Journal and Proceedings of the Royal Society of NSW, Vol. 131 Parts 1-2, 13-18
ISSN 0035-9173/98/01013-18 $4.00/1

Maldonite and Its Paragenesis at Kingsgate, New South Wales

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ABSTRACT. The occurrence of maldonite (Au_2Bi) in the molybdenite-bismuth quartz pipes of Kingsgate, in the New England region of New South Wales is described. This intermetallic compound is present as minute particles embedded in gold inclusions in native bismuth, with associated bismuth telluro-sulphides. Evidence that maldonite may be the product of solid-state diffusion between gold and bismuth is indicated where maldonite forms a reaction rim around corroded particles of gold embedded in bismuth. Rare myrmekitic intergrowths of gold and bismuth are considered to be breakdown products of metastable maldonite. Joseite (Bi_4TeS_2) and Joseite-B (Bi_4Te_2S) are the principal associated bismuth tellurosulphides, accompanied by a possibly new bismuth telluro-sulphide mineral ($Bi_{10}Te_2S_5$).

INTRODUCTION

Maldonite, Au_2Bi, is a relatively rare intermetallic mineral belonging to the cubic system and space group Fd3m. The mineral was originally found in the Nuggety and the Union gold-bearing quartz reefs at Maldon in central Victoria. Maldonite is bright silvery in colour with a faint pinkish overtone, it eventually tarnishes to brown and ultimately to a blackish colour, whereupon it became known to the miners as "black gold".

The mineral was named maldonite by Ulrich in 1870 and further characterised by him in 1875. Controversy ensued because the existence of a compound Au_2Bi was considered extremely doubtful since it was impossible to produce it experimentally from a melt of gold and bismuth. The matter was eventually resolved when the mineral was synthesised by solid-state diffusion as outlined by Edwards (1960); a natural example of this diffusion reaction is documented in this paper, along with other aspects of paragenesis.

Fig. 1. Map showing the location of Kingsgate.

TABLE 1
PRIMARY MINERALS OF THE KINGSGATE MOLYBDENITE PIPES
(After Lawrence and Markham 1962, with later additions)

Major components	
Molybdenite	MoS_2
Bismuth	Bi
Bismuthinite	Bi_2S_3
Minor components	
Pyrrhotite	$Fe_{1-x}S$
Pyrite	FeS_2
Chalcopyrite	$CuFeS_2$
Ikunolite	Bi_4S_3
Arsenopyrite	FeAsS
Joseite	Bi_4TeS_2
Joseite-B	$Bi_4(Te,S,Se)_{3-x}$
Unnamed phase	$Bi_{10}Te_2S_5$
Gold	Au (± Ag)
Tetradymite	Bi_2Te_2S
Cassiterite	SnO_2
Wolframite	$FeMnWO_4$
Galenobismutite	$PbBi_2S_4$
Cosalite	$Pb_2Bi_2S_5$
Accesssory components	
Galena	PbS
Sphalerite	ZnS
Pyrargyrite	Ag_3SbS_3
Maldonite	Au_2Bi

For some time maldonite was thought to be a mineral unique to the gold deposits of Maldon, but with the advent of the electron microprobe, numerous other occurrences have been recorded. It has been found in hydrothermal deposits at Cobar and at Rockley in New South Wales, in skarn at Nevoria near Southern Cross, Western Australia and in the Challenger Prospect in the Gawler Ranges, South Australia. Overseas, maldonite has been observed in ore from Akjoujt, Mauritania; in skarn from Rezbanya; from Ingham, Ontario, Canada; as a myrmekitic intergrowth in bismuth from Ishibashi, Japan; from Tyrnyauz and Transbaikalia, Russia; in hydrothermal veins at Zarmitan, Uzbekistan; in veins from Mokksrsko, Czec Republic; from Sierra County, New Mexico; in the Bushveld Complex, South Africa; and in hydrothermal veins in the Salsigne and Scoufour Cantal gold deposits in France. However, except at

Fig. 2. Reaction rim of maldonite (light grey) surrounding and filling corrosion voids in gold in an outer bismuth matrix which has reacted with the gold by solid-state diffusion. Reflected light photomicrograph, phase contrast enhanced electronically. Area of specimen shown 1.5 mm x 1.0 mm.

Maldon, where centimetre-size pieces of unaltered or tarnished maldonite ("black gold:) were obtained, all other occurrences to date are of microscopic dimension.

MICROPROBE ANALYSIS

The presence of maldonite at Kingsgate, albeit as an accessory component of a complex multimineralic ore, dominated by molybdenite and bismuth, is here confirmed by electron microprobe analysis.

The Kingsgate mining field is situated 30 km east-south-east of Glen Innes in the northern New England region of New South Wales (Fig. 1). The mines were significant producers of molybdenite and bismuth which occurred in pipe-shaped masses of lode quartz emanating from a silexite differentiate within a highly acidic granite (SiO_2 77.60%) of epi-Permian age. The deposits are of high temperature type with eventual development of some lower temperature minerals such as pyrargyrite, albeit in trace amounts. The mineralogy of the Kingsgate deposits is given in Table 1 (after Lawrence and Markham 1962).

A further study of polished sections of native bismuth from Kingsgate revealed the presence of numerous grains of gold as inclusions in the bismuth. The gold grains

TABLE 2
ELECTRON MICROPROBE ANALYSES OF MALDONITE AND ASSOCIATED ORE MINERALS

	Bismuth	Gold (a)	Gold (b)	Maldonite	Joseite-B	Unknown	Chalcopyrite	Pyyrhotite
					(wt%)			
Bi	100.7	<0.1	<0.1	32.4	75.8	83.0	0.2	0.1
Au	<0.1	94.7	98.8	67.1	<0.1	0.2	0.1	0.1
Ag	na	4.1	0.4	na	na	na	na	na
Fe	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	29.3	60.1
Cu	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	33.5	<0.1
Te	<0.1	<0.1	<0.1	<0.1	21.0	10.2	<0.1	<0.1
S	<0.1	<0.1	<0.1	<0.1	2.8	6.7	35.4	39.8
TOTAL	100.7	98.8	99.2	99.5	99.6	100.1	98.5	100.1

Note: (a) = Ovoid gold inclusions in bismuth; (b) = Myrmekitic gold with maldonite.
na = not analysed.

are often crudely ovoid in shape and from 0.05 mm to 1.75 mm long. Electron microprobe analyses in the present study show that they contain about 4 wt%Ag (Table 2). In addition to the gold, irregular shaped inclusions of joseite (Bi_4TeS_2) and, less commonly, joseite-B (with an analysed composition Bi_4Te_2S) occur in some of the bismuth specimens.

The larger of the gold grains are surrounded by a rim of another (unidentified) mineral. The polishing hardness of this mineral is slightly less than for gold (H 2.5 - 3), but similar to that of the bismuth matrix (H 2 - 2.5). The unidentified mineral (Fig. 2) has a high reflectivity, about the same as for bismuth, appears creamy white with a bluish-green overtone in plane-polarised reflected light, and is isotropic, and therefore cubic. The same mineral was observed as minute inclusions in gold within bismuth.

Electron microprobe analyses (Table 2) confirm that the previously unidentified mineral is maldonite. The associated minerals are bismuth, gold, chalcopyrite, pyrrhotite, joseite-B, and an unknown bismuth telluro-sulphide having a formula $Bi_{10}Te_2S_5$. This latter phase is apparently a new mineral and is currently being investigated in more detail.

The reaction rim texture of Fig. 2 clearly indicates that maldonite at Kingsgate has formed by solid-state diffusion reaction between gold and bismuth, although occasionally gold has been observed in contact with bismuth, embedded in molybdenite, without any sign of reaction between the two phases (Lawrence and Markham, 1962).

Detailed electron microprobe investigation of a myrmekitic intergrowth of gold and bismuth (Fig. 3) revealed a few minute (<10 µm) inclusions of maldonite within the gold (Fig. 4). The composition of the myrmekitic gold is essentially pure (Table 2), in marked contrast to the argentian composition of the ovoid inclusions described above. The myrmekitic texture is interpreted as the break down of maldonite into its elemental components and the inclu-

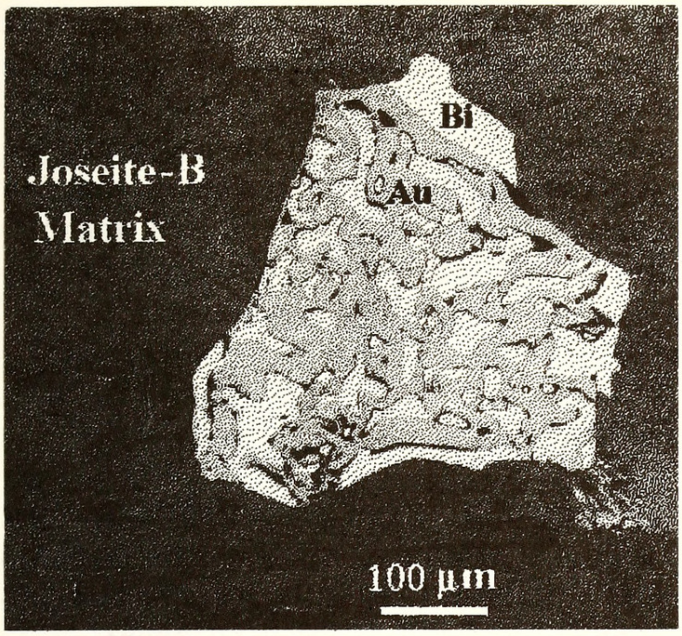

Fig. 3. Myrmekitic intergrowth of bismuth (white) and gold (light grey) embedded in joseite-B (dark grey). The texture is interpreted to result from breakdown of a particle of maldonite into its elemental components. Minute inclusions of relic maldonite occur in the gold (see Fig. 4). Backscatter electron image. Scale bar = 100 µm.

sions are interpreted as relic maldonite. Element concentration profiles for gold and bismuth across one maldonite inclusion (Fig. 5) show very sharp contacts between the maldonite and gold, consistent with this interpretation.

The results of this microprobe study suggest, further, that maldonite is a metastable compound, which may form or decompose depending upon the prevailing physicochemical environment:

$$2Au + Bi \rightleftarrows Au_2Bi.$$

CONCLUSION

The co-existence of maldonite both as reaction rims between gold and bismuth and as relic inclusions in gold-bismuth decomposi-

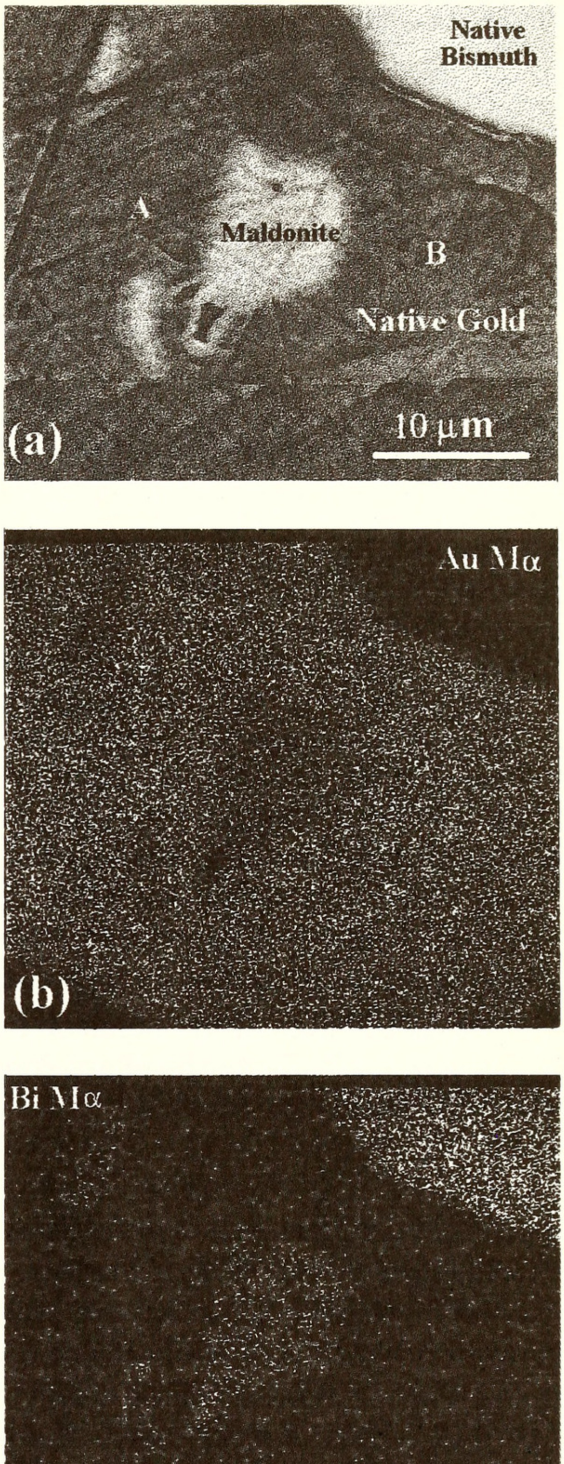

Fig. 4. Maldonite in a particle of myrmekitic gold and bismuth. (a) Backscatter electron image showing relic inclusion of maldonite (mid-grey) in gold (dark grey) with bismuth (white). Locations A and B. mark the start and end points of an electron beam line scan across the inclusion (see Fig. 5). Scale bar = 10 µm. (b) Element distribution map for gold (Au Mα X-rays). (c) Element distribution map for bismuth (Bi Mα X-rays).

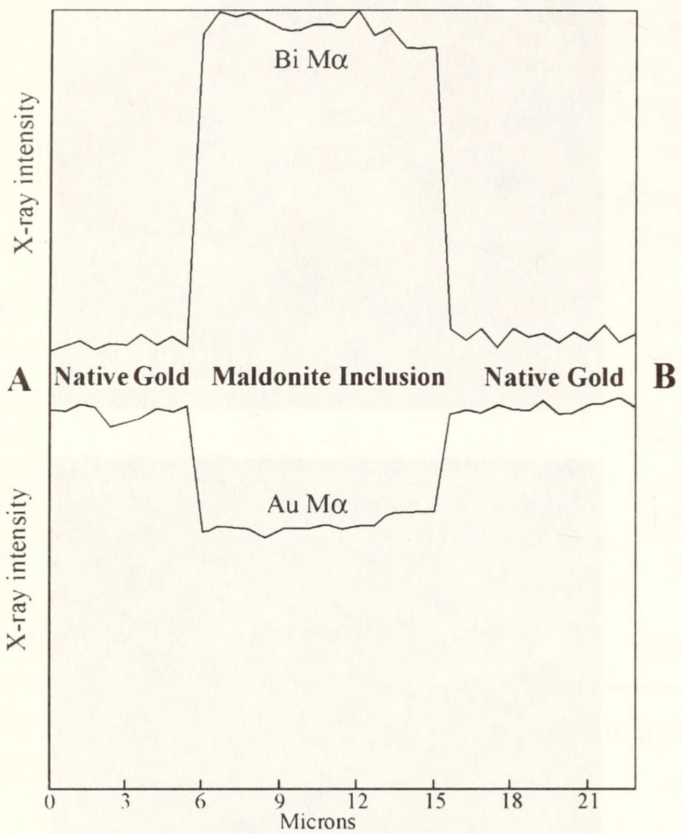

Fig. 5. X-ray intensity profiles for Au Mα and Bi Mα across the maldonite inclusion shown in Fig. 4 (line A - B). Note the sharp contacts between the maldonite and gold.

tion products suggests that conditions during formation of the Kingsgate bismuth-rich ores fluctuated close to the stability field for maldonite. As the ore fluids cooled, formation of maldonite would be favoured where short lived temperature increases resulted in atomic diffusion reaction between gold and bismuth, while decomposition of maldonite into gold and bismuth would be favoured where there was a slightly accelerated drop in temperature.

The occurrence of maldonite at Kingsgate differs from other recorded localities in respect to its paragenetic relationships: as reaction rims around and within myrmekitic gold grains, as particles of original maldonite embedded in the gold and as small decomposed grains seen now as myrmekitic intergrowths of gold and bismuth. The study further attests to the metastable nature of maldonite.

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Manuscript received 9.4.98