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Foliation-boudinage control on the formation of the Rosebery Pb–Zn orebody, Tasmania

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Abstract—The Rosebery Pb–Zn–Ag–Au massive-sulphide deposit occurs within the Middle-Cambrian Mount Read Volcanics of western Tasmania It is hosted by a tuffaceous slate lens that is surrounded by felsic volcanics. The volcanic belt and its Ordovician cover were deformed and metamorphosed during an Early to Middle Devonian orogeny (Tabberabberan orogeny). During this orogeny D_3 E–W shortening was partially accommodated by reverse bedding-parallel shearing within the slate unit and immediately underlying volcanic rocks. This caused reactivation and intensification of an early foliation (S_2), and the development of asymmetric chocolate-tablet foliation-boudinage structures with boudin necks parallel to the X- and Y-directions.

The mineralization occurs along extensional shear-planes that are associated with foliation-boudinage. Mineralogical zoning in the orebody can be directly related to dilational bends in shears associated with foliation-boudin-necks It is proposed that these structures gaped during the D_3-deformation, allowing infiltration of metalliferous hydrothermal-fluids along shear plane and cleavage directions into the fractured wall-rock. Progressive metasomatic replacement of the wall rock resulted in the formation of a sulphide–sulphate–silicate orebody.

The orebody is completely discordant to folds in the host rock; this observation confirms a structurally-controlled origin and refutes earlier interpretations of the deposit as a tightly-folded chemical sediment. Isotope data indicate that the orebody was probaby derived from volcanogenic sulphides within the Mount Read Volcanics The Rosebery orebody is best regarded as a metamorphogenic deposit that formed by dissolution, upward transport, concentration and re-precipitation of primary sulphides. The proposed macroscopic model complements separate microstructural evidence by the author indicating a syn-D_3-timing of mineralization

INTRODUCTION

THE Central Volcanic Belt or Central Sequence of the Mount Read Volcanics (of Corbett 1981, 1986) is 10–15 km wide and 200 km long, and consists of calc-alkaline lavas and pyroclastics of Middle- to Late-Cambrian age (Jago 1979, Adams *et al.* 1985) that were deposited in an elongate Cambrian volcano-sedimentary basin known as the Dundas Trough (Campana & King 1963) (Fig. 1). The development of this Cambrian basin and the age relationships between its units are complex and remain incompletely understood. For a detailed description of the regional geological history (summarized below), see Corbett (1981, 1986), Solomon (1981), Collins & Williams (1986), Corbett & Lees (1987) and Solomon *et al.* (1988).

The Dundas Trough is bounded by Precambrian rocks of the Tyennan Block to the east and the Rocky Cape Block to the west. The volcanism in the Central Volcanic Belt occurred during sedimentation in the western part of the Dundas Trough. Middle- to Late-Cambrian tectonism included possibly syn-sedimentary thrusting, block-faulting and uplift, and resulted in discordant deposition of a Late Cambrian to Early Ordovician conglomeratic sequence (Owen Formations) followed by the deposition of cover sediments until Early Devonian times. During the Middle Devonian deformation, correlated with the Tabberabberan Orogeny of south-eastern Australia, the Mount Read Volcanics were folded and metamorphosed to lower greenschist facies.

The Rosebery ore-deposit, discovered in 1893, is the largest of five known Pb–Zn massive-sulphide orebodies in the northern part of the central volcanic belt. Pre-mining ore reserves contained approximately 20 million tonnes that averaged 5% Pb, 16% Zn, 0.74% Cu, 155 g/t Ag and 2.9 g/t Au (Large *et al.* in press). From the start of geological investigations until 1965, a replacement origin controlled by Devonian structures was proposed (Finucane 1932, Stillwell 1934, Hall *et al.* 1953, 1965). These authors concluded that replacement of the host rock was controlled by the foliation. Stillwell (1934) documented aligned, cleaved, host rock fragments within the massive sulphides which he regarded as replacement relics or 'islands' and noted parallelism and transitional boundaries between the massive ore-banding and the host rock foliation. He further proposed a paragenetic replacement sequence based on a detailed petrographic study.

More recently, the deposit has been reinterpreted as a tightly-folded stratiform massive sulphide layer, formed by exhalation on the sea floor (Solomon 1965, Solomon *et al.* 1969, Brathwaite 1970, 1972, 1974, Green *et al.* 1981, Green 1983). Brathwaite concluded that the ore was generally parallel to both bedding and cleavage, and proposed that the deposit featured a stratified Kuroko-type mineral-zoning pattern that had been intricately folded during Devonian times. Sulphur-isotope studies (Green *et al.* 1981, Green 1983, Solomon *et al.* 1988) suggested that Cambrian seawater and volcanic rock was the source of sulphur.

Since the recognition of volcanogenic ore-deposits in the early 1960s, and the advancements in volcanogenic

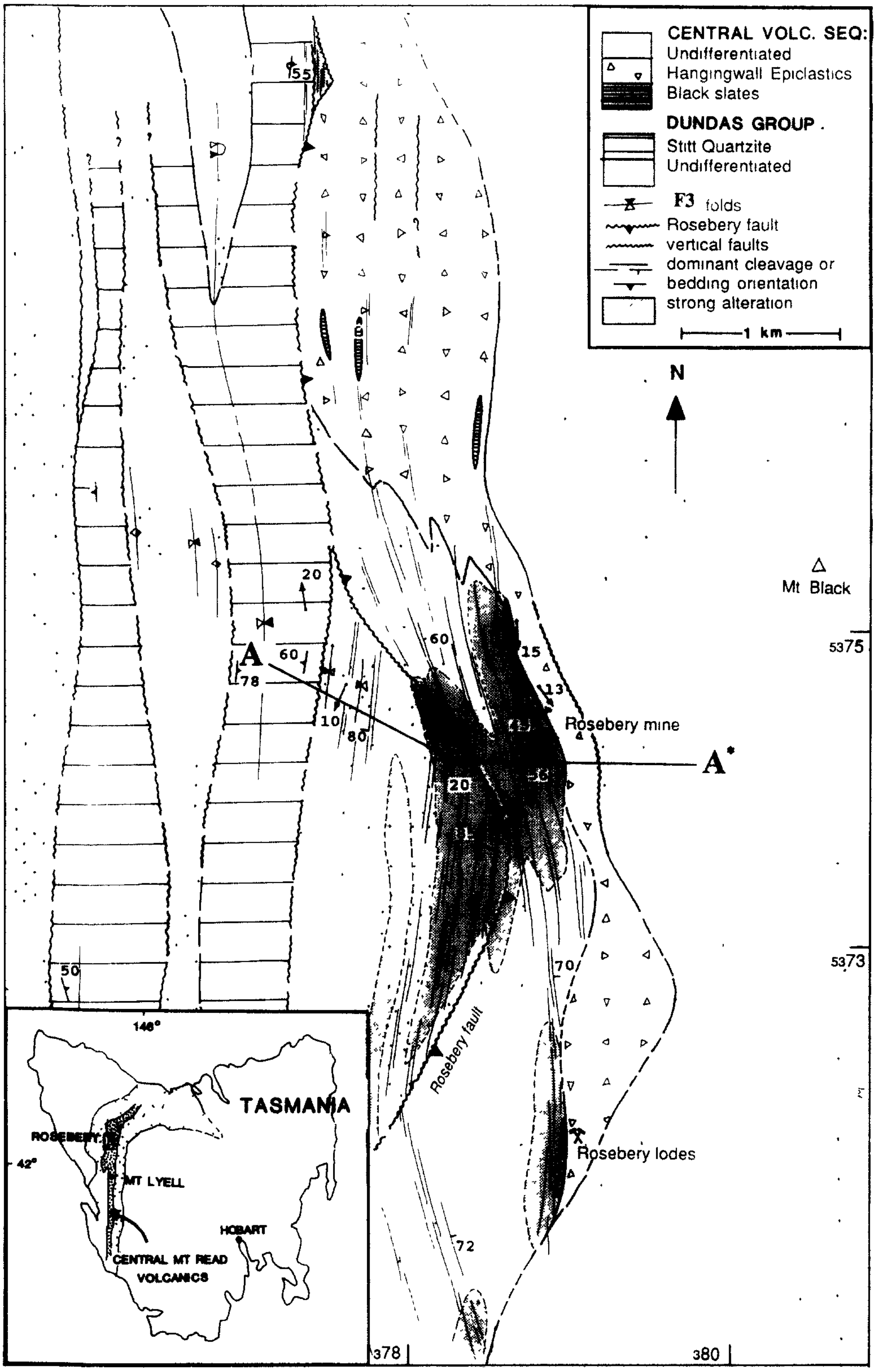


Fig. 1 Simplified geological map of the area around the Rosebery Mine, modified after Corbett & Lees (1987) Note that sericite–quartz alteration associated with the Rosebery orebody transgresses the Rosebery Fault. Inset map of Tasmania shows the Cambrian Dundas Trough (light stipple) between Precambrian basement rocks (blank). Younger formations partly cover the Cambrian and Precambrian rocks (not shown).

theories, most stratabound volcanic- and sediment-hosted massive sulphide bodies have been interpreted or re-interpreted as chemical precipitates on an ancient sea-floor. Such an origin was commonly claimed to be obscured by later metamorphism and deformation. Recent microstructural and structural studies, however, by Perkins (1984), Swager (1985), Bell *et al.* (1988) and De Roo (1989) at the Mount Isa and Elura massive-sulphide orebodies in Australia, have shown that these deposits were not stratabound and formed by structurally controlled replacement, refuting previous volcanogenic interpretations. Such metasomatic replacement

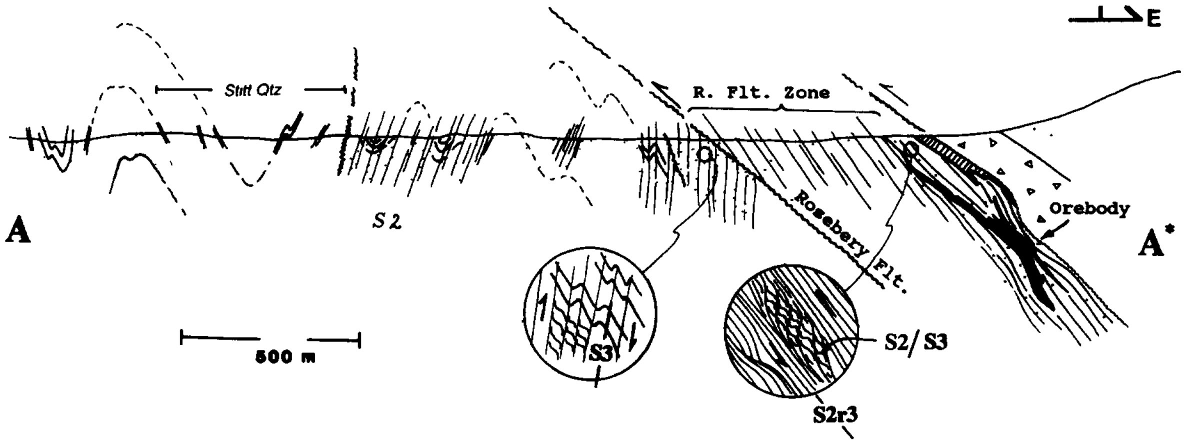


Fig. 2. East–west cross-section through the Rosebery Mine The dominant cleavage in the Rosebery fault zone (S_2r_3), formed by reactivation of S_2 and bedding, leaving S_3 preserved in low-strain domains.

orebodies were considered to have formed by metamorphic mobilization of primary (volcanogenic or diagenetic) sulphides and structurally controlled redeposition, at higher levels, as economic concentrations. The initial aim of this study was to investigate syndeformational sulphide-(re)mobilization through dissolution, fluid transport, and diffusion along an active developing cleavage (Bell & Cuff in press). Rosebery was chosen as an example of a volcanogenic massive sulphide (VMS) deposit within a zone of strong ductile deformation. However, microstructural examination showed that the sulphide- and silicate-minerals composing the orebody were largely undeformed and truncated strongly-foliated host rock by replacement overgrowth, during deformation (Aerden 1991). This paper presents a macroscopic model of syntectonic host-rock replacement, controlled by foliation-boudinage, and complements the microstructural timing evidence from the writer (Aerden 1991, in press).

GEOLOGICAL SETTING

Figure 1 illustrates the local geology around the Rosebery Mine. Two main lithological and structural units are present in the area: the Central Sequence (or Central Volcanic Belt), consisting of altered rhyolitic to dacitic lavas and pyroclastics, and the Dundas Group, which comprises a suite of volcaniclastic meta-sediments. The contact between the two units is a reverse fault named the Rosebery Fault (Corbett & Lees 1987). At Rosebery, this fault-contact forms the lower boundary to an approximately 1 km wide reverse-shear zone, named the Rosebery shear zone. Although the Central Volcanic Sequence overlies the White Spur Formation of the Dundas Group at Rosebery, the relative ages of these units is uncertain due to displacement along the contact and a lack of index fossils in the volcanic rocks. Radiometric age-dating of the Volcanic Belt has been unsuccessful due to Devonian metamorphism that reset the isotopic systems (Adams *et al.* 1985). Corbett & Lees (1987) interpreted the sediments of the Dundas Group to unconformably overlie the Central Volcanics, south of the mine area. The writer, however, observed that this contact cross-cuts folded bedding and stratigraphy on either side and regards it as a fault. The Rosebery fault zone is, as will be shown later, a bedding-parallel shear zone in which bedding was extended and not folded. It should therefore not be regarded as a thrust fault that would have caused a reversal of stratigraphy, proposed by Corbett & Lees (1987). On the basis of their structural relationship, it is likely that the Dundas Group is at least partially older than the normally overlying Central Volcanic Belt. The cleavage associated with the Rosebery fault zone is regionally developed and associated with other major fault-zones in the volcanic belt. In the Queenstown area (50 km south of the mine), the cleavage is developed in the Ordovician Owen Conglomerate, and radiometric K–Ar and Rb–Sr dating of micas in the Rosebery fault zone have yielded Devonian ages (Williams 1978, Cox 1981, Adams *et al.* 1985). Some authors have suggested that the Rosebery fault zone was a Cambrian structure that was reactivated during the Devonian (Campana & King 1963, Corbett & Lees 1987). Although this remains possible, no conclusive evidence has been presented, and attempts by Corbett & Lees (1987) to distinguish between Cambrian and Devonian deformations, on the basis of different fold-styles in different areas, received criticism from Leaman *et al.* (1987).

An E–W cross-section through the Rosebery Mine illustrates the structure of the area (Fig. 2). Upright, N–S-trending open folds occur in well bedded rocks of the Dundas Group with only a very weak axial-plane cleavage. Close to the Rosebery Fault, however, there is a strongly developed cleavage with a down-dip stretching lineation parallel to the axial planes of tight upright doubly-plunging folds. This fold generation is microstructurally timed as D_3 (see below) and compares with similar observations by Green (1983) near the Pieman River dam, 4 km north of Rosebery (Fig. 1). The dominant S_3-cleavage orientation east and west of the Rosebery-fault zone is sub-vertical with an approximately N–S strike. Cleavage within the fault zone dips on average 50° E, at a slightly steeper angle than the faulted hanging-wall contact in the mine, and is axial plane to sporadic but consistently W-verging, doubly-plunging parasitic folds, discussed further below.

Six kilometres east of the mine area, a dark tuffaceous slate unit termed the Farrell Slate, similar to the one at Rosebery, contains a subvertical cleavage, W-dipping bedding and E-verging parasitic folds. If the Central Belt is younger than the Dundas Group, a D_3-synclinorium could exist within the central Mount Read Volcanics between the Henty Fault and the Rosebery Fault, and the Farrell Slate could correlate with the thinner slate units at Rosebery (Fig. 2).

THE MINE SEQUENCE

Several massive sulphide bodies occur within or closely beneath slate lenses within the Central Sequence. It appears that at least some of those slates lie at different stratigraphic levels (Green 1983). A short description of the stratigraphic sequence at the Rosebery Mine is presented below. The reader is referred to Green (1983) and Corbett & Lees (1987), for a more detailed description and genetic interpretation of these rocks.

The volcanic rocks in the footwall to the mine consist of metasomatized feldspar-phyric lavas and pyroclastics. Close underneath the orebody, the footwall is completely silicified and is called quartz-schist or quartz-augen-schist because of the anastomosing character of the cleavage around ellipsoidal silicified domains. No significant vein-type mineralization is present in the footwall. The host rocks are mainly fine-grained, volcaniclastic phyllites that were altered to a sericite–silica–chlorite–carbonate assemblage with disseminated pyrite. Some late quartz–feldspar-bearing intrusives cross-cut bedding in the black slates (Finucane 1932). The contact between quartz-schist and sericite-schist (host rock) is gradational and, in detail, does not follow the stratigraphy. Black slates immediately overlie the host rocks. They appear relatively unaltered and are in places strongly veined with quartz–carbonate–sulphide assemblages. The hangingwall to the host rocks and black slates in the mine is a volcanic mass-flow (epiclastic) unit (R. L. Allen personal communication), the base of which probably represents a low-angle unconformity (Brathwaite 1970, 1974). The hangingwall epiclastic unit is overlain by the monotonous pile of Central Volcanics intermediate lavas, which except for being less altered, appear lithologically similar to the footwall volcanic units.

DEFORMATION IN THE HOST ROCKS

Deformation history

Microstructural- and field-observations within the Rosebery fault zone indicate that the dominant E-dipping, N–S-striking cleavage formed by reactivation of a crenulated schistosity, labeled S_2, late during D_3-folding. S_2 is the oldest recognized tectonic foliation in the Rosebery area, but 8 km further south, near the Hercules Mine, there is some evidence for a still earlier foliation (S_1), preserved as relics in the strain-shadows of large volcanic feldspars However, it is uncertain if this cleavage is tectonic or perhaps depositional or diagenetic in origin. No F_1-folds have been recognized.

Reactivation occurs in actively developing folds when the deformation partitioning pattern shifts from axial-plane-parallel, synthetic shearing to fold-limb-parallel, antithetic shearing (Bell 1986). Reactivation of the S_2-cleavage at Rosebery was controlled by the gross bedding orientation outlined by the hangingwall contact, and was an expected result of the susceptibility to deformation of a thin-layered sediment lens in otherwise massive volcanics. It resulted in sinistral rotation of the originally vertical S_3-cleavage to a lower angle with bedding, while F_3^2-crenulations were de-crenulated and S_2 became extended in the new bedding-parallel shearing direction (Figs. 2, 3 and 4a). Parasitic F_3-folds were progressively unfolded and are only preserved in ellipsoidal low-strain domains parallel to the dominant reactivated cleavage (Fig. 3). Reactivation of S_2 produced an intense cleavage, S_2r_3 (S_2 reactivated during D_3), with a down-dip stretching lineation. At an advanced stage of this deformation, foliation-boudinage structures progressively developed in the extending S_2r_3-fabric. These structures are characterized by pinch and swell of the cleavage associated with anastomosing, extensional shear planes.

Relict F_3^0 parasitic folds consistently verge to the west, which accords with the occurrence of mine stratigraphy on the eastern limb of a major antiform. The described structural and microstructural relationships indicate: initially, dextral shear in the vertical plane (looking north) during crenulation of S_2 by S_3 and F_3-fold development, and subsequently, antithetic (sinistral) shearing parallel to bedding producing the reactivated S_2r_3-fabric (Fig. 3). The maximum extension within the host rocks during reactivation occurred in an E–W, down-dip direction as shown by the stretching lineation on the S_2r_3-planes, pressure shadows on pyrite and feldspar, and foliation-boudinage structures (see next section) observed in vertical E–W sections (X–Z plane). Also, an important intermediate extension is recorded in N–S-striking sections (Y–Z), also perpendicular to the foliation, with smaller pressure shadows, boudinage of veins and foliation-boudinage

Foliation-boudinage structures

Cleavage in the mine (S_2r_3) is cross-cut by anastomosing N–S- to NE–SW-trending shears with dominantly reverse movements, indicated by cleavage drag and vein offsets. In section, the shears have two predominant orientations: (a) cleavage-parallel and (b) moderate E to SE dips at an angle of 20–30° lower than cleavage. These shears are associated with pinch and swell of the

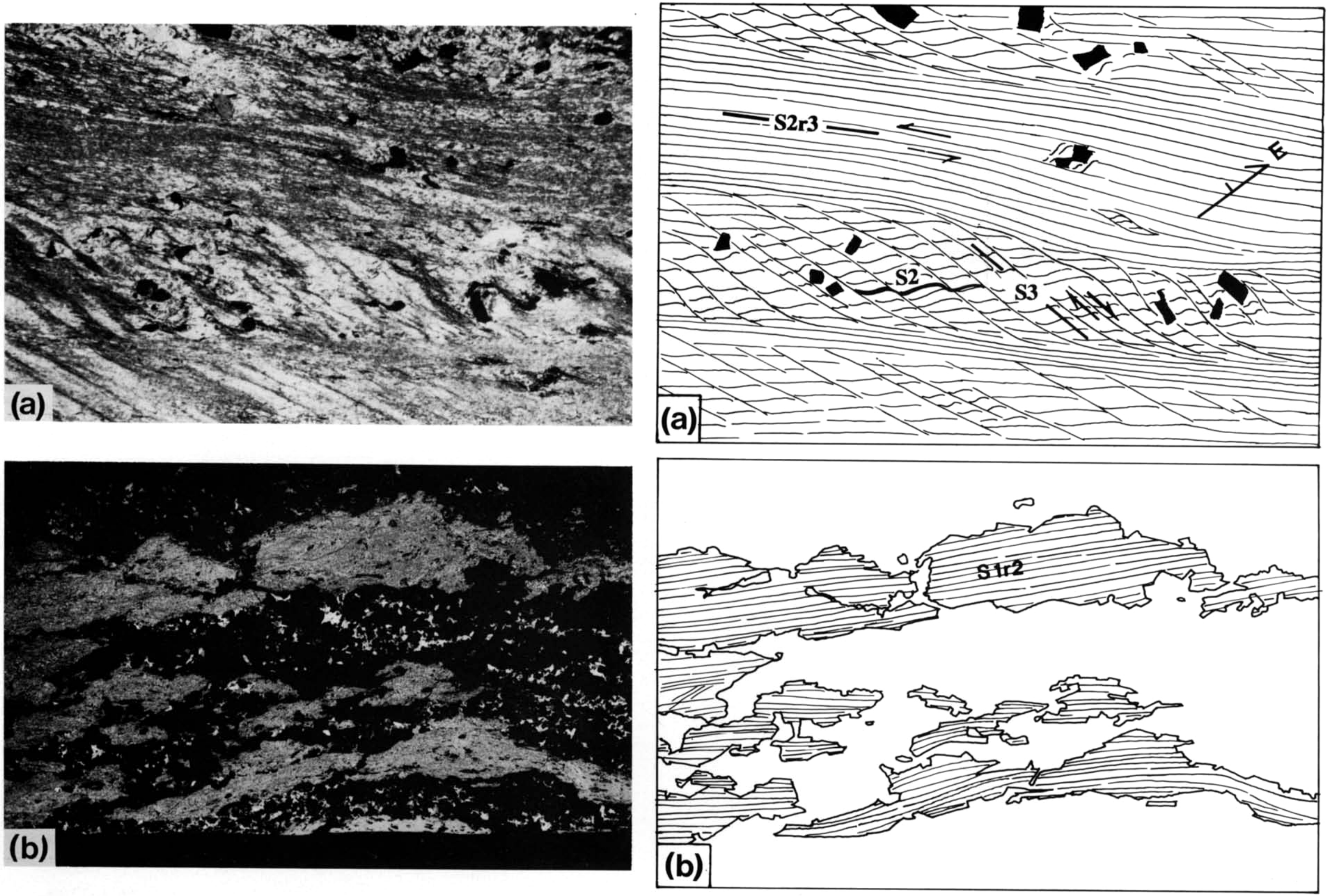


Fig. 4. Photographs with interpretations. (a) Typical microstructural reactivation-geometries in host rock During development of S_2r_3, S_3 becomes gradually destroyed by extension and decrenulation in the new layer-parallel shearing direction S_3 is preserved in S_2r_3-parallel low-strain-pods or -layers Field of view is 18 mm wide. (b) Semi-massive, pyrite–quartz mineralization containing host rock inclusions (E-lens, 15th mine-level). The constantly-oriented cleavage in the inclusions is sharply truncated by the undeformed mineralization across irregular mineralization fronts, controlled by fractures and cleavage in the host rock. This indicates that the host rock replacement occurred after cleavage formation Field of view is 40 mm wide.

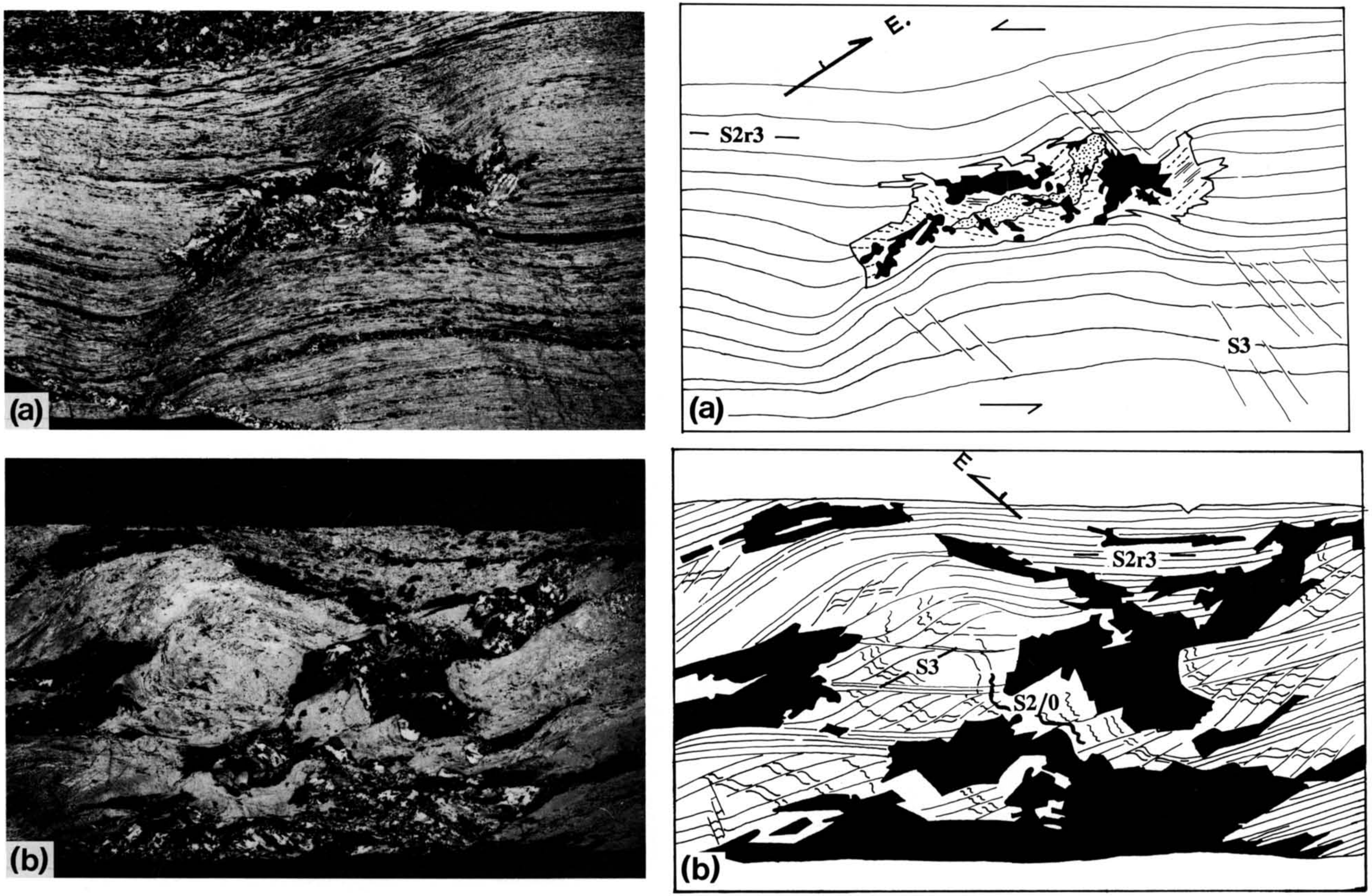


Fig. 9. Photographs and interpretations. (a) Small-scale example of a foliation-boudinage structure in which sphalerite–pyrite (black)–quartz (blank)–carbonate (stipple) replacement formed around a gape in the boudin-neck area. The weak crenulations in S_2r_3 are interpreted as a redeveloped S_3 in the last stages of D_3-deformation when the antithetic S_2r_3-shear-system (reactivation of S_2) became inactive. Field of view is 40 mm wide. (b) Coarse-grained sphalerite–pyrite–quartz replacement (black) truncates bedding (S_0) and S_2, S_3 and S_2r_3-cleavages indicating syn- or post-S_2r_3-cleavage replacement. The replacement was probably controlled by microfracturing and dilation during S_2r_3-parallel extension and influenced by the pre-extension microstructure. Field of view is 40 mm wide

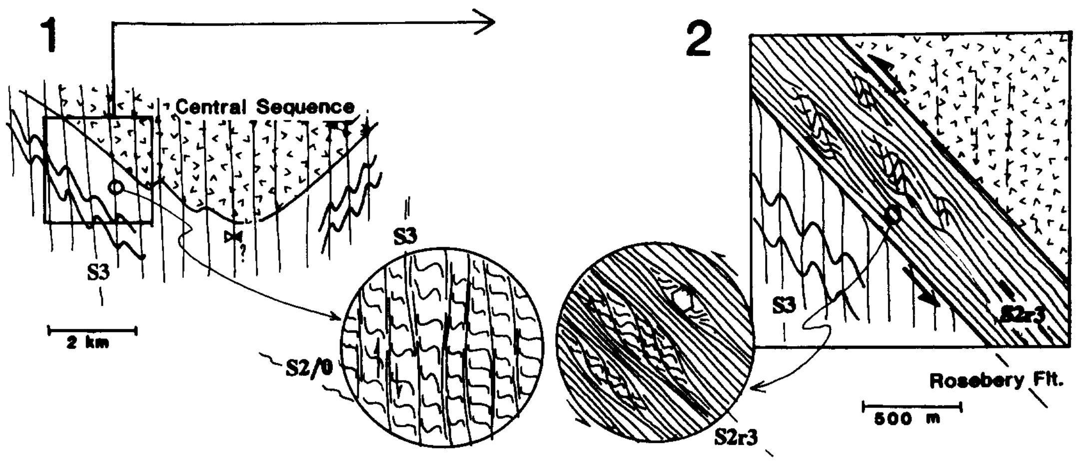


Fig 3. The sequence of events during D_3 folding in E–W cross-section pictured schematically. After initial steepening of bedding and S_3-crenulation-cleavage development (1), the Rosebery fault zone developed as a reverse-shear zone (2) Regional F_3-folding at Rosebery was further accommodated by antithetic reactivated shearing along bedding and S_3. Mesoscopic F_3-folds and F_3-crenulations were partially destroyed and extended in the new shearing direction to form a pervasive reactivation cleavage (S_2r_3) F_3-folds and S_3-cleavage are locally preserved in low-strain pods within the shear zone.

cleavage and foliation boudinage, consistent with an overall reverse sense of shear. Foliation boudinage has been elsewhere extensively described by Mitra (1979), Platt & Vissers (1980), Platt (1984) and Lacassin (1988), and documented in other extensional shear zones by Quinquis (1980), Van den Driessche (1986) and Gaudemer & Tapponnier (1987). At Rosebery, the foliation boudinage is commonly associated with a local flexure or perturbation in a cleavage-parallel shear plane where it curves into a lower angle and locally cross-cuts cleavage (Fig. 5). Shear strain is commonly unevenly distributed across the shear-plane flexure, as is indicated by the discontinuity of cleavage orientation on either side. In the upper block cleavage is dragged into a shear-plane-parallel orientation, whereas in the lower block the cleavage preserves a more acute angle. This geometry creates an 'extensional ramp' in the cleavage. Extensional structures like crack–seal veins, foliation boudinage and 'normal' boudinage (owing to competency heterogeneities) were also observed both parallel to the down-dip stretching lineation and in the horizontal N–S direction. These perpendicular directions correspond with the X and Y directions of the general strain ellipsoid.

Mapping of cleavage orientations and secondary

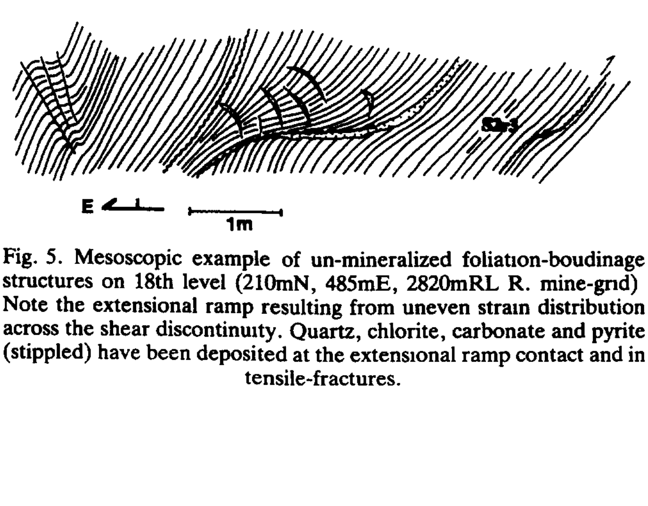
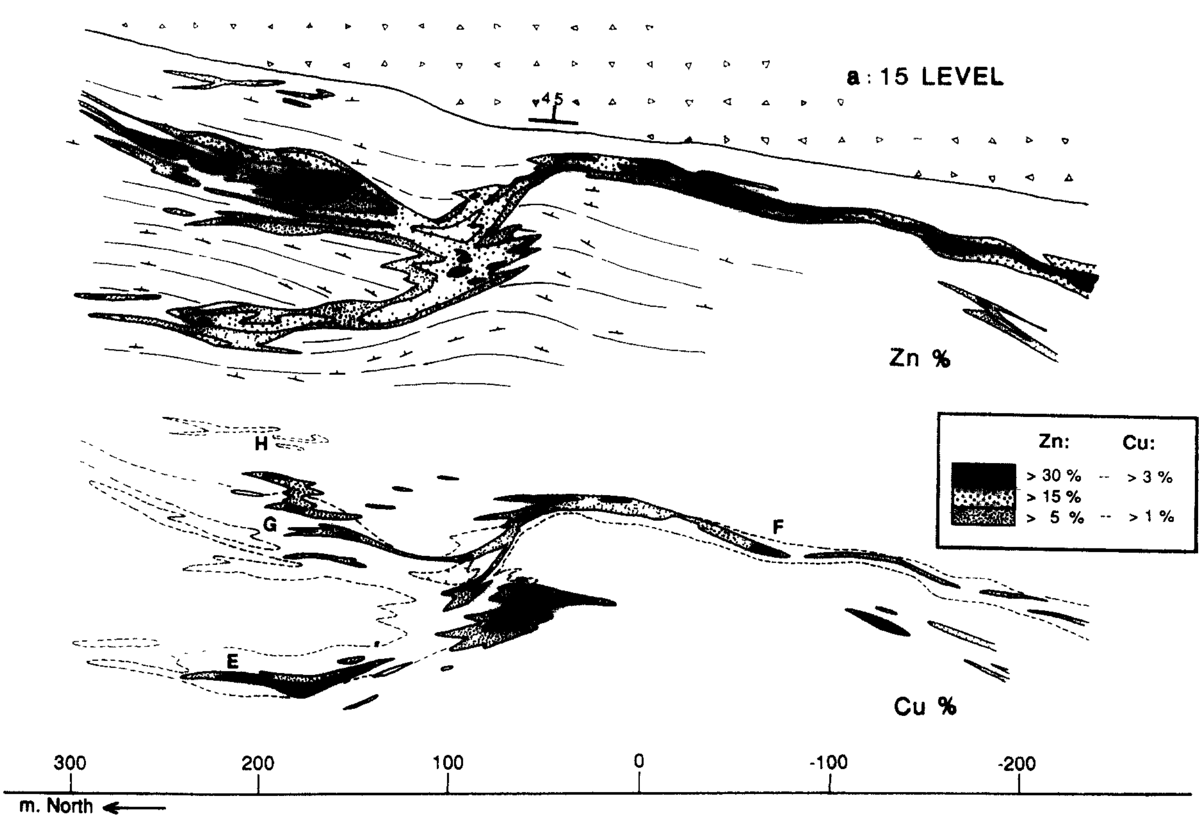


Fig. 5. Mesoscopic example of un-mineralized foliation-boudinage structures on 18th level (210mN, 485mE, 2820mRL R. mine-grid) Note the extensional ramp resulting from uneven strain distribution across the shear discontinuity. Quartz, chlorite, carbonate and pyrite (stippled) have been deposited at the extensional ramp contact and in tensile-fractures.

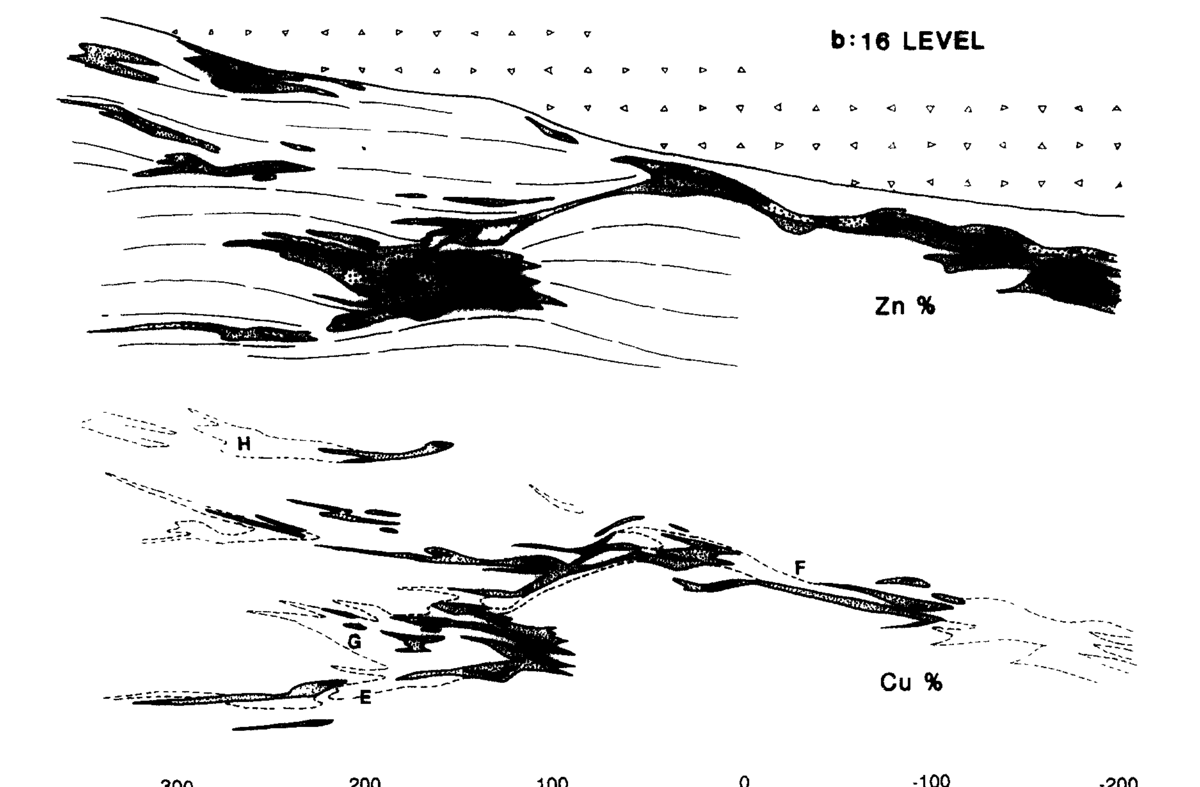
shears throughout the mine, revealed large-scale foliation-boudinage structures in both horizontal and cross-sectional planes (Figs. 6a & b and 7). The cross-sections were constructed by recording the dominant cleavage and shear-plane orientations on 3 m intervals in E–W drives and 1 m intervals on selected, reoriented drill holes lying on section. The foliation boudinage pattern mapped on the 15th mine-level suggests a sinistral shearing component along the Y direction (Figs. 6a and 8).

Both in plan and in cross-section, the foliation-boudinage structure can be described as two en échelon subsidary foliation-boudins with associated extensional ramps (Fig. 8). The area between these ramps is characterized by a lower cleavage-dip and increased extension, representing the neck of the large-scale foliation-boudin. Echelon strings of foliation-boudins have been described earlier by Lacassin (1988) in gneisses.

The geometrical relationships between the ore and foliation patterns (Figs. 8 and 9a & b), immediately suggest that foliation-boudinage pre-dated and controlled the mineralization. Foliation-boudinage structures typically develop in homogeneous rocks, purely as a result of the structural anisotropy of the rock imposed by the foliation (Platt & Vissers 1980, Platt 1984). Many essentially un-mineralized mesoscopic examples of foliation boudinage were observed in the Rosebery mine (e.g. Fig. 5). Significant competency heterogeneities would strongly influence deformation-partitioning, and cause the deformation patterns to deviate from those observed in homogeneous rocks. Examples are the concentration of deformation and cleavage around the margins of competent bodies, and conversely, the nucleation of shear zones within mechanical weaknesses. If the orebody at Rosebery pre-dated deformation, it would have influenced the deformation pattern and have precluded large-scale foliation boudinage, which requires homogeneity of the rock. Massive sulphides are, in most cases, thought to be relatively incompetent with respect



(a)



(b)

Fig. 6. (a) Copper- and zinc-distribution maps for the 15th mine-level, based on densely-spaced assay-data from over 200 drill-holes for each level. Cu- and Zn-concentrations are shown separately for the same area. The Zn distribution outlines have been transferred to the Cu diagram (dashed line) to show the limits of the orebody. Structural mapping revealed a large-scale foliation-boudinage pattern. (b) as above, but for the 16th level. The foliation-boudinage pattern is extrapolated from the 15th mine level, based on the geometry of the orebody on the 16th level.

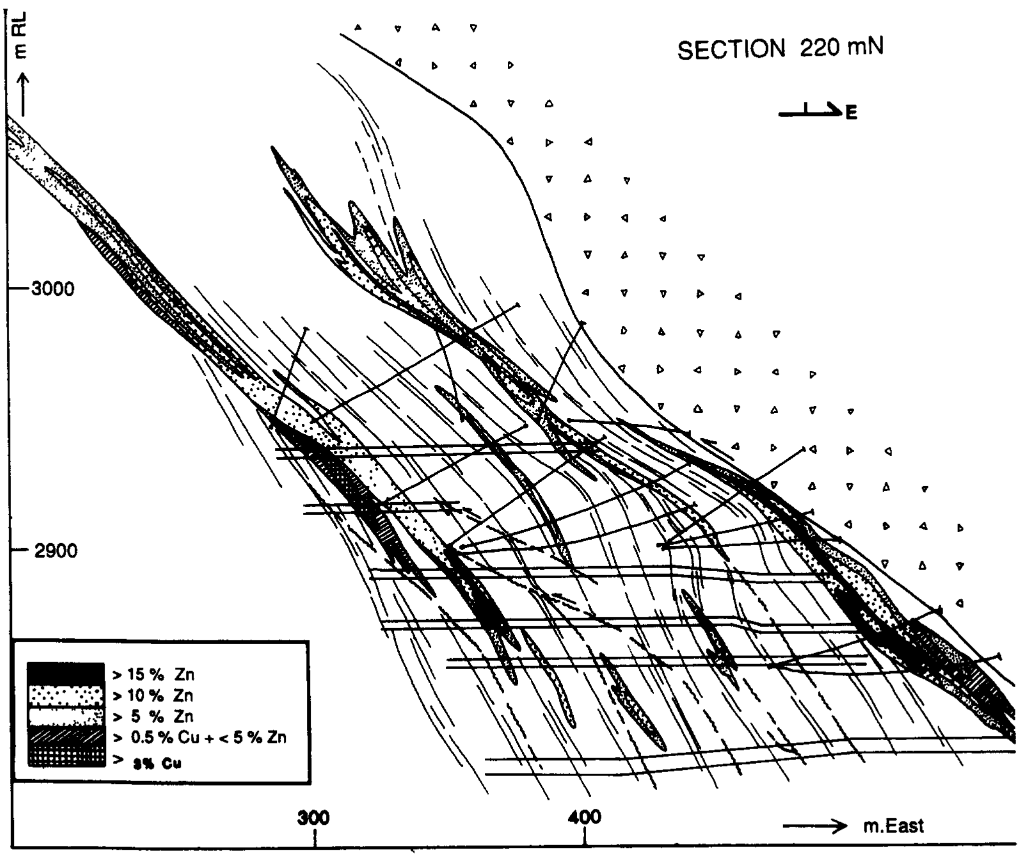


Fig. 7. Cleavage attitude and orebody geometry on the 220mN cross-section. The position of mine drives and drill-holes from which the structural data were obtained are shown. A large-scale foliation-boudinage pattern is observed in which the ore occupies the shear-zone- and extensional-ramp-positions (cf. Figs. 6a & 6b and 8). Note that the Cu- and Zn-rich areas occur at the down-dip end of individual ore lenses. The middle ore-lens has a narrow Cu-rich centre probably representing the shear-plane discontinuity.

to their host rocks (Vokes 1969, Mookherjee 1976, Gilligan & Marshall 1987). A pre-tectonic orebody at Rosebery would therefore probably have localized a significant component of shear deformation. In this situation, the orebody would be strung out in a planar cleavage-parallel shear zone, which is not observed (Fig. 10). The Rosebery orebody is relatively rich in the stronger sulphides (pyrite and sphalerite) and silicates and some authors have argued that such orebodies could under certain conditions behave as relatively competent bodies (Cox 1987, Gilligan & Marshall 1987). In that case, the cleavage at Rosebery should be intensified against and wrap around a pre-deformation orebody. This is not the case. Relationships between, the geometry and internal zoning of the orebody and the host-rock structure are examined below in more detail.

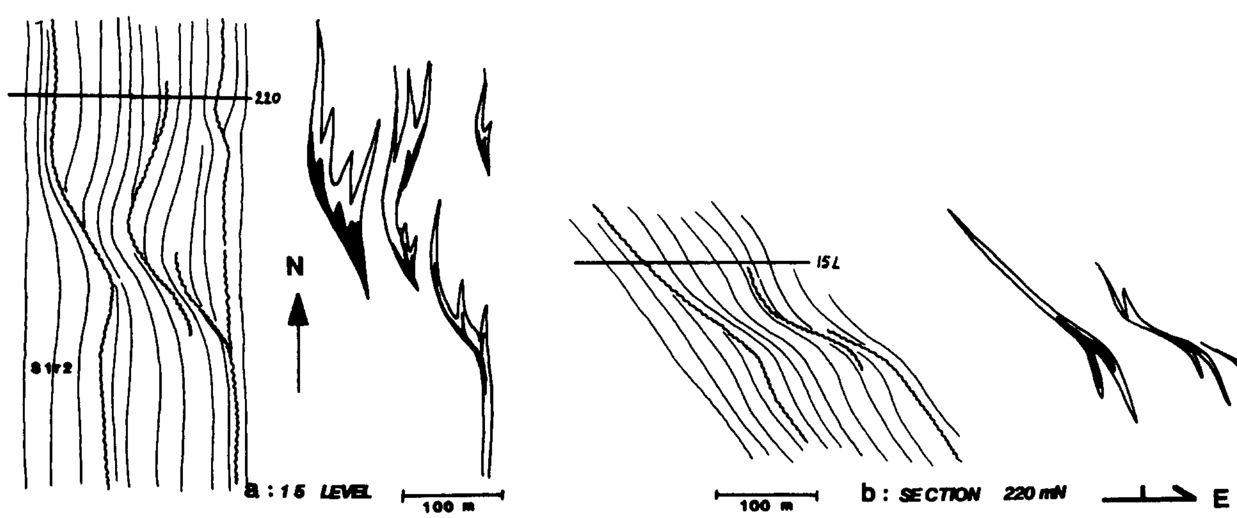


Fig. 8. Schematic interpretation of cleavage attitude in relationship with the orebody geometry on (a) 15th level and (b) for 220 mN cross-section. Cu-rich mineralization (black), is preferentially located in dilatant areas (cf. Figs. 7a and 8).

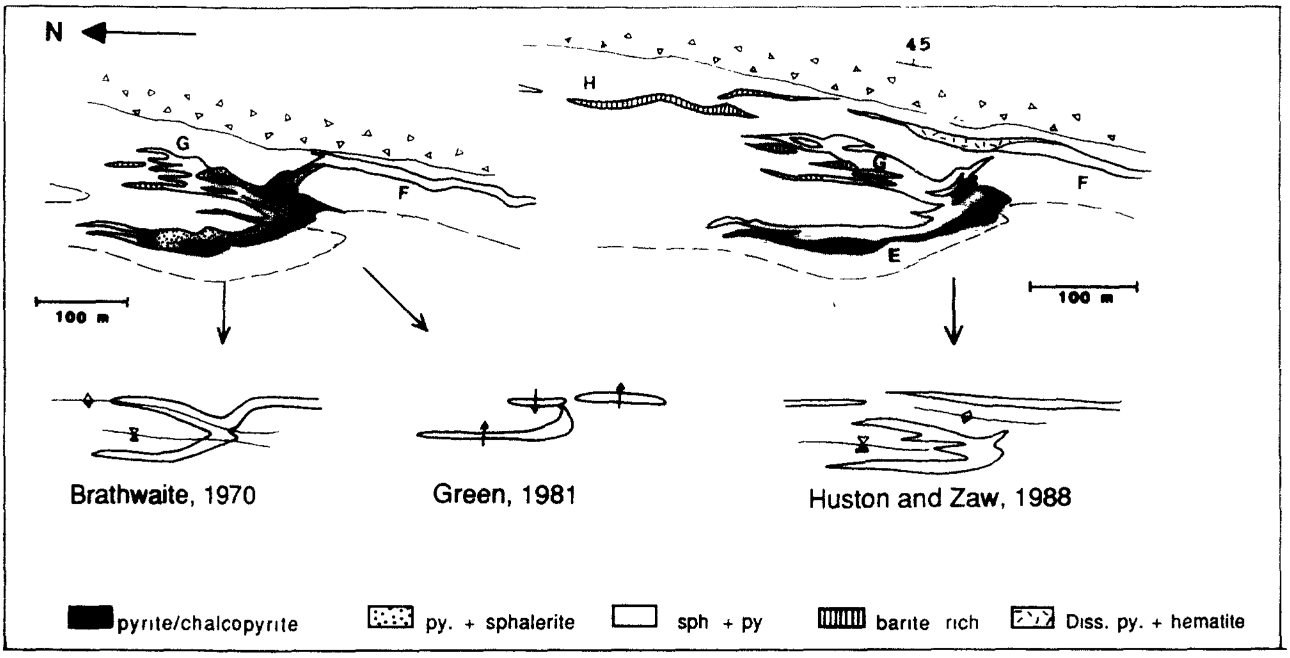


Fig 10 Previous volcanogenic interpretations of a folded, originally planar orebody: (a) Brathwaite 1970, (b) Green 1981, (c) Huston & Zaw 1988. For ease of discussion, different branches or lenses of the orebody have been designated with the same letter code used in earlier publications and by the mine geologists

Fold structure

Intense alteration in the host rocks has to some extent obscured the bedding. However, a number of doubly-plunging fold axes in bedding and bedding–cleavage intersection lineations were measured in both host rocks and black slates. These are shown on a longitudinal section, dipping parallel to the mine sequence (Fig. 11a). The bedding-folds are both relict F_3^0-folds with S_3 as axial plane and tightened and rotated F_2^0-folds with S_2r_3 as axial plane. As both F_3^0- and F_2^0-folds have the same vergence and approximate orientation they are difficult to distinguish macroscopically. The stereographic plot of Fig. 11(b), combines fold-axes measurements collected by Brathwaite (1970, 1972) at the 8th, 9th and 10th mine-levels and data collected by the writer at the lower mine-levels (15th–18th), surface outcrop and oriented drill-core. The stereogram reflects a fold-structure characterized by doubly-plunging fold-axes with pitch variations on the cleavage plane between 0° and 50°.

DISCORDANCE OF OREBODY WITH FOLDED BEDDING

The Rosebery orebody has previously been interpreted as a folded chemical-sediment-layer with a similar stratigraphic mineral zonation as the classic Kuroko VMS-deposit (Sato 1974) (Fig. 10). Typical VMS zoning, as observed at Kuroko, ideally consists of a pyrite–chalcopyrite assemblage at the stratigraphic bottom and centre of the deposit followed by a sphalerite–galena-dominated zone and a barite- and/or chert-rich zone at the top and extremities of the deposit (e.g. Large 1977).

Previous fold models for the Rosebery orebody (Fig. 10) were based purely on the geometry of the ore in plan view, using the mineral zoning trends as a stratigraphic facing criteria (Brathwaite 1972, Green *et al.* 1981, Huston & Zaw 1988) (Fig. 10). These models are inconsistent with the orebody shape in three dimensions, which cannot be described as a folded layer (Fig. 12). Furthermore, the orebody zoning-pattern has irregular characteristics that have no specific relationship to the geometry of a reconstructed pre-folding orebody (Aerden 1991). For example, the strongest zonation trend is in the down-dip direction with Cu-rich mineralization in the lower levels and barite-rich mineralization at higher levels. There is also a distinct lateral zoning from the Cu-rich centre of the orebody towards the Ba-rich extremities of all the major ore lenses. Within the previously proposed fold models, however, termination of the G- and H-lens (Fig. 10) would not have been the extremities of the original (unfolded) sulphide layer. As will be shown in a later section, the mineral-zoning characteristics may be explained more specifically by a metasomatic replacement model.

The geometry of the orebody was directly compared to the folding in the host rock (Fig. 11a). This comparison showed that the folding suggested by the outline of the orebody does not exist in the host rocks. Mesoscopic parasitic folds (up to several metres in width) in the host rock consistently verge west, eliminating the possibility of major folds within the mine sequence. Moreover, the previously inferred axes of the most prominent 'fold' interpreted in the orebody, the central E-/G-lens closure (Fig. 10), plunges steeply down-dip. Hence, the orebody and bedding do not conform with one another (Figs. 11a–c). Instead, the orebody must cross-cut folded bedding in the host rocks at meso- and macroscopic scales.

The discordant nature of the orebody is supported by recent drilling-results that show ore lenses locally transgress bedding in the host rock and black slate, in the northern part of the mine. Discordant relationships were also directly observed underground and in the open pit, where individual ore shoots, parallel to cleavage, cross-cut bedding which dips 15–25° more gently. In some outcrops, the hinges of folds were observed to be cross-cut by the ore along cleavage (Fig. 13). It is noteworthy that at the Hercules Mine, a Pb–Zn deposit 8 km south, the same discordant relationships were recorded by Hall *et al.* (1953) and Aerden (1991); however, relationships were more obvious at Hercules due to a well developed lithological layering and a constantly high angle between cleavage and bedding.

STRUCTURALLY-CONTROLLED MINERALIZATION

Assay-data for Zn and Cu mineralization in drill cores, within 5 m of a number of mine-levels and cross-sections, were extracted from a computerized database and contoured (Figs. 6a & b, 7 and 14). Section 110mN is by courtesy of Huston & Zaw (1988). The distribution of Cu vs Zn shows a strong correlation with mineral zoning

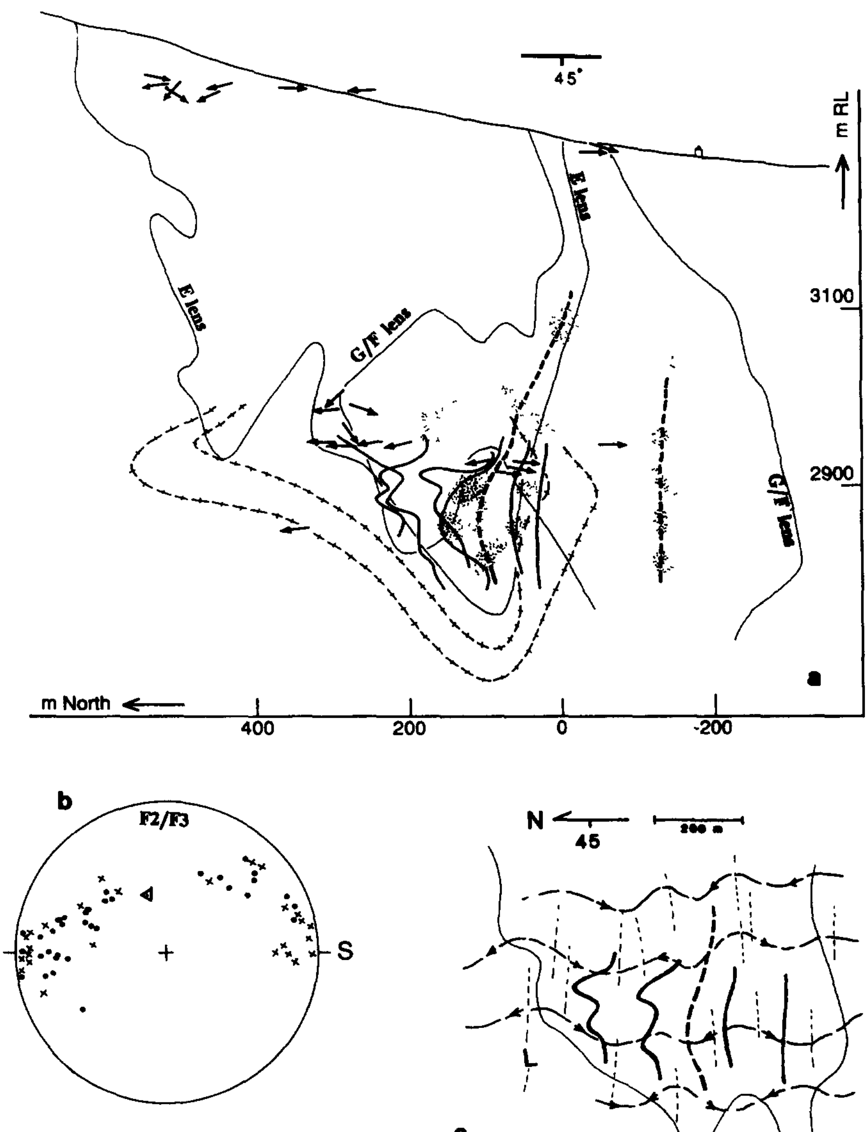


Fig. 11. (a) N–S longitudinal section parallel to the Rosebery ore deposit (dipping 45°E, facing east). Thin continuous lines outline the orebody. Arrows show the orientations of fold-axes measured by the author. The heavy dashed lines represent axes in the orebody where ore lenses merge. The crossed lines represent a closure in the footwall–host rock alteration contact. This closure envelopes and wraps around the lower side of the orebody and cross-cuts the bedding structure. Cu-rich zones (stippled areas) coincide with the axes in the orebody. (b) Equal-area projection of fold-axes in bedding and cleavage–bedding intersection lineations measured by Brathwaite (1970) and the author (respectively, dots and crosses). The stereogram shows a doubly-plunging fold structure, which is discordant to the central orebody axes (triangle). (c) Schematic illustration of the discordance between orebody and bedding in the same section as (a). Thin lines outline the orebody, heavy dashed line represent the central orebody axes, and dashed lines with arrows the trends of host rock folds. The latter trend are on average at right angles to both the orebody axes and the stretching lineation (L). Continuous heavy lines trace the terminations of individual ore-shoots. These were incorrectly interpreted by Brathwaite (1974) as fold axes outlined in the orebody–host rock contact.

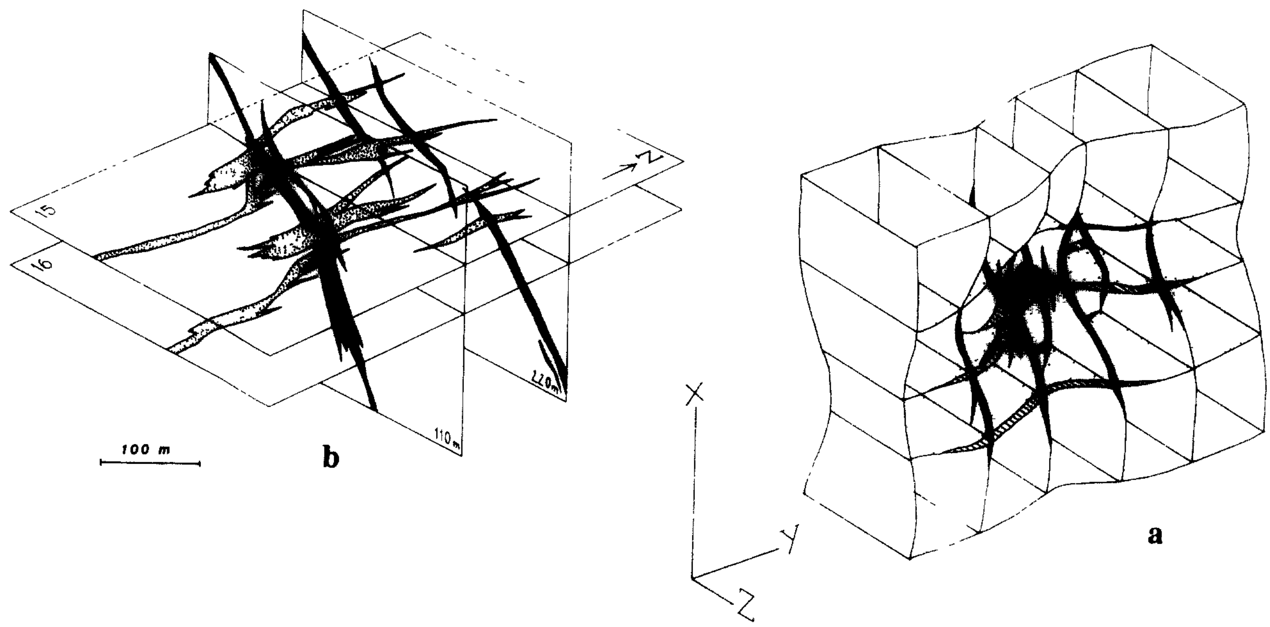


Fig 12 (a) Three-dimensional 'chocolate tablet'-boudinage model for the Rosebery orebody The orebody is localized at the intersection of two perpendicular boudinage axes, parallel to the principal directions of the strain ellipsoid (Y–Z planes stipple; ore in Y–Z plane: striped, ore in X–Z plane: solid). (b) The model in (a) is based on the relationship between the actual orebody geometry and the foliation-boudinage patterns in plan (stipple) and cross-section (solid)

in the orebody. Huston & Zaw (1988) reported that concentrations of Zn and Pb, and of Cu and Fe correlated closely, reflecting galena–sphalerite- and pyrite–chalcopyrite-dominated assemblages. Boundaries of the orebody are accurately outlined by overlapping the Cu and Zn distribution maps (Figs. 6a & b).

Comparison of the mineralization with the foliation-boudinage structures, on both plan and cross-section shows that the Cu-rich mineralization and the highest Zn-grades are conspicuously concentrated at the extensional ramps (Figs. 6a & b and 7a). The ore branches

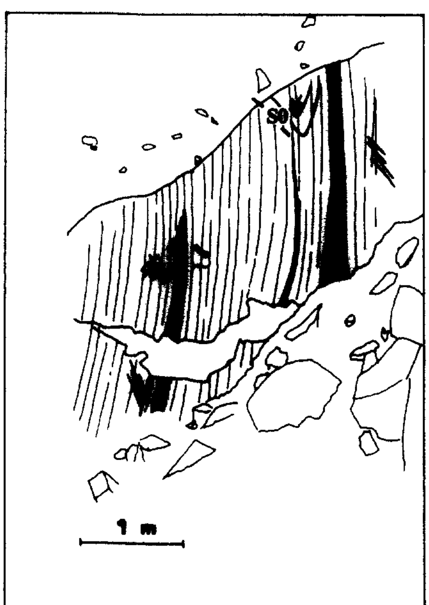


Fig 13 Field observation in the Rosebery open pit traced from photograph (co-ordinates 5,374,675 mN, 378,640 mE, AMG grid) Ore lenses (black) parallel the S_2r_3-cleavage (thin lines) and cross-cut folded bedding (S_0; heavy lines)

from these sites into the host rock, along cleavage-parallel shear-planes. The ore successively becomes lower grade and barite–carbonate–quartz-rich towards the extremities of ore-shoots. Figure 8 shows the relationship between cleavage orientation and the ore distribution in plan and cross-section.

Mineralogical zoning is generally a function of distance to the mineralization source and/or the mineralization-controlling structure. The relationship between metal-zoning and foliation-boudinage structure at Rosebery therefore suggests that mineralization originated at the extensional bends in the mine-scale shear planes. It is envisaged that gaping of these structures caused the host rock to brecciate and pull-apart along the cleavage, thereby allowing hydrothermal fluids to progressively infiltrate and react with the wall rock (Fig. 15). This produced the observed lateral ore zonation and the typical ore-lens geometries (e.g. E-, G- and H-ore-lenses) (Figs. 6a & b). From purely the geometry and zonation of particular ore-lenses (e.g. H-lens, 17th level, Aerden 1991), extensional ramps and foliation patterns around the ore could be predicted and tested proving that careful mapping of cleavage from reoriented drill-core could potentially be used to predict undiscovered ore-lenses in the vicinity of the orebody.

The central axis of the orebody is interpreted here as the steeply-dipping axis of a mine-scale foliation boudin-neck and not as a fold hinge. This explains why the E- and G-lens at higher levels become separated by a sliver of host rock; outlining the locations of two en échelon extensional ramps (Fig. 8). Huston & Zaw (1988) contoured zones of anomalous-high copper concentrations on a longitudinal section, which they interpreted as fossil hydrothermal vents on the sea-floor. These fluid sources (Fig. 11a) coincide remarkably with the central orebody

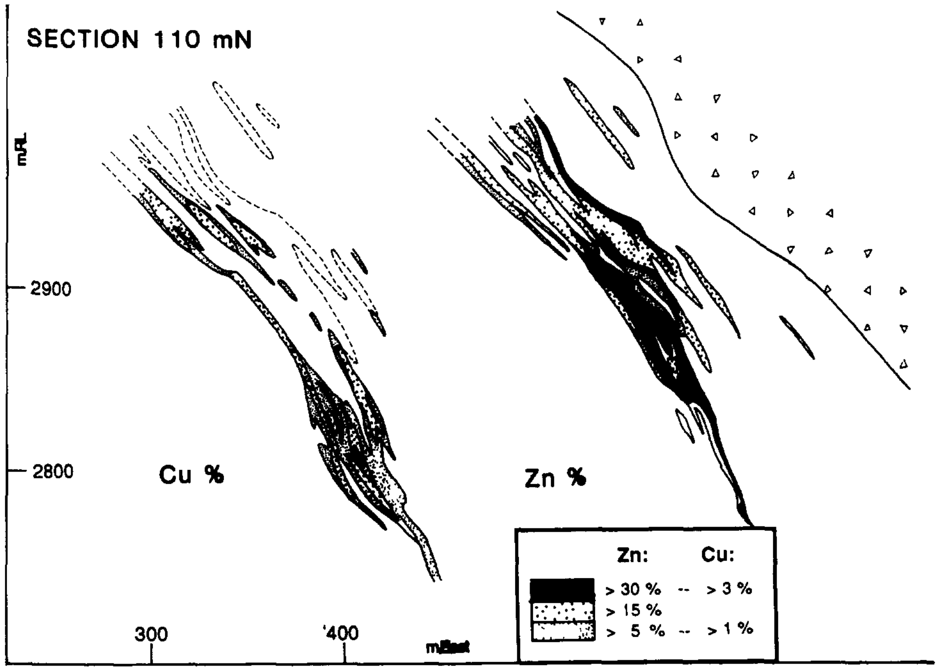


Fig. 14. Copper and zinc distribution on section 110mN. Note the separation between Cu- and Zn-rich mineralization in the down-dip direction.

axis and supports the model proposed here. A second linear high-Cu zone occurs at the south end of the mine in F-lens, corresponding with a second boudinage axis (Aerden 1991).

Outlines of the orebody on lower levels suggest that the foliation-boudinage pattern of the 15th level continues downwards, although the boudin neck gradually becomes less attenuated (e.g. 16th level, Fig. 6b). In three dimensions, the orebody is localized at the intersection of two perpendicular boudinage-necks, parallel to the principal extension-directions, X and Y. This point has undergone maximum extension parallel to cleavage (c.f. Ghosh 1988). A three-dimensional sketch (Fig. 12), based on actual mine plans and sections, illustrates the chocolate-tablet type foliation-boudinage in the mine, with the orebody as a three-dimensional star-shape at its centre.

In cross-section through the centre of the orebody, the orebody zoning occurs principally in the down-dip direction (Fig. 14), with Cu-rich, proximal assemblages at the base of the mine, and Zn-rich mineralization immediately above. The tips of individual ore lenses, especially at higher levels, contain the distal barite-rich assemblage. This down-dip trend of the zoning is consistent throughout the mine (Aerden 1991). It is interpreted to reflect the deposition of material from hydrothermal fluids that ascended in the Rosebery fault zone and were focused into the down-dip plunging boudinage-necks (Fig. 16).

TIMING OF MINERALIZATION

Detailed microstructural analysis of the ore textures indicates that the massive sulphides at Rosebery formed by replacement of the sericitic host-rock schist. Indeed, this was first pointed out by Stillwell (1934). He based his conclusions on: (1) relics of unreplaced, cleaved host-rock in undeformed mineralization; (2) truncation of the cleavage by sulphide overgrowth; (3) general parallelism between ore-shoots, ore-banding and cleavage, interpreted to be a result of replacement along the cleavage; and (4) the observation of paragenetic replacement relationships between the ore minerals.

My timing evidence (Aerden 1991) fully supports and refines Stillwell's evidence. Similar host-rock replacement relics were observed containing partially replaced folds and sharply truncated cleavages (Fig. 4b). Microscopic and mesoscopic examples of mineralization controlled by foliation boudinage show a remarkable resemblance with the mapped macrostructure (Figs. 9a & b and 17). Aerden (1991) showed that syn-kinematic metasomatic mineral-growth was generally controlled by micro-fracturing during cleavage-parallel extension and shearing. This fully supports a macroscopic model of foliation-boudinage controlled mineralization.

At the south end of the mine, a significant portion of the Pb–Zn ore is locally replaced by a pyrite–pyrrhotite assemblage. This assemblage is probably related to late magmatic-fluids (Brathwaite 1970, 1972, Green *et al.* 1981, Solomon *et al.* 1987) that interacted with ore along late fractures and kink-bands.

DISCUSSION

Comparison with previous folding interpretations

The boudinage model has a number of advantages over previous models:

(1) It is consistent with the cross-cutting nature of the ore relative to bedding. Economic geologists have in the past argued that a conformable massive-sulphide body could be mechanically remobilized into a discordant position by forcefully intruding the country rock (e.g. Sangster 1979, McClay 1983). Although these processes may be commonly superimposed on a large-scale conformable ore geometry, complete mechanical remobilization of an orebody without traces of original conformable material is unlikely, as pointed out by Gilligan & Marshall (1987) and Marshall & Gilligan (1987). These authors argued that complete orebody discordance is more likely a result of fluid-state mobilization of disseminated material.

Transposition by folding has also been proposed to explain the discordance of the ore to bedding and the parallelism with cleavage. Transposition however, is the disruption and re-orientation of the lithological layering parallel to cleavage by isoclinal folding and fold-hinge destruction (Turner & Weiss 1963, Hobbs *et al.* 1976). It does not lead to cross-cutting relationships between originally bedding-parallel planes, and bedding folds at Rosebery are not isoclinal.

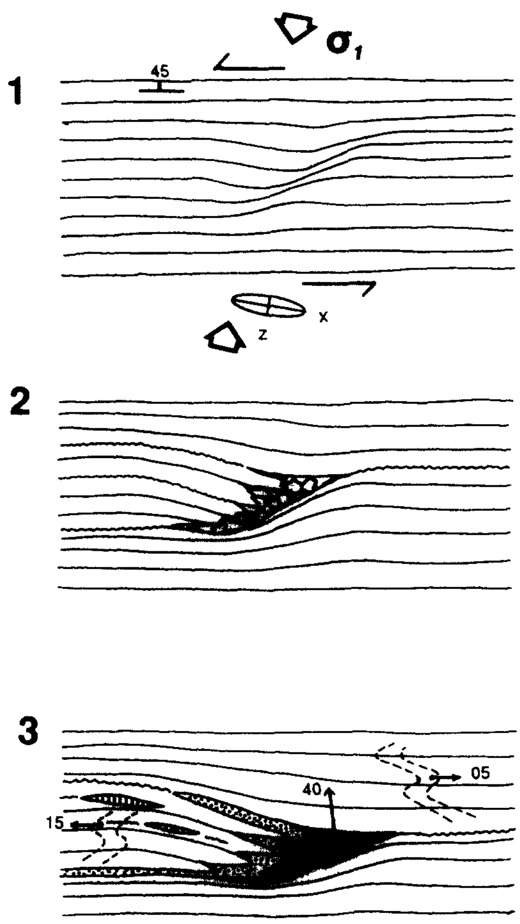


Fig. 15. Kinematic sketch showing the concept of foliation-boudinage-controlled mineralization in plan view. (1) Initiation of an asymmetric perturbation in the S_2r_3-foliation due to extension along cleavage with a sinistral shear component. (2) Development of shear discontinuities (wriggled lines) and an extensional ramp in a typical shear-band orientation (25° angle with cleavage planes). Dilation at the extensional ramp results in brecciation of the wall-rock where cleavage is oblique to the ramp contact. (3) Fluids access the fractured wall rock and progressively replace it along shear-plane and cleavage directions. The resulting ore lens resembles a folded layer with a down-dip fold axis, but in fact cross-cuts doubly-plunging folds in the surrounding bedding (dashed lines). Proximal Cu-rich (black), intermediate Zn-rich (stippled) and distal barite-rich (striped) assemblages are developed relative to the extensional-ramp controlling the mineralization (cf. Figs. 6a & b).

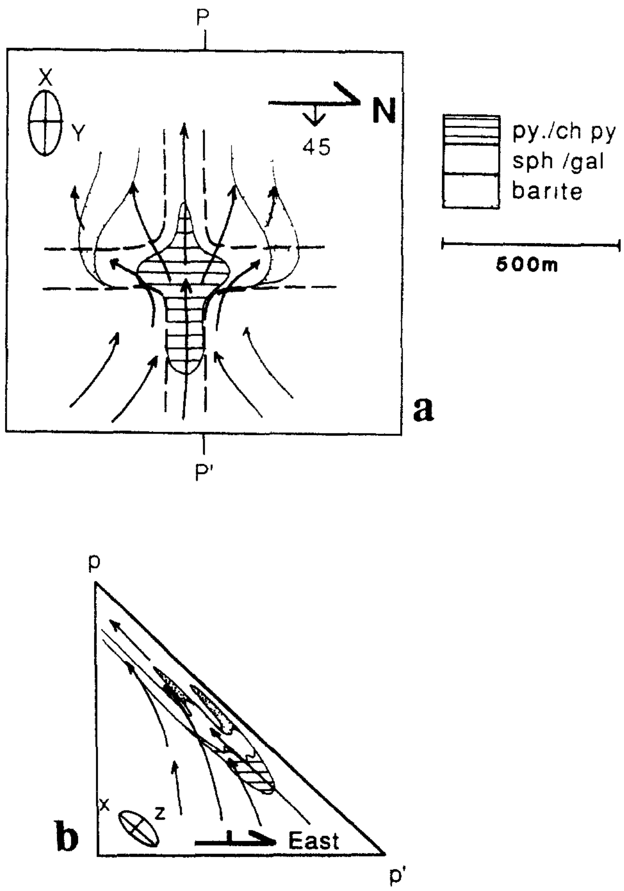


Fig. 16. Conceptual fluid-flow pattern around a chocolate-tablet foliation-boudinage structure. Fluid-flow was focused into the down-dip dilatant necks and moved into the horizontal boudin necks. (a) In longitudinal projection (X–Y plane) and (b) in cross-section (X–Z plane). Lateral and down-dip mineral-zoning trends develop as a result of progressive wall rock replacement directed away from the dilatant sites of brittle deformation.

(2) The new model predicts the down-dip and lateral zoning-trends within the orebody and within individual ore-lenses. Although the mineral zoning does not oppose volcanogenic models, it has an unpredictable erratic relationship to hypothetical pre-folding geometries of the orebody.

(3) The relationship between the geometry of the orebody and attitude of the foliation in the mine is rationalized and has a predictive capability. Previous folding models were largely based on geochemical and mineralogical patterns in the ore without consideration of three-dimensional orebody geometry and structures in bedding and cleavage. For example, Brathwaite (1970, 1972) interpreted an isoclinal anticline within G-lens (Fig. 10). This however implied, that H-lens lay at a higher stratigraphic level. The spatial association of the H lens with the rest of the orebody would then be coincidental. Green *et al.* (1981) envisaged that G-lens had rotated 180° relative to the rest of the orebody on the

basis of an inverted trend in sulphur isotope values. However, in that case, the F-lens would be attached to the 'wrong' end of G-lens (Fig. 10). The fold interpretation by Huston & Zaw (1988) is inconsistent with the connection that exists between G- and F-lens (Fig. 8a). In fact, at higher levels, these lenses continue along their strike into each other and form a single planar lens.

Thrust model for Rosebery

An alternative structural model has recently been suggested by Berry (1990) (Fig. 18) in which the en échelon pattern of ore lenses in cross-section resulted from a thrust repetition of the ore along cleavage-parallel, reverse-shear planes. In this model, the central zone of the orebody is a lateral thrust ramp. Mapping by the writer, however, shows that cleavage is sub-parallel to the ore lenses (Fig. 7) and can not be responsible for thrust offsets in the ore horizon as shown on Berry's cross-sections (Fig. 18). This would require that major faults dip more steeply than the cleavage, but such faults have not been recorded by either Berry or the author. If thrusting had occurred, the sulphide horizon would most likely have acted as a décollement or thrust surface and not as a passive, sliced marker horizon. The cross-cutting of bedding on either side of mesoscopic ore shoots still opposes a conformable ore horizon (Fig. 13). Thrust stacking of the ore is further opposed by the down-dip mineral zonation trends of individual ore lenses that generally do not match the upper termination of the lens below. As pointed out earlier, the major sinistral movements in the mine occurred during a phase (D_3) in which the stratigraphic layering and the foliation was boudinaged. The reverse shears should be regarded as extensional structures (relative to bedding) rather than (compressional) thrust faults.

Source of mineralization

From sulphur- and lead-isotope studies by Green (1981), Solomon *et al.* (1988) and Gulson & Porritt (1987) it has been proposed that the major massive sulphide deposits of the Mount Read Volcanic Belt partially derived their sulphur from Cambrian seawater, and sulphur and lead from the volcanics themselves. This interpretation is consistent with a metamorphogenic origin of the Rosebery ore, through deformation-driven dissolution, fluid flow and solution-transfer diffusion, and concentrated redeposition of Cambrian lead and sulphur (Aerden 1990, in press a). Considering the degree of foliation development in the footwall volcanics during the Devonian, and hence the potential for leaching disseminated sulphides of possible volcanogenic origin (Fyfe *et al.* 1978, Gilligan & Marshall 1987, Bell & Cuff, in press), metamorphogenic sulphide-deposits are likely to have formed in structural traps where the dissolved material could be redeposited.

Comparison with other deposits in the area

Microstructural analysis of ore textures at the Hercules Pb–Zn deposit, 8 km south of Rosebery, revealed a similar timing for sulphide replacement as at Rosebery (Aerden 1991). At both deposits replacement of the host rock occurred during D_3 and exhibits the same paragenetic mineral-growth sequence (Aerden 1991). In the light of these findings, there is a need for reassessment of volcanogenic interpretations at other massive-sulphide ore-deposits in the area, including the Hellyer, Chester and Que River deposits. The Que River deposit has recently been interpreted as a Rosebery-style tightly-folded, volcanogenic sulphide layer by Large *et al.* (1988). Their interpretation however, relies on

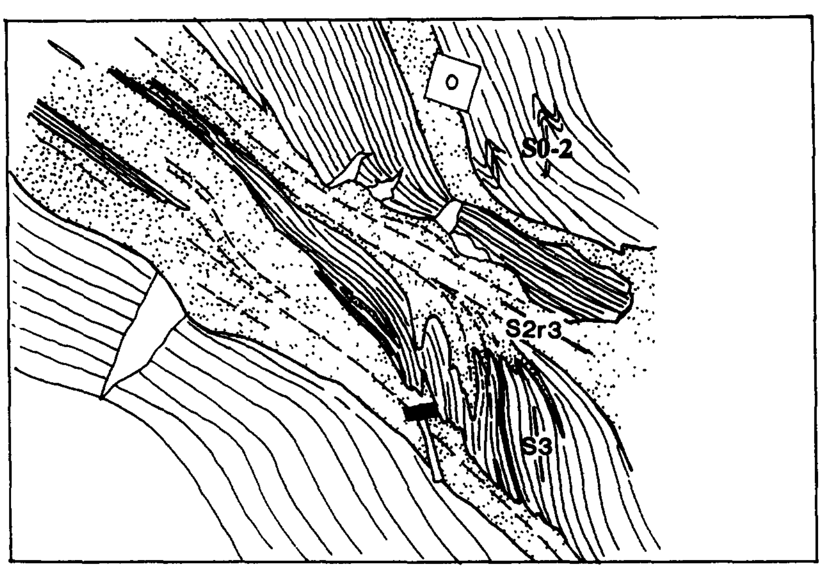


Fig. 17. Traced photograph of barite-rich replacement mineralization (stippled), controlled by shear-plane and cleavage orientations (15th level, H lens, 280mN). Note that folds in the host rock are truncated by the mineralization. Banding in the ore is inherited from the replaced wall-rock foliation. Coarse-grained quartz–carbonate veins (blank) formed late during the deformation at the ore–wall-rock contact due to ductility contrasts between the two. Note 25 cm long hammer for scale.

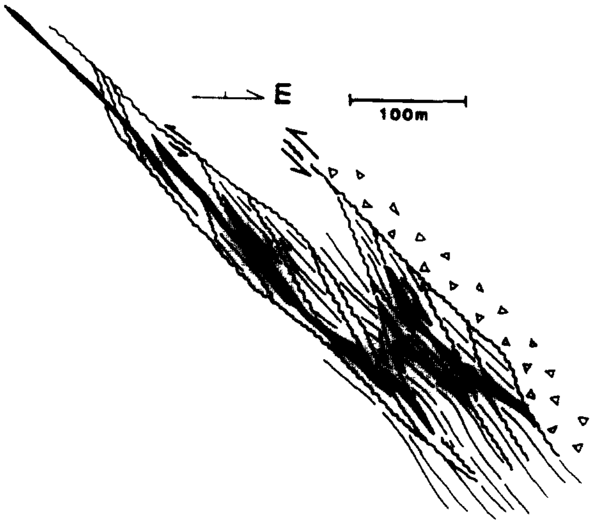


Fig 18 Thrust model for the Rosebery orebody by Berry (1990). Cleavage attitude (thin lines) from the 220mN cross-section of Fig 9. has been added to Berry's interpretation of cross-section 244mN (presented at the 10th AGC conference in Hobart, 1990) The ore lenses (solid) are interpreted by Berry as the offset portions of a once continuous sulphide layer The hypothetical thrust planes in Berry's model would have to be steeper than cleavage However, major faults with such an orientation have neither been observed by the author nor by Berry

patterns in the metal zoning and ignores the geometric relation to folded bedding in the host rock. Their model is supported by observations of folds in the ore with axial-planar foliations defined by galena streaks. However, alternative explanations of the mesoscopic ore textures they describe may be possible. These are briefly mentioned below.

Large *et al.* (1988) do not examine the microstructural characteristics of the ore-banding foliation. At Rosebery, compositional banding in the ore is parallel to cleavage in the host rock and sometimes resembles a tectonic sulphide-foliation. The ore-banding formed as a result of directional replacement along the host-rock cleavage, during heterogeneous cleavage-parallel extension and shearing (Aerden 1991) (Fig. 17). The ore is not deformed, except for the earliest pyrite generation, which is fractured, and consistent paragentic replacement relationships exist between the different ore components (Aerden 1991).

At Que River, Large *et al.* (1988) show moderately-folded pyritic layers with an axial-planar cleavage defined by narrow galena streaks (Fig. 10a). The complete discordance of the galena to continuous bedding demonstrates that galena was not mechanically transposed by isoclinal folding and shearing, but strongly argues for solution-transfer and galena formation along a pre-existing cleavage, as proposed at Rosebery. The galena could have been derived from dissolved, primary material in the orebody itself, but, if most of the galena in the mine occurs along cleavage and cross-cuts bedding, an external source is more likely. The folded pyrite layer could be either interpreted as pre-deformation volcanogenic material, but could also represent host-rock layers that became preferentially replaced early in the mineralization event Preferential replacement by sulphides and ghosting of bedding have been observed at Rosebery (Aerden 1991), the Elura Mine (De Roo 1989) and at Mount Isa (Perkins unpublished data). A microstructural study on the timing of mineralization relative to foliation development and folding in the host rock is clearly needed to establish a primary or secondary origin of the Que River ore and other massive sulphide deposits in the Mount Read Volcanics Finally, metal zoning trends and 'fold'-patterns in the Que River orebody are generally parallel to the external foliation. This could be either interpreted as a result of folding or of cleavage-controlled replacement.

CONCLUSIONS

The Rosebery mineralization is generally parallel to the dominant external cleavage, but discordant to folds in the host rock. This conflicts with previous volcanogenic interpretations of the orebody, as a conformable sediment layer. During D_3-deformation, reverse shearing along the Rosebery fault zone caused intensification and extension of the S_2-foliation and the formation of anastomosing shear-planes associated with foliation boudinage. Material transport was channeled through the Rosebery fault zone. Gaping of extensional ramps caused fracturing and brecciation of the wall rock, infiltration of the hydrothermal fluids and replacement of the host rock by sulphides and silicates. The hydrothermal fluids potentially derived their metals and sulphur from disseminated primary sulphides in the footwall volcanics to the deposit.

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