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Evidence of lateral thermomechanical erosion of basalt by Fe-Ni-Cu sulfide melt at Kambalda, Western Australia

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ABSTRACT

The Fe-Ni-Cu sulfide ores at Kambalda, Western Australia, are interpreted to be the result of thermomechanical erosion of underlying rocks by the host komatiite lava flows. However, there is a long-standing argument about the extent of the erosion process, and the degree to which the linear embayments that host the ores were eroded by lava as opposed to formed by tectonic processes. This controversy has fundamental implications for the origin of magmatic sulfide ore, as well as for sinuous rilles on terrestrial planets. The controversy at Kambalda hinges on pinchout features, where sulfide ore at the edges of embayments penetrates laterally into footwall rocks. The most recently published studies of these features interpret them as forming by thrusting of basalts over sulfide-komatiite contacts along the margins of tectonic embayments. Field evidence and X-ray fluorescence element mapping on underground exposures in the Moran deposit demonstrate that sulfide liquid melted its way both downward and laterally into basalt, generating complex plumose melt layers, melt emulsions, and hybridized chromite-decorated contacts. These observations confirm an origin for the pinchouts by thermomechanical erosion, driven by the high temperature, high density, and low viscosity of the sulfide melt. They also provide some intriguing insights into the nature of interactions between sulfide melt and melting silicate rocks in magmatic Ni-Cu-platinum group element sulfide ore deposits in general.

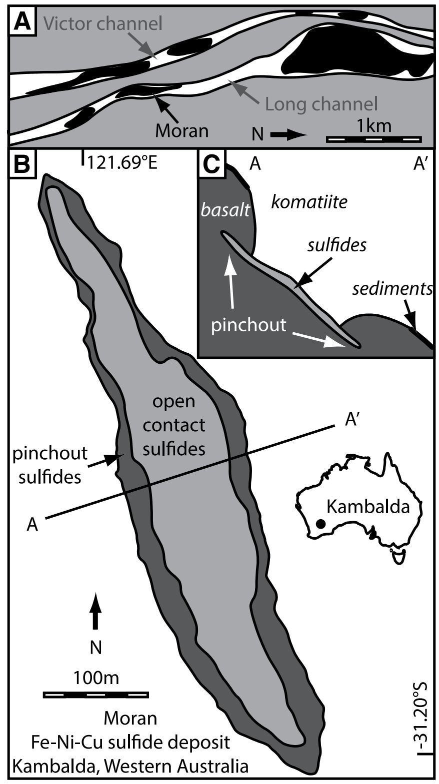

Figure 1. A: Profile along the eastern limb of the Kambalda Dome (Western Australia) showing the location of Moran within the Long channel. B: Map (projected to horizontal plane of footwall contact) of open and pinchout contacts of the Moran Ni-sulfide deposit, Kambalda. The pinchout termination is undulating and surrounds the elliptic orebody completely. Sediments are found on the flank but are absent in the channel. C: Profile of open and pinchout contacts.

INTRODUCTION

The Kambalda (Western Australia) orebodies are the type examples of magmatic nickel sulfide ores associated with komatiite lava flows (Gresham and Loftus-Hills, 1981; Cowden, 1988; Lesher, 1989; Beresford et al., 2002; Barnes, 2006). The presence of ribbon-like massive sulfide orebodies within linear to elliptical embayments (locally referred to as troughs) along the contacts between the lava channels and underlying basalt supports the currently favored model of thermomechanical erosion of substrate by komatiite lava (Lesher et al., 1984; Huppert and Sparks, 1985). However, arguments are ongoing about whether the embayments are entirely thermal erosional (Huppert and Sparks, 1985), primary volcanic topographic features modified by thermal erosion and deformation (Lesher, 1989), or produced entirely by folding and thrusting during deformation (Stone and Archibald, 2004; Stone et al., 2005). The evidence for a structural origin hinges on the nature of the basalt-sulfide-basalt pinchouts at the margins of many embayments (Fig. 1), and on the shortage of direct evidence for footwall melting. We present new evidence for a primary magmatic origin of an exceptionally well preserved pinchout, illustrate some of the complex silicate-sulfide melt interactions, and demonstrate that sulfide melt played a major role in the thermomechanical erosion process.

PAST THEORIES OF THE ORIGIN OF EMBAYMENT AND PINCHOUTS

Most of the Kambalda orebodies are hosted by linear to elliptical, steep-sided embayments developed within the upper contact of the underlying basalt. These features coincide with the thickest and most olivine-rich portions of the immediately overlying komatiite flows characteristic of lava channels or tubes (Lesher et al., 1984; Lesher, 1989). Pinchouts are features located at the margins of embayments, where massive sulfides are both underlain and overlain by basalt, as opposed to the normal setting where they are between a basalt footwall and the overlying host komatiite (Fig. 1). The first ore intersection at Kambalda, drilled 50 yr ago, was through a pinchout (Woodall and Travis, 1970).

Several theories have been developed to explain embayments and pinchouts. Many in the 1980s favored a magmatic origin (Lesher et al., 1984; Huppert and Sparks, 1985), but aside from the absence of footwall contact sediment within the embayments, there was limited field evidence for magmatic erosion. Groves et al. (1986) and Barnes et al. (2016) reported evidence of sulfide melt eroding the spinifex zone of an underlying komatiite lava flow, with silicate-melt plumes rising into the sulfides, but this was from unusual settings where sulfides are present within the komatiite flow sequence, not at the basal contact. Groves et al. (1986) argued that thermal erosion was only possible in the presence of sulfide melt. Lesher (1989) showed evidence for original pillow and flow top contacts and chromite-decorated magmatic intrusive contacts between massive sulfide and pillowed basalt in pinchouts, implying a primary origin by lateral thermal erosion, but reported an absence of evidence for melting along planar

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contacts with footwall basalt, which he interpreted as original basalt flow tops.

Cowden (1988) argued for embayment formation due to subsequent folding, based on field relationships in the highly deformed Durkin Shoot, assuming that pinchouts were thrust faults. Brown et al. (1999) suggested, based on comparison with synvolcanic faulting in Iceland, that the embayments formed as linear grabens during syneruption tectonism. Based on observations in some of the most deformed regions of the Kambalda Dome, Stone and Archibald (2004; and see Stone et al., 2005) concluded that the embayments were formed entirely by fold-related thrusting.

Recent development in the Long-Victor mine has produced new exposures of these embayments, including underground outcrops of primary igneous textures along the sulfide-silicate interface around the pinchouts that flank the Moran deposit. In this study we combine detailed underground and drill-core observations with decimeter-scale microbeam X-ray fluorescence mapping of rock slabs to provide incontrovertible evidence for a magmatic origin of the pinchouts.

GEOLOGY OF KAMBALDA AND THE MORAN DEPOSIT

The 2.7 Ga Fe-Ni-Cu sulfide hosting komatiite lava flows at Kambalda are part of the Kalgoorlie terrane in the Yilgarn craton, Western Australia (Goscombe et al., 2009, and references therein). The lowermost unit is the Lunnon Basalt, which is overlain by sulfidic cherty sediments (Gresham and Loftus-Hills, 1981). The lower komatiite member, located above these sediments, hosts the Fe-Ni-Cu sulfides at the base of channelized lava flows (Lesher et al., 1984). Sediments are absent beneath the channels, but are still preserved beneath flanking sheet flows. Subsequently, the entire stratigraphy was folded into the present-day dome geometry, cut by magmatic dikes and intrusions and metamorphosed to upper greenschist or lower amphibolite facies (Gresham and Loftus-Hills, 1981). In most cases, the metamorphism preserved primary magmatic textures.

The Moran deposit, containing 50,000 t of Ni, occurs within an elliptical embayment that is 40 m deeper relative to the original horizontal contact surface of the sediment-covered flanks (Fig. 1). Moran is flanked around its entire margin by a basalt-sulfide-basalt pinchout (Fig. 1). Ore in the center of the embayment includes 20 cm of massive and up to 5 m of matrix sulfides, whereas ore in the pinchout comprises as much as 4 m of massive sulfides and no matrix sulfides, similar to other embayments at Kambalda (Lesher, 1989).

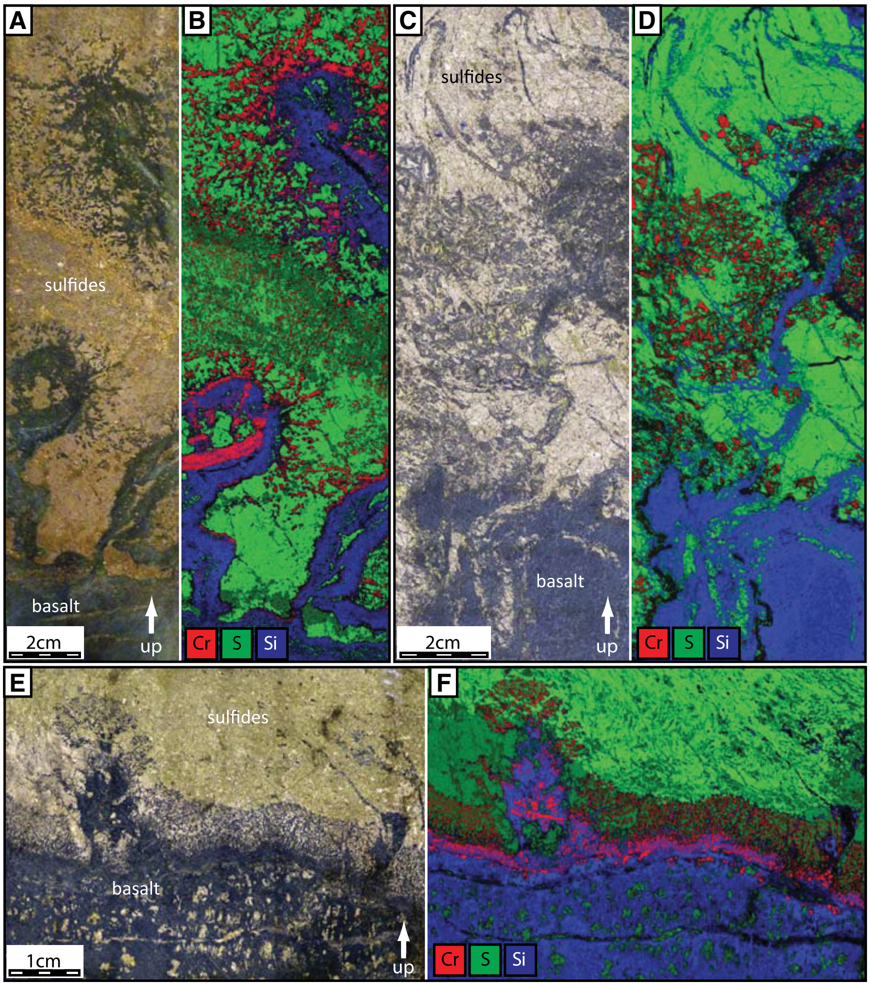

Figure 2. Photos (left) and microbeam X-ray fluorescence chemical maps (right) of polished samples of basal contact of massive sulfide with basalt undergoing melting. A and B: Half core showing basalt melt plumes rising into massive sulfides. C and D: Half core, dendritic ferrichromite associated with fine sinusoidal basalt melt plumes and trails. E and F: Polished slab of hand sample showing undulating contact with, from bottom to top, basalt with abundant interconnected sulfide inclusions; detaching layer of molten basalt; layer of sulfide with fine skeletal chromite, and basal part of massive sulfide layer (dark green pentlandite, light green pyrrhotite). Chemical maps are false color images, each element normalized to maximum abundance.

DESCRIPTION OF PINCHOUT ENVIRONMENTS

Sulfides in the pinchout extend 5–25 m laterally into the basalt footwall. Based on underground mapping and close-spaced drilling programs, the lateral limit of the Moran pinchout is irregular and undulating (Fig. 1). At the lateral terminations the sulfides end abruptly with no evidence for truncation by younger structures.

The basal contact in the pinchout is indistinguishable from other basal contacts within the embayment, consisting of a gently undulating surface with frequent plume-like domes and fingers of basalt rising into the sulfides. The contacts of these plumes (Fig. 2) are characteristically decorated with skeletal ferrichromite. Immediately beneath the contact is a 3–5 mm layer of sulfide-free basalt containing abundant skeletal ferrichromite underlain by a 1–3 cm layer of basalt containing abundant sulfides, filling microfractures or forming small blebs. In the sulfides immediately above the contact, a 1–2 cm layer of skeletal ferrichromite occurs together with minor silicates.

The upper pinchout contact is marked by a 1–10-cm-thick zone of prismatic actinolite, probably replacing original pyroxene, closely intergrown with sulfides, with a preferred orientation normal to the contact. This actinolite is rimmed by finely intergrown ferrichromite (see the GSA Data Repository[1]). This assemblage occurs on every contact where sulfides are overlain by basalt. Occasionally, a sulfide-silicate

[1]GSA Data Repository item 2016349, Figure DR1 (simplified geological map of the Kambalda Dome), Figure DR2 (photo of hand specimen and photomicrographs of chromite-actinolite intergrowth from the upper pinchout contact), Table DR1 (representative chemical analyses of chromite from the basal and upper pinchout contact), and Movie DR1 (moving slices through 3-D medical computed tomography image of sample illustrated in Figure 2E), is available online at http://www.geosociety.org/pubs/ft2016.htm or on request from editing@geosociety.org.

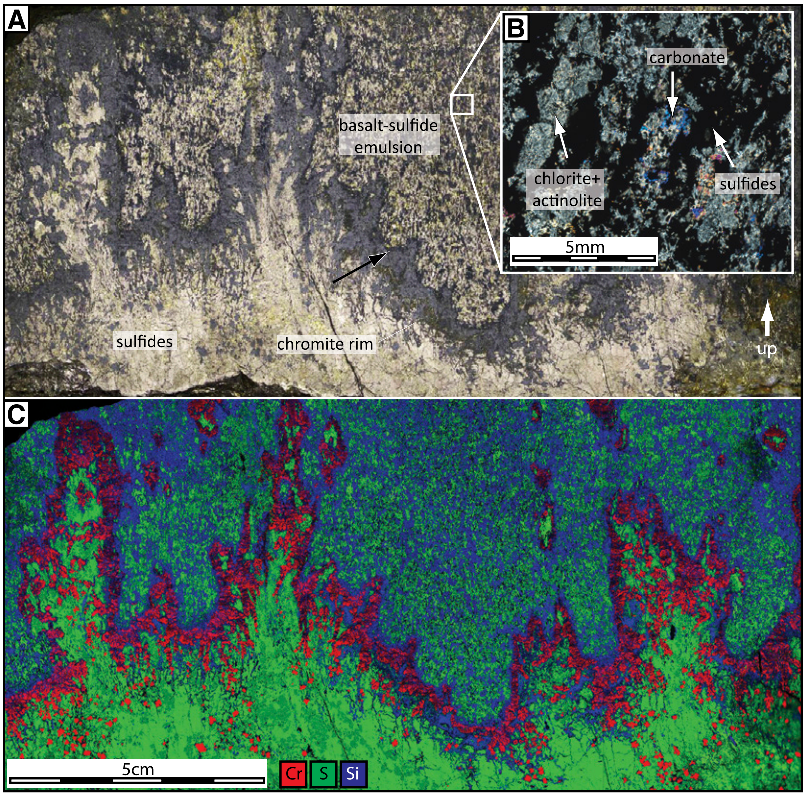

Figure 3. A: Photo of hand specimen. B: Photomicrograph of emulsion shown in A. C: Chemical map of specimen shown in A of polished slab of the upper pinchout contact with a basalt-sulfide emulsion overlaying massive sulfides. From bottom to top: top of massive sulfide layer (green), containing descending trails of subhedral chromite (red); egg-carton–shaped undulating contact decorated by skeletal chromite intergrown with actinolite; and emulsion layer (blue-green) consisting of finely intermixed Fe-Ni-Cu-sulfide with silicates and carbonate.

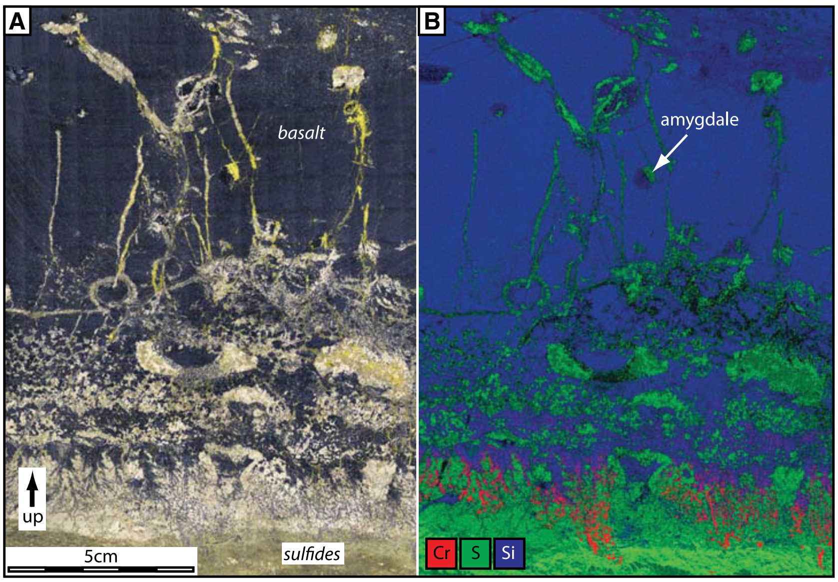

Figure 4. A: Photo of polished slab of the upper pinchout contact of Moran (Western Australia). B: Chemical map of A. From bottom to top: top of massive sulfide layer (green), containing descending trails of subhedral to dendritic chromite (red); finely layered mixture of sulfide and fine-grained amphibole representing mixed emulsion layer (note the presence of composite flattened amygdales containing a concentrically arranged mixture of sulfide and medium-grained basalt); layer of medium-grained basalt containing composite amygdales and vertical veinlets or trails of sulfide connecting the amygdales; uppermost layer of medium-grained basalt; black indicates presence of secondary calcite.

(actinolite-chlorite) mixture interpreted as an emulsion of sulfide and basalt melt is observed above the silicate crystal layer. The sulfide-emulsion contact (Fig. 3) shows a characteristic egg-carton geometry, with interpenetrating plume-shaped domes of sulfide and chromite-sulfide-silicate mixtures. At that contact, ferrichromite crystals form downward-oriented trails into the sulfides below, whereas the emulsion is mainly free of chromite (Fig. 3). Small sulfide domes (Fig. 4), containing basalt inclusions in their center, occur on the upper sulfide-basalt contact. In places along the upper contact, medium-grained basalt forms a homogenous 10–30-cm-thick layer with abundant composite amygdales, which are absent elsewhere in the upper member of the Lunnon Basalt (Squire et al., 1998). Minor overprints of the Moran pinch-out are evidenced by metamorphic S-C fabric of sulfides and calcite veins as thick as 1 cm along parts of it.

INTERPRETATION OF OBSERVED TEXTURES

A tectonic origin of the embayments and especially the pinchouts can be discounted due to their elliptical geometry (Lesher, 1989) as well as the clearly primary contact features described here. In particular, basalt plumes (Fig. 2) and basalt-sulfide emulsions (Figs. 3 and 4) at Moran cannot have formed by structural, metamorphic, or hydrothermal processes, and represent incontrovertible proof for a magmatic origin of the contacts by melting of basalt. This is supported by ferrichromite, which occurs on all basalt-sulfide contacts and shows clearly magmatic skeletal morphologies (Fig. 2B) as described from sulfide-silicate contacts in a number of other deposits (e.g., Groves et al., 1977; Lesher, 1989; Dowling et al., 2004; Houlé et al., 2012).

We interpret the complex amygdaloidal basalt layer (Fig. 4) as a basaltic xenomelt, initially derived from the floor, having ascended to become trapped beneath the solid upper basalt forming a vesiculating silicate scum layer. The vesicular nature of this layer, as opposed to the nonvesicular Lunnon Basalt, is due to seafloor hydration that took place between the deposition of basalt and komatiite. Fluids from fractures and hydrous minerals of the basalt are incorporated in solution into the molten basalt, but then exsolve as vesicles during solidification of the xenomelt layer above the sulfides.

We interpret the distinctive silicate-sulfide intergrowth at the upper pinchout contact (Fig. 3) as an emulsion formed by entrainment of sulfide liquid into the accumulated basaltic melt. The silicate-sulfide emulsion layer overlies denser silicate-free sulfide melt, but an inverse-density plumose interface is developed at the contact, probably due to accumulation of ferrichromite at the basal contact of the emulsion. This pure Fe-Cr spinel had a specific gravity of 5.45 g/cm^3

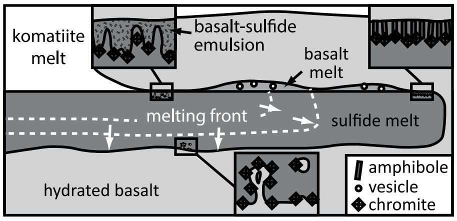

Figure 5. Summary of the magmatic features observed in embayments of komatiite-lava channels. On the basal contact the uppermost layer of basalt is melting, forming a continuous chromite-bearing layer that forms plumes once it becomes too thick and instable. Basalt plumes detach from their base and ascend through the sulfides into the komatiite melt. In pinchout positions this melt is trapped and forms a layer of floating basalt above the sulfides. In addition, the upper sulfide-basalt contact is characterized by a layer of intergrown silicate and chromite as well as sulfide-filled amygdales in places.

at 1500 °C (Sack and Ghiorso, 1991), denser than both the sulfide and silicate liquids at 4.3–4.5 g/cm^3 and 2.8 g/cm^3, respectively (e.g., Robertson et al., 2015). The ferrichromite sank within the emulsion, forming a dense boundary layer that sank into the underlying sulfide; evidence for this is the trail of coarse chromite beneath the downward-facing terminations of the undulating contact (Fig. 3). This remarkable set of structures can only be interpreted as melting of basaltic footwall and gravity-driven advection into and through the sulfide melt.

SUMMARY AND IMPLICATIONS

Results of this study show, for the first time, direct textural evidence for a primary magmatic origin of the Moran pinchout, in the form of a basal melt layer, ascending basaltic plumes, ferrichromite rims, emulsion layers, and an upper silicate scum layer of amygdaloidal basalt (Fig. 5).

Many pinchouts in komatiite-hosted Fe-Ni-Cu sulfide deposits are tectonically overprinted, or some could be entirely structural in origin, and given a lack of direct evidence for the thermomechanical erosion process, this has led to defensible arguments for a tectonic origin. We show here that the embayments and their flanking pinchouts can be explained by primary magmatic processes: sulfide melt penetrates downward in the embayment and laterally in the pinchout positions through melting and displacement of buoyant basaltic melt. The reason for the lateral rather than purely vertical propagation of the erosion path may be related to an excess magmastatic pressure in the sulfide liquid relative to the basalt footwall at the edge of the orebody.

The ability of liquid sulfides to melt and interact with their host rocks is likely to play a role in many other magmatic sulfide deposits where sulfides infiltrate the country rocks. Sulfide-silicate melt emulsions at basal contacts have been reported at Sudbury (Canada; Hawley, 1962) and Silver Swan (Western Australia; Dowling et al., 2004) and observed by us in a number of deposits including Talnakh (Russia), Eagle (Canada), and Nova-Bollinger (Western Australia). Whereas physical embayments are commonly cited as being the cause of accumulation of sulfide deposits, they may in some cases be the consequence.

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