Massive Copper-Lead-Zinc Deposits in Felsic Volcanic Sequences of Japan and Australia: Comparative Notes.

I. B. Lambert*

Abstract: Massive Cu-Pb-Zn deposits in the Lachlan Fold Belt of Australia are compared with the Kuroko ores in the Green Tuff Belt of Japan. Whilst the deposits of both these important provinces formed in submarine felsic volcanic-sedimentary environments, the Australian deposits are relatively rarely associated with felsic lava domes, and they characteristically have lower Cu/(Pb+Zn) ratios, better developed depositional banding and little graded or breccia ore. It appears that most of the major Australian deposits formed in basins peripheral to volcanic centres, in contrast with the proximal deposition of the main Japanese ores.

Introduction

In the western Pacific region, massive Cu-Pb-Zn-(Ag-Au) sulphide deposits are being mined in two important metallogenic provinces—the Green Tuff Belt (Kuroko zone) of northeastern Japan and the Lachlan Fold Belt of southeastern Australia. The deposits in both provinces occur as stratabound lenses within sequences dominated by felsic volcanics. They have been regarded as belonging to the same general ore-type (e.g. Lambert and Satô, 1974), but there is no publication which compares and contrasts their characteristic features. The purpose of the present paper is to do this in a succinct manner, drawing on recent publications, papers in press and the author's experience in both countries.

In the interests of brevity and clarity, only specialized information is directly referenced in the text. The main sources of information (in English) on the general features of the Japanese deposits are the book edited by Ishihara (1974) and the reviews by Matsukuma and Horikoshi (1970) and Lambert and Satô (1974). The characteristic features of most of the Australian deposits are available from the descriptions of individual deposits in the books edited by Knight (1975) and Markham and Basden (1974), the report edited by Ramsden and Ryall (1978), and the papers by Ayres (1978), Braithwaite (1974), Felton et al. (1975), Malone (1978), Petersen et al. (1977); Petersen and Lambert (1978), and Stanton (1955). Ore genesis considerations are only touched on briefly and the interested reader is referred to the recent Kuroko issues of Mining Geology (nos. 4 and 5, 1978), which incorporate a number of ideas additional to those discussed in Ishihara (op. cit.) and Lambert and Satô (op. cit.).

General Features

(i) Regional setting

The massive Cu-Pb-Zn deposits of both Japan and Australia occur in elongate, narrow (less than 100 km wide) belts of predominantly submarine, calc-alkaline, volcanics and associated sedimentary rocks (Fig. 1). The thickness of these volcano-sedimentary sequences average around 1 km, but range up to a maximum of about 3 km. The calc-alkaline nature of the volcanics is based largely on lithological observations as there is a paucity of chemical data for unaltered rocks, but it is supported by analyses of relatively unaltered volcanics selected from the lithochemical data for northeastern Japan (e.g. Tatsumi and Clark, 1972) and for the Woodlawn area (Petersen et al., 1977; Gulson and Rankin, 1978).
The unmetamorphosed Kuroko Belt is of middle Miocene age and it formed in a tensional stress regime above subducting oceanic lithosphere (e.g. SATO, 1974). The low-grade metamorphosed belt in southeast New South Wales (N.S.W.) is of middle to upper Silurian age, whilst the separate area of felsic volcanics in northeast Victoria probably formed earlier in the Silurian. The weakly metamorphosed belt in northwest Tasmania is of Cambrian age. The tectonic environments of formation of these Australian volcano-sedimentary belts have been envisaged as similar to those for the Green Tuff Belt (e.g. SOLOMON and GRIFFITHS, 1972; SCHEINER and MARKHAM, 1976; GRIFFITHS, 1977), but D. WYBORN (1977) and L. WYBORN (1978) see no evidence for subduction.

The locations of the main Cu-Pb-Zn sulphide deposits in these belts are shown in Fig. 1. No major volcanogenic massive Cu-Pb-Zn deposits have yet been found elsewhere in Australia, although significant prospects occur at Halls Peak in northeast N.S.W. (Permian; DENGELING and POGSON, 1977), Mount Chalmers in southeast Queensland (probably Permian; LARGE and BOTH, 1978) and at several localities in the Pilbara Block of Western Australia (Archaean; REYNOLDS et al., 1975)*1. The major stockwork pyritic Cu-Au mineralization at Mount Morgan (Devonian), near Mount Chalmers, also appears to have Kuroko affinities.

(ii) Clustering and alignment of deposits

The massive sulphide deposits of both Japan and eastern Australia occur in clusters, but the number of deposits per cluster is generally greater in Japan. It has recently been proposed that the Kuroko clusters formed in large submarine calderas (OHMOTO, 1978), or cauldron subsidence basins (KOUDA and KOIDE, 1978). In some cases, there is a tendency for the distances between clusters to be fairly constant (SOLOMON, 1976; RAMSDEN and RYALL, 1978), but spacings vary from belt to belt and further assessment is needed before this can be used as a prospecting guide.

Many Kuroko deposits are related to sets of large-scale linears and, within individual mining areas, they tend to align along smaller lineaments (e.g. SCOTT, 1978). In Tasmania (e.g. SOLOMON, 1976) and N.S.W. (e.g.}

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*1 The structurally-complex, Devonian Cu-rich deposits in the Cobar region of central N.S.W. (BROOKE, 1976) do not have obvious spatial relationships with igneous rocks.
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RAMSDEN and RYALL, 1978), many of the deposits are aligned along major submeridional linears. Only in some cases have these linears been mapped as faults in the mineralized volcanics; many of them probably reflect basement structures. The deposits in southeast N.S.W. lie close to the extrapolated boundary between I-and S-type granite provinces (CHAPPELL and WHITE, 1976).

(iii) Favourable stratigraphic level

Throughout northeastern Japan, the major Kuroko deposits occur within a narrow stratigraphic interval which relates to the waning stages of a particular felsic volcanic cycle (e.g. SATO, 1974). This may also be the case for the massive Cu–Pb–Zn ores within each of the southeast Australian belts, but stratigraphic correlations are not adequate to prove it at present. In some mines, there are two or more massive lenses stacked through an interval up to a few hundred metres thick (e.g. Woodlawn, Que River in Australia; Yokota in Japan).

(iv) Associated rock types

Coarse lithic tuffs and tuff breccias of dacitic to rhyolitic compositions are commonly spatially associated with the massive deposits in both Japan and Australia. The felsic lava domes which are features of the Kuroko ores (e.g. HORIKOSHI, 1969) are not common in the Australian deposits, with the possible exception of the Que River prospect (WEBSTER and SKEY, 1977). Some relict welded textures occur in tuffs roughly 500 m in a general strike direction from ore lenses at Woodlawn (PETERSEN et al., 1977) and Rosebery (GREEN, 1976); these suggest that some subaerial eruptions occurred in these areas, although fine-grained sedimentary rocks in the immediate ore environments were obviously deposited under subaqueous conditions. Tuffaceous sedimentary strata are typically present near massive ores in both countries and some are rich in carbonaceous matter. Andesitic and basic igneous rocks can be moderately abundant, particularly in footwall sequences.

(v) Proximal and peripheral deposits

The major Kuroko deposits formed in close proximity to both felsic volcanic vents and/or fluid outlets (stockwork mineralization). HORIKOSHI and SHIKAZONO (1978) divided Kuroko-type deposits into black ore, composite ore and yellow ore sub-types and noted the tendency for each sub-type to occur in different parts of a given mining district, with the black ore being farthest (usually less than a kilometre) from volcanic centres. The major Australian deposits most resemble the black ore subtype, which comprises generally small deposits and constitutes the least important group amongst the Kuroko deposits. With the notable exceptions of the Que River and Mount Chalmers prospects, the main Australian deposits formed around the peripheries of palaeovolcanoes, with the closest eruptive centres being up to several kilometres away; furthermore, some deposits (e.g. Rosebery, Captains Flat) do not have significant stockwork mineralization. Compared with the main Kuroko deposits, the Australian deposits have relatively well-developed depositional banding and little breccia or graded-bedded ore.

(vi) Sizes and average grades (Table 1).

Most Kuroko mines do not exceed 10 million tonnes, but the greatest tonnage of ore in a single mining field is ~45 million tonnes occurring in numerous deposits within an area some 4×2 km incorporating Hanaoka and Shakanai mines. In Australia, Rosebery is the largest massive ore, with production and reserves totaling approximately 18 million tonnes (but ore limits are open to the north and at depth). The recently opened Woodlawn mine has published reserves in the vicinity of 10 million tonnes (plus additional unassessed mineralization), but other mines and prospects in southeastern Australia are less than 7 million tonnes. Mount Lyell mine contains approximately 120 million tonnes of ore at 1.2% Cu, but this is largely as stockwork mineralization; there are no known stockwork deposits approaching this size in Japan.

The overall average (arithmetic mean) metal grades for the main Kuroko mines in
northeastern Japan are 2% Cu, 5% Zn and 1.5% Pb. The average grades for the massive mines plus the Que River prospect in southeastern Australia are 0.9% Cu, 12% Zn and 5% Pb. It is clear that, compared with the Kuroko deposits, the Australian ores are generally richer in Pb and Zn, but poorer in Cu.

(vii) **Mineralogy**

Chalcopyrite typically occurs throughout the Japanese and Australian ore bodies, although it is not a major component in most of the latter (except Woodlawn), or in some of the Kuroko black ore sub-type (e.g. the Uwamaki deposits, Kosaka mine). Galena and sphalerite are enriched in the upper parts of the ore bodies, but are relatively minor constituents in the Kuroko yellow ore sub-type. In some cases there are separate massive to sub-massive chalcopyrite-pyrite lenses underlying polymetallic lenses (e.g. Woodlawn, Que River). Significant Ag commonly occurs near the top of the Pb-Zn-rich deposits, largely in galena and/or minor tetrahedrite-tennantite. Minor amounts of Au can also be concentrated near the top of the deposits; in the Kuroko ores this has been shown to occur mainly as electrum.

Pyrite is abundant throughout all the massive Cu-Pb-Zn deposits, but pyrrhotite and magnetite are, at best, minor constituents. Barite is abundant at the top of most Kuroko deposits, occurring within the Pb-Zn-rich ore and in separate lenses. Barite is also abundant in the Tasmanian belt: it occurs at the top of Rosebery and Que River, and in

<table>
<thead>
<tr>
<th>Kuroko, Japan</th>
<th>Southeast Australia</th>
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</thead>
<tbody>
<tr>
<td>Total tonnage of crude ore in largest mining field</td>
<td>~45 mill. t. (Shakanai-Hanaoka)</td>
</tr>
<tr>
<td>Approximate overall average grades</td>
<td>Cu = 2%</td>
</tr>
<tr>
<td></td>
<td>Pb = 1.5%</td>
</tr>
<tr>
<td></td>
<td>Zn = 5%</td>
</tr>
<tr>
<td>(Arithmetic means of mines and significant prospects)</td>
<td>Ag = 95 g/t</td>
</tr>
<tr>
<td></td>
<td>Au = 1.5 g/t</td>
</tr>
<tr>
<td>Number of significant deposits per mining field</td>
<td>2 to 12</td>
</tr>
</tbody>
</table>

* Excluding Woodlawn (1.7% Cu). ** Excluding Rosebery (18.2% Zn).
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a probable exhalite layer at the top of the Mount Lyell mineralization. However, barite only occurs in minor amounts in most of the New South Wales deposits, although there are several small barite deposits with only minor associated base metals in this belt. Gypsum/anhydrite is a feature of Kuroko deposits, either at the top of the stockwork ore or beside the massive ore. In contrast, none of the major Australian deposits contains primary calcium sulphates.

Bedded chert, often containing chlorite, hematite±minor pyrite is developed at the top of many Kuroko deposits and can extend well beyond the limits of the sulphide mineralization. Pods of chert can also occur within siliceous stockwork mineralization, massive ore and country rocks. Similarly, chert is a feature of most of the massive deposits in New South Wales; at Captains Flat, chert lenses extend along the ore horizon for many kilometres. In contrast, however, chert is not a feature of the Tasmanian massive deposits, although it occurs at Mount Lyell. In the Rosebery-Hercules area, and at Mount Chalmers, carbonate lenses of possible exhalative origin occur at the extremities of the deposits.

The main silicate gangue minerals in the Kuroko deposits are sericite, Mg-rich chlorite, with local kaolinite, interstratified clays and quartz. In the Australian deposits, the dominant gangue minerals are chlorite, quartz, sericitic muscovite and, in some cases, talc (e.g. Woodlawn).

(viii) Hydrothermal alteration

Volcanic and sedimentary rocks are hydrothermally altered for variable distances around the Japanese (IIJMA, 1974; SHIROZU, 1974; UTADA et al., 1974; IZAWA et al., 1978) and Australian (PETERSEN et al., 1977; PETERSEN and LAMBERT, 1978; RAMSDEN and RYALL, 1978) deposits. Highly altered rocks close to mineralization grade into more extensive zones in which the alteration is commonly difficult to discern in hand-specimen. Alteration patterns are basically similar for the Japanese and Australian deposits.

Alteration is best developed in foot wall rocks, but has been detected for up to 200 m into the hanging wall and for up to several kilometers along the ore horizon. The alteration essentially involves chloritization and sericitization at the expense of primary ferromagnesian minerals and feldspars. Silicification is a feature of the hydrothermally altered rocks, but also occurs in volcanics beyond the limits of chloritic and sericitic alteration. Outside phyllosilicate-rich alteration zones, carbonate minerals are commonly present in minor veinlets and concretions on a semi-regional scale.

The main chemical changes observed in the hydrothermally altered rocks are major addition of Fe, Mg, S and Si, more sporadic addition of Cu, Pb, Zn, Ba, Mn, K, Ag, Hg, Ag and Sn and major depletion of Ca, Na and Sr. The ratio Na/Mg is a good indicator of hydrothermal alteration.

Stringer and disseminated mineralization (pyrite→chalcopyrite, sphalerite, galena) occurs in minor to very significant amounts in the country rocks around massive deposits. It is generally most abundant in the stratigraphic foot wall and in rocks between “stacked” massive lenses (Woodlawn and Que River). Studies in the Woodlawn region indicate that pyrite close to massive ores is characterized by minute inclusions of copper, lead and zinc sulphides and by higher Hg contents than pyrite in “barren” volcanics (RYALL, 1977).

(ix) Associated mineralization

In both Japan and Australia, fault-controlled, epithermal vein deposits (Cu with or without significant amounts of Pb and Zn; Au; Ag; Hg) occur within the same sequences as the massive ores, as well as in related terrestrial volcanics. A number of deposits of this type are being mined in Japan, but few have warranted exploitation on a significant scale in Australia.

It is noteworthy that porphyry-copper deposits are not known in the submarine sequences hosting the massive sulphide deposits of either country.
Effects of low grade regional metamorphism and deformation

The low grade regional metamorphism of the Australian volcano-sedimentary rocks has caused a number of mineralogical changes including the development of muscovite from sericite, feldspars from zeolites plus clays, and chlorite and talc from Mg-rich clay minerals. There is a contentious possibility that the absence of gypsum/anhdydrite in and around the Australian deposits can be ascribed to dissolution or mineralogical reactions during post-depositional processes.

Shearing is a feature of many of the Australian deposits; this is probably a function of the concentration of stresses in the sulphide lenses and phyllosilicate-rich country rocks during tectonic deformation, reflecting the unusual physical properties of these rocks. Shearing can also cause transposition of sulphides into cleavage directions, and enhancement of primary depositional banding.

Isotopic Data

(i) Strontium

There are few Sr isotopic data for felsic volcanics associated with the massive Cu–Pb–Zn deposits. These indicate contrasting initial \(\text{Sr}^{87}/\text{Sr}^{86}\) ratios of 0.703—0.705 and 0.710, respectively, for the Green Tuff (SHUTO, 1974) and Woodlawn (GULSON and RANKIN, 1978) volcanics.

Sr isotopic compositions of barite and anhydrite from the Kuroko deposits have been determined by FARRELL et al. (1978) who found these had \(\text{Sr}^{87}/\text{Sr}^{86}\) ratios around 0.708, which are closer to the ratios in Miocene seawater than to those in the volcanics. This suggests hydrothermal leaching of the Green Tuff sequence was not the major source or Sr in the ore fluids.

(ii) Sulphur

A number of S isotope studies of Kuroko deposits (TATSUMI, 1965; SAKAI et al., 1970; KAJIWARA, 1971; KAJIWARA and DATE, 1971) have established the following characteristic \(\delta^{34}S\) ranges: pyrite: +3.1\(^{\circ}/_{oo}\) to +8.2\(^{\circ}/_{oo}\) (average +6\(^{\circ}/_{oo}\)); chalcopyrite: +2.1\(^{\circ}/_{oo}\) to 6.9\(^{\circ}/_{oo}\) (average +4.5\(^{\circ}/_{oo}\)); sphalerite: +3.5\(^{\circ}/_{oo}\) to +6.9\(^{\circ}/_{oo}\) (average +5\(^{\circ}/_{oo}\)); galena +1.0\(^{\circ}/_{oo}\) to +3.4\(^{\circ}/_{oo}\) (average +2\(^{\circ}/_{oo}\)); barite: +22.2\(^{\circ}/_{oo}\) to +25.4\(^{\circ}/_{oo}\) (average +23.5\(^{\circ}/_{oo}\)); gypsum-ahnydrite: +22.2\(^{\circ}/_{oo}\) to +25.4\(^{\circ}/_{oo}\) (average +25.5\(^{\circ}/_{oo}\)). These data indicate isotopic equilibrium between coexisting sulphide minerals at \(\sim 250^\circ\text{C}\), which is in general accord with fluid inclusion temperatures (e.g., MARUTANI and TAKENOUCHI, 1978). There is a general trend for \(\delta^{34}S\) values to decrease slightly from the yellow ore, through the composite ore, to the black ore subtypes (HORIKOSHI and SHIKAZONO, 1978).

Results from Woodlawn (AYRES et al., 1978) are similar to the Kuroko data except that the minor primary barite has slightly higher \(\delta^{34}S\) values, and coexisting sulphides appear to have equilibrated at temperatures closer to 300\(^\circ\text{C}\). However, Rosebery shows a somewhat different pattern, with a lack of isotopic equilibration between the sulphides (SOLOMON et al., 1969; GREEN, 1977). Here, \(\delta^{34}S\) values for pyrite and sphalerite increase from +7\(^{\circ}/_{oo}\) to +17\(^{\circ}/_{oo}\) from the pyrite-zone, through the Cu-zone, into the Pb–Zn zone, and barite values are around +33\(^{\circ}/_{oo}\). Thus, the \(\delta^{34}S\) changes in this orebody are much greater than in the Kuroko deposits and Woodlawn, in addition, they are in the opposite sense to the variations found at Shakanai by KAJIWARA (1971).

In all cases, the average \(\Delta^{34}S\) (barite–sulphide) values are in the range +14\(^{\circ}/_{oo}\) to +20\(^{\circ}/_{oo}\) fitting the world-wide pattern observed for volcanogenic ores. SANGSTER (1968) argued this pattern indicated derivation of the sulphur in the ores from seawater, and this was later quantified by RYE and OHMOTO (1974). Whilst there can be little doubt concerning the seawater sulphur component in the Rosebery deposit, ISHIHARA and SASAKI (1978) have drawn attention to the similar \(\delta^{34}S\) values of sulphide minerals in Japanese Miocene granitoids, veins and the Kuroko deposits as possible evidence of deep-seated sulphur sources.

(iii) Lead

The Pb isotopic compositions of the Kuroko
deposits have been determined by SATO and SASAKI (1973) and SATO et al. (1973); those of Rosebery, Captains Flat and Halls Peak deposits have been determined by OSTIC et al. (1967) and Woodlawn by GULSON (1977). In all cases, the ores plot close to the primary lead growth curves. However, the Pb "model ages" are younger than the geological ages by varying amounts; Rosebery is the extreme case having a geological age of ~500 m.y and a "model age" of ~160 m.y. This may be at least in part a function of post-depositional addition of radiogenic Pb from decay of U and Th in the deposits. In this respect, it is noteworthy that GULSON (1977) found variable U contents in pyrite at Woodlawn and that PETERSEN et al. (1977) documented significant levels of U and Th in Woodlawn mineralization.

In Japan and at Woodlawn it has been established that the ore Pb is isotopically compatible with that in the associated volcanosedimentary rocks. Furthermore, the distinct isotopic composition of Pb in Ordovician rocks beneath the Woodlawn deposit (GULSON, 1976, 7) precludes derivation of the bulk of the ore metals by "basement" leaching.

**Conclusions**

It is evident that the massive, stratabound Cu–Pb–Zn deposits of southeastern Australia belong to the same general ore-type as the Kuroko deposits of northeastern Japan. Some minor Australian deposits are indistinguishable in most respects from Kuroko deposits. However, compared with the main Kuroko ores, the main Australian deposits have low Cu/(Pb+Zn) ratios and they formed as larger units with better developed depositional banding and little breccia or graded ore. Furthermore, few of the Australian deposits have spatially associated felsic lava domes, and none have primary gypsum-anhydrite.

The Woodlawn volcanics have different initial Sr$^{87}$/Sr$^{86}$ ratios from those associated with Kuroko deposits. In terms of S and Pb isotopes, Woodlawn shows analogous features to the Kuroko ores, but Rosebery exhibits significantly different trends.

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Geol., 69, 826~842.


日本およびオーストラリアの火山性塊状銅・鉛・亜鉛鉱床：比較研究

I. B. ランバート

要旨：オーストラリア、ラチラン褶曲帯の塊状銅・鉛・亜鉛鉱床を日本黒鉛鉱床と比較した。両者は珪長質な海底火山－堆積性環境に産出し、一般には同じ型の鉱床であり、とくにオーストラリアの小さい鉱床は全く類似する。しかし主要な鉱床は比較的まれにしか溶岩ドームと関連せず、低い銅／鉛鉱鉱体比を有する。また、鉱床の一部は大きく緑状堆積構造が発達する反面、角礫鉱石や分級構造はまれである。初生の石英類は産出しない。オーストラリアの鉱床は火山活動の中心からはなれた盆地の周縁部に生成したものと考えられ、日本の主要鉱床が火山体の近くに生じたのと対照的である。同位体データについても若干の考察をおこなった。