Se)₂Se₂], a new member of the pearceite–polybasite group from the De Lamar mine, Owyhee County, Idaho, USA. Can. Mineral. (accept.).


Cho, Seung-Am & Wuensch, B.J. (1974): The crystal structure of plagiomine, Pb₂Sb₂S₁₇, the second member in the homologous series Pb₂₋ₓSb₂S₂ₓ₋₂. Z. Kristallogr., 139, 351-378.


— — (2006c): Structure and phase transition in the Se-rich variety of antimonpearceite, [(Ag, Cu)₉(Sb, As)₂(S, Se₂)][Ag₉(Cu, Se₂)Se₂] in Acta Cryst., B62, 768-774.


... — (1967): The crystal structure of nowackiite, Cu₆Zn₃As₃₁₄. Z Kristallogr., 124, 351-368.
... — (1965): The crystal structure of rathite-1. Z Kristallogr., 122, 433-456.
... (1965): The crystal structure of rathite-1. Z Kristallogr., 122, 433-456.
... (1969): The crystal structure of dufrénoysite, Pb₁₆As₃₁₄S₆₀. Z Kristallogr., 124, 409-419.
of pillaité, Pb$_8$Sb$_{10}$S$_{27}$ClO$_{3}$, an expanded monoclinic derivative of hexagonal Bi$_2$(Sb$_2$S$_3$)$_3$. *Eur. J. Mineral.*, 13, 779-790.


——(1975b): The crystal structure of krupkaite, CuPb$_5$S$_7$, from the Juno Mine at Tennant Creek, Northern Territory, Australia. *Am. Mineral.*, 60, 300-308.


——(1980b): The crystal structure of nordströmite Cu$_5$Bi$_3$(S, Se)$_{14}$, from Falun, Sweden: a member of the junoite homologous series. *Can. Mineral.*, 18, 343-352.

——(1980c): Weibullite A$_{50-1}$(Pb$_{0.89}$Bi$_{0.11}$)$_{55}$Se$_{0.08}$S$_{11.92}$ from Falun, Sweden: a higher homologue of galenobismutite. *Can. Mineral.*, 18, 1-12.

— (1989): The crystal structure of Pb105(Sb3.75Bi0.28)S10.72Se0.28: boulangerite of near ideal composition. N. Jb. Miner. Mh., 1989 (11), 498-512.


— (1983): Laffitteite, AgHgAsS4: crystal structure and second occurrence from the Getchell mine, Nevada. Am. Mineral., 68, 235-244.


— (1971): The crystal structure of vrbait Hg5Tl4As8Sb2S6. Z. Kristallogr., 134, 360-380.


Pinto, D., Bonaccorsi, E., Babić-Žunić, T., Makovicky, E.: The crystal structure of vurroite, Pb$_2$Bi$_2$S$_4$. Z. Kristallogr., 215, 373-376.


Sabelli, C., Nakai, I., Katsura, S. (1988): Crystal structure of cetineite and its synthetic analogue Na$_3$(Sb$_2$O$_3$)$_3$(SbS$_3$) (OH)$_{0.4}$2.4H$_2$O. Am. Mineral., 73, 398-404.


of layered compounds in the PbTe-Bi₃Te₂ and PbTe-Sb₂Te₃ systems. *Inorg. Mater.*, **40**, 1264-1270.


Topa, D., Makovicky, E., Paar, W.H., Brodkorb, M.K. de (2004): The crystal structure of anglelita, Cu₆AgPbBi₅S₉₀, a new mineral species from Angola mine, Province of Chubut, Argentina. 32nd IGC, Florence, 20–28 August (abstract).


Received 12 September 2007
Accepted 20 September 2007