THE JAMESONITE – BENAVIDESITE SERIES

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ABSTRACT

Phase relations in the systems PbS–FeS–Sb₂S₃ and PbS–MnS–Sb₂S₃, on the plane Pb₄Sb₆S₁₃–FeS–MnS and along the join Pb₄FeSb₆S₁₄–Pb₄MnSb₆S₁₄, were studied using the conventional sealed-capsule technique. Pb₄FeSb₆S₁₄ (jamesonite) and Pb₄MnSb₆S₁₄ (benavidesite) form a complete series of solid solutions, with melting temperature varying from 583 ± 3 to 592 ± 3 °C, respectively. On the plane, solid solutions in equilibrium with pyrrhotite have compositions covering almost the entire series, whereas solid solutions that coexist with alabandite are limited to the Mn-rich end. Compositions ranging from Fe-rich to Mn-rich in the solid-solution series were found at Dachang, China; there, jamesonite is the most abundant sulfosalt. It formed as acicular or capillary crystals in cavities, as a result of late-stage processes.

Keywords: jamesonite, benavidesite, solid-solution series, natural examples, synthesis experiments, Dachang deposit, China.

INTRODUCTION

Jamesonite, Pb₄FeSb₆S₁₄, one of the relatively common sulfosalt minerals, occurs in close association with pyrrhotite, pyrite, and other iron-bearing sulfides in hydrothermal deposits. In general, the chemical composition of jamesonite does not vary much (Chang & Knowles 1977). Metallic elements that are normally present in geological environments where sulfosalts form do not substitute extensively for the constituents of jamesonite because of structural restrictions. The Fe atom has a distinct structural position, co-ordinated by six sulfur atoms in a distorted octahedron in association with PbS₂ and PbS₅ (Niizeki & Buerger 1957). As a result, silver and copper are present only in small amounts. On the other hand, metallic elements that are suitable for the jamesonite structure are not abundant in the environments of sulfosalt formation. Jamesonite rarely contains nickel or cobalt, although a jamesonite-type phase has been synthesized in the systems PbS–NiS–Sb₂S₃ and PbS–CoS–Sb₂S₃ (Chang, unpubl. data).

With the identification of benavidesite from Uchucchacua, Peru and Sättra, Sweden (Oudinet et al. 1982), manganese appears to represent the element that bridges the gap between these two groups of metallic elements. Benavidesite has an ideal composition Pb₄(Fe,Mn)Sb₆S₁₄, with a Mn:Fe ratio varying from 73:27 to 62:38. The purpose of this investigation is to study the jamesonite–benavidesite series in the system PbS–FeS–MnS–Sb₂S₃, and its natural occurrence in the Dachang ore field, China.

THE Pb₄FeSb₆S₁₄–Pb₄MnSb₆S₁₄ SERIES IN THE SYSTEM PbS–FeS–MnS–Sb₂S₃

Experimental procedure

Starting compositions were prepared from reagent-grade lead, antimony, iron, manganese and sulfur; all have 99.99% purity or better. Synthesis and heat treatment were made in muffle furnaces using the conventional technique of sealed, evacuated glass capsules (Kullerud & Yoder 1959). Generally, the duration of treatment ranged from 120 days at 400°C to 45 days at 500°C, to 5 days at and above 600°C. X-ray powder diffraction, reflected-light microscopy, and electron-microprobe analysis were used for
characterization of phases. Cell dimensions (± 0.02 Å) were computed using a least-squares refinement program.

To check for equilibrium, a different procedure of synthesis was used in selected experiments. The charges were heated to complete melting, quenched, and annealed at the desired temperatures for the same length of time as their counterparts prepared by the direct union of the elements. There is no difference in the phase assemblages produced by these two procedures.

**Jamesonite in the system PbS-FeS-Sb$_2$S$_3**

The formation of jamesonite in the system was studied by Chang & Knowles (1977). At 500°C, jamesonite has a range of solid solution elongated toward Sb$_2$S$_3$, and forms equilibrium assemblages with all phases on the related joins except galena. The extent of solid solution is very sensitive to temperature change. At 400°C, it is limited to within 1 or 2 mole% around the ideal composition. In this study, additional compositions were prepared and treated at 500°C. From the results obtained, several minor modifications were made to the phase relations in the system (Fig. 1): (1) the width of the field of jamesonite solid-solution along the 45 mole% PbS line was reduced; (2) the composition of jamesonite solid-solution in equilibrium with berthierite and pyrrhotite is Pb$_{3.7}$Fe$_{1.2}$Sb$_6$S$_{14}$, and (3) the region occupied by the assemblage of robinsonite + jamesonite solid-solution is slightly enlarged.
**Bolangerite**

$2\text{PbS-Sb}_2\text{S}_3$

**Robinsonite**

$\text{Zinkenite}$

**Phase relations in the system PbS-MnS-Sb$_2$S$_3$ at 500°C**

"B" represents the Pb$_4$MnSb$_6$S$_{14}$ solid-solution.

**Benavidesite in the system PbS-MnS-Sb$_2$S$_3**

As shown in Figure 2, phase relations in the system PbS-MnS-Sb$_2$S$_3$ at 500°C are very similar to those in the system containing FeS. End-member benavidesite, Pb$_4$MnSb$_6$S$_{14}$, is a jamesonite-type phase, and the two display similar solid-solution relationships. Its relations with other phases in the system are also similar to those of jamesonite in the system PbS-FeS-Sb$_2$S$_3$ except that a 3:1 phase (Mn$_3$Sb$_2$S$_3$) takes the place of the 1:1 phase (FeSb$_2$S$_3$). At 400°C, Pb$_4$MnSb$_6$S$_{14}$ has a much reduced range of solid solution.

**The jamesonite–benavidesite series**

A complete solid-solution series extends between Pb$_4$FeSb$_6$S$_{14}$ and Pb$_4$MnSb$_6$S$_{14}$ (Fig. 3), with cell dimensions varying within a very narrow range: $a$ 15.75, $b$ 19.17, $c$ 3.99 Å, $\beta$ 91°22' for jamesonite and $a$ 15.74, $b$ 19.14, $c$ 4.04 Å, $\beta$ 91°20' for the Mn end-member. Pb$_4$(Mn$_{0.70}$Fe$_{0.30}$)Sb$_6$S$_{14}$, a composition of benavidesite reported by Oudin et al. (1982), has $a$ 15.74, $b$ 19.14, $c$ 4.03 Å, $\beta$ 91°30'. Melting relations in the series were determined by examining polished sections of quenched samples using reflected-light microscopy. Pb$_4$FeSb$_6$S$_{14}$ becomes sintered at 550°C and melts congruently at 583 ± 3°C, whereas Pb$_4$MnSb$_6$S$_{14}$ melts at 592 ± 3°C without apparent sintering. The two-phase region cannot be well defined because of the narrow separation between liquidus and solidus. This feature is obviously due to the small difference in melting points of the end members.
As shown in Figure 4, the jamesonite – benavidesite series is stable in the plane \( \text{Pb}_4\text{Sb}_3\text{S}_3 \) (robinsonite) – FeS – MnS at 500°C. Solid solutions in equilibrium with pyrrhotite have compositions covering almost the entire series, whereas solid solutions in equilibrium with alabandite are limited in their compositions to the Mn-rich end of the series. At 400°C, the ranges of the two-phase region vary in accordance with the decrease of mutual solubilities between FeS and MnS, but the composition of the jamesonite – benavidesite series that defines the three-phase region remains unchanged, as verified by electron-microprobe analysis.

**The Jamesonite – Benavidesite Series from Dachang Ore Field, China**

**Geological occurrence**

The Dachang district, located in northwestern Guangxi, China, is a polymetallic ore field dominated by cassiterite–sulfide deposits, and contains abundant sulfosalts minerals. These sulfosalts are widely distributed in the ore field and occur in almost all types of deposits (Li & Zhang 1980). Of the sulfosalts minerals, jamesonite is by far the most abundant and most widespread.

At Dachang, jamesonite has seven distinct modes of occurrence: (1) massive with ferroan sphalerite and pyrite, (2) granular and columnar in pyrite, (3) in cavities, acicular or capillary, in association with calcite and pyrite, (4) in plumose and sheaf-like forms, (5) in veins with ferroan sphalerite, arsenopyrite, pyrite and pyrrhotite, (6) disseminated in calcite, and (7) in thin plates, some radiating, on joint planes. Among these, only the acicular or capillary jamesonite that occurs in cavities contains significant Mn.

Most of the sulfosalts minerals at Dachang, including jamesonite, are products of late-stage mineralization. Solid solutions of the jamesonite – benavidesite series are among the latest minerals to crystallize. Their restricted occurrence in cavities of orebodies as acicular or capillary crystals indicates that the ore-forming solution underwent a late enrichment in Mn.
**Chemical composition**

Electron-microprobe results of jamesonite and benavidesite from all major ore assemblages of the Dachang deposit are presented in Table 1. An average of the first 12 compositions listed gives (wt. %) Pb 40.44, Fe 2.66, Sb 34.03, S 21.84, Mn 0.10, Zn 0.02, Cu 0.10, Mg 0.01, Sn 0.26, As 0.16, Bi 0.34 (0.17 without sample 84002), In 0.02 and Ag 0.05, for a total of 99.98. The theoretical chemical composition of jamesonite is Pb 40.15, Fe 2.71, Sb 35.59 and S 21.75%. Bi, Mn and Sn are present in all grains of jamesonite analyzed.

Among the eight samples of jamesonite with significant amount of Mn, one (W1028) has a Mn:Fe ratio comparable to benavidesite as proposed by Oudin *et al.* (1982). Samples W274, 85823 and 85896 represent iron-rich members of the series, whereas sample 84828 is a Mn-rich member. The remaining three samples have a Mn:Fe ratio close to one.

**Physical properties**

Members of the jamesonite – benavidesite series at Dachang occur as acicular or capillary, closely packed crystals measuring on average 0.4 mm long and 0.02 mm wide, and with the maximum dimensions of 0.8 × 0.03 mm. They are lead-grey in color, with a metallic lustre and a dark greyish streak. Attempts to determine their density failed, but the hardness is estimated to be 2 – 2.5 on the Mohs scale.

Under reflected light, the jamesonite – benavidesite minerals are white with a pale greenish tint and
## TABLE 1. CHEMICAL COMPOSITIONS OF JAMESONITE - BENAVIDESITE SERIES FROM DACHANG, CHINA

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Pb</th>
<th>Sb</th>
<th>As</th>
<th>Bi</th>
<th>Fe</th>
<th>Mn</th>
<th>Zn</th>
<th>Cu</th>
<th>In</th>
<th>Sn</th>
<th>Ag</th>
<th>S</th>
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<th>Pb</th>
<th>Fe</th>
<th>Mn</th>
<th>Sb</th>
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<td>VT77 (4)</td>
<td>0.23</td>
<td>0.000</td>
<td>21.84</td>
<td>99.58</td>
<td>3.99</td>
<td>0.55</td>
<td>-</td>
<td>5.77</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BS266 (4)</td>
<td>0.20</td>
<td>0.012</td>
<td>0.001</td>
<td>0.000</td>
<td>0.012</td>
<td>0.016</td>
<td>0.005</td>
<td>0.011</td>
<td>0.001</td>
<td>0.009</td>
<td>0.009</td>
<td>0.005</td>
<td>0.058</td>
<td>0.008</td>
<td>21.89</td>
<td>100.12</td>
<td>4.12</td>
</tr>
<tr>
<td>W007 (3)</td>
<td>0.012</td>
<td>0.016</td>
<td>0.005</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>21.89</td>
</tr>
<tr>
<td>W244 (3)</td>
<td>0.20</td>
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<td>0.001</td>
<td>0.000</td>
<td>0.012</td>
<td>0.016</td>
<td>0.005</td>
<td>0.011</td>
<td>0.001</td>
<td>0.009</td>
<td>0.009</td>
<td>0.005</td>
<td>0.058</td>
<td>0.008</td>
<td>21.89</td>
<td>100.12</td>
<td>4.12</td>
</tr>
<tr>
<td>W1403 (1)</td>
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<td>0.012</td>
<td>0.001</td>
<td>0.000</td>
<td>0.012</td>
<td>0.016</td>
<td>0.005</td>
<td>0.011</td>
<td>0.001</td>
<td>0.009</td>
<td>0.009</td>
<td>0.005</td>
<td>0.058</td>
<td>0.008</td>
<td>21.89</td>
<td>100.12</td>
<td>4.12</td>
</tr>
<tr>
<td>BS267 (1)</td>
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<td>0.012</td>
<td>0.001</td>
<td>0.000</td>
<td>0.012</td>
<td>0.016</td>
<td>0.005</td>
<td>0.011</td>
<td>0.001</td>
<td>0.009</td>
<td>0.009</td>
<td>0.005</td>
<td>0.058</td>
<td>0.008</td>
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<td>4.12</td>
</tr>
<tr>
<td>W1142 (4)</td>
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<td>0.000</td>
<td>0.012</td>
<td>0.016</td>
<td>0.005</td>
<td>0.011</td>
<td>0.001</td>
<td>0.009</td>
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<td>0.005</td>
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<td>4.12</td>
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<td>W1600 (3)</td>
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<td>0.012</td>
<td>0.001</td>
<td>0.000</td>
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<td>0.016</td>
<td>0.005</td>
<td>0.011</td>
<td>0.001</td>
<td>0.009</td>
<td>0.009</td>
<td>0.005</td>
<td>0.058</td>
<td>0.008</td>
<td>21.89</td>
<td>100.12</td>
<td>4.12</td>
</tr>
<tr>
<td>BS267 (4)</td>
<td>0.20</td>
<td>0.012</td>
<td>0.001</td>
<td>0.000</td>
<td>0.012</td>
<td>0.016</td>
<td>0.005</td>
<td>0.011</td>
<td>0.001</td>
<td>0.009</td>
<td>0.009</td>
<td>0.005</td>
<td>0.058</td>
<td>0.008</td>
<td>21.89</td>
<td>100.12</td>
<td>4.12</td>
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<tr>
<td>W1403 (1)</td>
<td>0.20</td>
<td>0.012</td>
<td>0.001</td>
<td>0.000</td>
<td>0.012</td>
<td>0.016</td>
<td>0.005</td>
<td>0.011</td>
<td>0.001</td>
<td>0.009</td>
<td>0.009</td>
<td>0.005</td>
<td>0.058</td>
<td>0.008</td>
<td>21.89</td>
<td>100.12</td>
<td>4.12</td>
</tr>
<tr>
<td>BS267 (1)</td>
<td>0.20</td>
<td>0.012</td>
<td>0.001</td>
<td>0.000</td>
<td>0.012</td>
<td>0.016</td>
<td>0.005</td>
<td>0.011</td>
<td>0.001</td>
<td>0.009</td>
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<td>0.058</td>
<td>0.008</td>
<td>21.89</td>
<td>100.12</td>
<td>4.12</td>
</tr>
</tbody>
</table>

* Number of grains analyzed by electron microprobe. Analytical conditions: mixed metal and sulfide standards, 20 kV, 0.03 mA, ZAF correction.

**SUMMARY AND CONCLUSION**

Pb$_2$Fe$_2$Sb$_6$S$_{14}$ and Pb$_2$Mn$_2$Sb$_6$S$_{14}$ form a complete series of solid solutions in the system PbS-FeS-MnS-Sb$_2$S$_3$, with melting temperature varying continuously from 583 ± 3°C (Fe) to 592 ± 3°C (Mn). Compositions of this solid-solution series ranging from Fe-rich to Mn-rich were found in the Dachang ore field, in which jamesonite is the most abundant sulfosalt mineral. They formed as acicular or capillary crystals in cavities, representing products of late-stage processes.

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**REFERENCES**


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