The Bawdwin Mine, Myanmar: a review of its geological setting and genesis

Historical and geological context

The Bawdwin Mine, a Pb–Zn–(Cu–Ag–Ni) deposit sited in the northern Shan States, is probably the most famous historical mine in Myanmar. One of several world-class mineral deposits within the country, it has seen near-continuous mining since the early 1400s to the present for a range of commodities including: silver, lead, zinc, copper and nickel. Originally exploited as a silver deposit, Bawdwin is derived from baw, the Shan word for silver and literally means ‘silver mine’, it was redeveloped in the early twentieth century as a dominantly lead–zinc producer, making it one of the largest producing lead mines in the world before the Second World War. The geology was first described early in the twentieth century and its nature and origin have been much debated since, but its genesis has remained enigmatic. In this paper we review both published and unpublished reports on work carried out at Bawdwin during the last century, and propose a new geological model based on these reports. Following a more recent classification scheme for volcanogenic massive sulphide (VMS) deposits, we assign Bawdwin to the siliciclastic–felsic VMS-type.

History of the mine

Bawdwin was first exploited in the early fifteenth century by the Chinese. It has been estimated that from 1412 until the late 1800s 10 million ounces of silver were extracted from primitive mining operations (United Nations 1966); this continued until c. 1868, when the owners and operators fled on account of the Pantay–Taiping rebellions in Yunnan (Brinckmann & Hinze 1981). Between 1868 and 1885, the Burmese kings Mindon Min and Thibaw made ultimately unsuccessful attempts to revive mining and smelting at the site (BGR 1976). In the early 1900s Martin (1916), who claimed to be the first Westerner to visit Bawdwin in 1900, recognized economic value in the slag heaps left from the earlier Chinese operations, estimating contents of up to 60% Pb–Zn and 2–4 oz/t Ag. Subsequently, the Great Eastern Mining Company Limited (GEMC), registered in London in 1902 to prospect the deposit, initiated the building of a narrow gauge railway in late 1903 to transport this lead-rich slag from the mine site down to the Tiger Tun-nel at Namtu. This endeavour was mired in contractual disagreements, however, and by 1905 construction had barely begun. Herbert Hoover, the future US President and at that stage a mining engineer, came to hear of Bawdwin from one of Great Eastern’s directors while on a cruise in 1904. A company in which he was a partner (Bewick, Moreing & Co) initiated an evaluation of the deposit for its potential ore reserves as much as the slag value and, sensing that the Great Eastern Mining Company was in financial trouble, formed the Burma Railway and Smelting Company Ltd in 1906 (henceforth Burma Corporation) which bought out the GEMC with the view to developing the mine itself (Nash 1983).

Mining commenced in earnest in 1909 by way of reopening the old Chinese workings in the shape of the ‘Dead Chinaman Tunnel’ (DCT) and then forging excavation ever deeper into the deposit; also in that year the narrow-gauge railway linking Bawdwin and Namtu was finally finished. After attempts to smelt at a plant in Mandalay, smelting moved to a new plant at Namtu in 1912. In 1913, the DCT finally penetrated the massive ore body that became known as the Chinaman Lode, estimated at 180 m (600 ft) long and 20 m (50 ft) wide, vindicating Hoover’s belief that there was a huge deposit below the original Chinese workings. In 1914 excavation started on the Tiger Tunnel (completed in 1916), linking the 6th level with the Tiger Camp. Discovery of the Chinaman Lode marked the start of the halcyon years for Bawdwin, when up to 500 000 tons of ore was produced annually until 1942 and occupation by the Japanese during the Second World War (BGR 1976).

During the years 1942–45 the Japanese continued to work the mine and, during this period, extracted an estimated 200 000 tons of high-grade ore (Goosseens 1978). In 1945 the Burma Corporation retook control and continued to work the mine until 1965 when, in common with all major mines in Burma, the asset was nationalized. It is currently owned and operated by Mining Enterprise No. 1 (ME1) of the Myanmar Ministry of Mines.

History of exploration

Bawdwin has been the subject of a number of both academic and commercial studies since the early 1900s. The first known geological report (unpublished) was compiled in 1906 by MacLaren, which is referenced by La Touche & Coggin Brown (1908). Subsequently, Coggin Brown (1918) published a report of the ‘Geology and ore deposits of the Bawdwin Mines’.

During the pre-Second World War period, the mine was the focus of a number of studies. Detailed underground geological mapping was undertaken in the 1930s (e.g. Hobson 1933). Between 1936 and 1938, Dunn (1938) made studies of the ore mineralization; in his seminal volume, The Mineral Resources of Burma, Chhibber (1934) described the geology of the Bawdwin area.

By the 1950s the average grade of recovered ore had declined; in response the Burma Corporation engaged Hunting Technical Services Ltd to carry out a number of surveys with
the aim of identifying other nearby high-grade ore bodies. During 1957–58 Hunting undertook air photo surveys, topographic mapping and geochemical and electromagnetic surveys in and around the Bawdwin mine area. In 1962–64 a United Nations Drilling Programme operated at Bawdwin, putting down 14 exploratory boreholes. During the years 1973–74, the Canadian International Development Agency sank 15 exploratory drill holes with the aim of locating additional low-grade ore reserves and outlining a large-scale open pit.

At the bidding of the Burmese Directorate of Geological Survey and Exploration (DGSE), a German Geological Mission undertook extensive work between 1973 and 1976, involving detailed geological mapping, radiometric dating and petrological studies of the ore and surrounding host rocks (for a summary see Brinckmann & Hinze 1981). As part of this exercise, 22 boreholes were drilled at Bawdwin in an attempt to delineate the boundaries of mineralization (BGR 1976). The BGR study, undoubtedly the most comprehensive geological work on the deposit to date, took place in an environment where the understanding of the genesis of massive sulphide ore bodies was becoming more sophisticated. An important conclusion of the study was that Bawdwin was a volcanogenic-massive-sulphide-type deposit with affinities to those of the Kuroko district in Japan.

In the mid 1980s, under the auspices of the Australian Development Assistance Bureau Mining Industry Project, a study of the Bawdwin Mine was undertaken in order to prepare both an economic evaluation of the deposit and propose a development programme for the property (Hopwood 1985).

Operations

Over the course of its history, the Bawdwin Mine has comprised both an underground and an open-pit operation. The underground operation is accessed through the 522 m deep Marmion Shaft (Fig. 30.1b), and consists of 13 underground levels following the three major lodes. Level 6, Tiger Tunnel, is the main access tunnel, a 2.4 km long adit connecting the underground system to the Tiger Camp and onwards by way of the narrow gauge railway to Namtu, where the ore was processed and smelted. The Namtu smelter was incorporated in the Canadian International Development Agency sank 15 exploratory drill holes with the aim of locating additional low-grade ore reserves and outlining a large-scale open pit.

Reserves and production

Bawdwin, as a resource, is notable for being extremely silver-rich, and was originally exploited as a silver mine prior to later development as a primarily lead–zinc deposit. In 1928 the quoted reserves and grades were 350,000 tons of ore averaging 13% Pb, 8% Zn, 7% Cu and 18 oz/ton Ag (Chhibber 1934). At these grades, and at today’s metal prices the most valuable commodity in this portion of the high-grade Bawdwin ore would be copper followed, in decreasing order, by silver, lead and zinc.

Following on from their extensive survey and drilling, the BGR estimated the total Bawdwin reserve to be 802,100 tons ore comprising 6.8% Pb, 1.38% Zn at a cut-off grade of 5% (Pb + Zn), giving rise to reserves of 54,500 tons Pb and 11,000 tons Zn (BGR 1976). As of 2010, the Myanmar Ministry of Mines quotes the Bawdwin reserve as 3.55 Mt of underground ore and 8.6 Mt of open-pit ore, at an overall 7.67% Pb, 3.18% Zn and 4.19 oz/t Ag.

Production has varied over the years, with peak production in the 1920s and 1930s. Chhibber quoted a total output of 297,000 tons lead in the period up to 1928, and a figure of 2573 tons Cu over 1912–15 (Chhibber 1934). Table 30.1 details average production figures up to 1980.

Geological setting

Bawdwin is situated in northern Shan State at 23° 7’ N, 97° 18’ E, some 250 km NE of Mandalay and 80 km from the Chinese border, at an altitude of approximately 1000 m (Fig. 30.2). It is sited on the Shan Plateau, occupying the Eastern Highlands, directly east of the Shan Scarp. The plateau is bounded on the west by high-grade pelites and marbles of the Mogok Metamorphic Belt, and by the mudstones and wackes of the Slate Belt or Mergui Series (Mitchell 1992). The rock units that form the Shan Plateau consist of Late Precambrian wackes and mudstones which dip to the SE, and are locally overlain by Cambrian volcanics and a thick succession of Upper Permian–Mesozoic carbonates.

The Bawdwin ore bodies lie within a broad, NW-trending, structurally controlled and steeply dipping zone of alteration and mineralization, some 2.5 km long by 200 m wide (Hopwood 1985). This zone is located within a thick pile of volcanoclastic agglomerates and tuffs, intruded by several rhyolitic porphyry bodies. The ore deposit consists dominantly of three bodies of massive sulphide ore, hosted both within the Bawdwin Volcanic Formation and in the Pangyun Formation. The ore bodies are surrounded by stockwork and associated lower-grade ore deposits; Figure 30.3 shows a cross-section through the northern Shan Plateau, including the Bawdwin locality.

Bawdwin geology

The Bawdwin locality is underlain by Cambro-Ordovician volcanoclastic sediments of the Bawdwin Volcanic Formation and metasediments of the Pangyun Formation. The volcanoclastic sediments are a phase prior to the intrusion of extensive rhyolite porphyries (BGR 1976); these form lenticular volcanic masses at the base of the Pangyun Formation and extending upwards into it. Metasediments of the local Chaung Magyi Group and a large granite batholith, the Taung Peng Granite, occur some 5–10 km to the west of Bawdwin. The Chaung Magyi Group is a Cambrian turbidite sequence with shales, slates, greywackes and phylmites with local sandy units (Hopwood 1985). Figure 30.4a, b show a geological map and cross-section of the Bawdwin locality. The basic stratigraphy of the area is described in Table 30.2, with a stratigraphic log in Figure 30.5. A more comprehensive treatise of the regional geological successions is to be found in Mitchell et al. (1977).

The Pangyun Formation comprises coarse purple conglomerates, purple and white quartzites, green siltstones, sandstones and occasional dolomites exhibiting cross-bedding. In places this directly and unconformably overlies the Chaung Magyi Group; in others it grades into volcanoclastic sediments of the Bawdwin Volcanic Formation. A Late Cambrian–Early Ordovician age for the Pangyun Formation is assumed on the basis of the presence of Upper Cambrian trilobites (Myint Lwin Thein 1973). This evidence is bolstered by an ascribed Middle Ordovician age, also from fossil evidence, for the overlying Naung Kangyi Beds (Cowper Reed 1908). The Bawdwin Volcanic Formation can be divided broadly into a series of intrusive rhyolites and volcanoclastic sediments comprising tuffs and agglomerates. Carpenter (1964) proposed that these volcanoclastics were, in fact, altered Pangyun
Fig. 30.1. Two recent photographs taken at the Bawdwin site. (a) The Gossan Quarry, the current open and worked pit. This is the top of the Chinaman Lode; note the deep V-shaped valley within which the Bawdwin locality sits. (b) The original headgear and winding shed sited at the top of the Marmion Shaft. Despite the shaft being flooded below level 6, the winding gear still operates. Both taken December 2013 (NJG).

Table 30.1. Average production statistics from Bawdwin up to 1980

<table>
<thead>
<tr>
<th>Year</th>
<th>Operator</th>
<th>Ore (t)</th>
<th>Refined Pb (t)</th>
<th>Zinc concentration (t)</th>
<th>Silver (oz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1909–10</td>
<td>Burma Corp</td>
<td>717</td>
<td>9142</td>
<td></td>
<td>37 132</td>
</tr>
<tr>
<td>1911–13</td>
<td>Burma Corp</td>
<td>3369</td>
<td>8960</td>
<td>371</td>
<td>93 858</td>
</tr>
<tr>
<td>1914–19</td>
<td>Burma Corp</td>
<td>32 469</td>
<td>15 498</td>
<td>8553</td>
<td>1 166 060</td>
</tr>
<tr>
<td>1920–29</td>
<td>Burma Corp</td>
<td>301 887</td>
<td>51 446</td>
<td>1050</td>
<td>5 138 686</td>
</tr>
<tr>
<td>1930–39</td>
<td>Burma Corp</td>
<td>451 650</td>
<td>72 802</td>
<td>65 116</td>
<td>4 773 568</td>
</tr>
<tr>
<td>1940–45</td>
<td>Japanese</td>
<td>200 000 (est)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1946–50</td>
<td>Burma Corp</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1951–59</td>
<td>Burma Corp</td>
<td>93 344</td>
<td>14 291</td>
<td>14 260</td>
<td>1 033 574</td>
</tr>
<tr>
<td>1960–64</td>
<td>ME1</td>
<td>161 845</td>
<td>17 600</td>
<td>15 216</td>
<td>1 436 907</td>
</tr>
<tr>
<td>1965–69</td>
<td>People’s Bawdwin Industries</td>
<td>161 027</td>
<td>11 040</td>
<td>9306</td>
<td>690 224</td>
</tr>
<tr>
<td>1970–79</td>
<td></td>
<td>147 076</td>
<td>6879</td>
<td>5759</td>
<td>529 277</td>
</tr>
</tbody>
</table>

Summarized from BGR (1976).
sediments, but this has been refuted by Brinckmann & Hinze (1981). In their opinion the interdigitation of Bawdwin volcanics and the Pangyun Formation is due to synchronous volcanism and sedimentation.

The volcaniclastic sediments are alternately agglomerate, arkosic and volcanic greywackes and tuffs merging into one another, collectively and colloquially known as the ‘Bawdwin Tuff’, part of the Bawdwin Volcanic Formation (Brinckmann & Hinze 1981). The agglomerates and greywackes are medium-grey grainy rocks, with millimetre–centimetre- scale inclusions in a fine-grained quartz and alkali feldspar groundmass. The coarser inclusions are in general rounded grains of types of rhyolite, alkali feldspar, quartz, quartzites and shales. The agglomerate is massive, unstratified and poorly bedded, grading from the centre outwards into bedded volcaniclastic arkoses and greywackes. These grade into the sandstones and quartzites of the Pangyun Formation. There is therefore a gradual transition outwards from massive agglomerate to bedded arkoses and greywackes into the Pangyun Formation sediments (BGR 1976; Hopwood 1985).

BGR mapping showed strong evidence of inter-fingering of the volcaniclastic sediments with the surrounding Pangyun Formation, observed on all sides of the sedimentary sequence and both vertically and laterally (BGR 1976). There is a uniform dip to the east and SE for both sedimentary and volcaniclastic formations in this area (BGR 1976) (Fig. 30.4); the oldest sediments are therefore found towards the NW within the Upper Pangyun Valley. Here, the BGR mapped the oldest
Fig. 30.3. Geological map and associated cross-section through the Northern Shan Plateau showing the regional sequences, the Tawng Peng granite and the Bawdwin Mine area. The Bawdwin Mine map is taken from Coggin Brown (1918) and Clegg (1914), excluding faults. Section from Coggin Brown (1918) and Brinckmann & Hinze 1981. The stratigraphic nomenclature of units shown in the section follow the regional stratigraphy as described by Mitchell et al. (1977).
intercalation of the Bawdwin volcaniclastic sediments and the Pangyun Formation, described as follows:

Red friable sandstone, with lenticular cross-bedded quartzite layers up to 20 m thick, grade upwards into arkosic and volcaniclastic greywackes. These greywackes contain dm-scale fragments of feldspar, rhyolite and shale, and grade back into another layer of reddish Pangyun shales, and then back into the cross-bedded quartzite. Finally, this quartzite grades back into the fine silts and fine-grained sandstones of the Pangyun Formation (Brinckmann & Hinze 1981, p. 20).

This type of intercalation is observed elsewhere across the Bawdwin region. Lateral interfingering is observed in the central part of the Bawdwin volcaniclastics, where massive unstratified arkosic agglomerates grade into volcanic greywackes, arkoses, and finally to Pangyun sediments, both to the SW and NE (BGR 1976). This is most clearly observed in the Herschel Valley, where repeated alternations of Bawdwin volcaniclastics and Pangyun Formation sediments occur. In fact, the evidence observed by the BGR assumes they are co-depositional, which implies a similar Late Cambrian–Early Ordovician age for both successions if the trilobite biostratigraphic marker is correct.

In the Bawdwin locality volcaniclastic sediments are surrounded on all sides by the Pangyun Formation (see Fig. 30.4a, b). This is not a local dome feature, as evidenced by the consistent regional dip of all successions. Given this, and the co-depositional nature of both facies, we conclude that the local dominance and thickening of the Bawdwin volcaniclastic sediments immediately surrounding the ore bodies is due to enhanced volcanic sedimentation in the vicinity of Bawdwin.

Both sets of sediments were deposited prior to the intrusion of the Bawdwin rhyolites; these represent massive volcanic intrusions, obliquely transgressive to the local stratigraphy, and also oblique to cross-cutting faults. The intrusions are large, with the principal rhyolite massif being 4 km long, 400–1400 m in width and extending to a depth of 800 m. The Tiger Tunnel is almost exclusively bored into rhyolite.

The rhyolites have otherwise been referred to as ‘intrusive porphyries’ and have been recognized as representing two phases of magmatism, termed the Loi Mi and the Nam La by Hobson (unpublished data); Carpenter (1964) considered the Loi Mi body to be intrusive into the Nam La. The Loi Mi is a grey-white, often highly altered, quartz-feldspar volcanic rock that contains 5–10% 0.5–3 mm glassy ‘quartz eye’ phenocrysts (Hopwood 1985) and forms discontinuous lenticular bodies along the Bawdwin Fault Zone. Hopwood noted that this type of quartz porphyry is associated with 43 out of 45 major Cu–Pb–An–Ag–Au deposits he had worked on worldwide. The Nam La porphyry is more massive, and less altered. It is characterized in outcrop by reddish iron oxide colouring. While Brinckmann & Hinze (1981) suggested that there was little or no petrographic distinction between the Loi Mi and Nam La, Hopwood (1985) noted recognizable differences in the field.

The neighbouring Tawng Peng Granite is a batholith-scale porphyritic quartz, potassium feldspar, plagioclase, muscovite and biotite granite (Mitchell et al. 1977) with occasional tourmaline (Coggin Brown 1918), and is foliated with associated pegmatites. Such a two-mica granite is typical of the ‘Main Range’ granites of Cobbing et al. (1986) and it is possible that this intrusion represents an extension of their Central Belt, extending northwards from Western Malaysia and through Western Thailand.

Structure

All sedimentary units dip to the SE, the dip becoming shallower with successively younger units; this is a regional characteristic of the Shan Plateau. The area is simply folded (F1),
Fig. 30.4. (Continued) (b) Geological map of the Bawdwin area, after BGR (1976). Dotted rectangle indicates location of Figure 30.6.

THE BAWDWIN MINE

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with a number of broad and gently plunging anticlines and synclines plunging \( c. 20–30^\circ \) down the dip of the regional stratigraphy.

The ore bodies themselves are considered to lie within a complex, steeply dipping, NW–SE-trending (335°), structurally controlled zone of alteration and mineralization known as the ‘Bawdwin Fault Zone’ (Fig. 30.6). This zone is defined by a series of parallel longitudinal faults (e.g. the Hsenwi Fault), which split and merge along their length and are located within the volcanic agglomerates and tuffs, approximately 2.5 km long by 200 m wide (Hopwood 1985). Such faults are vertical and broadly parallel to the plunge of \( F_1 \) fold axis, such that

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### Table 30.2. Stratigraphic sequence descriptions in the Bawdwin vicinity

<table>
<thead>
<tr>
<th>Unit</th>
<th>Thickness (m)</th>
<th>Age</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shan Dolomite Group</td>
<td>3000</td>
<td>Devonian–Triassic</td>
<td>Brecciated dolomite and limestone; micritic and bioclastic dolomite</td>
</tr>
<tr>
<td>Kongsha Marl Member</td>
<td>600</td>
<td>Silurian</td>
<td>Buff-pink marls and local red sandstones</td>
</tr>
<tr>
<td>Namshim Formation</td>
<td>600</td>
<td>Silurian</td>
<td>Cross-bedded and massive quartzites, silty sandstones and siltstones</td>
</tr>
<tr>
<td>Pandsha-pye Formation</td>
<td>60</td>
<td>Silurian</td>
<td>Black, grey, white graptolitic shales</td>
</tr>
<tr>
<td>Naungkangyi Formation</td>
<td>1600</td>
<td>Ordovician</td>
<td>Red crioidal sandstones, calcareous siltstones, grey limestones, calcareous siltstones</td>
</tr>
<tr>
<td>Pangyun Formation</td>
<td>2000</td>
<td>Cambrian–Late Ordovician</td>
<td>Mudstone conglomerates, cross-bedded and massive quartzites</td>
</tr>
<tr>
<td>Bawdwin Volcanic</td>
<td>2000</td>
<td>Cambrian–Late Ordovician</td>
<td>Quartz-rich tuffs, quartzites, quartz rhyolites</td>
</tr>
<tr>
<td>Formation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chaung Magyi Group</td>
<td>3000</td>
<td>Late Precambrian–Cambrian</td>
<td>Greywacke, shale; rare conglomerates; rhyolite dykes; Tawng Peng Granite</td>
</tr>
</tbody>
</table>

After Mitchell et al. (1977).
Refer to Figure 30.5 for associated stratigraphic log.

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Fig. 30.5. Stratigraphic log of the Yadanatheingi area. The inferred zone of mineralization is marked. Modified from Mitchell et al. (1977).
Fig. 30.6. Detail of the Bawdwin Fault Zone showing the Shan, Chinaman and Meingtha lodes and the cross-cutting Yunnan and Hsenwi faults, after BGR (1976).
some workers have considered that this fault zone acted as a locus for the mineralization, controlling the main zone of alteration and ore deposition and as such pre-dating ore formation (Khin Zaw et al. 1993).

As well as these longitudinal faults, the mine area is cut by cross-faults (e.g. the Yunnan Fault). Carpenter (1964) believed movement on these faults separated two distinct phases of mineralization post Pb–Zn, but before Cu–Ni–Co. However, Brinckmann & Hinze (1981) could find no compelling evidence for large lateral displacements post-mineralization, suggesting that the three separate lodes could have formed independently of one another. Most recently, Hopwood (1985) inferred that these cross-faults did cut-off and dismember what was originally a continuous ore zone. He asserted that the Yunnan Fault separated the Chinaman and Shan ore bodies, as evidenced by consistent displacement along the 3rd (vertical) dimension and the occurrence of drag-folds on the 9th level. Equally, the longitudinal Hsenwi Fault displaces the Chinaman Lode from the Meingtha Lode, although the evidence for this is less compelling.

In terms of regional tectonics, there is a marked thickening of the Pangyun Formation sequence associated with the growth of the tuffs of the Bawdwin Volcanic Formation centred on the Bawdwin locality. This thickening is associated with a marked change in the strike of the Pangyun Formation from north–east to north–south. Hopwood (1985) asserted this was coincident with the Momeik–Twinnge Fault, a major tectonic feature, and in his opinion the fundamental deep ligament responsible for the localization of the Bawdwin Volcanic Formation and associated intrusive porphyries.

Mineralization

Ore bodies

The massive sulphide bodies which constitute the high-grade mineralization at Bawdwin are concentrated in the NW–SE-trending Bawdwin Fault Zone. From north to south, three principal ore bodies are developed: Shan Lode, Chinaman Lode and Meingtha Lode (for dimensions see Fig. 30.7). A fourth body, the Chin Lode, is found further north and has distinct mineralization. As well as being the first ore body to be discovered, the Chinaman Lode remains the most important due to its size and thickness; the upper part dips c. 70° W, trending to the vertical at depth. The hanging wall is defined as being to the west of the massive sulphide lens, and the footwall to the east shows stockwork and subsidiary lower-grade ore mineralization. The Chinaman Lode is the only one of the three major lodes to crop out on the surface. Figure 30.7 shows an isometric projection of the three principal lodes.

The Shan and Meingtha lodes are significantly thinner than the Chinaman Lode, but show a similar orientation. The Chin Lode dips more gently west and, uniquely, is hosted exclusively by rhyolite at the boundary between the Loi Mi and Nam La rhyolites.

The three principal ore bodies are surrounded by a lower-grade halo extending to the east and north, with a maximum width of 150 m around the Chinaman Lode. As noted by Brinckmann & Hinze (1981), observations underground showed that the hanging wall of the Chinaman Lode (the western boundary) is sharply defined, whereas the footwall (to the...
east) is a stockwork containing high-grade ore and sited within the lower-grade halo. These veins unite with the main ore body at depth. The other lodes show similar features; the Shan Lode also has a number of subsidiary veins at depth on its western flank of such a high grade they are collectively referred to as the Burman Lode.

**Mineralogy**

The ore bodies are both massive and disseminated. Although there is some variation between lodes, the principal minerals found in the three main massive sulphide lodes are galena and sphalerite. The high-grade ores are essentially massive intergrowths of these two sulphide minerals with little gangue; where encountered, gangue minerals are principally quartz and calcite. Other sulphide minerals present are pyrite and chalcopyrite. Müller & Weiser (1981) undertook detailed petrology and mineralogy of the ore deposits and, in their view, other sulphide minerals are present only as inclusions within the galena and sphalerite. The high-grade silver ore is usually associated with galena, and is present commonly as argentite or pyrargyrite inclusions (Hopwood 1985). Figure 30.8 shows reflected-light photomicrograph detail of mineralogical samples from the upper part of the Chinaman Lode, and Table 30.3 details the variety of mineralization found (after Dunn 1938).

The Chin Lode differs from the three main lodes in that it is much richer in copper (Brinckmann & Hinze 1981) and contains mainly pyrite with associated chalcopyrite and chalcocite, and only minimal galena–sphalerite mineralization.

**Stages of mineralization and zonation**

Mineralogical conformity does not exist within or between the different lodes. Early workers noticed distinct vertical mineralogical zoning within the different ore bodies, which led to...

![Figure 30.8](http://mem.lyellcollection.org/)

**Fig. 30.8.** Reflected light photomicrographs of samples of ore collected from the upper Chinaman Lode: (a) intergrowth of sphalerite, galena and quartz with a strong fabric, and associated pyrite crystals; and (b) pyrite 'stringers' along the quartz–sphalerite boundary.
Table 30.3. A summary of the main ore-forming minerals found at Bawdwin

<table>
<thead>
<tr>
<th>Lead minerals</th>
<th>Copper minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galena 5PbS, Sb2S3</td>
<td>Native Cu</td>
</tr>
<tr>
<td>Boulangerite 2PbSCu2SbS2</td>
<td>Chalcopyrite CuFeS2</td>
</tr>
<tr>
<td>Bouroninite 2PbSCu2SbS2</td>
<td>Digenite Cu2−S</td>
</tr>
<tr>
<td>Cerussite PbCO3</td>
<td>Covellite CuS</td>
</tr>
<tr>
<td>Anglesite PbSO4</td>
<td>Chalcocite CuS</td>
</tr>
<tr>
<td>Zinc</td>
<td>Iron sulphides</td>
</tr>
<tr>
<td>Sphalerite ZnS</td>
<td>Pyrite FeS2</td>
</tr>
<tr>
<td>Silver</td>
<td>Ni-cobalt</td>
</tr>
<tr>
<td>Argentite</td>
<td>Gersdorffite (Ni,Co,Fe)As</td>
</tr>
<tr>
<td>Pyragyrite 3Ag2Sb2S3</td>
<td>Ullmanite NiSbS5</td>
</tr>
<tr>
<td>Native Cu</td>
<td>Azurite Cu(OH−CO3)2</td>
</tr>
</tbody>
</table>

After Dunn (1938).

the suggestion of staged mineralization (e.g. Dunn 1938; Carpenter 1964). Perhaps the most striking zonation evident at Bawdwin is the vertical distribution of copper–cobalt–nickel in most of the lodes (Fig. 30.9). Cu–Co–Ni are confined to the peripheral and lower levels of the Meingtha and Chin lodes (Soe Win 1970; Brinckmann & Hinze 1981; Hopwood 1985), whereas Pb–Zn–Ag and Ba are concentrated towards the upper part of the ore bodies (Khin Zaw et al. 1993). High-grade silver ores are found associated with increased copper contents in the Chinaman Lode (BGR 1976). Carpenter (1964) asserted that, on the basis of the observed copper zonation, a distinct copper–cobalt–nickel paragenesis might represent a later event following the main lead–zinc mineralization.

The Chinaman Lode is the most zinc- and lead-rich of all the lodes, and the least copper- and nickel-rich. Conversely, the Chin Lode is principally copper-rich in contrast to the three main lead–zinc lodes. Copper is also more abundant in the Shan Lode alongside high silver grades, but interestingly mainly in its central levels, becoming lead- and zinc-rich at depth (Brinckmann & Hinze 1981). Also evident at Bawdwin is a component of horizontal zoning, which is perhaps most marked in the Chinaman Lode where the hanging wall to the west is lead-rich and the footwall more zinc-rich (BGR 1976) (Fig. 30.9). For a summary of zonation within the lodes see Table 30.4.

The massive sulphide ores are evidently deeply weathered. Soe Win et al. (1968) studied the oxidation process in the complex sulphide ores and concluded that the oxidation extends to a depth of 70 m below the surface, with no marked enrichment of copper, zinc or silver. This can be observed in the Gossan Pit where grades are lower than in primary ore mined underground.

Relationship of mineralization to host rocks

The sheet-like bodies of massive silver-rich galena-sphalerite ore lie transgressive to the bedding, within shear zones (see Fig. 30.10a). These ore bodies are not only hosted by the Bawdwin volcanoclastic sediments, but also by the rhyolites and the Pangyun Formation; the ore bodies themselves appear to have preferentially exploited the more permeable volcanoclastic sediments (Brinckmann & Hinze 1981).

There are commonly areas of disseminated or stringer ores which halo the massive ore, and alteration of all the host rocks occurs at the contact zones as varying degrees of sericitization and silicification. In places these alteration zones show major element change consistent with sericitization, silicification and chloritization, as evidenced by increases in K, Si, Mg and Fe and decreasing Ca and Na (Hopwood 1985). Müller & Weiser (1981) assumed a later age of alteration, due to no significant distinction in the degree of silicification and sericitization between the volcanic sediments and the rhyolites. Carpenter (1964) described nine stages of hydrothermal alteration from weak kaolinization of porphyry feldspars to late silicification along fractures; Table 30.5 summarizes these stages.

There is a marked difference in the grade of mineralization in relation to the differing host rocks, especially developed in the vicinity of tuff contacts, leading to the conclusion that mineralization is preferentially developed in the volcanoclastic sediments (see Fig. 30.10b). The grade is observed to fall sharply where the ore body passes from a Bawdwin Volcanic Formation tuff host to a Pangyun Formation host; lead values obtained from host-rock cores show a range of 200–14 000 ppm Pb in the tuffs compared to 0.05–1200 ppm Pb in the Pangyun formations (Hopwood 1985).

As noted above, the ore bodies are surrounded by subsidiary stockwork and veining in the footwalls. The up to 150 m long veins (BGR 1976) often comprise high-grade ore, and occur solely on the footwall of the massive ore lenses. These could represent the feeder stockwork associated with the genesis of the massive ore.

Age determination

There are several major magmatic intrusions in the vicinity of the Bawdwin locality. The Tawng Peng granite, some 10 km distant from the Bawdwin locality (Fig. 30.3), was the subject of Institute of Geological Sciences (IGS) dating in the 1970s. Brook & Snelling (1976) obtained ages from 44 ± 1 Ma to 253 ± 5 Ma from K–Ar dating of biotites and feldspars and 341 ± 17 Ma from Rb–Sr dating, although they thought this unlikely to be the age of intrusion based on the high mean square weighted derivative (MSWD) of 5.6. Using an initial whole-rock 87Sr/86Sr ratio of 0.705 they assumed apparent ages from three samples of 434–535 Ma, giving a Cambro-Ordovician age.

The oldest isotopically dated rock within Myanmar is the Sedawgyi biotite gneiss, some 35 km north of Mandalay on the eastern margin of the Mogok Metamorphic Belt. Here, U–Pb zircon ages give a date of 491 ± 4 Ma, interpreted as the magmatic age of the granite protolith (Mitchell et al. 2012). Over the border in Yunnan on the continuation of Sibusum, Liu et al. (2009) measured U–Pb ages of zircons from monzogranites of 499–502 Ma. These Late Cambrian ages are comparable with the stratigraphic Late Cambrian–Early Ordovician age given to both the Pangyun Formation and the inter-fingered Bawdwin Volcanic Formation tuffs and associated rhyolites on the basis of a trilobite marker.

As part of the BGR work, Lenz & Müller (1981) carried out whole-rock Rb–Sr radiometric age determinations of the Bawdwin Volcanic Formation. Samples were taken from surface exposures and from underground, where tunnels cut through the rhyolite both outside and within the Bawdwin Fault Zone, the latter showing more intense hydrothermal alteration. Lenz & Müller (1981) found an average age of 212 ± 4 Ma with a high initial 87Sr/86Sr ratio of 0.7553, and suggested that this age was a much younger event of hydrothermal alteration and therefore indirectly the date of mineralization. However, this was in direct contradiction to their BGR colleagues...
Brinckmann & Hinze (1981), who considered the mineralization at Bawdwin to be directly related to the rhyolite intrusions.

**Discussion**

To better understand the genesis of the Bawdwin deposit, we need to attempt to constrain the age relationships of the Bawdwin Volcanic Formation, both the volcaniclastic sediments and the porphyry intrusions, the mineralization, and localized and major faulting, and explain the role of the nearby Tawng Peng Granite.

If we believe both the Late Cambrian–Early Ordovician age for the Bawdwin Volcanic Formation and the 212 Ma Rb–Sr age of mineralization, as assumed by Lenz & Müller (1981), then the formation of the ore bodies was significantly later, some 100 Ma after the volcanic activity. This would suggest the volcanics are merely acting as hosts to the mineralization, playing no part in its genesis. Age data for Bawdwin mineralization and its host rocks are, however, tenuous. The 212 Ma age is possibly reset with an extremely high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio; however, the Cambro-Ordovician age given to the Panyun Formation and therefore assumed for the Bawdwin volcaniclastic sediments, is based on a single trilobite biostratigraphic age.

There are two possible scenarios that might explain the 212 Ma ‘mineralization’ age (Lenz & Müller 1981) as a later thermal overprint, and either of these scenarios crucially allows the genesis of the ore bodies to be older and opens the door for a direct relationship to the Cambro-Ordovician Bawdwin Volcanic Formation.

On the basis of its petrological characteristics and geographical location, it is possible that the Tawng Peng Granite is an extension of the Main Range Granite Belt of Cobbing et al. (1986), as some workers have already accepted (e.g. Khin Zaw 1990). Significant granitoids were emplaced in a broadly north–south granite belt during the Indosinian Orogeny, with typical ages falling in the range 198–220 Ma (Searle et al. 2012). If the Tawng Peng Granite is related to this orogenic event, then the 212 Ma date may therefore represent a thermal

![Fig. 30.9. Schematic of observed Pb, Zn and Cu zoning in the Shan, Chinaman and Meingtha lodes, after BGR (1976).](http://mem.lyellcollection.org/Downloaded from)
Table 30.4. Lode-by-lode summary of observed metallogenic zoning

<table>
<thead>
<tr>
<th>Ore body</th>
<th>Zoning characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chin Lode</td>
<td>Flat copper-rich vein in rhyolite, very early workings above level 1 (102 level)</td>
</tr>
<tr>
<td></td>
<td>Cu more abundant, Ag values high; Ag values associated with higher Cu in upper levels.</td>
</tr>
<tr>
<td></td>
<td>Pb values increase at depth. From levels 1 to 5, Zn is low and Cu is high; Zn increases</td>
</tr>
<tr>
<td></td>
<td>below level 5, and between levels 6 and 9 the ore contains the same Zn contents as the</td>
</tr>
<tr>
<td></td>
<td>Chinnaman Lode</td>
</tr>
<tr>
<td></td>
<td>Chalcopyrite increases relative to Zn in northern end of lode. Zn values are constant</td>
</tr>
<tr>
<td></td>
<td>at 20.5% from levels 1 to 4; Zn decreases to 9.1% at level 9. Pb values are consistent</td>
</tr>
<tr>
<td></td>
<td>from top to bottom of mine. Ag decreases from 31.4 oz on level 4 to 14.6 oz on level 9;</td>
</tr>
<tr>
<td></td>
<td>ratio of Ag/total metal is best on levels 3, 4 and 5.</td>
</tr>
<tr>
<td>Shan Lode (northern ore body)</td>
<td>Lower overall Ag, Pb and Zn than Chinnaman Lode, but slightly higher Cu and Ni. Both Zn and Cu increase at depth. There are two ore types: (1) above level 6, overall Pb-Zn-Cu is similar to Chinnaman Lode but with lower Pb, higher Cu and the same Ag/metal ratios; and (2) below level 6, the ore is Cu-rich with only a little Pb or Zn, but containing high Ni + Co. Best Ag values on levels 5–7.</td>
</tr>
<tr>
<td>Chinaman Lode (central ore body)</td>
<td>Lower overall Ag, Pb and Zn than Chinnaman Lode, but slightly higher Cu and Ni. Both Zn and Cu increase at depth. There are two ore types: (1) above level 6, overall Pb-Zn-Cu is similar to Chinnaman Lode but with lower Pb, higher Cu and the same Ag/metal ratios; and (2) below level 6, the ore is Cu-rich with only a little Pb or Zn, but containing high Ni + Co. Best Ag values on levels 5–7.</td>
</tr>
<tr>
<td>Meingtha Lode (southern ore body)</td>
<td>Lower overall Ag, Pb and Zn than Chinnaman Lode, but slightly higher Cu and Ni. Both Zn and Cu increase at depth. There are two ore types: (1) above level 6, overall Pb-Zn-Cu is similar to Chinnaman Lode but with lower Pb, higher Cu and the same Ag/metal ratios; and (2) below level 6, the ore is Cu-rich with only a little Pb or Zn, but containing high Ni + Co. Best Ag values on levels 5–7.</td>
</tr>
</tbody>
</table>

After BGR (1976).

overprint related to its emplacement, and not the age of mineralization. The intrusion has been dated using several different techniques, with ages reported from 253 to 341 Ma and extrapolated as far back as 535 Ma; for all of these measured or inferred dates, however, certain caveats were raised on the basis of sample size or initial strontium ratio values. Furthermore, it is possible that the Tawng Peng Granite is actually a composite pluton composed of Cambro-Ordovician, Mesozoic and even Cenozoic components, thereby accounting for the wide spread in age data. Fundamentally, we require better age constraints to determine the role of this intrusion. However, Lenz & Müller (1981) considered that due to their measured high initial 87Sr/86Sr ratio from the Bawdwin Volcanic Formation, the dated event ‘cannot have been an intrusion process’. An alternative hypothesis is that the 212 Ma age is tectonic in origin and records an overprint related to the migration of hydrothermal fluids migrating as a result of the Indosinian Orogeny.

With regards to the role of faulting, there is considerable evidence to suggest that several phases of deformation have affected the massive sulphide ore bodies and surroundings, and at least two phases of faulting and one phase of folding have been well documented. The role of faulting on the mineralization is, however, key; does the twinned Hsenwi–Yunnan Fault System pre-date mineralization, potentially act as a locus, or post-date it? On the basis of field observations, Coggins Brown (1918) wrote that the ores were deposited in a faulted zone. In their summary, Bruckmann & Hinze (1981) considered the location of the ore bodies to be determined by the Bawdwin Fault Zone with associated development of the Yunnan/Hsenwi fault systems prior to mineralization, and that the three ore bodies developed as separate lodes; they believed this was followed by considerably younger regional tilting of some 40–50°. However, we tend to believe Hopwood (1985) who, presented with the evidence of constant displacement among ore bodies and drag-folds, considered that the cross-faults post-date the mineralization, cutting up possibly a single ore body into the multiple lodes seen today. Furthermore, the ore bodies themselves have been considerably deformed and tilted, being steeply dipping to vertical, and it is likely this deformation is also subsequent to mineralization. The structure seen today within the Bawdwin Fault zone is therefore, we believe, a structure superimposed on the pre-existing ores and one that, due to competency differences, results in potential reconfiguration of the ore bodies with their host rocks.

Previous models

Early ideas for the genesis of the Bawdwin ore bodies pre-date the modern understanding of ocean-floor exhalative processes, and considered the mineralization to be structurally controlled. Chhibber (1934) recognized the role of fluids in the formation of the ore bodies, and assumed that ‘thermal solutions containing sulphides of lead, zinc silver and copper’ were fault-controlled and replaced the tuffs along the shear zone. Dunn (1938) also considered the faults crucial to the ore body genesis, maintaining that hydrothermal fluids moved through the Bawdwin ‘Arch’, depositing a single ore body within one fault that was subsequently cut-up by the Yunnan and Hsenwi faults into the multiple lodes seen today (Dunn 1938). Carpenter (1964) assumed two stages of mineralization and also emphasized the role of faulting, stating that the twinned Hsenwi–Yunnan faults developed before lead–silver–zinc mineralization and ‘in part’ before copper–nickel–cobalt mineralization (Carpenter 1964). He dismissed Coggins Brown’s (1918) assumption that the Tawng Peng Granite and Bawdwin have direct association on the basis of a lack of conclusive stratigraphic data and an absence of age data. In his view, mineralization occurred due to the ascent of ore-bearing fluids depositing their ores in a complex network of stringers. Lenz & Müller (1981) also favoured an epigenetic origin based on the Late Triassic age of alteration, spatially related to the mineralization.

Several workers (Bruckmann & Hinze 1981; Hopwood 1985) ultimately classified Bawdwin as a volcanogenic massive sulphide (VMS) Kuroko-type deposit, similar to both the Miocene felsic-hosted deposits of Japan and the Permian examples of California, USA. Bruckmann & Hinze (1981) considered that the Bawdwin mineralization was closely associated with the Lower Palaeozoic rhyolitic volcanism of the Bawdwin Volcanic Formation. Furthermore, they concluded the geological history to have had three distinct phases: an Early Phase, comprising volcaniclastic eruption; a Middle Phase, dominated by the rhyolite magma intrusion; and a Late Phase, with the sulphidic ore formation. They concluded:

The Kuroko stockwork and fissure-filling vein types do not have such an extremely high galena concentration as the three lodes of the Bawdwin deposit have. But it is shown... parts of the Shan and Meingtha Lodes with their high chalcopyrite content (Cu values exceed 10%) seem to be comparable to the pyrite/chalcopyrite/quartz mineralization of the Kuroko stockwork ore type (Bruckmann & Hinze 1981, p. 32).

Myint Lwin Thien & Than Naing (1983) also assigned a Kuroko-type classification to the deposit, suggesting that Bawdwin was equivalent to other massive, base-metal-rich stratiform deposits. Most recently, Hopwood (1985) concluded that Bawdwin was a typical volcanogenic deposit of the Palaeozoic or Archaean type.

A number of features make the Kuroko VMS model compelling. The Kuroko deposits of Japan are described as typically zoned, massive stratiform volcano-sedimentary deposits dominated by felsic tuffs, lava and shallow intrusives. They are usually oval-shaped in plan, and have funnel-shaped lower-grade stockwork in the footwall. The boundary between the stratiform ore and the hanging wall (e.g. tuffs) is usually sharp and, laterally, the ore body lenses out rather abruptly in most cases.
(Lambert & Sato 1974). Most notably, there is distinct vertical zoning of the constituent minerals, reflecting different phases and recognized zones; the deposit is typically underlain by copper-rich zones with progressive zinc, lead and silver enrichment vertically and laterally away from the vent centre (Taylor et al. 1996).

How does Bawdwin compare with such typical Kuroko-type deposits, and also with other felsic volcanic-hosted VMS deposits such as those of the Archaean Superior Province in Canada? There are certainly strong similarities: the ore bodies are hosted within felsic tuffs of the Bawdwin Volcanic Formation, as well as shallow-marine sediments; there are also associated shallow intrusives in the shape of the rhyolites. There is marked thickening and grading of the Bawdwin volcanoclastic sediments towards the ore bodies themselves, suggesting co-genesis. There is a clear headwall and footwall to the main ore bodies, with extensive lower-grade stockwork and high-grade veining in the footwall; the latter may represent the feeder veins. The ore bodies in Bawdwin are conspicuously zoned. The mineralization is intricately related both spatially and, we believe, temporally to felsic volcanism and magmatism, which itself is inter-fingered and co-depositional with the surrounding Pangyun Formation; furthermore, we believe the mineralization pre-dates the faulting and folding, so it might plausibly have formed as a single, zoned ore body that was later cut up.

There are also a number of key differences. There is no evidence for baryte or anhydrite mineralization; there are also no mudstones or deeper pelagic sediments, the Bawdwin locality being dominated by clastic sediments of the Pangyun Group with minor shales. There are discordant styles of mineralization relative to tuffs and sediments instead of a sharp boundary, but this might suggest later deformation or deeper stockwork level of exposure. Although Bawdwin has traditionally been thought of, and exploited as, a Pb–Zn–Ag producer, it might actually be more copper-rich than generally presumed. It evidences distinct Cu–Co–Ni zonation in its major lodes, as well as footwall–hanging-wall zonation in Pb and Zn grades; however, in general there is no systematic increase in copper across all lodes with depth.

Fig. 30.10. (a) Detail showing the transgressive relationship of the Bawdwin ore bodies to the host sedimentary sequences. (b) Development of mineralization at the contact zone with volcanoclastic sediments of the Bawdwin Volcanic Formation. Both after Hopwood (1985).
Stage 1 Weak kaolinization of orthoclase, both in the porphyries and in the altered sediments.

Stage 2 Secondary overgrowth of orthoclase on orthoclase; kaolinite forms a fringe within the envelope of secondary orthoclase. The entire grain is often slightly kaolinized.

Stage 3 Intense silicification as microgranular quartz; 5–30% of the total silica is secondary.

Stage 4 Local development of fairly weak to moderately strong illite (hydromica). It replaces euhedral grains of quartz and selectively replaces feldspars.

Stage 5 Penninite (a chlorite) often forms a fine rim around clasts. Some specimens contain up to 15% of chlorite. Clay clasts included in the clastic sediments are highly chloritized.

Stage 6 The vein stage appears here.

Stage 7 Sericitization (post-vein) permeated rocks along fractures and replaced siliciclastic matrix, quartz clasts, etc.

Stage 8 Late silicification along fractures, which appears to be local.

Stage 9 Siderite occurs locally in cracks and fractures. It cuts all earlier stages of mineralization. Pyritization in the form of small disseminated grains of pyrite was continuous from Stage 1 through Stage 6.

After Carpenter (1964).

New model

Ultimately, older classifications of VMS deposits only really considered Kuroko and Besshi types (e.g. Taylor et al. 1996) and, in our opinion, there is nothing particularly specific about a Kuroko-type VMS deposit. More recently, numerous workers have attempted to classify VMS deposits using differing paradigms (e.g. metal sources, type examples, geodynamic setting; see Franklin et al. 1981; Lydon 1984). It is therefore entirely appropriate that we revisit Bawdwin according to more recent classifications, which are based largely on the type of volcanic rocks and their associations.

One of the recent classification schemes that has gained ground with practising economic geologists is that which classifies VMS deposits according to their setting and rock associations, as summarized by Barrie & Hannington (1999) and Franklin et al. (2005). In this scheme, VMS deposits are assigned to one of five subclasses: mafic associated; bimodal–mafic; mafic pelite; siliciclastic–felsic; and bimodal–felsic (key features of these are summarized in Table 30.6). These all differ both in terms of their volcanic rock association but also, crucially, in terms of their tectonic setting. Deposits in the first three types are predominantly copper–zinc, while the last two contain significant lead. A further subdivision and refinement of these five models is the dominance of one of three end-member lithofacies: flow, volcaniclastic or sedimentary.

We believe Bawdwin fits into the siliciclastic–felsic model, with associated volcaniclastics. Most obvious is the association between felsic volcanics, both agglomerates, tuffs and rhyolite porphyries. Bawdwin is also intricately associated with continent-derived shallow-marine sedimentary sequences in the shape of the Pangyun Formation sandstones, mudstones and conglomerates. Furthermore, Bawdwin has a zinc–lead–rich metal assemblage. Franklin et al. (2005) defined the siliciclastic–felsic type as: 'Siliciclastic–felsic … occur in mature epicontinental backarcs, typified by continent-derived sedimentary and volcaniclastic strata [and] contain significant Pb'.

There are anomalies, however. Bawdwin has a high silver content, with little if any gold. Furthermore, VMS-type deposits are usually to be found in clusters (e.g. Galley et al. 2007) but, to date, no other VMS-type deposits have been found in the vicinity of Bawdwin.

Table 30.5. A summary of the nine stages of alteration observed in both the Pangyun Formation and the Bawdwin Volcanic Formation

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Weak kaolinization of orthoclase, both in the porphyries and in the altered sediments.</td>
</tr>
<tr>
<td>2</td>
<td>Secondary overgrowth of orthoclase on orthoclase; kaolinite forms a fringe within the envelope of secondary orthoclase. The entire grain is often slightly kaolinized.</td>
</tr>
<tr>
<td>3</td>
<td>Intense silicification as microgranular quartz; 5–30% of the total silica is secondary.</td>
</tr>
<tr>
<td>4</td>
<td>Local development of fairly weak to moderately strong illite (hydromica). It replaces euhedral grains of quartz and selectively replaces feldspars.</td>
</tr>
<tr>
<td>5</td>
<td>Penninite (a chlorite) often forms a fine rim around clasts. Some specimens contain up to 15% of chlorite. Clay clasts included in the clastic sediments are highly chloritized.</td>
</tr>
<tr>
<td>6</td>
<td>The vein stage appears here.</td>
</tr>
<tr>
<td>7</td>
<td>Sericitization (post-vein) permeated rocks along fractures and replaced siliciclastic matrix, quartz clasts, etc.</td>
</tr>
<tr>
<td>8</td>
<td>Late silicification along fractures, which appears to be local.</td>
</tr>
<tr>
<td>9</td>
<td>Siderite occurs locally in cracks and fractures. It cuts all earlier stages of mineralization. Pyritization in the form of small disseminated grains of pyrite was continuous from Stage 1 through Stage 6.</td>
</tr>
</tbody>
</table>

After Carpenter (1964).

Table 30.6. Five-stage classification of VMS type deposits

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mafic associated</td>
<td>VMS deposits associated with geological environments dominated by mafic rocks, commonly ophiolite sequences. The Cyprus and Oman ophiolites host examples and ophiolite-hosted deposits found in the Newfoundland Appalachians represent classic districts of this subclass.</td>
</tr>
<tr>
<td>Bimodal–mafic</td>
<td>VMS deposits associated with environments dominated by mafic volcanic rocks but with up to 25% felsic volcanic rocks, the latter often hosting the deposits. The Noranda, Flin Flon–Snow Lake and Kidd Creek camps would be classic districts of this group.</td>
</tr>
<tr>
<td>Mafic–siliciclastic</td>
<td>VMS deposits associated with sub-equal proportions of mafic volcanic and siliciclastic rocks; felsic rocks can be a minor component and mafic (and ultramafic) intrusive rocks are common. Metamorphic terranes may be known as pelitie or mafic-associated VMS deposits. The Besshi deposits in Japan and Windy Craggy, BC represent classic districts of this group.</td>
</tr>
<tr>
<td>Felsic–siliciclastic</td>
<td>VMS deposits associated with siliciclastic sedimentary-rock-dominated settings with abundant felsic rocks and less than 10% mafic material. These settings are often shale-rich siliciclastic–felsic or bimodal siliciclastic. The Bathurst camp, New Brunswick, Canada; Iberian Pyrite Belt, Spain and Portugal; and Finlayson Lake areas, Yukon, Canada are classic districts of this group.</td>
</tr>
<tr>
<td>Bimodal–felsic</td>
<td>VMS deposits associated with bimodal sequences where felsic rocks are in greater abundance than mafic rocks with only minor sedimentary rocks. The Kuroko deposits, Japan; Buchans deposits, Canada; and Skellefte deposits, Sweden are classic districts of this group.</td>
</tr>
</tbody>
</table>

After Franklin et al. (2005).

Geological summary

We agree with the German Mission (BGR 1976; Brückmann & Hinze 1981) that the volcaniclastic sediments of the Bawdwin Volcanic Formation were deposited within a marine environment and mixed with the detritus that now constitutes the Pangyun Formation (their 'Early Phase'). This was followed by the intrusion of numerous large rhyolite bodies ('Middle Phase'), which are generally concordant with a NW–SE-striking fissure system, and linked to the development of regional folding. However, we do not agree that the mineralization was a late-stage event, but instead propose that it formed concurrently with the volcaniclastic sedimentation as an exhalative deposit.

Finally, at some later stage, significant faulting and folding was imposed on the mineralized body, cutting it into the multiple ore lodes seen today. A thermal overprint was imposed on the mineralization in the Late Triassic, linked to the Indosinian Orogeny; this overprint may have been caused either by intrusion of the nearby Tawng Peng Granite or by orogenic hydrothermal fluids related directly to the tectonic event.

Regional tectonic setting

Key to understanding the genesis of VMS-type ore bodies is the tectonic setting in which they are formed, and this is one of the
criteria used in the most recent classification schemes. Siliciclastic–felsic VMS deposits are believed to have originated in an epicontinental back-arc setting (Franklin et al. 2005) and, in order to determine the setting of Bawdwin, regional plate tectonic palaeo-reconstructions are helpful.

Reconstruction of the assembly of Gondwana in the Late Proterozoic–Early Palaeozoic is a major research goal (e.g. Ali et al. 2013). Sibumus (after Metalcliffe 1984) is the basement that underlies the Shan Plateau where Bawdwin is sited. Sibumus has been interpreted in the Early Palaeozoic (540–490 Ma) to have been located on the Australian Gondwanan proto-Tethys margin in an Andean-type magmatic–arc setting (e.g. Zhu et al. 2012). The occurrence of regional Late Cambrian intrusives within Sibumus (e.g. the Šedawgyi gneiss) supports the presence of a magmatic arc during that time, and this in turn suggests the potential for a back-arc setting.

Regarding the role of the major twinned fault system observed at Bawdwin, some workers have suggested that one favourable setting for the genesis of VMS deposits is a subma- rine caldera (e.g. Ryutuba 1994), and that asymmetric caldera collapse can create a series of faulted blocks that act as a spatial control for VMS-type mineralization (e.g. Stix et al. 2003). Although we believe that faulting at Bawdwin is likely to have post-dated mineralization, the caldera collapse scenario has some merit and might provide an alternative setting.

Conclusions

(i) We believe the genesis of Bawdwin is directly associated with the Late Cambrian–Early Ordovician Bawdwin Volcanic Formation and, as such, the mineralization dates from this period.

(ii) We infer that Bawdwin is a siliciclastic–felsic volcanioclast- ic VMS-type deposit.

(iii) The ‘Bawdwin Fault Zone’ is a post-mineralization structure imposed on the ore body, which is strongly folded and faulted.

(iv) The Indosinian Orogeny is likely to be responsible for a Late Triassic overprint on the Bawdwin Volcanic Formation and associated mineralization, either through the emplacement of the neighbouring Tawng Peng Granite or through orogenic hydrothermal fluids.

As this chapter was being prepared (April 2014), Bawdwin was celebrating its centenary; it has been 100 years since excavation commenced for what was to become the Tiger Tunnel. The current mining operation is solely of the open-cut variety, and the underground workings have been mothballed and there is a concentrating plant at Bawdwin itself to process the open-cut ore. While carrying out further exploration at Bawdwin over the last 10–15 years, a number of companies have expressed interest in redeveloping the mine.

Other lead–zinc deposits in Shan State

The isolated nature of the Bawdwin VMS-style mineralization is anomalous in Myanmar, although other Pb–Zn mines are recognized in the Shan Plateau. Moho Chaung Mine is sited 50 km NE of Bawdwin, and is a sandstone-hosted SEDEX-type Pb–Zn–Ag deposit. Yadana Theingi Mine is sited some 50 km south of Bawdwin in northern Shan State, and hosts galena–barite ores within a NW-striking shear zone, interpreted as Mississippi Valley-type (MVT) mineralization (Mitchell et al. 1977). The Bawsaing (or Theingon) Mine sited near HeHo in southern Shan State is also a Pb–Zn–Ag deposit, and is considered to be a stratotabular, carbonate-hosted MVT deposit (e.g. Khin Zaw et al. 1993).

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