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*INTERSPINIFEX Ni SULFIDE ORE FROM THE CORONET SHOOT, KAMBALDA: CHARACTERIZATION USING MICROBEAM X-RAY FLUORESCENCE MAPPING AND 3-D X-RAY COMPUTED TOMOGRAPHY**

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Abstract

Interspinifex ores are developed where pools of sulfide liquid overlie thermally eroded komatiite flows, such that sulfide occupies the space between spinifex olivine plates. Microbeam X-ray fluorescence mapping and 3-D X-ray computed tomography have been used to investigate microstructures and chemical zonation within interspinifex ores from Coronet shoot, Kambalda. Sulfide compositions in the interspinifex space match the composition of the overlying sulfide pool. Aluminous silicate, interpreted as displaced silicate melt, forms a film at the silicate-sulfide interface, locally developing dome-like plumes. The film and plumes are characterized by fine skeletal chromite that diminishes in abundance over about a decimeter downward into the interspinifex zone. These relationships are strong evidence for a primary magmatic origin for this ore type, driven by the strong tendency of dense, inviscid sulfide liquid to infiltrate and melt underlying rocks. Such infiltration-melting interfaces may be a common feature at the base of massive sulfide ores, taking different forms depending on the lithological and fracturing characteristics of the footwall rocks.

Introduction

The Kambalda orebodies remain the iconic examples of magmatic nickel sulfide ores associated with komatiite lava flows (Gresham and Loftus-Hills, 1981; Cowden, 1988; Lesher, 1989; Cowden and Roberts, 1990; Beresford et al., 2002; Stone et al., 2005; Barnes, 2006). Many aspects of these deposits have been documented over the nearly 50 years since their discovery, but significant new geologic observations still emerge from time to time and deliver new insights into ore-forming processes. In this short contribution, we bring some new characterization technologies to bear on a remarkable example of one of the more spectacular ore types seen at Kambalda and in rare examples elsewhere: interspinifex ore. This ore type has been held up as one of the definitive lines of evidence for the prevalent substrate erosion model for the genesis of komatiite-hosted Ni sulfide ores (Groves et al., 1986; Barnes, 2006), but questions have been raised about its primary nature and genetic significance (Cas and Beresford, 2001; Stone and Archibald, 2004). We present new evidence for the primary magmatic, prealteration origin of this distinctive ore texture and discuss some inferences about the physical behavior of silicate-sulfide liquid mixtures that have broader implications for magmatic sulfide ore deposits as a whole.

General Setting of Interspinifex Ores

Interspinifex ore is a distinctive, sulfide-rich ore type where magmatic sulfides (the solidification products of original magmatic sulfide liquid) occupy the interstitial space between original dendritic plates of olivine, formed within the spinifex-textured A zone that caps a differentiated, olivine-rich komatiite lava flow (Fig. 1). These textures are developed in unusual settings whereby massive sulfide, formed as pools of immiscible sulfide liquid at the base of a lava tube or channel, has an earlier-differentiated komatiite flow as its substrate, rather than the more normal situation at Kambalda, where the mineralization occupies the basal flow of the stack and the underlying substrate is basalt. Examples of interspinifex ore in this setting have been reported from Fisher and Lunnon shoots, Kambalda (Gresham and Loftus-Hills, 1981; Woolrich et al., 1981; Groves et al., 1986), the Langmuir deposit in the Abitibi greenstone belt in Ontario (Green and Naldrett, 1981), and the subject area of this paper, Coronet shoot at Kambalda (Beresford et al., 2005). Interspinifex ores have also been reported from within basal flows at Durkin, Kambalda, and Alexo, Ontario (Lesher, 1983; Houle et al., 2011).

The interspinifex ore setting was first described in detail at Lunnon shoot, Kambalda (Groves et al., 1986), following its discovery and photographic documentation by M.J. Donaldson (pers. commun., 2005). Groves et al. (1986) provide only schematic sketches but no photographs. Photographs of those exceptional (but mined out) underground exposures have been reproduced by Stone and Archibald (2004) and Barnes (2006). A massive sulfide layer overlies the basal komatiite flow, which has been eroded such that the A1 and A2 quenched flow top and random spinifex zone have been removed, leaving the coarse parallel-plate A3 spinifex zone in direct contact with the base of the sulfide pool (Fig. 1). The original silicate melt component of this A3 zone is missing, and the space is now occupied by a typical magmatic Fe-Ni sulfide assemblage that has either replaced or displaced that silicate melt component. The spinifex olivine plates are broken, bent, and slightly crumpled; a lack of penetrative fabrics or consistent fold orientations implies that this is not post-emplacement tectonic deformation. At the top of this zone, at the interface with the massive sulfide, small blebs and plumes of quenched silicate melt of basaltic composition about 5 to 10 cm in size are partially enclosed within the lower few cm of the sulfide pool. Each bleb has a narrow rim of fine, skeletal Cr spinel, a hallmark of primary contacts between massive sulfide ores and komatiite melt (Ewers et al., 1976; Frost

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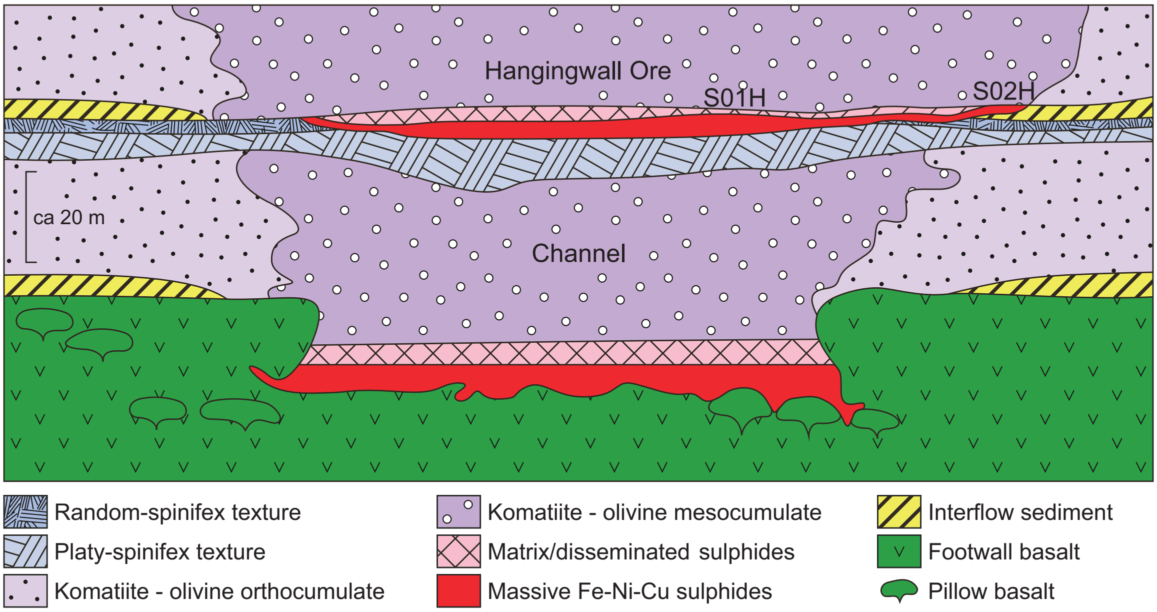

Fig. 1. Setting and essential features of interspinifex ore at Coronet and Lunnon, modified from Groves et al. (1986).

and Groves, 1989; Heath et al., 2001; Dowling et al., 2004; Fonseca et al., 2008). Groves et al. (1986) concluded that heat from the sulfide had caused interstitial silicate melt between the olivine plates to be physically displaced upward by dense, downward-percolating sulfide liquid. Several tens of centimeters at least of originally quenched komatiite flow top must have been removed altogether.

The textural evidence appears compelling, but the interpretation has been controversial. Stone and Archibald (2004) assert that the textural relationships are entirely the result of solid-state replacement during hydrothermal alteration, contending that the present-day mineral assemblages are entirely secondary and not the result of magmatic processes, and that the silicate domes at the top contact are tectonic folds controlled by ductility contrast between silicate and sulfide. The argument has been hampered by a lack of published petrographic description at sample scale and a lack of availability of samples from the Lunnon locality. However, samples are available from an equally spectacular locality in the Coronet orebody on the northwestern side of the Kambalda dome (see digital supplement for location map). This locality has been described previously (Beresford et al., 2005), but detailed petrographic and hand sample-scale descriptions of the interspinifex ore have not previously been reported.

If, as we argue here, the essential features of interspinifex ore are in fact pseudomorphically preserved igneous textures, then the process implications extend beyond the Kambalda localities. Groves et al. (1986) concluded from the Lunnon interspinifex ore locality that substrate erosion is possible only where massive sulfide is present, and that the high thermal conductivity of the sulfide is an essential condition. Arndt (1986) argued that the presence of a high-conductivity layer is unnecessary, as the essential condition is only that heat be conducted from the base of the flowing lava to the floor. We argue below that the Arndt (1986) conclusion is essentially correct, but that the presence of sulfide liquid may indeed enhance the process of substrate incorporation. This conclusion has implications for magmatic Ni-Cu deposits in mafic intrusive as well as komatiitic settings.

Geologic Setting of Coronet "Cathedral" Locality

Coronet is a komatiite-hosted Ni-Cu-(platinum group element) ore deposit within the northwestern part of the Kambalda dome. Coronet South and North are typical Kambalda contact ore shoots, at the basal contact between the Kambalda Komatiite Formation and Lunnon Basalt. The two shoots are offset by an NW-SE–trending fault. The Coronet orebody occupies a typical linear trough structure (Gresham and Loftus-Hills, 1981; Lesher et al., 1984; Lesher, 1989). The orebody consists of five major ore surfaces: Coronet South, Coronet North (NO1C), and three hanging-wall ore surfaces, DO1H (or Coronet West), SO1H, and SO2H (Beresford et al., 2005). The rocks at Coronet have undergone polyphase deformation and upper greenschist to lower amphibolite facies metamorphism. Hanging-wall and contact orebody massive sulfides have similar compositions (Beresford et al., 2005).

One footwall and three hanging-wall ore surfaces or horizons have been identified. The trend of the SO1H and SO2H surfaces is north-northwest to south-southeast (i.e., oblique to the NW-SE NO1C basal contact ore shoot). These contrasting trends between contact and hanging-wall ore shoots are unusual at Kambalda; more commonly, the orientation of the hanging-wall ore shoots mimics the orientation of the basal ore horizon (Gresham and Loftus-Hills, 1981; Groves et al, 1986).

The SO1H (the focus of this contribution) is a hanging-wall ore shoot spatially associated with the base of the second komatiite flow unit (as viewed from the base) and is predominantly interspinifex in nature, closely similar to the setting described by Groves et al. (1986) from the Lunnon ore shoot (Fig. 1). The SO2H surface follows a trend similar to that of the SO1H and is inferred to represent the lateral continuation of the SO1H into a position where the footwall to the ore zone is sedimentary. Beresford and Cas (2001) described various primary contacts between sulfide-bearing komatiite and sedimentary units that they interpreted as primary magmatic contacts between the komatiite and the host sediments. They interpreted these contacts to record the passage of a sulfide-bearing invasive lava flow over and into cool wet sediments. The transition from the SO2H to SO1H is interpreted to represent an increasing degree of thermal erosion of the underlying sedimentary unit and komatiite lava flow.

The SO1H consists of matrix and massive sulfide (up to 3.9 m in thickness) underlain by interspinifex sulfides (Fig. 2). Massive sulfide is in sharp contact with plate spinifex with the interstices now occupied by sulfides (Fig. 2), in an interval about 2 m thick. Rare localities exist (Fig. 2A) where random spinifex with interstitial sulfides is present between the massive and plate spinifex zones. The contact between the massive sulfide and interspinifex zone is irregular. Interspinifex sulfides pinch and swell in thickness along the ore horizon as at both Fisher and Lunnon, where the interspinifex ore zone is up to about 30 cm thick (Woolrich et al., 1981; Groves et al., 1986).

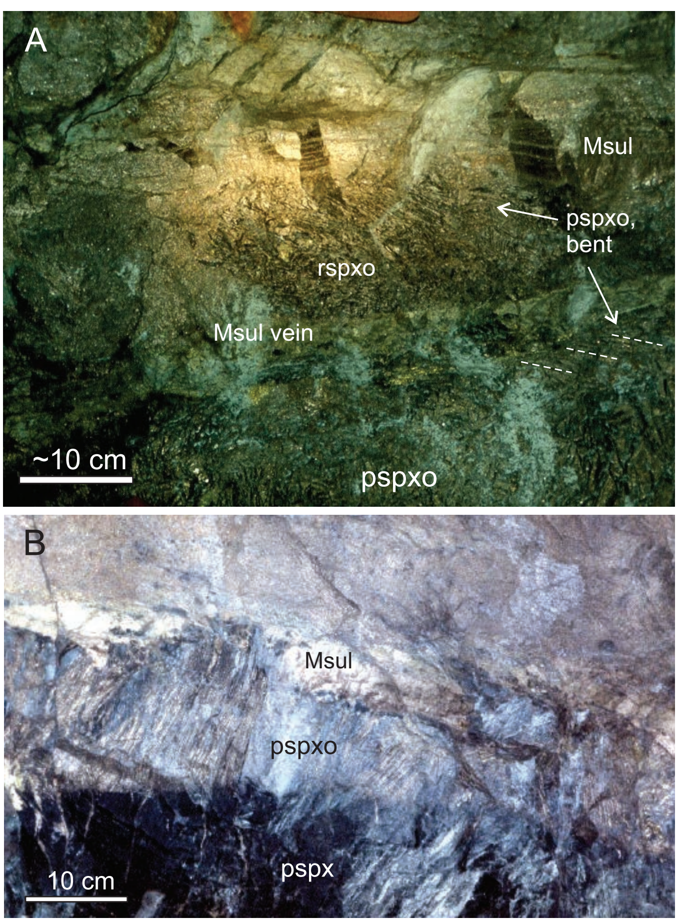

Fig. 2. Underground face photo of interspinifex ore in the S01H orebody. Msul = massive sulfide (note pentlandite-pyrrhotite banding in upper part of A), pspx = plate olivine spinifex, no sulfide, pspxo = plate spinifex-textured ore, rspxo = random spinifex-textured ore.

Analytical Methods

The main analytical technique employed in this study is microbeam scanning X-ray fluorescence analysis on roughly polished rock slabs, accomplished with the Bruker Tornado™ desktop equipped with a rhodium target X-ray tube operating at 50 kV and 500 nA without filters and an XFlash® silicon drift X-ray detector. Maps were created using a 40-μm spot size on a 40-μm raster with dwell times of 10 to 20 ms per pixel. Maps are represented as unquantified background-corrected peak height data for Kα peaks for each element, scaled linearly between minimum and maximum measured counts over the sample. X-ray spectra for each 40-μm pixel are stripped and quantified using the Bruker ESPRIT software, which gives standardless semiquantitative analyses for elements heavier than Na, with estimated detection limits for the given operating conditions and dwell times of about 1,000 to 2,000 ppm for first-row transition metals.

The Medical X-Ray Computed Tomography (CT) system used for this study is a SOMATON Definition AS Medical CT Scanner. This instrument is composed of a rotating X-ray source producing a fan-shaped X-ray beam, along with a rotating set of detectors (Multislice UFC™ detectors), and a 100-kW generator. The source is fitted with a STRATON MX P High Performance CT-X-Ray tube, with intensity and voltage ranging from 20 to 800 mA and from 70 to 140 kV, allowing the X-rays to be transmitted through dense and complex material such as disseminated to blebby magmatic nickel sulfides. Reconstruction to produce the tomographic dataset was done on the Syngo® acquisition workspace. An animated 3-D image is presented as electronic supplementary material.

Petrography and Chemical Structure of Coronet Interspinifex Ore

The mesoscopic features of Coronet interspinifex ore are shown in a set of images of a 20- × 20-cm rough-polished slab of the top of the zone (Fig. 3). Figure 3A is an optical photomosaic, collected at an original resolution of about 10 μm, and the other images are false-color and grayscale element concentration maps showing semiquantitative analyses of Cr, Fe, Ca, Ni, Cu, and S.

A number of features are evident on the images. The spinifex-textured komatiite itself, where not invaded by sulfide, shows the characteristic texture of original parallel "master" plates of original olivine, particularly well shown on the Fe concentration map (Fig. 3D), now replaced by an intergrowth of talc and fine-grained orthoamphibole (Fig. 4), and separated by plate-like interconnected domains of interstitial liquid now replaced primarily by chlorite. Coarse porphyroblastic carbonate overprints the entire assemblage, with a preference to being developed along chlorite-rich areas interpreted as the alteration products of original olivine spinifex plates (Fig. 4G).

The basal contact of the massive sulfide layer is separated from the spinifex flow top by a film of Cr-enriched, altered komatiite melt, now preserved as an aggregate of talc, chlorite, and fine tremolite. This assemblage also contains finely skeletal, Cr-rich spinel (ferrian chromite with very low Al and Mg content), particularly well developed along both upper and lower contact of the melt film (Fig. 4A, B). This melt film

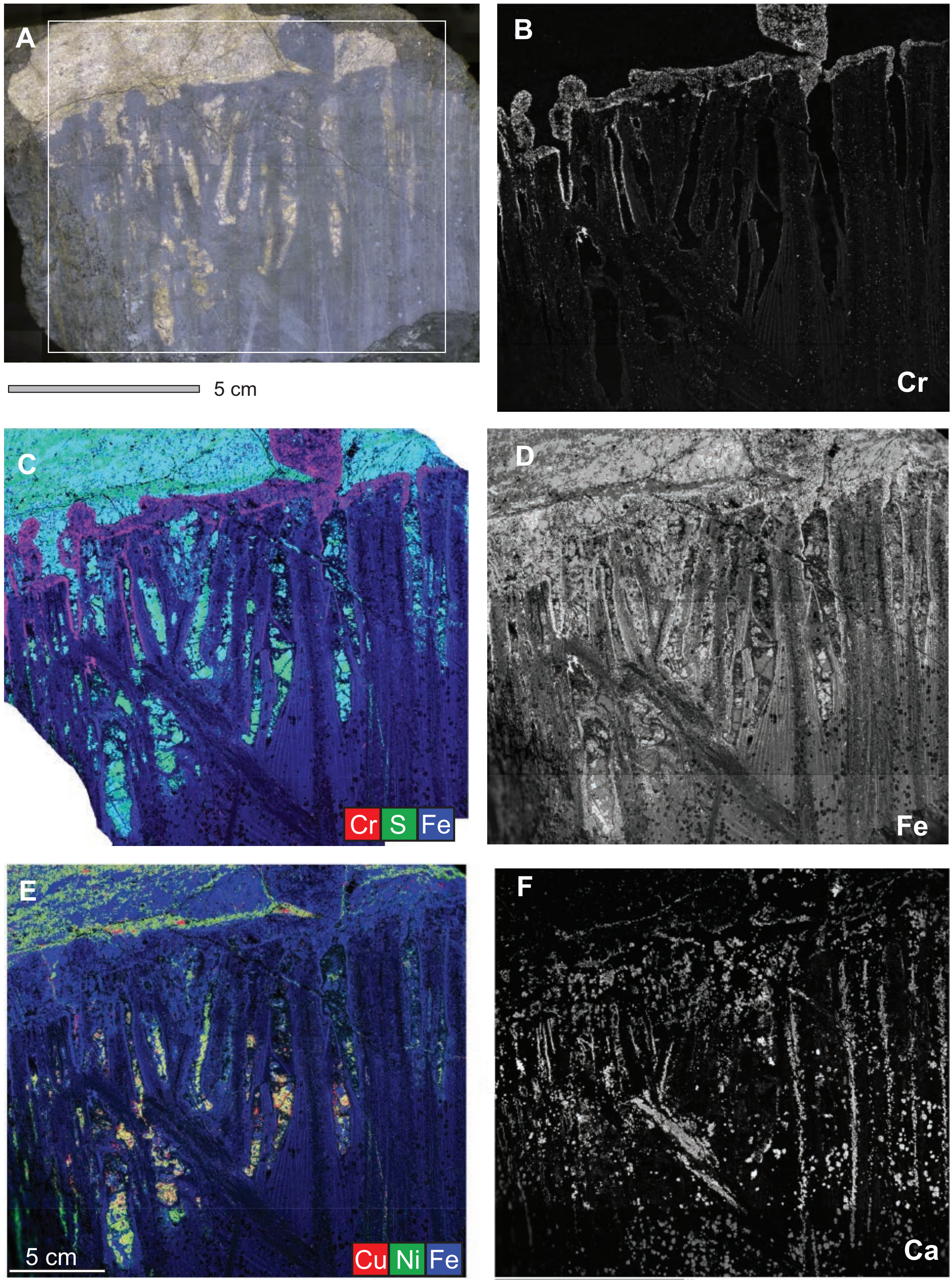

Fig. 3. Tornado images. A. Optical photomosaic. B-F) Microbeam XRF element maps. C. False-color three-element concentration image showing relative normalized concentrations of Cr in red, Fe in blue, and S in green. E. Same, with Cu in red, Ni in green, and Fe in blue—pentlandite appears turquoise in this image, and silicate component dark blue. B, D, F. Single-element normalized grayscale images of Cr (showing distribution of Cr-rich spinel associated with displaced silicate melt), Fe (showing detail of distribution of olivine plates in spinifex zone), and Ca (distribution of secondary calcite/dolomite) picking out serpentinized olivine plate cores.

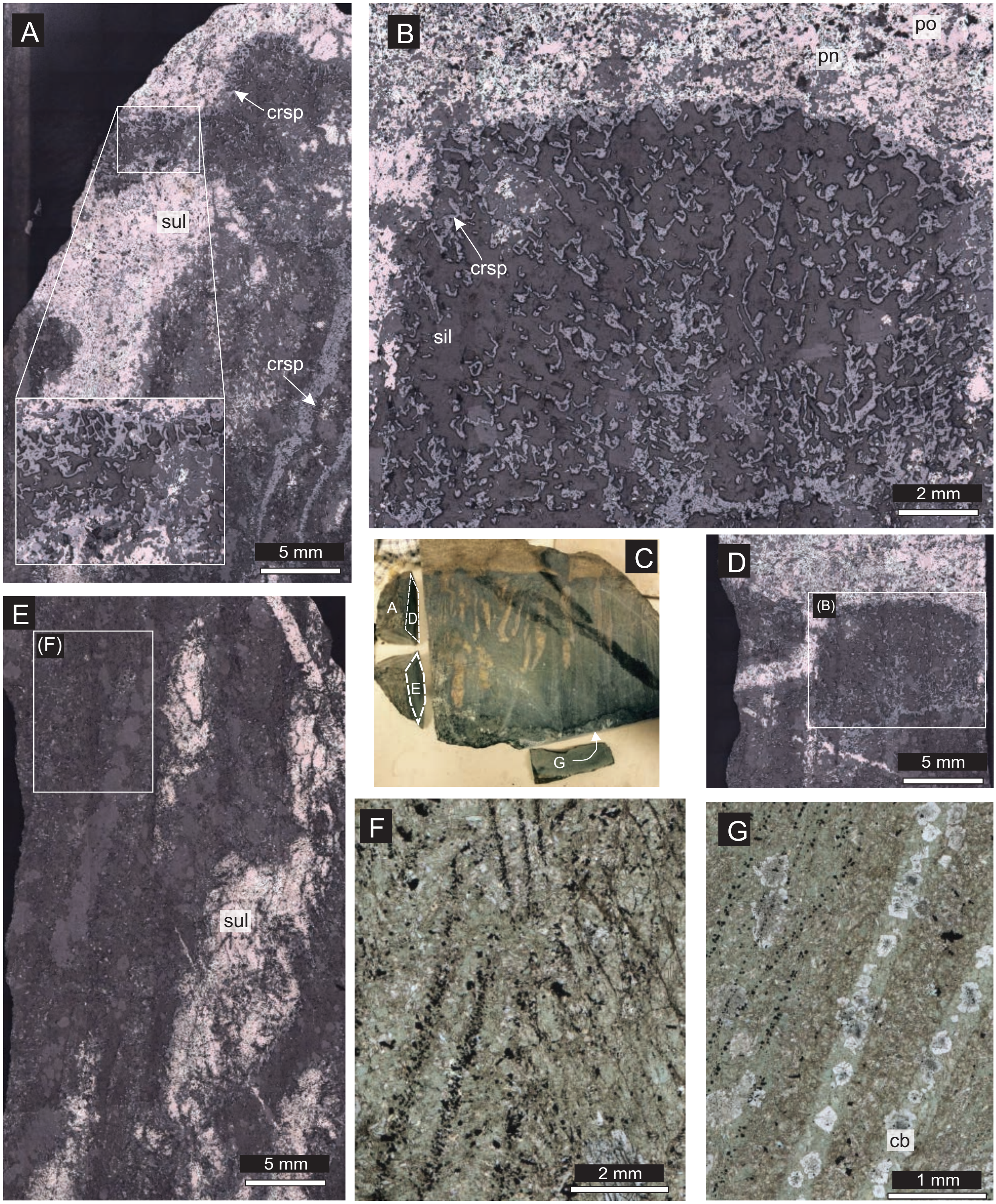

Fig. 4. Photomicrographs of spinifex textures, melt films, and chrome spinels, transmitted and reflected light. A. Reflected light mosaic of entire polished thin section (PTS), showing Cr spinel (crsp, mid gray) associated with upper contact of percolating sulfide (sul), and morphology of silicate melt plumes. B. Detail of skeletal Cr spinel within and around edge of silicate melt plume, mainly composed of fine-grained chlorite and serpentine (sil, dark gray). Po = pyrrhotite (pink), pn = pentlandite (white). C. Photograph of polished slab shown in Figure 3, showing location of thin-section blocks. D. Reflected light photomicrograph of polished thin section showing lower-magnification view of silicate plume in (B). E. Reflected light photomicrograph of polished thin section, cut normal to main sulfide contact and to long axis of spinifex plates within interspinifex ore zone. F. Transmitted plane-polarized light photomicrograph of indicated area of E. Primary igneous Cr spinel (black) decorates margins of original (now chlorite-carbonate altered) olivine spinifex plates. G. As in F, but sample cut parallel to main sulfide contact. Carbonate (cb) porphyroblasts developed along original olivine plates.

forms a number of upward-bulging plumes or domes, the largest of which (upper right) appears to be partially separated by a fracture at its base. The film also extends downward between the master olivine spinifex plates, showing the same development of a rind of skeletal spinel at the margin of the film. The spinel rind diminishes within about 4 cm of the base of the massive sulfide and is not developed at all in the lower half of the sample. Here, spinel takes the form of chains of fine euhedral or locally skeletal grains developed along the edges of the original spinifex plates (Fig. 4F, G) in the typical morphology observed within olivine spinifex-textured komatiites (Godel et al., 2013). The "dome" morphology at the base of the massive sulfide pool (Fig. 4B) is identical to that described by Groves et al. (1986), although these authors did not identify that the domes form part of a semicontinuous interfacial melt film.

The composition of the sulfide component has been estimated semiquantitatively from relative Ni and Fe peak heights in the Tornado spectra, integrated over selected areas of the scanned slab (Fig. 5). Sulfide compositions are similar between massive layer and interspinifex patches, an average value of 3.8 for Fe/Ni for the interspinifex sulfide patches comparing with 3.4 for the bottom 2 cm of the massive sulfide. This implies that massive and interspinifex ores formed as liquids, above onset of sulfide crystallization at about 1,100°C.

X-Ray Tomography—Morphology of Plates and Melt Plumes from Medical CT Scan

Three-dimensional images of the Coronet spinifex ore sample were collected at an approximate spatial resolution of 400 μm, and are represented as a series of vertical slices in Figure 6 and a "moving slice" animation in the digital supplementary material. These images add a number of useful insights. The silicate "plumes" or "domes" do indeed have mildly elongated dome-type morphologies, with a slight inclination toward the left-hand side of the samples (as viewed in Fig. 6), implying that that the sulfide pool may have still been undergoing some low-energy flow at the time of plume formation. However, the lack of a predominant fabric within the silicate film suggests

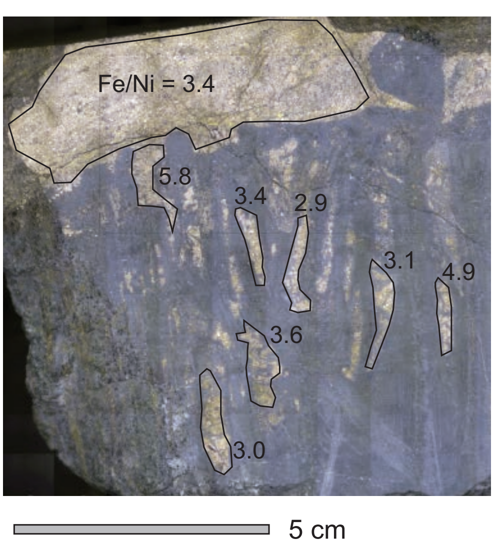

Fig. 5. Semiquantitative Fe/Ni from Tornado spectra integrated over selected sulfide-rich areas.

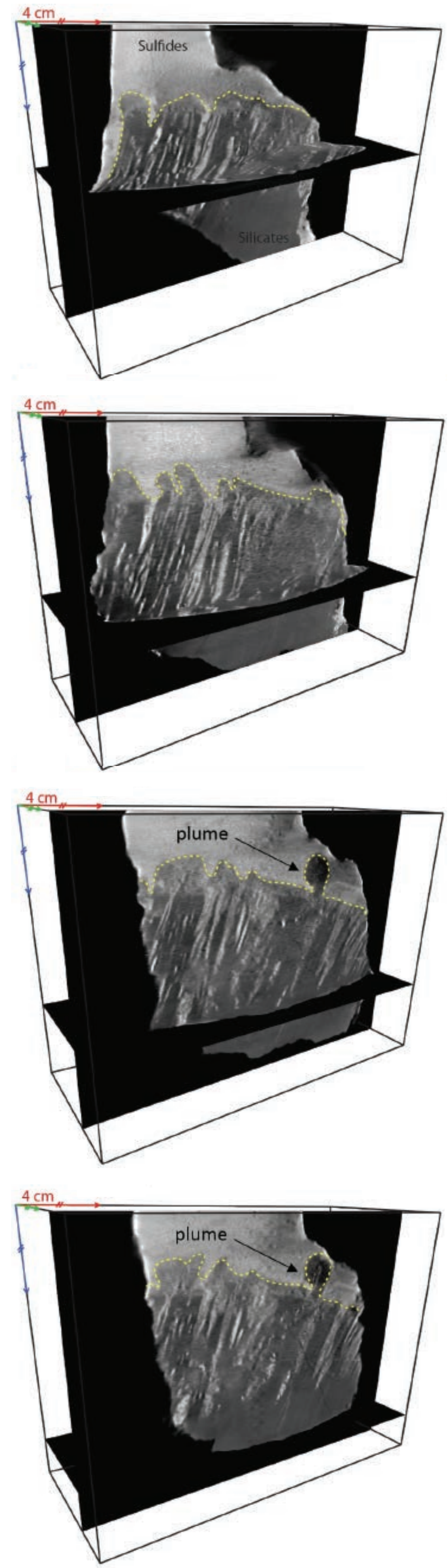

Fig. 6. Perspective view of "moving slice" 3-D medical CT scan. See digital supplementary materials for animated version of this image.

that the melting process happened under relatively static conditions after cessation of the main phase of lava flow. The penetrating interspinifex sulfide blebs themselves are poorly interconnected with one another below the massive sulfide interface and form broad blade- or irregular finger-shaped morphologies that pinch out downward and sideways (Fig. 7).

Discussion

Primary magmatic vs. secondary replacement?

A number of lines of evidence lead to the conclusion that the interspinifex ore is magmatic in origin, with superimposed secondary hydration and carbonation overprinting the magmatic textures:

1. The interspinifex sulfide is almost entirely interstitial to the larger spinifex plates (apart from a few late veinlets).
2. Sulfide is absent where the finer spinifex plates splay downward; this presumably reflects the inability of downward-percolating sulfide to penetrate between the upward closures of olivine "books."
3. Chrome spinel is only found close to the upper contact between massive sulfide and interspinifex ore and diminishes down into the spinifex zone, being entirely absent at sulfide-silicate contacts more than a few cm below the massive sulfide (Fig. 3). This is impossible to explain if the chromite formed as a metamorphic reaction, as would be required by the Stone and Archibald (2004) hypothesis of a secondary replacement origin for interspinifex ores.
4. Sulfide compositions are similar and Ni rich between the basal massive sulfide and the interspinifex patches. A hydrothermal replacement process to form the spinifex ores would be expected to produce substantial fractionation between Fe and much less soluble Ni.
5. Stone and Archibald (2004) considered the "silicate domes" at the top contact of the interspinifex ore in the Lunnon shoot locality to be tectonic folds generated by ductility contrast along the silicate-sulfide contact. This interpretation is not compatible with the geometry and composition of the very similar plume structures we observe at Coronet.

Physical Mechanisms

Interspinifex ore provides some of the most compelling field evidence that melting of substrate rocks occurred during the formation of komatiite-hosted massive sulfide pools.

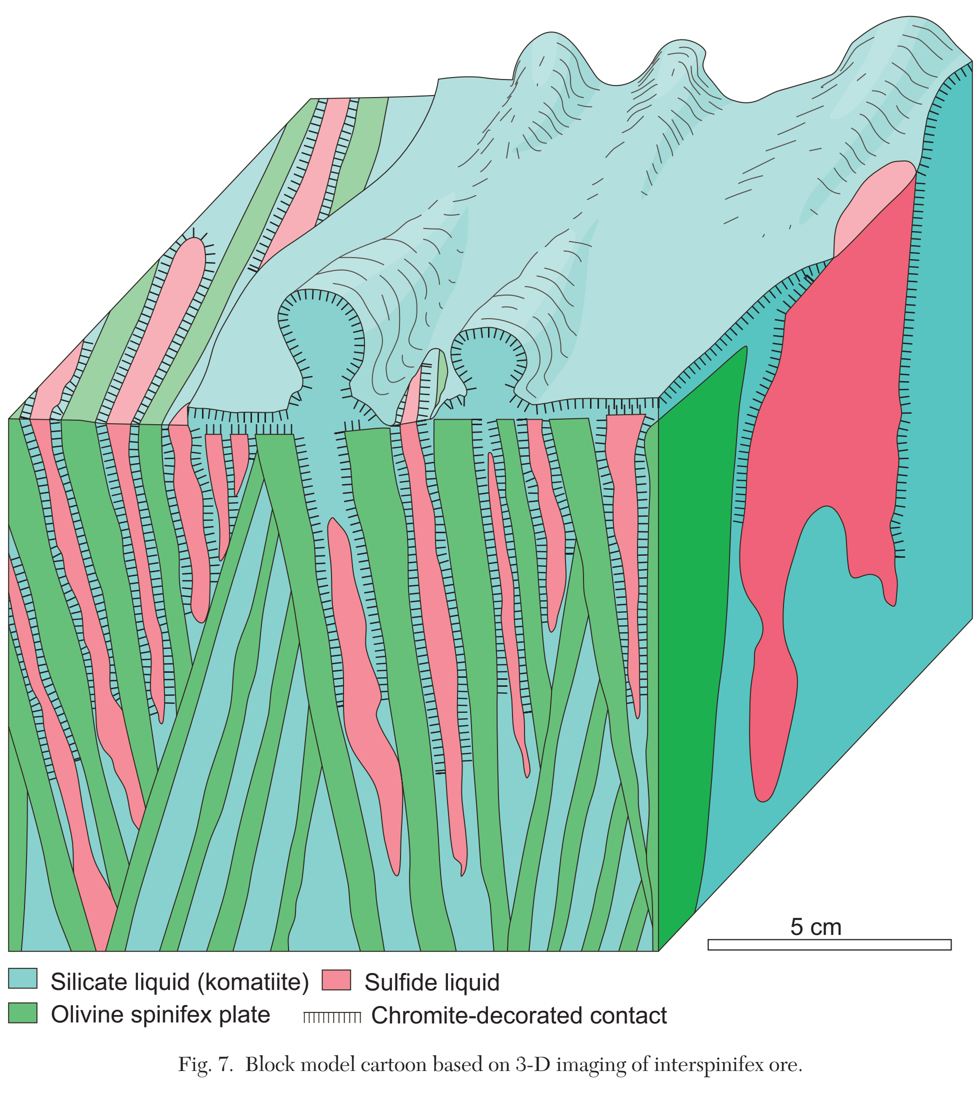

Fig. 7. Block model cartoon based on 3-D imaging of interspinifex ore.

Furthermore, the process was sufficiently effective to melt and remove ultramafic liquids by a mechanism of physical displacement by downward-percolating sulfide melt. The extent of the spinifex ore at Coronet and Lunnon shoots indicates that this processes operated on length scales of decimeters. The geometry of the intergrowths, particularly the presence of a locally domed melt film along the eroding top contact of the komatiite flow, suggests that the mechanism is driven by the following cyclic process. Heat conduction from superheated sulfide liquid into the floor produces a thin film of silicate melt at the immediate contact. This melt reacts with the sulfide melt to form chromite: Cr from the melting komatiite liquid combines with Fe and O from the sulfide liquid (Groves et al., 1977; Frost and Groves, 1989; Dowling et al., 2004; Fonseca et al., 2008), producing an Al- and Mg-poor chromite compositionally distinct from the typical liquidus chromite in the komatiites. The presence of a silicate melt layer beneath denser sulfide melt produces a Rayleigh-Taylor instability, giving rise to localized ascent of domes of silicate melt; once these exceed a critical size, their buoyancy overcomes the surface tension force keeping the silicate melt in contact with solid silicates beneath, and the domes become plumes that break off to ascend into the sulfide liquid above. This ascent is rapid, owing to the high buoyancy of the silicate melt and the low viscosity of the sulfide liquid (Terasaki et al., 2001). Removal of the plumes brings fresh sulfide liquid into contact with unmelted komatiite. The interspinifex textures arise from the relatively low melting temperature, probably as low as 1,200°C, of the evolved interspinifex komatiite liquid compared with the coarse refractory olivine plates. Density-driven displacement of the silicate melt by downward-percolating sulfide melt within the interspinifex "slots" causes a counter flow: sulfide melt fingers percolate downward while silicate melt percolates upward against the olivine plates, wicking along the upper sulfide-flow contact to replenish the unstable melt film at the base of the massive sulfide pool. The downward disappearance of chromite along the silicate-sulfide contact may reflect one or both of two limiting effects: limited time for reaction at the propagating tip of the down-going sulfide finger relative to that at the hot interface with the massive sulfide, and diffusion-limited availability of oxygen from the sulfide liquid pool.

This process is an excellent example of density-driven infiltration of sulfide melt into silicate crystal mushes, as investigated experimentally and theoretically by Chung and Mungall (2009) and Mungall and Su (2005). In typical cases, this process is limited by surface tension; the gravitational force driving percolation is opposed by the capillary force acting on the sulfide melt meniscus within the pore space of partially molten cumulates. In this case, however, the sulfide is traveling through parallel-sided channels several mm wide (Fig. 7), such that the capillary force acting at the propagating tip of the sulfide column is small and gravitational forces predominate. This gives rise to a form of compositionally driven slot convection (Tritton et al., 1992) within the interspinifex porosity.

The process is enhanced by the substantial thickness of the overlying sulfide pool, which gives rise to a driving hydrostatic head that generates an overpressure at the propagating tips of the down-going sulfide liquid fingers, well in excess of opposing capillary forces (Mungall and Su, 2005). The process is self-enhancing: as the rise height of the connected sulfide liquid column increases, the overpressure at the propagating tip increases proportionately, such that sulfide liquid can penetrate into smaller pores and cracks, transferring heat conductively into the adjacent silicate.

More broadly, interspinifex ore is an example of a melting-infiltration front at the base of thick pools or networks of interconnecting sulfide liquid. This process can drive sulfide liquid on length scales of decimeters and possibly meters into footwall rocks, giving rise to mixed zones of hard-walled and soft-walled injection veins and silicate-sulfide melt emulsions that are found in a number of deposits of various types besides komatiite-hosted ores (Barnes et al., 2015). Excellent examples are reported at Moran shoot, Kambalda, by Staude et al. (2015, in prep.) and at Silver Swan by Dowling et al. (2004). The key to the process is the high density and low viscosity of the sulfide melt, which facilitate the mechanism by which downward-percolating sulfide physically displaces buoyant silicate floor fragments and melts upward into and eventually through the sulfide pool. Hence, although we agree with Arndt (1986) that sulfide liquid pools or layers are not a precondition for substrate erosion, the presence of sulfide liquid enhances the footwall melting process through physical advection of heat into fractures and porosity in the immediate substrate. Late-stage massive sulfide vein-breccia systems, as reported from Norilsk and Voisey's Bay, among others, may be a large-scale manifestation of the melting-infiltration front process we report here. Such fronts take a variety of different forms, depending on the lithological and permeability characteristics of the footwall rocks at the time of ore emplacement.

A puzzling observation in a number of Kambalda ore shoots studied by Lesher (1983) is that the basal contact sulfide accumulations, in many cases, overlie basalt that has evidently not undergone melting, whereas interspinifex ores testify to melting of komatiite. Intuitively, it is expected that basalt would melt more readily than komatiite. One possible interpretation (Lesher, pers. commun., 2016) could be that the komatiite flow that melted was still hot at the time of the emplacement of the overlying flow, as would be expected if successive flows arrived in rapid succession on a time scale of a few years (Gole et al., 1990). However, this is unlikely here, given that the successive flows are separated outside the ore zones by several decimeters of presumably slowly accumulated sulfidic cherty sediment. Detailed discussion of the evidence for and against basalt melting is beyond the scope of this paper and is discussed in detail by Staude et al. (2015, in prep.), but we suggest that the resolution may lie in the dynamics of the komatiite flow in question. Melting of basalt or komatiite may have taken place in some cases where the flow was more vigorous and more prolonged, but not in others where flow velocities and durations were smaller, and only sediment was removed prior to the onset of solidification of the basal sulfide liquid layer. This further suggests a test: where footwall melting of silicate substrates took place under more dynamic conditions, sulfide liquids may have been better mixed with transporting flows such that they had higher platinum group element and Ni tenors. However, the complexities of dynamic flow channels may be too great for this simple association to hold. We look forward to continuing revelations from detailed investigations of melting and emplacement processes using new imaging techniques.

Acknowledgments

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