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Structural controls on nickel sulphide ore shoots in Archaean komatiite, Kambalda, WA: the volcanic trough controversy revisited

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Abstract

Structural evaluation of the extensive exploration database for the Kambalda–Tramways area (Archaean Yilgarn Craton, Western Australia) is addressing the long outstanding issue of whether the trough structure embayments that partly confine the nickel sulphide (NiS) ore shoots are volcanic or tectonic in origin. The trough structures are complex linear domains associated with talc–carbonate alteration overprinting thickened komatiite overlying footwall basalt. Two end-member trough structure types are recognised: (1) re-entrant trough structures, and (2) open trough structures. The re-entrant trough structures are narrower at the top than at the base, strongly asymmetric in cross-section, restricted in distribution to Kambalda Dome, and transgress and truncate ore. The open trough structures are wider at the top than at the base, weakly asymmetric in cross-section, prevalent outside Kambalda Dome, and are mineralised along their lateral margins. In addition to trough-associated ore, other NiS ore shoots overlie near-planar komatiite-basalt contacts and are overlain by serpentinite with relict igneous textures. All these features indicate the possibility that the trough structures reflect structural folding, thickening and alteration at rock contacts marking different competency during regional fold–thrusting. Consequently, NiS exploration strategies should consider structural and metamorphic features, as well as volcanologic and stratigraphic features. Recognition of folding and thrusting patterns related to major competency contrasts in favourable komatiite–basalt stratigraphy near the crest of regional anticlines and domes would aid exploration success.

Keywords: Archaean; Kambalda; Nickel sulphide; Folding and thrusting; Trough structure; Competency contrasts; Komatiite

1. Introduction

Confinement of nickel sulphide (NiS) ore shoots to depressions or trough structures in the Archaean Kambalda Komatiite Formation–Lunnon Basalt Formation contact, Kambalda (Western Australia) has been interpreted to reflect primary controls on sulphide deposition (Lesher, 1983; Lesher et al., 1984) and superimposed effects of deformation (Cowden and Archibald, 1987; Cowden, 1988). The strong association with ore means that the origin of the trough structures is critical to a full understanding of ore deposition and exploration targeting in this major nickel ore district (Stone and Masterman, 1998) and in similar districts elsewhere. The relative merits of primary versus secondary control models have been hotly debated (Lesher, 1989; Cowden and Roberts, 1990; Stone and Masterman, 1998). However, studies have been limited by incomplete exposure, lack of marker horizons and mine closure.

The volcanic models for the origin of the trough structures are based on the assumption that the original distribution of volcanic facies and depositional relationships can be reconstructed with confidence. However, the volcanic models have been proposed without a full understanding of the effects of structural and metamorphic overprints, which are severe (Cowden and Archibald, 1987; Cowden, 1988; Cowden and Roberts, 1990). This situation is despite the recommendations of Barrett et al. (1977) and Groves et al. (1979) that the overprinting effects must be understood prior to any modelling of volcanic processes.

This paper examines the role of structural deformation in the origin of the trough structures at the Kambalda Dome and Tramways Belt in the Archaean greenstones of the

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Norseman–Wiluna Belt, Western Australia. Specifically, the roles of folding and faulting are investigated. The approach involves analysis of interpreted solid geology maps and sections and three-dimensional (3-D) digital models of the extensive exploration–drilling database. The inclusion of Tramways Belt in the study permits study of a wider spectrum of trough geometries than is available at Kambalda Dome. Consideration of macroscopic and mesoscopic data and 3-D modelling demonstrates that the trough structures can be explained by parasitic folding and thrusting along the favourable komatiite–basalt contact during regional deformation (D2). These results have implications for ore genesis models and exploration targeting strategies.

2. Geological setting of Kambalda–Tramways

2.1. Stratigraphy

The stratigraphy of the Kambalda–Tramways area (Cowden and Roberts, 1990) comprises the Kalgoorlie Group, Black Flag Group and Merougil Beds Group. This is the local stratigraphic scheme, which has been revised by Krapez et al. (2000) on a more regional scale. The Kalgoorlie Group consists of komatiites of the Kambalda Komatiite Formation and basalts of the Lunnon Basalt, Devon Consols and Paringa Basalt Formations. The komatiite–basalt sequence is overlain by the felsic volcanic–volcaniclastic rocks and clastic sedimentary rocks of the Black Flag Group. The Black Flag Group is unconformably overlain by the Merougil Group. The unconformity represents a significant break in deposition from deep marine sediments (Black Flag) to terrestrial river sediments (Merougil Group) (Cowden and Roberts, 1990).

The stratigraphic units most closely associated with NiS ore are the Lunnon Basalt Formation (footwall) and the Kambalda Komatiite Formation (host rock and hanging wall) (Cowden and Roberts, 1990; Fig. 1). The Kambalda Komatiite Formation is divided into a lower mineralised member (Silver Lake Member) and an upper unmineralised member (Tripod Hill Member) (Gresham and Loftus-Hills, 1981; Thomson, 1989). The Silver Lake Member has traditionally been considered to consist of up six highly magnesian (up to 45%) komatiite flows 40–100 m thick and is more closely associated with the NiS ore shoots and interflow sulphidic meta-sedimentary rocks (Bavinton, 1981). More recently, Stone et al. (2004) have shown that the Silver Lake Member is composed of >20 flows, thin flows are spatially associated with thick flows, the basal flow is not necessarily thickest, and thin flows host massive sulphide bodies.

The NiS ore environment (ore plus immediate wall rocks) is characterised by four fundamental geologic features (Gresham and Loftus-Hills, 1981; Stone et al., 2004): (1) embayment or trough structure in the upper surface of the Lunnon Basalt; (2) NiS ore partly confined by the trough structure (contact ore) and, more rarely, at the base of overlying flows (hanging wall ore); (3) lack of sedimentary rocks in the trough; and (4) thickened, MgO enriched ultramafic rocks or channel facies komatiite in the immediate hanging wall. The lateral flanking contact environments are characterised by a planar Lunnon Basalt surface, minor NiS mineralisation, sulphidic sedimentary horizons on the contact and at interflow positions, and thinner flanking facies komatiite with lower MgO contents. These features of the ore and non-ore environments have been interpreted to reflect strong primary volcanic controls. Prevailing ore genesis models are based on thermal erosion of sulphidic sediment substrate to lava channels in distal volcanic settings (Lesher et al., 1984; Williams et al., 1998). Exploration strategies emphasise the identification of volcanic channels defined by deep footwall embayments (trough structures), thick high-MgO volcanic flows, and absence of sedimentary rock.

Contact ore constitutes 80% of the nickel resource and occurs as tabular to linear ore shoots up to 2.5 km long, 300 m wide, generally <5–10 m thick, and <0.6– ~ 12 Mt in size. Individual sulphide (pyrrhotite + pentlandite ± pyrite ± chalcopyrite) bodies are vertically zoned. Massive ore (>80 wt% sulphide) at the base is overlain by, or contains blocks of, matrix ore (40–80 wt%) or disseminated-blebby ore (<40% sulphides) (Groves et al., 1979). Massive ore shows tectonic fabrics (Ostwald and Lusk, 1978; Seccombe et al., 1981), which preserve evidence of the entire regional deformation sequence (Cowden and Archibald, 1987; Stone et al., 2004).

Although hanging wall ore positions constitute a relatively minor proportion of the nickel resource, several research projects have been directed at documenting and interpreting their many interesting geological features (e.g. Groves et al., 1986; Lesher and Groves, 1986). The best-known hanging wall ore shoots are Lunnon and McMahon (Fig. 2), which show very different features (Gresham and Loftus-Hills, 1981; Groves et al., 1986; Stone et al., 2004). At Lunnon, ore is present at the base of the second flow unit, directly overlying inter-spinifex textured ore in the top of the basal flow unit. The massive ore is strongly banded and its lower contact is penetrated by centimetre-size silicate domes. The silicate domes have been considered evidence for partial melting of the underlying spinifex-textured flow top during thermal erosion of pre-existing sedimentary units (Groves et al., 1986). Indeed, the hanging wall ores and lack of sedimentary rocks overlying the top of the basal flow unit of the Silver Lake Member (i.e. sediment-free window of Gresham and Loftus-Hills (1981)) have been attributed to thermal erosion about stacked lava channels. However, recent studies (Stone et al., 2004) have demonstrated the presence of meta-sedimentary units up-section of the mineralised basal flow unit. The McMahon ore shoot, on

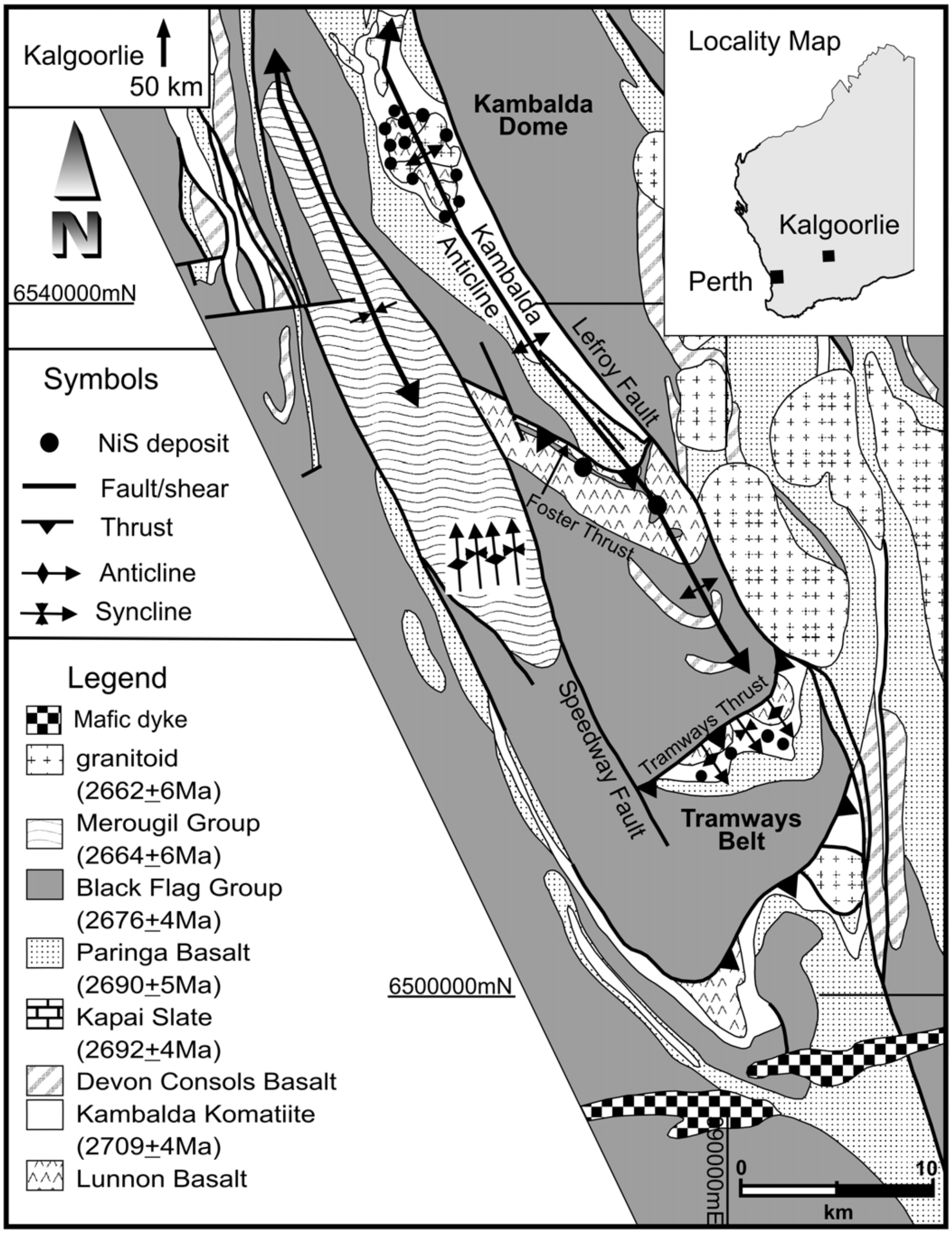


Fig. 1. Location and regional geologic setting of the Kambalda Dome–Tramways Belt area (modified from Bader, 1994 and Stone and Masterman, 1998). Age dates from Compston et al. (1986) and Claoué-Long et al. (1988).

the NW flank of the Loreto thrust wedge (Fig. 2), is mainly in a hanging wall position partly within interflow sedimentary rocks overlying the top of the basal unit of the Silver Lake Member. The hanging wall ore, unlike that at Lunnon, appears to lack any association with underlying contact ore.

2.2. Regional deformation and metamorphism

Detailed knowledge of the structural sequences at the Kambalda Dome and Tramways Belt is required to establish a framework for understanding the trough structures. Three fundamental structural features are evident from the distribution of stratigraphic sequences (Nguyen, 1997; Swager, 1997) (Fig. 1). One is the structural repetition of stratigraphy, with older sequences emplaced on younger sequences. The best examples of such structures (D1) are the Foster Thrust and the Tramways Thrust (Fig. 1). Another fundamental structural feature is the upright anticlinal structures (D2) with NNW-trending axial traces, the best example of which is the Kambalda Anticline (Fig. 1). A third fundamental feature is the Lefroy Fault zone (mainly D2, though with a complex structural history), which

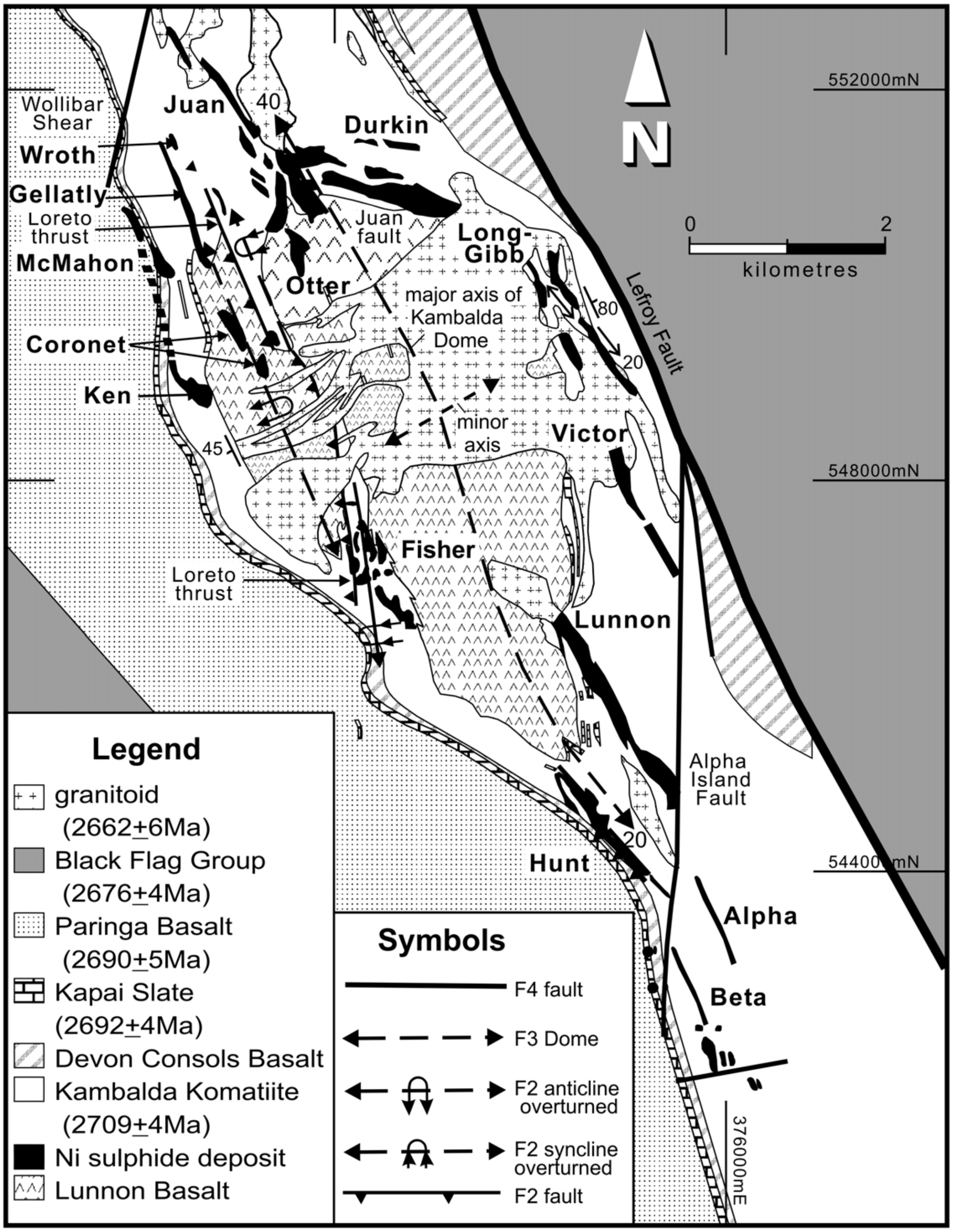


Fig. 2. Interpreted geologic map of the Kambalda Dome showing the distribution of rock units and major structures (modified from Cowden and Roberts, 1990 and Stone and Masterman, 1998). The NiS ore shoots are shown in plan projection to surface.

truncates the Kambalda Anticline to the east. All these structures are cut by felsic intrusions and offset along N–NNE-trending D4 structures.

Metamorphism involved seafloor alteration, progressive regional metamorphism, contact metamorphism and retrogressive metamorphism (Cowden and Roberts, 1990). Komatiitic peridotite has been hydrated to serpentine-dominated mineral assemblages, which preserve relict volcanic textures and minerals (Cowden, 1988; Lesher, 1989). The serpentinites subsequently altered to talc–carbonate mineral assemblages synchronous with D1, and most intense near major faults (Cowden and Roberts, 1990). Talc–carbonate alteration and progressive metamorphism involved porphyroblast overgrowth and development of cleavage overprinting relict primary textures and depositional relationships under conditions of 480–530 °C at 2–3 kb. Potassium metasomatism, in the form of biotite–phlogopite replacement of chlorite, is evident in the ultramafic rocks adjacent to contacts with felsic intrusions.

3. Methods and techniques

The nature and origin of the trough structures and their relationships to associated NiS ore shoots and volcanic channels at the Kambalda Dome and Tramways Belt were evaluated using 3-D digital models and conventional 2-D maps and cross-sections drawn from the exploration drilling database and mapping of underground exposures. In order to visualise trough structures, the drilling data were manipulated to compute variography and indicator kriged 3-D surfaces of the upper Lunnon Basalt surface at the Kambalda Dome and Tramways Belt. The computational routines utilise irregularly-spaced data points to interpolate the contact position for every block in a regular 3-D grid. The advantage of this block modelling technique compared with conventional wireframing techniques is that the model can be cross-sectioned at any angle, rather than solely along the E–W drill traverses.

Similar grids were utilised to image the NiS ore shoots and komatiite volcanic channels, by fitting 3-D contours (isosurfaces) to the assay data field. Models for ≥1500 ppm Ni in sulphide-poor ultramafic rocks were constructed, because raw geochemical data suggest that komatiite lava (non-cumulate) emplaced at Kambalda and Tramways Belt contained 1500 ppm Ni. Given the compatibility of Ni in olivine, the isosurface models for ≥1500 ppm Ni in $50 \times 50 \times 10$ m size blocks of sulphide-poor ultramafic rock are inferred to reflect linear domains of olivine accumulation formed in the original volcanic lava channels. Further details of the 3-D modelling and visualisation techniques are provided by Stone et al. (1998).

4. Structural setting

4.1. Kambalda Dome

The structural geology of Kambalda Dome has received little attention in most research studies Macroscopically, Kambalda Dome (D3) is a doubly-plunging anticline on the crest of the major regional Kambalda Anticline (D2). It is cored by the Lunnon Basalt, intruded by granitoid, and flanked by the Kambalda Komatiite (Fig. 2). Dips on the east flank (up to subvertical) are steeper than on the west flank (45–60°). Plunges are steeper in the north (40°) than in the south (10–20°) and steeper than the Kambalda Anticline (5–10°). The amplitude of the Dome appears in deep drilling to be of the order of 1000 m, such that the Lunnon Basalt is thickest (at least ~2 km) in the core and the Kambalda Komatiite is thickest (~1 km) on the north (above Juan shoot) and south (above Beta shoot) flanks. The Kambalda Komatiite on Lunnon Basalt sequence is repeated on the west flank by the Loreto Thrust and related folds (D2), and truncated on the east flank by the Lefroy Fault Zone (mainly D2).

All the D2 and D3 structures are cut by intermediate to silicic intrusions. They exhibit a range of temporal relationships from deformed and altered granodiorites and porphyritic dacites intruded subconcordant to layering, to undeformed and unaltered discordant granites and porphyritic rhyolite. The intrusions, in turn, are cut and deformed by the N–NNE trending faults related to the D4 Alpha Island Fault zone and the Woolibar Shear zone (Fig. 2).

Although the metamorphic temperatures for the major part of the Kambalda Dome appear to have been 480–530 °C, in detail the conditions of peak metamorphism are more variable. Metamorphic olivine porphyroblasts at Long-Gibb, in the Lefroy Fault Zone on the east flank of Kambalda Dome, indicate temperatures of 530–570 °C. The elevated metamorphic conditions at Long-Gibb probably reflect contact metamorphism adjacent to a swarm of silicic intrusions (Cowden and Roberts, 1990).

4.2. Tramways Belt

The structural setting of the Tramways Belt is dominated by the Tramways Thrust, along which the Lunnon Basalt has been emplaced onto the younger Black Flag Group (Fig. 3). Overturning is evident in the immediate hanging wall to the Tramways Thrust.

The D1 deformation is localised along the Tramways Thrust and along a series of sub-parallel faults in the hanging wall, which cut the Silver Lake Member–Lunnon Basalt contact. Sequences in the immediate hanging wall to the Tramways Thrust are extensively deformed and dominantly downward facing. The Lunnon Basalt domes are defined by WSW-trending anticlines (D1) and folded about an array of closely-spaced SSE-trending anticlines and synclines (D2). Development of south-dipping S1 fabrics decreases rapidly away from the thrust and becomes confined to less competent horizons such as massive ores and meta-sedimentary rocks. Close-spaced D2 upright open folds are superimposed on the D1 thrust and related folds and faults, and plunge ~30° to the south in the east part of the Tramways Belt and ~25° to the SE or SSE in the west part of the Tramways Belt. These folds appear to have wavelengths and amplitudes of the order of hundreds of metres. Steep upright NNW-trending D3 faults and related foliation cut the limbs of the D2 folds. The conditions of peak regional metamorphism appear to have been similar to the major part of the Kambalda Dome (Ison, 1999).

The NiS ore shoots are most closely associated with the contact between the Lunnon Basalt and the Kambalda Komatiite, as at Kambalda Dome. Intrusive rocks are mainly intermediate to silicic in composition, as at

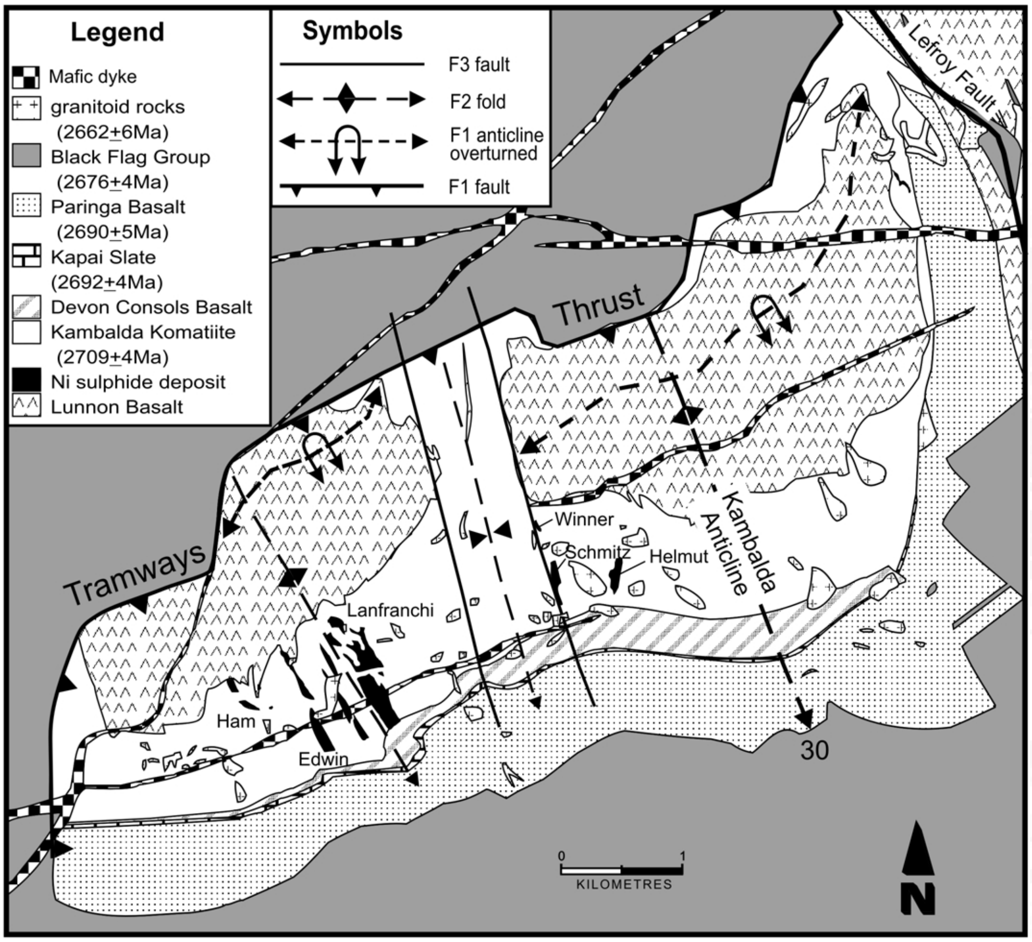


Fig. 3. Interpreted geologic map of the Tramways Belt showing the distribution of rock units and major structures (modified from Cowden and Roberts, 1990). The NiS ore shoots are shown in plan projection to surface. Note the marked differences in structural setting compared with Kambalda Dome.

Kambalda. However, the Tramways Belt appears to lack a large felsic pluton.

5. Trough structures

The Kambalda Komatiite–Lunnon Basalt contact at the Kambalda Dome is generally planar, except in the vicinity of the NiS ores, where it is marked by a distinctive embayment or trough structure in the top of the Lunnon Basalt (Gresham and Loftus-Hills, 1981). Much debate has focused on the significance, original nature, and subsequent tectonism of the trough structures. Most stratigraphic and volcanic studies (Ross and Hopkins, 1975; Gresham and Loftus-Hills, 1981; Lesher et al., 1984) interpret the trough structures to be original syn-volcanic features, though subsequent structural modification is generally acknowledged. Other studies (Cowden and Archibald, 1987; Stone et al., 2004) emphasise the importance of deformation processes in trough structure formation at Kambalda. However, to date, the specific nature of such processes and detailed information on the morphology of the Kambalda Komatiite–Lunnon Basalt contact outside of the Kambalda Dome remain to be presented in the scientific literature.

The geometry and dimensions of the trough structures have been well defined by exploration and mining activities. In general, the trough structures exhibit a spectrum of shapes between two end-member forms (Claoué-Long, 1986; Gresham, 1986): (1) re-entrant trough structures, which are wider at the base than at the top; and (2) broad, open trough structures, which lack re-entrant margins and are wider at the top than at the base. The distinction of re-entrant geometry and open geometry type appears in part to be geographical. Re-entrant trough structure shapes are restricted in distribution to the Kambalda Dome, whereas the open trough structure geometry is prevalent at Tramways Belt and elsewhere (McQueen, 1981; Stoltz and Nesbitt, 1981). Many research projects have documented and interpreted the re-entrant trough structures (e.g. Lunnon shoot; Ross and Hopkins, 1975; Cowden, 1988; Lesher, 1989), but the open type has received much less attention. Little knowledge exists on the relationship between the two end-member trough structure types.

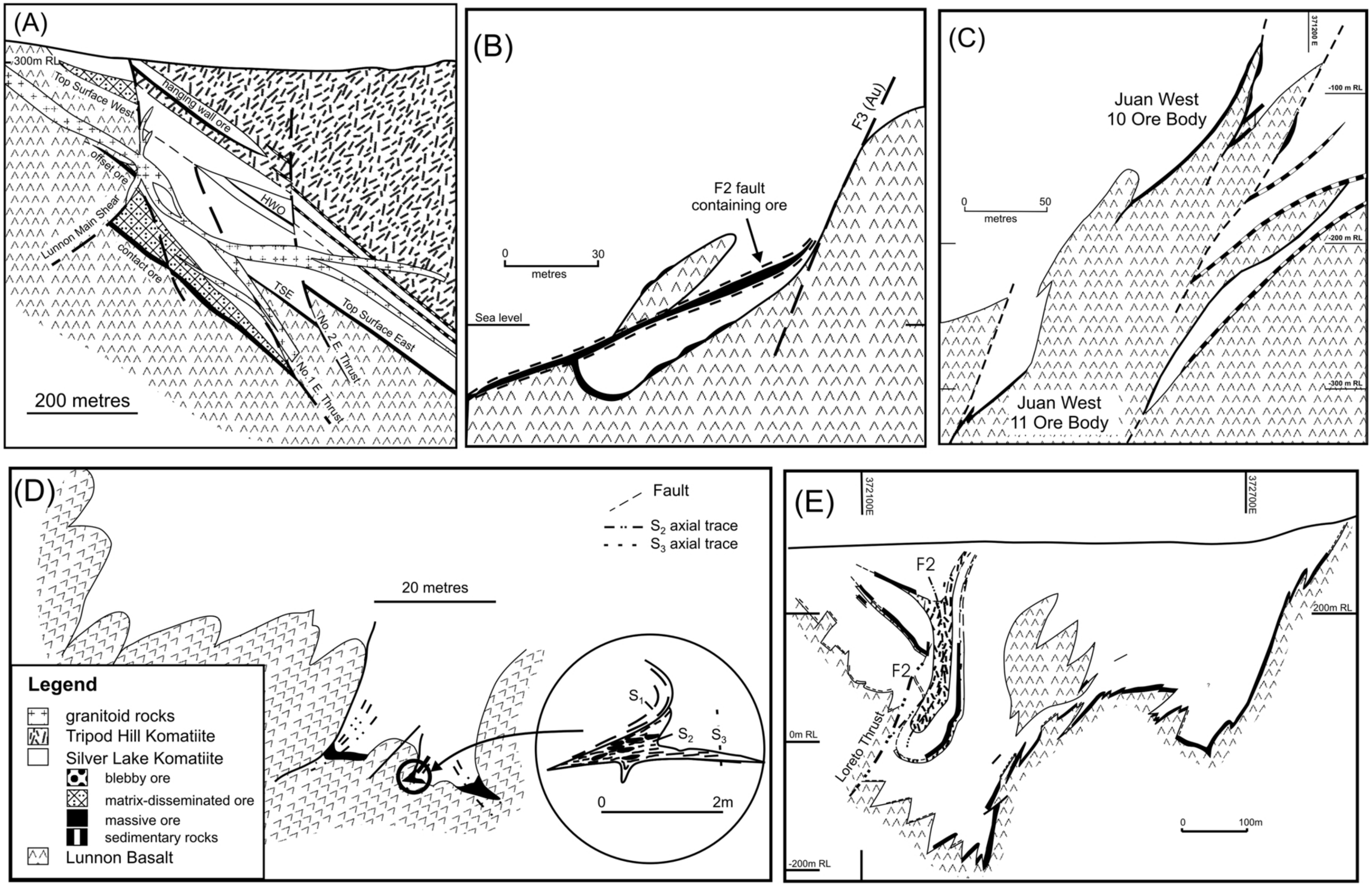


Fig. 4. Re-entrant and down-dip over up-dip vergence trough structures. (A) Geologic cross-section 546250 mN of Lunnon shoot, illustrating the down-dip over up-dip vergence on the east flank of Kambalda Dome (modified from Cowden and Roberts, 1990). (B) Cross-section 44 of Hunt shoot, west flank of Kambalda Dome, showing structural offset of contact ore into hanging wall position along thrust fault at the west margin of the trough structure (modified from Cowden and Roberts, 1990). (C) Cross-section 551420 mN through the Juan complex, north flank of Kambalda Dome, showing disruption of the 10 and 11 ore bodies by major reverse-thrust faults (modified from Cowden and Roberts, 1990). Note the presence of ore immediately below the faults. (D) Cross-section 84 through Hunt shoot (D Zone Deeps) showing D2 mesoscopic folds and related massive ore fabrics (modified from Cowden and Archibald, 1987). (E) Diagonal cross-section through Fisher shoot, west flank of Kambalda Dome, showing a very complex trough structure, the leading edge of the Loreto Thrust and footwall syncline (modified from WMC Internal Report).

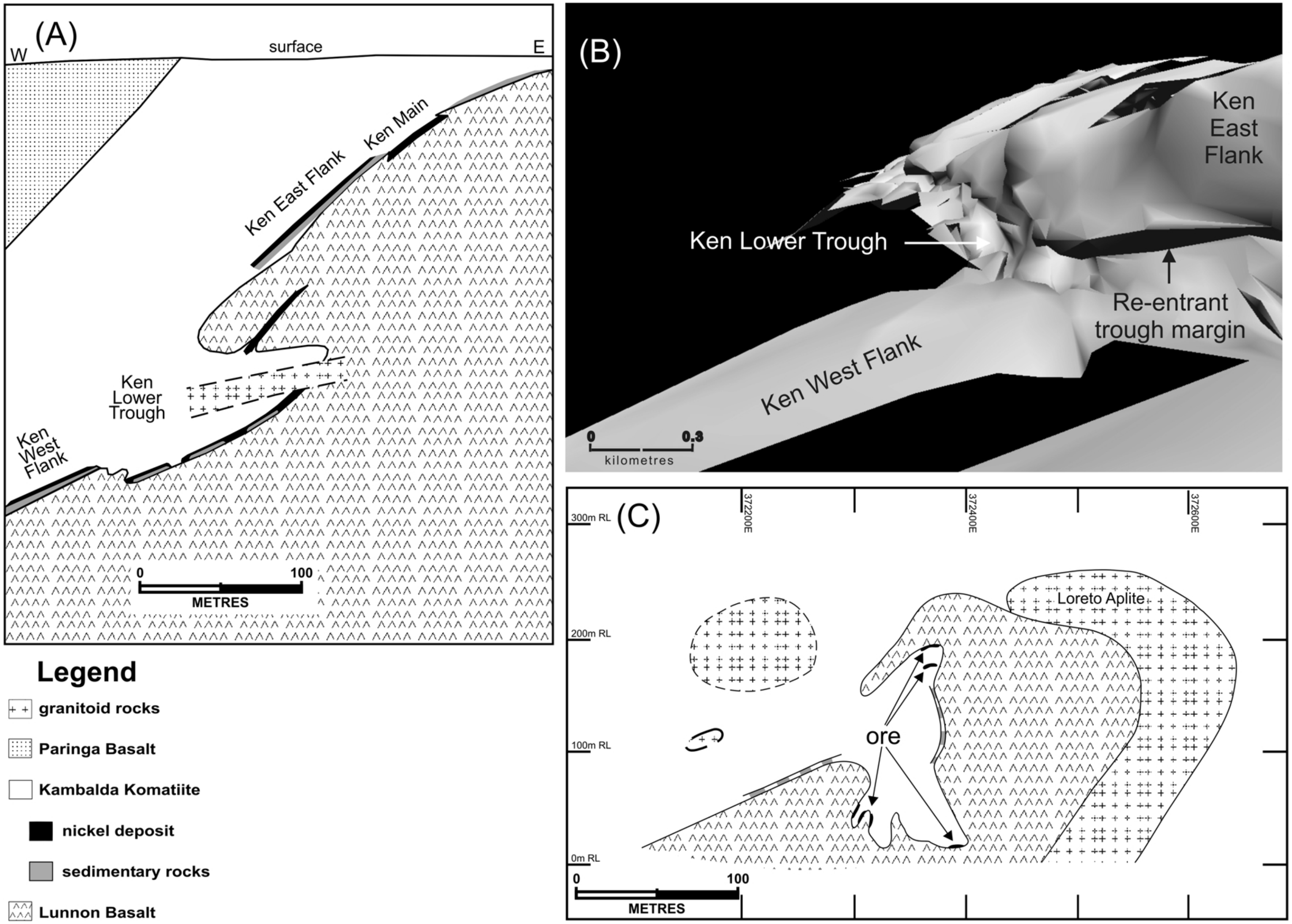


Fig. 5. Re-entrant trough structures showing up-dip-over-down-dip vergence, Loreto Thrust wedge. (A) E–W cross-section 549083 mN showing the up-dip over down-dip asymmetry of the margins of Ken Lower Trough. Note the position of the Ken Main ore body on the up-dip flank of Ken Lower Trough, which is essentially barren and contains meta-sedimentary rocks. (B) Three-dimensional model of the Lunnon Basalt upper contact showing the well defined margins and the extensive linearity of the Ken Lower Trough (looking north). (C) E–W cross-section 551156 mN of the Gellatly shoot, showing the up-dip over down-dip vergence of the margins (modified from WMC Internal Report). Note the presence of overturned contact ore and meta-sedimentary rocks.

5.1. Re-entrant trough structures

The re-entrant trough structures are highly elongate, linear features up to 3 km in plunge extent and a few tens to hundreds of metres wide (Figs. 4 and 5). In cross-section, the re-entrant trough structures are up to 100 m deep, with a relatively flat floor. The meta-sedimentary rocks overlying the Lunnon Basalt elsewhere are absent from the floor and from a narrow zone laterally up-dip and down-dip of the trough structures. Most trough structures (e.g. Lunnon, Juan, Long) trend NNW, parallel to the regional structural fabric, and so may have developed during or prior to peak deformation. A few trough structures trend N–NNE (e.g. parts of Fisher and part of Ken Lower Trough), NW (e.g. Hunt, Ken East Flank, Coronet, parts of Fisher) and WNW (west part of Durkin), slightly but significantly oblique to the regional trend.

The lateral margins of the re-entrant trough structures are generally asymmetric and defined by fold–thrust couplets, termed pinchouts, at the down-dip margin and upright faults at the up-dip margin (Fig. 4A–E). The asymmetry of the lateral trough margins suggests down-dip-over-up-dip vergence, essentially up-flank toward the crest of the Kambalda Anticline/Dome. These trough structures parallel the NNW regional structural fabric, host the larger, more continuous ore shoots, and lack sedimentary units. In comparison, trough structures on the Loreto Thrust wedge (Ken Lower Trough, Gellatly-Wroth) and locally on the north flank of the Kambalda Dome (Otter, Durkin Deeps) exhibit reverse asymmetry; that is up-dip-over-down-dip vergence (Fig. 5A–C). Some ‘reverse asymmetry’ trough structures contain sedimentary rocks and small, thin and discontinuous NiS ore shoots.

The relationship of re-entrant trough structures and NiS ore is very complex (Fig. 6). At the macroscopic scale, trough structures only partly confine ore (e.g. Fig. 6A and B) and in places truncate it (Fig. 6A). Ken Lower Trough, probably the longest and best defined at Kambalda, lacks significant ore bodies. The largest ore body on the Loreto Thrust, Ken Main, is located on the up-dip flank of Ken Lower Trough (Fig. 6A). Mesoscopically, massive ore in pinchout positions exhibits complex overprinting fabrics geometrically consistent with the fold–thrust couplets at the lateral trough margins (Fig. 6B and C). Approaching the floor of the trough structures, massive ore exhibits a progressive increase in the intensity of layering and development of S2 blastomylonitic fabrics (Cowden, 1986; Cowden and Archibald, 1987). Conversely, approaching the contact from below, relict pillows and pillow breccias are preserved in the Lunnon Basalt, even immediately below the contact (Squire et al., 1998). Ore occurs in pillow interstices (Lesher and Keays, 1984) and in sulphide and quartz–carbonate veins (Heath et al., 2001). Unmineralised Kambalda Komatiite–Lunnon Basalt contacts are marked by zones of intensely foliated to massive amphibole–chlorite, chloritite and biotite. The zones are up to 1 m thick and represent metasomatic reaction zones (Marston and Kay, 1980; Heath et al., 2001; Fig. 6C). Overlying ore, the Kambalda Komatiite is talc–carbonate-altered ultramafic rock devoid of relict igneous texture.

The strong contrast of gneissic and blastomylonitic fabrics in the massive ore and the preservation of pillows and breccias in the immediate footwall indicates the possibility that the massive ore–Lunnon Basalt contact is a structural dislocation rather than a conformable contact, at least in the ore environment. This interpretation is consistent with dyke offsets of up to hundreds of metres across massive ore, inclusions of veins and surrounding rock types in massive ore, and evidence for relocation massive sulphide into wall rock during tectonism (Barrett et al., 1977; Groves et al., 1979; Marston and Kay, 1980; Lesher and Keays, 1984; Paterson et al., 1984). Talc–carbonate alteration elsewhere in the Norseman–Wiluna Belt is spatially associated with major shear zones (Rödsjö et al., 2004) and, in general, there is no reason to regard the alteration at Kambalda–Tramways any differently (i.e. the talc–carbonate alteration could represent major shear zones). Conversely, the Silver Lake Member–Lunnon Basalt contact in flanking, unmineralised environments appears to be planar, preserves depositional contact and stratigraphic relationships, and might be conformable (Cas and Beresford, 2001; Beresford et al., 2002). However, research has been directed at documenting and interpreting these environments in only a very few studies.

Whereas the trough structures are embayments in the top surface of the Lunnon Basalt, primary volcanic channels are potentially represented by elongate >10-m-thick, Ni-enriched, sulphide-poor ultramafic domains (Fig. 7) in the basal unit of the Silver Lake Member, Kambalda Komatiite Formation. In plan view, the volcanic channels appear to be generally coincident in trend with the trough structures. However, a few volcanic channels trend slightly to strongly oblique to the general NNW trend. At Lunnon (Fig. 7A), the volcanic channel trends slightly, but significantly, more towards the west (325°) than the trough (335°), such that the south part of the ore shoot occupies a flanking position down-dip to the east of the main trough. Two parallel, NW-trending (315°) volcanic channels at Fisher are truncated at the west margin of a deep, continuous N-trending (360°) trough structure (Fig. 7B), defined by the Loreto Thrust. The WNW-trending (275°) volcanic channel at Ken Main appears in plan to be dextrally transposed into and disrupted along the NNW-trending (330°) Ken Lower Trough. Obviously, in these cases, the trough structures postdate the volcanic channels.

5.2. Open trough structures

The open trough structures (Fig. 8) are elongate, linear features up to 1000 m long, >100 m wide and ~100 m deep. In cross-section, they are broad, saucer-shaped and

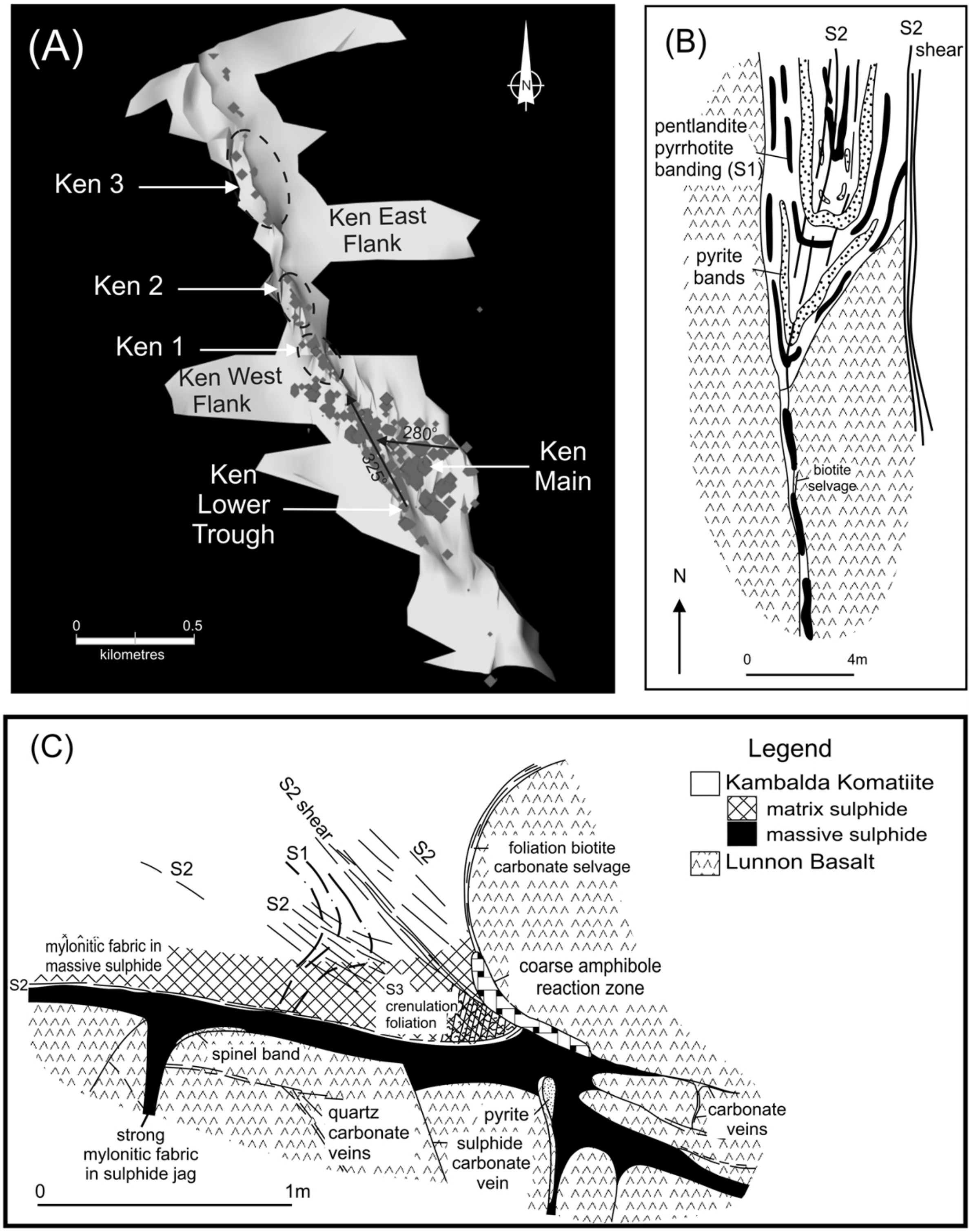


Fig. 6. Re-entrant trough structure–contact ore relationships. (A) Plan view of the 3-D Lunnon Basalt upper contact model overlain by ore (represented by dark grey isosurface models) for Ken complex. Note that the Ken Main ore body (trending 280°) along the Ken Lower Trough on the up-dip flanking position appears down-dip to be dextrally transposed into and disrupted along the Ken Lower Trough structure (trending 325°). (B) Evidence for folding of S1 banding about S2 gneissosity in massive ore in pinchout, Ken North ore drive. (C) Geological map of a basalt–ore–basalt pinchout formed by an F2 fold–thrust couplet, Juan 1210/1-2 east wall, south pinchout. Note the truncation of the S1 fabric by the S2 contact–parallel foliation.

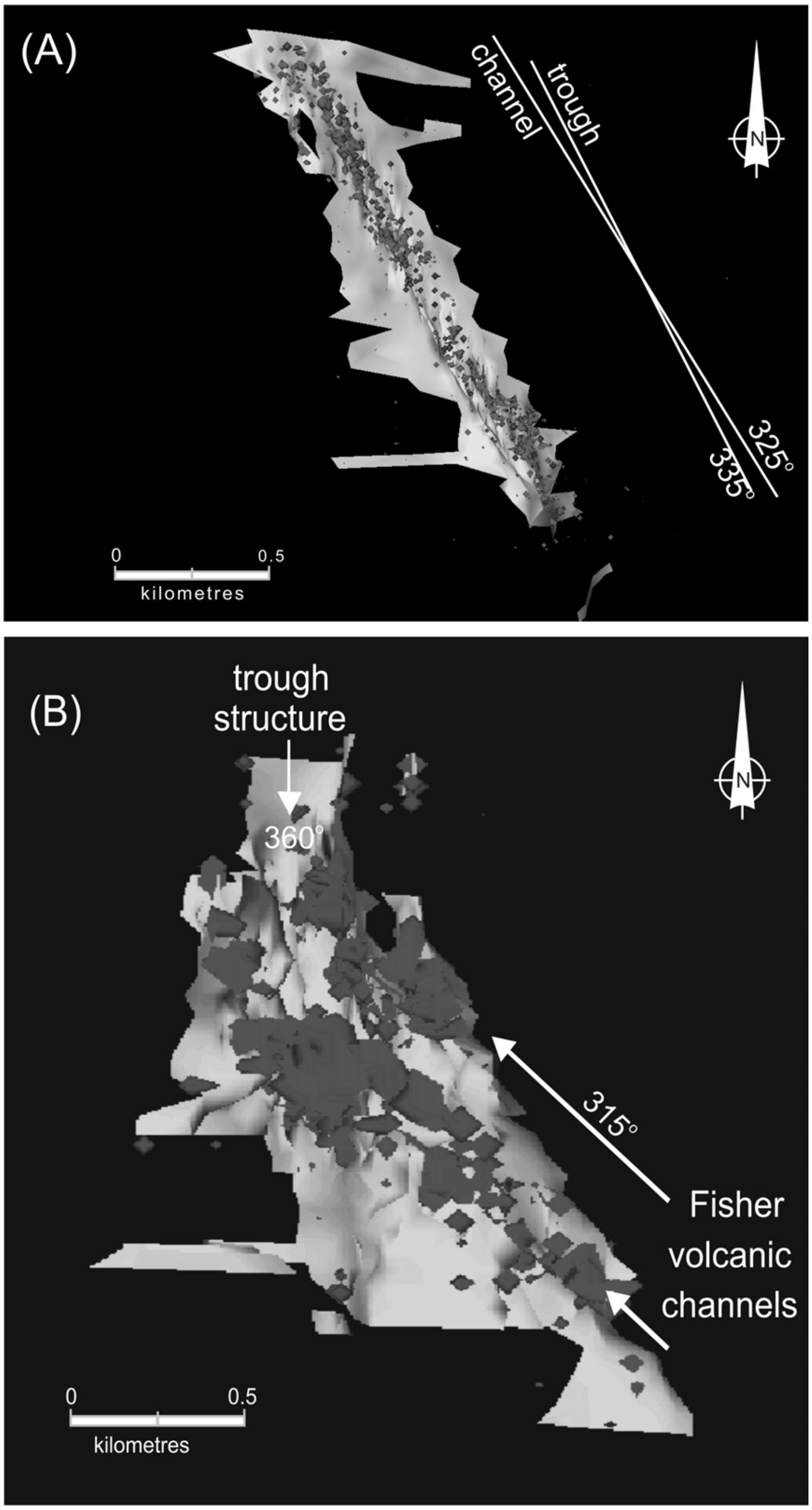


Fig. 7. Re-entrant trough structure and volcanic channel relationships. (A) Plan view of the 3-D Lunnon Basalt upper contact model overlain by Silver Lake Member channel facies (represented by dark grey isosurface models). (B) Plan view of the 3-D Lunnon Basalt upper surface model overlain by Silver Lake Member channel facies komatiite (represented by dark grey isosurface models) at the Fisher shoot complex. Note the apparent truncation of the NNW-trending volcanic channels by the west margin of the trough structure, which is probably the leading edge of the Loreto Thrust.

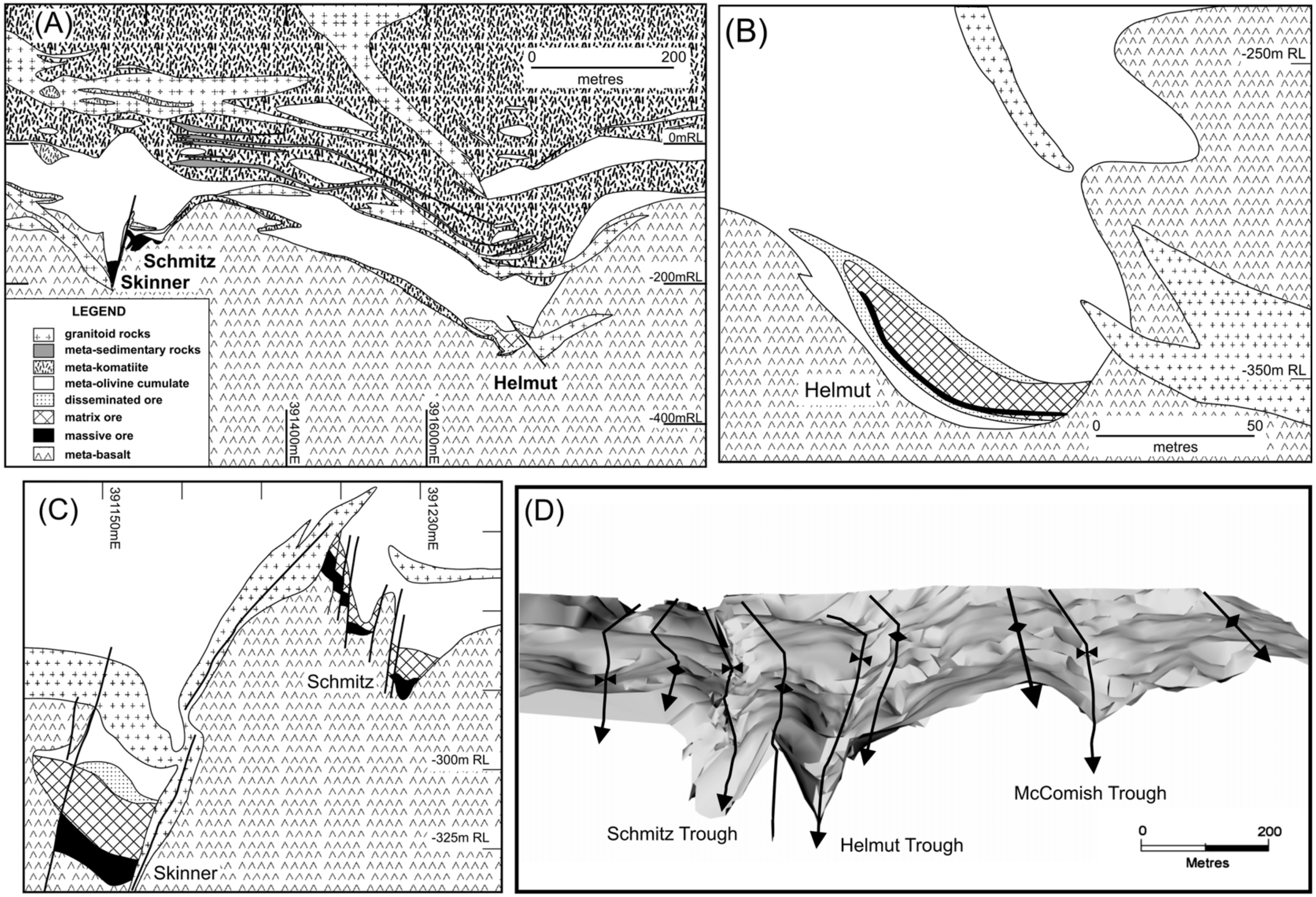


Fig. 8. Open trough structures at Tramways Belt. (A) E–W cross-section 514370 mN illustrating the open shapes of the Schmitz and Helmut trough structures and thickening of the basal unit of the Silver Lake Member above the trough structures and thinning above the intervening anticlines (modified from Stone and Masterman, 1998). (B) E–W interpreted cross-section 514310 mN through the Helmut deposit. Note the internal position of the ore deposit relative to the floor of the trough, dominance of disseminated and matrix ore, and apparent upwards zonation of disseminated to massive to matrix to disseminated ore (modified from Curl, 1997 and Stone and Masterman, 1998). (C) E–W cross-section 514120 mN through the Schmitz–Skinner deposits. Note the offset of Skinner from Schmitz along a D3 fault, which is marked by a sheared felsic dyke (modified from Ison, 1999). (D) NNW-looking oblique view of the 3-D Lunnon Basalt upper surface model. Note that the form of the folded contact defines lobate-crested anticlines (i.e. mini-domes) and cuspate–'troughed' synclines. The synclinal 'troughs' at Schmitz–Skinner and Helmut host major NiS ore deposits.

slightly asymmetric (Fig. 8B and C). In contrast to the re-entrant trough structures, major pinchouts are generally absent and sedimentary rocks are present on the upper Lunnon Basalt surface, either overlapping the sides or flooring the entire trough. Many of the open trough structures at Tramways Belt are cut by upright faults (D3; Fig. 8C).

The trough–ore relationships in the open trough structures are not straightforward. The trough structures generally confine ore, but at Helmut the NiS ore–Lunnon Basalt contact is on the east margin rather than the floor (Fig. 8B). The Silver Lake Member rock underlying the ore is a 4–7-m-thick interval of talc–carbonate altered ultramafic rock with <1 wt% Ni (Curl, 1997). The Helmut ore profile is dominated by heavily disseminated to matrix sulphides. However, 400 m to the west, the Schmitz–Skinner ores are dominated by massive to matrix sulphide. Skinner is offset down-dip from Schmitz along a steeply west-dipping D3 fault (Fig. 8C).

Trough structure–volcanic channel relationships at Tramways Belt are also complex. Generally, the trough structures appear to be concordant to volcanic channels (as defined at Kambalda Dome). However, in addition to a trough structure in the Lunnon Basalt contact, the basal unit of the Silver Lake Member at Schmitz and possibly at Helmut appears to define a ‘mirror’ or anti-trough structure at its upper contact (Fig. 8A). Macroscopically, the form of the folded upper Lunnon Basalt surface shows broad, rounded anticlines (wavelength large relative to amplitude) separated by narrow, sharp synclines (wavelength small relative to amplitude) (Fig. 8D). Such fold patterns appear, at least superficially, to resemble cuspate–lobate fold patterns elsewhere (Ramsay and Huber, 1987).

Mesoscopically, approaching the contact (<3 m) with the Silver Lake Member overlying the trough floor, Lunnon pillow basalt passes upward to a well developed foliated zone of alternating amphibole and carbonate bands cut by extensive carbonate veins. The Silver Lake Member immediately adjacent to the contact is marked by an up to 1-m-thick zone of amphibole–chlorite rock (Curl, 1997). Overlying the contact (and ore), the Silver Lake Member is talc–carbonate altered; only ~10% at Helmut and McComish is serpentinite with preserved igneous textures (Moore et al., 2000). Evidently, the Silver Lake Member–Lunnon Basalt contact is sheared and therefore likely to be a structural discontinuity, at least in the ore environment, rather than a conformable contact. The discontinuity is interpreted to be a D1 thrust fault (Curl, 1997), related to the major F1 Tramways Thrust. In contrast, volcanic textures and depositional relationships are preserved in the flanking and hanging wall Silver Lake Member away from the trough structure (Curl, 1997; Moore et al., 2000), as at the Kambalda Dome.

6. Non-trough ore settings

In contrast to trough-associated shoots, a small number of NiS shoots overlie an essentially planar or faulted footwall contact (e.g. Victor, Durkin, and Coronet at Kambalda Dome and Lanfranchi at Tramways Belt) (Fig. 9), or occupy hanging wall positions within the Kambalda Komatiite (e.g. Lunnon, McMahon and Coronet West at Kambalda Dome) (Fig. 10). Indeed, whereas the Victor Main ore overlies a near-planar contact, the deep and well-defined trough structure at Victor West is essentially barren (Fig. 9A). In contrast to the trough-associated ore shoots, the hanging wall to the Victor and Durkin shoots is dominated by serpentine rather than talc–carbonate alteration, and relict igneous textures and minerals are preserved (Fig. 9B). Igneous textural preservation is also evident at Coronet (Fig. 9C), despite talc-carbonate alteration. At Lanfranchi, ore is not confined by structure (Fig. 9D), but terminates at lateral cut-off grades on a planar footwall contact (Cowden, 1988). Porphyroblastic talc–carbonate alteration destroyed igneous textures. In all these ore shoots, sedimentary units are absent.

With regard to the hanging wall ores, the structural setting, textures and fabrics suggest that their present positions at Lunnon and McMahon may at least in part be secondary and structurally determined. The silicate domes (Fig. 10A) lack evidence for contact metamorphism and, with their relatively broad crests and sharp trough structures, bear a strong resemblance to cuspate–lobate folds (e.g. Ramsay and Huber, 1987). Such features are generated by folding along the contact between incompetent and competent rock types during layer-parallel compression. Petrographic studies at Coronet suggest Fe–Ni sulphide replacement of spinifex and equant olivine grains through remobilisation of massive sulphide during deformation (Cas and Beresford, 2001). Detailed analysis of the 3-D models reveals the hanging wall ore at Lunnon (and at Hunt shoot) to be displaced slightly, but significantly up-dip relative to the position of spatially-associated contact ore, consistent with the vergence of the trough margins. At McMahon (Fig. 10B), the vergence of folds and fabrics, convergence of the hanging wall ore with the footwall contact down-dip to the west, strong breccia textures, and inclusions of wall rocks strongly suggest the possibility of thrust emplacement along the interflow sedimentary unit from a contact position down-dip. Evidently, the structural setting and fabrics of the hanging wall ores at Kambalda reflect strong secondary processes.

7. Origin of the trough structures

Three main models for trough formation have been proposed: (1) primary volcanic topography, either topographic lows between non-overlapping basalt lava flows (Lesher, 1983; Lesher et al., 1984) or syn-volcanic faulting (Ross

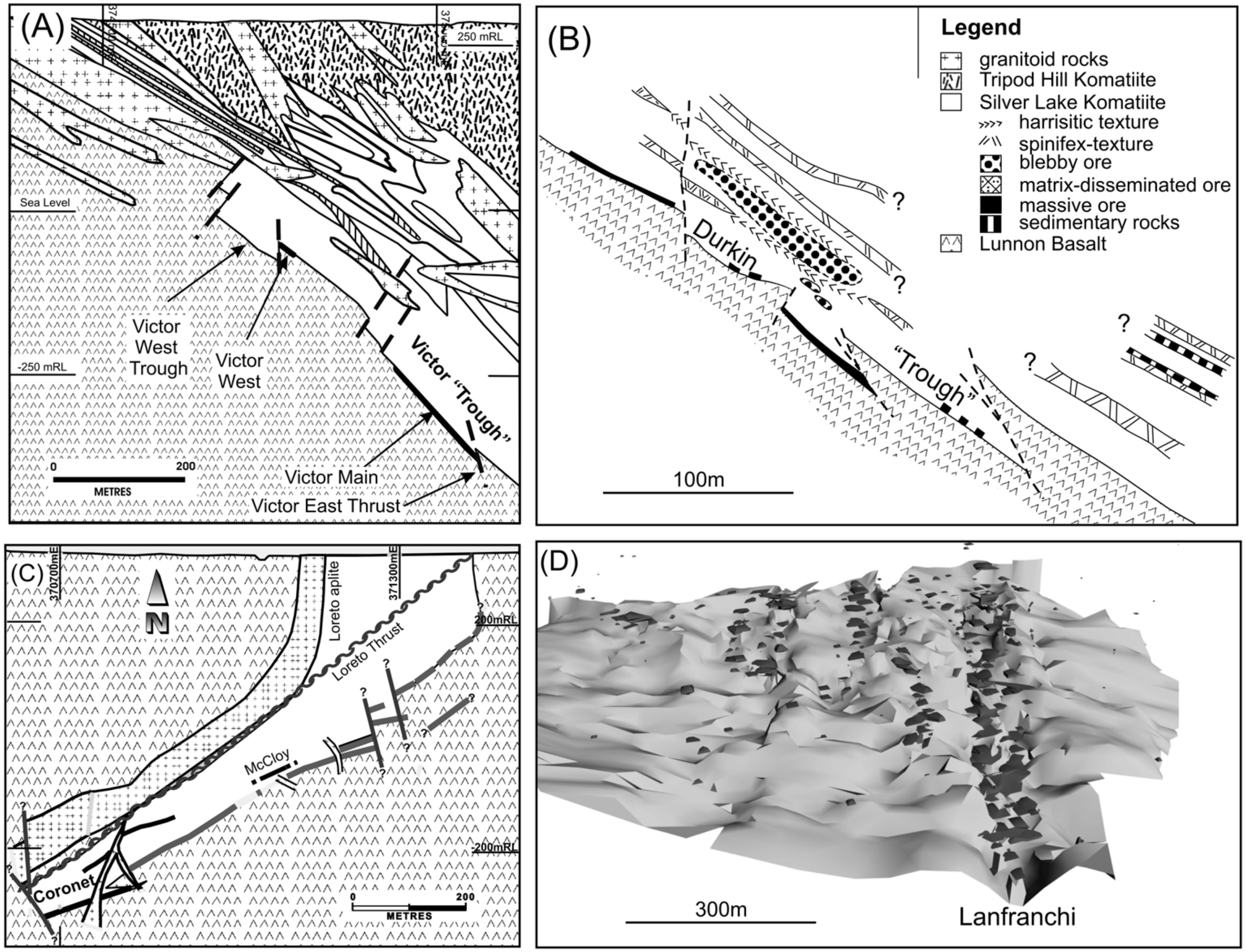


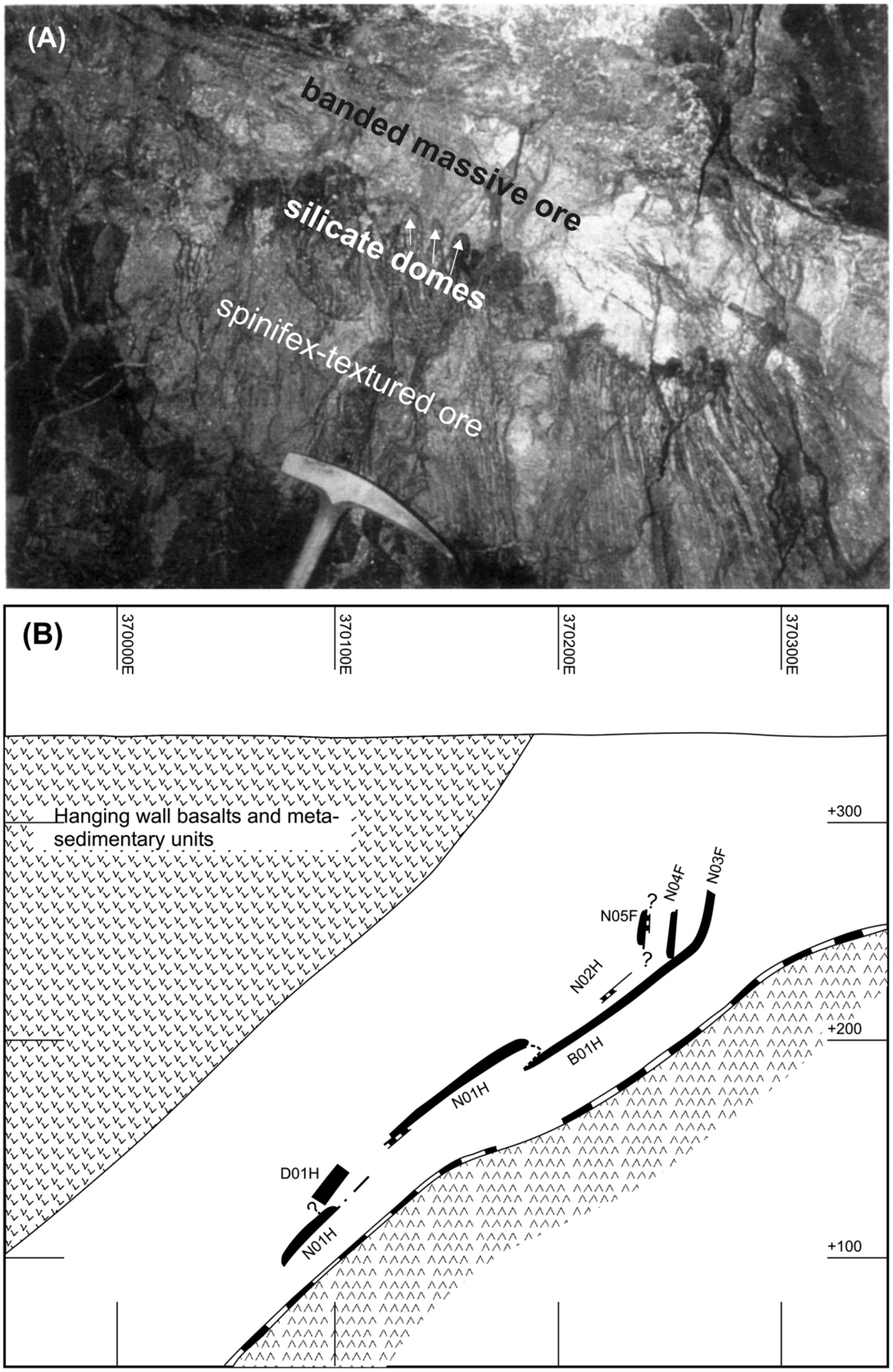
Fig. 9. Non-trough structure associated ores. (A) Geologic cross-section 547925 mN through the Victor ore shoot, east flank of Kambalda Dome (modified from WMC Internal Report). Note that, whereas the footwall contact to the Victor Main ore is only weakly disrupted by faulting, that at Victor West defines a strong trough structure but lacks significant mineralisation. (B) Geologic cross-section at 372927 mE through the Durkin shoot, north flank of Kambalda Dome, showing fault disruption of an essentially planar contact and preservation of primary igneous textures in the serpentinite hanging wall (modified after Cowden, 1988). (C) Geologic cross-section showing Coronet ore shoot overlying a fault-disrupted essentially planar contact below the Loreto Thrust, west flank of Kambalda Dome (modified from Stone and Masterman, 1998). (D) NNW-looking oblique view of the Lunnon Basalt upper surface at the Lanfranchi deposit, west dome, showing the shallow nature of the trough and only partial confinement of ore (represented by dark grey isovolume models).

and Hopkins, 1975; Gresham and Loftus-Hills, 1981; Gresham, 1986; Brown et al., 1999); (2) thermal erosion channels (Huppert et al., 1984; Huppert and Sparks, 1985; Williams et al., 1998); and (3) post-volcanic deformation (Cowden and Archibald, 1987; Cowden, 1988; Cowden and Roberts, 1990). In the primary models, the trough structures originated as topographic depressions that channelled the komatiite lava. This model was developed originally at Lunnon shoot, where Ross and Hopkins (1975) proposed that removal of apparent offsets on boundary structures in 2-D left a component of primary topography. Volcanic thermal erosion models (Huppert et al., 1984) involve the melting and removal of Lunnon Basalt by hot flowing komatiite lava. Such erosion reflects the high liquidus temperature and turbulence and low viscosity of komatiite. Williams et al. (1998) mathematically modelled the erosion potential of channelled komatiite lavas at Kambalda, based on inferred geologic relationships (Lesher et al., 1984; Lesher, 1989). They suggested the trough structures formed by erosion of a <5-m-thick sediment with undercutting of basalt in pre-existing topography, and subsequent modification by deformation. Brown et al. (1999) further developed the Ross and Hopkins (1975) model through comparison with modern basalt flow fields on Iceland and proposed syn-volcanic (half-graben) faulting as the mechanism for trough formation.

Trough formation models based on primary topography, syn-volcanic faulting and thermal erosion are contradicted by many lines of evidence: (1) the linearity of the trough structures contrast markedly with the complex surface topography of modern basalt flow fields and the highly sinuous lunar trough structures (rilles) generated by thermal erosion (Gresham, 1986); (2) detailed structural analysis indicates that 3-D polyphase deformation can explain trough formation from roughly planar contacts at Lunnon shoot (Cowden, 1988) and at Foster shoot (Fig. 1) (Evans et al., 1989); (3) the Lunnon Basalt footwall and basalt fragments in massive ore lack evidence for a contact metamorphism that can be related to komatiite emplacement; (4) zones of massive ore at the Mt Edwards deposit, Widgiemooltha and at the Blair deposit, Golden Ridge (Stone and Masterman, 1998) overlie sulphidic metasedimentary rocks that lack any evidence of thermal erosion and contact aureole development (Gresham, 1986; Marchiori, 1995). This lack of evidence for contact metamorphism in the Lunnon Basalt and in the meta-sedimentary rocks contrasts with the evidence for contact metamorphism related to felsic intrusion on the east flank of Kambalda Dome; (5) the upper Lunnon Basalt surface at Foster shoot is a preserved depositional contact (Squire et al., 1998); (6) the basal unit of the Silver Lake Member lacks geochemical evidence for significant contamination (Gresham, 1986; Foster et al., 1996); (7) careful numerical modelling fails to substantiate the notion of thermal erosion (Cas and Beresford, 2001; Rice and Moore, 2001); (8) the thickness of the basal unit of the Silver Lake Member in the trough structures is such that it would form topographic ridges projecting above the flanks of the trough structures. Subsequent komatiite lavas are unlikely to flow along the top of such a ridge; and (9) modern basalt flow fields are undeformed and unaltered and lack komatiites and NiS ores. They are therefore unlikely direct analogues of Archaean komatiites.

For the reasons listed above, primary topographic relief on the upper Lunnon Basalt contact as a key control on trough formation (Lesher, 1989; Brown et al., 1999) is open to question. The NNW sub-parallelism of the trough structures has been considered to reflect primary control on flow direction (Brown et al., 1999). However, the thinning of the Kambalda Komatiite across Kambalda Dome indicates the possibility of east-to-west flow direction (Gresham, 1986; Beresford et al., 2002). Furthermore, the usage of primary volcanic rather than secondary alteration nomenclature for the rocks and the lack of fabric mapping in the volcanic studies, reflect interpretation based on inference rather than observation. The notion of a role for palaeo-topography or syn-volcanic faults in the formation of the trough structures cannot be entirely discounted, but the transgression of the ore shoots and the severe structural overprint indicate the possibility of a secondary deformation origin. The plunge direction of the trough structures is generally consistent with that of the linear fabrics. The plunge of the trough structure at Long shoot, for example, varies from sub-horizontal in the north to 20°S in the south, parallel to the Kambalda Dome (see Fig. 1). Consequently, the consistent orientation of the trough structures and other linear fabrics is more simply explained by deformation overprint than by palaeo-topography or syn-volcanic faulting. Based on cursory structural analysis, Cowden (1988) suggested that almost all the trough structures can most easily be explained by simple synclinal folding. However, the validity and significance of this suggestion remains to be systematically evaluated.

The evidence of folding in the pinchouts, hanging wall ore positions, and top of the Lunnon Basalt all strongly support the possibility that the open and re-entrant trough structures formed originally as synclinal folds during D2 (Fig. 11). The weak cleavage reveals significant folding in the Silver Lake Member. The open trough structures represent open, weakly-asymmetric synclines (Fig. 11A). The re-entrant trough structures at Kambalda Dome represent more strongly asymmetric synclines developed through parasitic fold–thrusting on the flanks of Kambalda Anticline (Fig. 11B–D). The folds and thrusts nucleated on the highly-plastic massive sulphides and talc–carbonate altered ultramafic rocks. The dominance of overprinting structural fabrics, boundaries and alteration mineral assemblages relative to the flanking planar contacts indicate the trough structures to be linear domains of anomalous structural complexity. Such domains of complexity suggest tangential longitudinal strain-style folding (Ramsay, 1967),


(A)
banded massive ore
silicate domes
spinifex-textured ore
(B)
370000E
370100E
370200E
370300E
Hanging wall basalts and meta-sedimentary units
+300
+200
+100
N05F
?
N04F
N03F
?
N02H
B01H
N01H
D01H
?
N01H

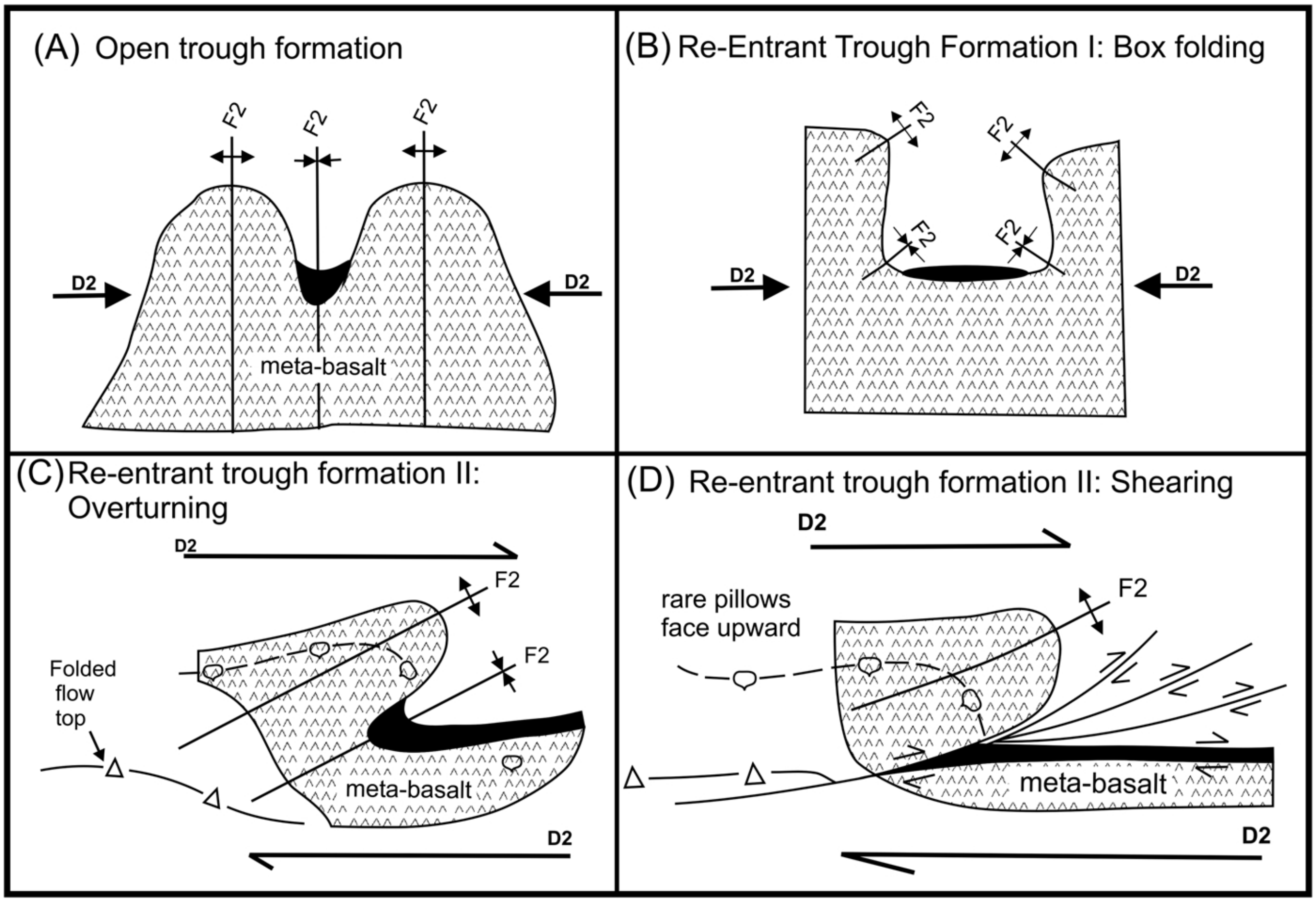


Fig. 11. Formation of the trough structures as synclinal folds. (A) Generation of the open trough structures by upright folding. (B) Re-entrant trough formation stage 1: box folding. (C) Re-entrant trough structure formation stage 2: flexural-slip and inclination of folds with down-dip over up-dip vergence. (D) Re-entrant trough structure formation stage 3: flexural-slip thrusting with down-dip over up-dip vergence.

where maximum strain occurs in the hinge zone (i.e. the troughs) (Price and Cosgrove, 1994). The form of the folds and presence of the double fold axes (e.g. Fig. 4C and D) suggests the possibility of re-entrant trough formation as double hinge folds, perhaps even conjugate folds of the box fold-type (Johnson, 1956; Ramsay, 1962; Price and Cosgrove, 1994). Progressive deformation during bedding-parallel compression at Kambalda led to flexural-slip thrusting (Ramsay, 1967), development of the re-entrant geometry and the pinchouts and, ultimately, overturning of fold limbs and even relocation of ore into the hanging wall (e.g. Fig. 4B). Pinchout-like structures have been produced through flexural-slip fold–thrusting in experimental systems (Ramsay, 1967).

8. Controls on trough structure geometry

The evidence that the trough structures are linear domains of anomalously complex deformation indicates preferential accommodation of strain in the basal part of the Silver Lake Member relative to the underlying Lunnon Basalt, because of major differences in competency and structural setting. A model for the influence of competency contrast on fold form is summarised by Ramsay and Huber (1987). The model is based on a competent layer and incompetent wall rocks. High contrast leads to higher amplitude, larger wavelength ptygmatic folds, whereas low contrast leads to low amplitude, smaller wavelength cuspate–lobate folds.

Fig. 10. Hanging wall ores. (A) Lunnon hanging wall massive ore overlying inter-spinifex textured ore in the top of the underlying basal flow unit of the Silver Lake Member, looking roughly north. Note the strong tectonic banding in the massive ore, apparent intrusion of the latter by the silicate domes, and the cuspate–lobate form of the massive ore-interspinifex ore contact. Photograph courtesy of the Kambalda Nickel Operations Library. (B) Cross-section 550333 mN through the McMahon hanging wall ore. Note the association of ore with interflow sedimentary horizons, down-dip over up-dip asymmetric folding of the ore (i.e. N01H and B01H), and presence of meta-sedimentary units rather than ore on the underlying Silver Lake Member-Lunnon Basalt contact (modified from WMC Internal Report).

In the case of Kambalda–Tramways, an opposite version of the Ramsay and Huber (1987) model is evident. Macroscopically, the incompetent layer (Kambalda Komatiite) lies between competent wall rocks (basalt units; Figs. 2 and 3). The competency contrast resulted in small wavelength and amplitude folds, such that the amplification rate of buckling was relatively small during layer-parallel shortening. An array of upright, symmetrical synclines and anticlines formed, which was relatively short in wavelength and cuspate–lobate in outline (Fig. 12A). Very small-scale examples of such folding appear to be evident at the Lunnon hanging wall. At Tramways Belt, structural folding and thickening in the synclines appears (e.g. Fig. 8A) to have been accommodated through structural extension and thinning in the adjacent anticlines. Very large-scale examples of this style of deformation are evident at the contacts of basement and cover sequences in more recent terranes elsewhere (e.g. Fig. 7-43 in Ramsay, 1967).

On the other hand, the Kambalda re-entrant trough structures represent major modification of pre-existing synclines to strong asymmetrical and even overturned parasitic folds or pinchouts through flexural-slip deformation during the development of the major Kambalda Anticline (Fig. 12B). Ultimately, major reverse and thrust faults developed on the fold limbs (e.g. Loreto Thrust). The apparent higher amplitude and longer wavelength of the Kambalda Anticline at Kambalda compared with Tramways Belt may perhaps reflect major variations in compressive strain and movement history along the adjacent Lefroy Fault zone. Hence, the proposed fold–thrusting model elucidates a possible relationship of the open and re-entrant trough types. The model also explains the general NNW alignment of the trough structures, which is perpendicular to the WSW–ENE principal direction of movement during D2 (Nguyen, 1997). Similar orthogonal relationships are documented for conjugate fold systems elsewhere (Johnson, 1956). The detailed overall variation in trough orientation at Kambalda is consistent with strong competency contrasts during deformation (e.g. Ramsay, 1967). It suggests variation in the direction of compressive strain within the basal unit of the Silver Lake Member during D2, or the effects of successive superimposed deformations (e.g. D1–D4). Certainly, their opposite geometry suggests the ‘reverse vergence’ re-entrant trough structures (e.g. Fig. 5) formed prior to the Kambalda Anticline, perhaps during D1 and tectonic inversion of the original depositional basin.

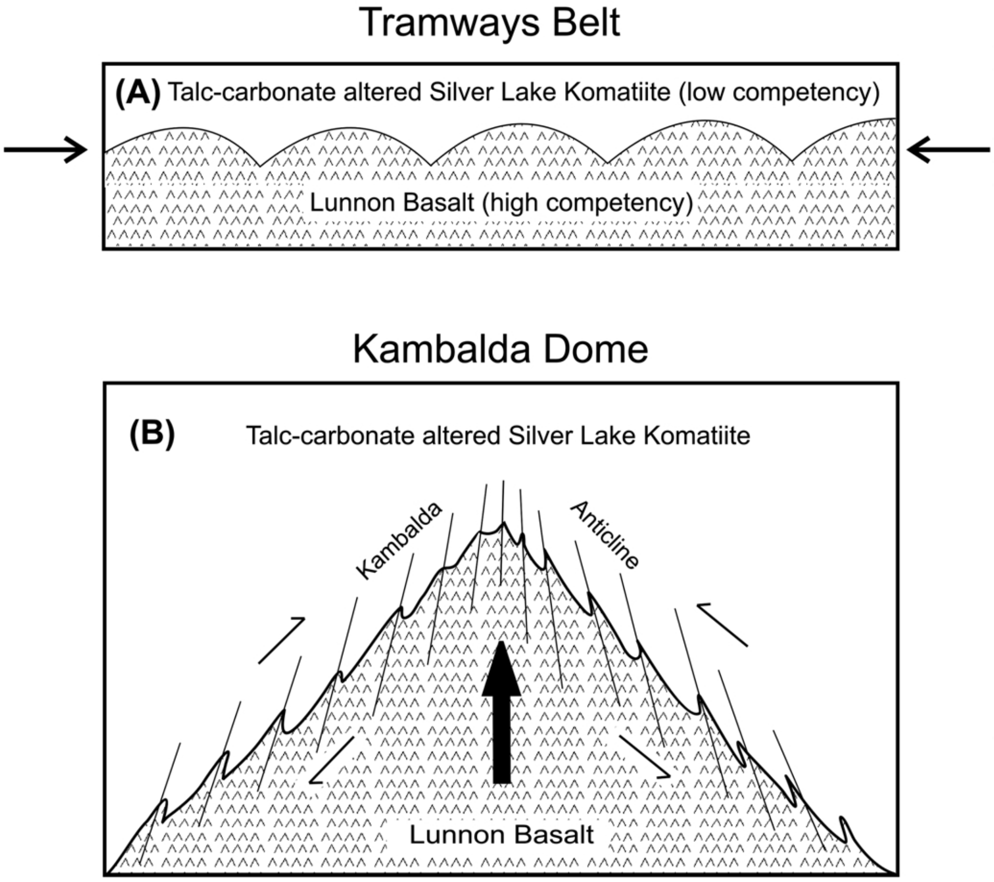


Fig. 12. Influence of competency contrast and structural setting on the fold form of the trough structures. (A) Schematic model of layer-parallel shortening along the contact of incompetent and competent rock types produced an array of upright, symmetrical cuspate synclines (i.e. open trough structures) and lobate anticlines at Tramways Belt (not to scale) (modified from Park, 1983). (B) Major buckling and flexural-slip thrusting produced asymmetrical parasitic folds (i.e. re-entrant trough structures) during the development of the higher amplitude, longer wavelength Kambalda Anticline at Kambalda (not to scale).

Detailed structural analyses are required, but access to underground workings is now the major limiting factor.

In contrast to the trough-associated ore shoots, the minor offsets of the contact, prevalence of serpentine alteration, and preservation of volcanic textures in the non-trough associated ore shoots indicate that these examples represent low strain domains during deformation. For example, Victor shoot and Coronet shoot could be in strain shadows of the Lefroy Fault zone and the Loreto Thrust, respectively. The Durkin shoot may be in the pressure shadow of Kambalda Dome, and therefore best preserves the original depositional relationships. If correct, the strain shadow setting of these deposits could have limited deformation through folding.

9. Implications for ore genesis and exploration targeting

Conventional exploration strategies for Kambalda-style NiS ores reflect the thermal erosion models for ore genesis (Lesher et al., 1984; Groves et al., 1986). Such strategies highlight identification of deep thermal erosion trough structures, thick high-MgO komatiite channels, and sulphidic sedimentary units (Lesher, 1989; Hill et al., 1995; Lesher et al., 2001). The sedimentary units are assumed to represent potential sulphur sources for ore genesis (see summary in Stone, 1996). Derivative exploration strategies are applicable in pristine volcanic terranes, but difficult to apply effectively in overprinted terranes such as Kambalda and elsewhere, where deep trough structures and thickened ultramafic units may be structural in origin.

This study confirms the distinction of trough structures (embayments) and volcanic channels (Ni enriched sulphide-poor ultramafic rock), and demonstrates that the trough structures post-date volcanic channels. The NiS ore shoots are generally associated with channels, but not necessarily with deep trough structures. The examples of essentially unmineralised deep trough structures indicate that such features and associated thick, high-MgO units are not necessarily associated with significant ore. The deformation of the S1 fabrics in ore (Figs. 4C and 6B and C) suggests that trough formation postdates sulphide deposition. The latter probably occurred during volcanism, but most likely on a near-planar contact surface.

The antithetic distribution of massive ore and meta-sedimentary rocks in the ore environment has been attributed to thermal erosion (Lesher et al., 1984) and to physical erosion (Cas and Beresford, 2001) during komatiite volcanism. The absence of sedimentary units in the non-trough associated ores implicates removal of sediment during volcanism rather than subsequent deformation. The paucity of evidence for thermal erosion favours the physical erosion model. Accordingly, sulphidic sediment substrate should have been physically removed in the initial stages of komatiite flow prior to any thermal erosion. Film boiling at the interface of water-saturated sediment and flowing komatiite lava led to fluidisation, mobilisation, erosion and suspension of the sediment. In this process, sulphur may be transferred from the sediment to the komatiite lava, leading to sulphide saturation and ore deposition (Barnes et al., 2001). Consequently, the physical erosion model is favoured here, at least for the removal of the sedimentary units.

Given the strong structural controls on NiS distribution in the Kambalda–Tramways area and elsewhere (De-Vitry et al., 1998; Stone and Masterman, 1998), exploration strategies should also consider tectono-metamorphic features, in addition to volcano–stratigraphic features. As demonstrated above, the trough structures are linear domains of anomalous structural complexity that partly confine structurally thickened massive ore and altered ultramafic units. Indeed, structural complexity is a characteristic feature of the Kambalda ore environment (Gresham and Loftus-Hills, 1981), though it has yet to be thoroughly considered for applications in exploration.

Alteration affects rock strength and influences deformation style and strain distribution (e.g. Escartin et al., 1997). At the district scale, the example of Kambalda–Tramways area indicates that structural anticlines and domes with greenschist facies metamorphosed komatiite–basalt stratigraphy near the crest should represent high priority targets with potential for clusters of major NiS ore deposits. In this structural setting, parasitic synclines may have nucleated at or near massive sulphide bodies, and therefore represent favourable sites for the concentration of massive ore. At deeper structural levels in anticlines and domes, parasitic synclines would be more highly sheared and associated ore more poddy to vein-like in distribution (e.g. Mariners and Redross shoots at the Widgiemooltha Dome; Stone and Masterman, 1998). The example of Kambalda–Tramways further suggests that, in the absence of major early fault zones, fold wavelengths may be larger and amplitudes higher. Trough structures in these environments are highly prospective and may be recognised through detection and interpretation of anomalous structural complexity. In addition, if major faults (e.g. Loreto Thrust) are within perhaps tens to hundreds of metres of a prospective komatiite–basalt contact, the trough structures are likely to be shallow and associated NiS ore relatively thin (e.g. Coronet shoot) and sheet-like (e.g. Long shoot).

Development of criteria with which to reliably distinguish mineralised and barren trough structures could be a major breakthrough in exploration targeting. In addition to structurally complex footprints, the nature and extent of Ni and related metal enrichment in wall rocks should be investigated. Metals appear to be dispersed about leaky ore shoots during deformation and metamorphism (Curl, 1997; Heath et al., 2001). The distribution patterns of more mobile metals S and Cu, in combination with less mobile metals Ni and PGE, together with knowledge of deformation styles, may provide powerful vectors to hidden NiS deposits.

Consequently, in view of the spectrum of trough geometries and trough–ore-channel relationships in the Kambalda–Tramways area, exploration strategies should focus on recognising particular styles of folding and faulting along prospective contacts, major faults that may influence strain partitioning, and metal dispersion halos at the regional, district and deposit scales.

10. Conclusions

A re-evaluation of the structural geology of the trough structure embayments at the Kambalda Dome and Tramways Belt leads to the following conclusions:

1. The geometries and cross-cutting relationships of trough structures to ore shoots and volcanic channels strongly indicate the possibility of a deformation origin for at least some of the trough structures. Clearly, in addition to volcanology and stratigraphy, structural geology has important applications in understanding Kambalda-style NiS ores.
2. The trough structures are products of synclinal folding during the regional D2 fold–thrusting event. The open trough structures formed originally as simple cuspate synclinal folds. The re-entrant trough structures are a result of thrust modification of previously formed synclinal folds during the development of the much higher amplitude, longer wavelength Kambalda Anticline. The siting of the fold–thrusts was controlled by major competency contrasts at the contacts of incompetent massive ore and talc–carbonate altered ultramafic rock and competent basalt during peak deformation.
3. Exploration models should highlight structural features, in addition to volcanological and stratigraphic features, in the search for NiS districts and ore shoots. The structural setting and deformation styles could reflect major competency contrasts related to the distribution of primary volcanic facies, and present a footprint (e.g. structural domes) for the presence of favourable stratigraphy. The results of the present study clearly highlight the critical importance of collection, analysis and modelling of structural and metamorphic data during exploration and mining.
4. The key structural process in trough formation appears to be differential behaviour of talc–carbonate altered ultramafic rock relative to metabasalt during deformation. A full understanding of the process requires detailed geometric and kinematic analyses and careful experimental deformation studies to constrain the mechanisms and scale of sulphide and talc–carbonate relocation during secondary deformation.

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