



Interspinifex Ni sulfide ore from Victor South-McLeay, Kambalda, Western Australia

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Abstract

Spinifex-textured olivine plates hosted in sulfides are usually named “interspinifex ore” in komatiite-hosted sulfide deposits. This ore type is rare but provides important genetic information on sulfide deposits, komatiite volcanology and thermomechanical erosion processes. Occurrences in Victor South-McLeay and Moran South (Kambalda, Western Australia) differ significantly from previously reported occurrences in their stratigraphic location, position within the ore profile and textural appearance. Thus, their formation process has to be reconsidered. Interspinifex ore reported here is situated in the lower portion of the basal lava flow between massive and net-textured sulfides in the centre of the embayment and between massive sulfides and older basalt in a “pinchout” where the sulfides melted sideways into older basalt on the embayment edge. Interspinifex ore is composed of up to 10-cm-long aggregates of parallel plates in the upper portion of massive sulfides and is overlain by barren komatiite. The texture does not allow for a classic single explanation. Thus, two possible formation mechanisms are envisaged: (1) A younger komatiite melt intrudes into its own olivine and sulfide liquid cumulate pile, while the sulfides are still liquid. The injection on top of the sulfides causes the formation of an emulsion, from which the spinifex forms due to the temperature gradient between the melts. (2) Interspinifex ore is a relic of an early komatiite flow formed in a series of successive pulses of komatiite and sulfide liquid. The spinifex of the komatiite is invaded by a younger batch of sulfide liquid replacing interstitial silicate melt.

Keywords Interspinifex ore · Kambalda · Komatiite-hosted Ni sulfide deposit · Emulsion · Sulfide infiltration

Introduction

Interspinifex ores and their significance

The textures of magmatic sulfide ores contain important clues to the physical processes of emplacement and migration of Fe–Ni–Cu–Co-bearing sulfide ore magmas (Barnes et al. 2017, 2018). Textural studies have revealed a remarkable ability of sulfide liquid pools to partially melt solid substrate rocks and displace silicate melt, forming distinctive

infiltration and percolation textures that can extend in some cases several metres from the original contact (e.g. Staude et al. 2016; Barnes et al. 2018). The first recognition of this phenomenon came with the discovery of “interspinifex ore”, found in the komatiite-hosted orebodies at Kambalda (Western Australia; Fig. 1). In this distinctive texture, first recognized at the Lunnon mine by M.H. Donaldson (pers. comm.), interstitial sulfides occupy the space between spinifex-textured olivine plates in a komatiite flow underlying a pool of massive sulfide ore in the flow above (Fig. 2). Detailed examination of typical occurrences at Lunnon (Groves et al. 1986) and also at Coronet mine at Kambalda (Barnes et al. 2016) showed that the upper chilled margin of the underlying flow had been eroded, and sulfide liquid had melted and displaced the komatiite melt component interstitial to large sub-vertical olivine plates in the spinifex zone beneath. These remarkably preserved structures were the first direct field evidence for the operation of the substrate thermal erosion process that is now almost universally regarded as the critical process in the formation of komatiite-hosted magmatic sulfide ores (Leshner et al. 1984; Barnes 2006; Staude et al. 2016, 2017a). However, the

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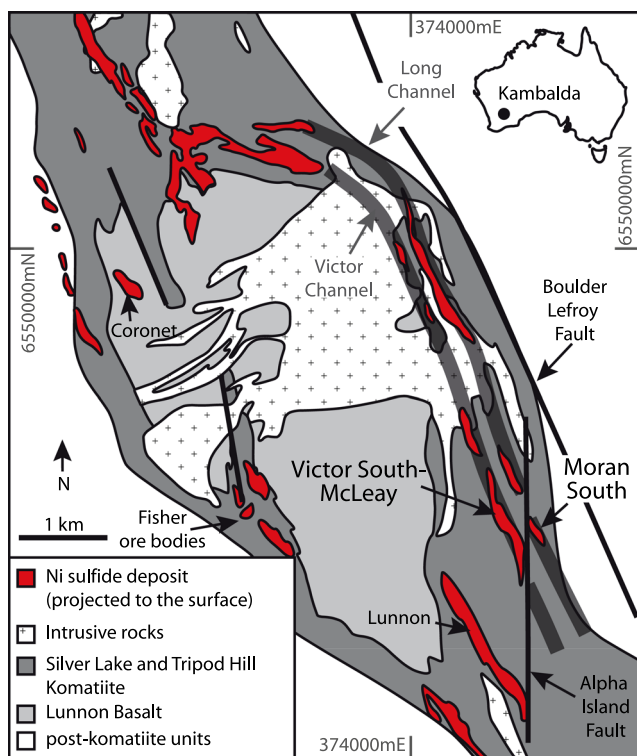


Fig. 1 Simplified geology of Kambalda showing the Ni sulfide deposits mentioned in the text

discovery of the Lunnion occurrence ignited a prolonged debate about the role of the sulfide liquid in the thermal erosion of underlying rocks, with some authors contending that erosion is only possible where sulfide liquid is already present (Groves et al. 1986; Cowden 1988), others arguing that thermal (or more accurately thermo-mechanical) erosion is demonstrable and almost inevitable beneath channelized komatiite flows, with sulfides playing an incidental role (Arndt 1986; Williams et al. 1998; Houlié et al. 2012). Others again deny a role for thermal erosion altogether (Beresford and Cas 2001; Stone and Archibald 2004). Barnes et al. (2016) and Staude et al. (2016, 2017a) argued on textural evidence that the presence of sulfide liquid at the very least greatly enhances the process of thermal erosion through a variety of mechanisms: self-reinforcing infiltration into fractures in underlying hydrated rocks, buoyant ascent of displaced silicate xenoliths and formation of hybrid melt emulsions. The essential driving force is the combination of high heat capacity, high density and very low viscosity of sulfide liquids (Kress et al. 2008; Robertson et al. 2016), particularly in komatiite flow settings.

In this contribution, we describe newly discovered occurrences of interspinifex ores from Kambalda in detail. We consider this new finding as significant, because the observed textures differ significantly from previously described localities and require new thinking about how such textures can develop.

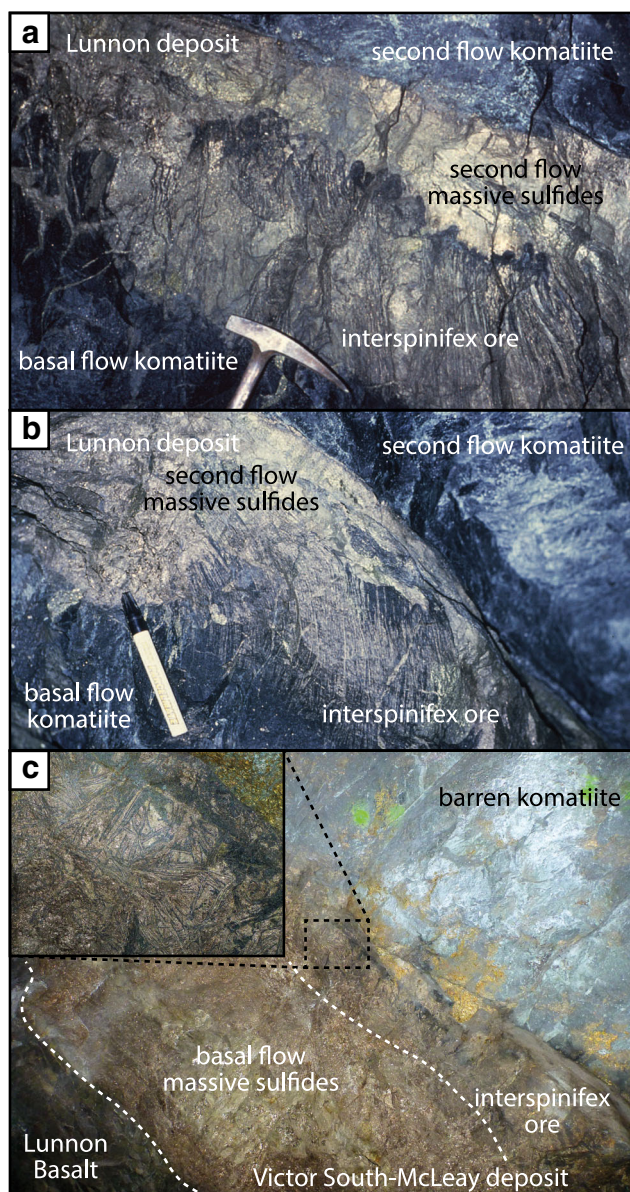


Fig. 2 Underground photos of interspinifex ore from Lunnion (a and b) and from McLeay (c). The Lunnion interspinifex ore is composed of long single plates arranged parallel with melt plumes on their top, due to the infiltration of sulfide melt (Barnes et al. 2016). The McLeay interspinifex ore on the other hand is composed of patches with short parallel plates, with individual patches having different orientations. The Lunnion sulfides are found above interspinifex ore whereas the McLeay sulfides are found underneath interspinifex ore. Photos (a) and (b) from Lunnion were taken by Mike Donaldson (Perth, Western Australia)

Occurrences of Interspinifex ore

Interspinifex ore has been described from Langmuir and Kelex (Abitibi greenstone belt, Canada; Green and Naldrett 1981; Houlié and Leshner 2011) and from the Coronet, Fisher and Lunnion (Fig. 1) deposits (Groves et al. 1986; Barnes et al. 2016) at Kambalda (Western Australia). The interspinifex ore from Lunnion and Coronet (see Fig. 1 for locations) is situated

in each case on the top of the basal komatiite lava flow and at the base of massive sulfides (termed hanging-wall ores) of the second lava flow. In both cases, detailed studies show that the interspinifex ore originated by thermally driven infiltration and displacement of the interstitial silicates by younger sulfide melt of the second lava flow. The upper quenched flow top and random spinifex zones of the basal lava flow were eroded, and the interstitial silicate of the coarse parallel-plate spinifex beneath were replaced by sulfides forming interspinifex ore of about 30 cm in thickness. The interspinifex ore forms by infiltration of sulfide liquid between sub-parallel spinifex plates that are approximately perpendicular to the original flow top; in some cases, the weight of the overlying sulfide pool resulted in bending and buckling of the coarse spinifex plates (Fig. 2b). On top of the interspinifex ore are centimetre-sized silicate plumes surrounded by massive sulfides (Fig. 2a). The plumes have been interpreted to originate from the displaced interstitial silicate material (Groves et al. 1986; Barnes et al. 2016).

The occurrences of interspinifex ore at the Victor South-McLeay deposit (denoted as McLeay in the text) and Moran South mineralization differ significantly from the above-described interspinifex ore in a number of aspects which are therefore documented in detail in this contribution. In both new occurrences, the interspinifex ore is located at the top of massive sulfides of the basal komatiite lava flow and is overlain by sulfide-poor komatiite (Fig. 2c). Therefore, this interspinifex ore cannot have formed in exactly the same way as those at Lunnon and Coronet, and a more complex explanation is needed. The observed textures in combination with geochemical data of the observed komatiites are presented in this study. This combination, however, does not allow to be explained unequivocally by one model that explains all observations. Therefore, two possible models for the origin of this type of interspinifex ore will be discussed.

Geology of Kambalda

The Kambalda Dome, hosting several komatiite-hosted Ni sulfide deposits accounting for over 3 million tonnes of Ni on a pre-mining basis, is part of the Kalgoorlie Terrane of the Archean Yilgarn Craton (Western Australia; Gresham and Loftus-Hills 1981; Goscombe et al. 2009, Gole and Barnes 2020). The stratigraphy at Kambalda is well established, the oldest unit being the tholeiitic Lunnon Basalt which is overlain by up to 10 m of pyrrhotite-bearing sediments (Bavinton 1981). The next unit above is the Silver Lake Komatiite, the host to all of the Kambalda Ni orebodies. Most of the ores are hosted within the basal lava flow. In a few localities, the second lava flow of the sequence also contains basal sulfide accumulations (Gresham and Loftus-Hills 1981). These are the hosts of all occurrences of interspinifex ore so

far described in the literature (Groves et al. 1986; Barnes et al. 2016). The Silver Lake Komatiite is overlain by the Tripod Hill Komatiite, comprising multiple episodically emplaced compound flows with dozens of individual spinifex-textured lobes (Gresham and Loftus-Hills 1981; Barnes 2006; Gole and Barnes 2020). Several more volcanoclastic and sedimentary units were deposited after the komatiites, and the whole sequence was intruded by felsic to mafic melts forming dikes, sills and stocks (Gresham and Loftus-Hills 1981). This whole stratigraphy was overprinted by upper greenschist to lower amphibolite facies metamorphism. Igneous textures are preserved in many units (Gresham and Loftus-Hills 1981; Staude et al. 2020), and hence, the prefix “meta” is usually omitted in literature.

The basal komatiite lava flow of the Silver Lake Member is subdivided into channel and flank facies. In flanking positions, the komatiite conformably overlies the contact sediments, and the basal flow is composed of thin (< 10 m)-sheeted cooling units. Within the ore-bearing channels, the komatiite flows occur as olivine cumulate-dominated units up to 150 m thick; the contact sediment is missing as a result of thermomechanical erosion (Gresham and Loftus-Hills 1981). The erosion was enhanced by infiltration of the basal sulfide melt pool into hydrated fractures in the underlying basalt, generating hydrofracture breccias, infiltration-melting fronts and basalt melt plumes along the melt interface contact (Staude et al. 2017a). Typically, and particularly well-developed at Moran, the orebodies form elongate ellipsoidal or ribbon-like bodies, flanked by features called “pinchouts” where the sulfides are bound by older basalt from above and beneath. Debate has been ongoing for decades over the origin of these features, but based on exceptional underground exposures at Moran, Staude et al. (2016) were able to demonstrate a primary origin by erosional undercutting. In the final stages of embayment formation, the sulfide melt pool propagated sideways by melting laterally into the older basalt. Typically, the pinchouts host only sulfides, in some cases with remelted basalt that floated through the sulfide to pond beneath the pinchout roof, but little or no komatiite.

Occurrences of interspinifex ore at McLeay and Moran South and sample description

The McLeay deposit is part of the Victor lava channel, whereas the Moran South mineralization is part of the Long channel (Staude et al. 2017b; Fig. 1). McLeay forms several mineralized ore lenses which are separated by (partly mineralized) faults, but igneous textures are preserved in large portions of the orebody. Moran South is separated from the northern part of the Long channel by the steep N-S trending Alpha Island Fault (Fig. 1). The mineralization is not well known due to its sub-economic

nature and because of difficulties associated with drilling through faults. The largest known part of this mineralization forms a thin (<0.5 m) shear zone. A 30-m-wide zone with in situ massive sulfides including igneous textures and interspinifex ore is restricted to the eastern pinchout. Both of these occurrences show some significant differences to the previously described examples of interspinifex ore. These have implications for genetic models and for this reason are described in detail here.

Interspinifex ore in McLeay occurs in patches all over the orebody (Fig. 3), although the exact location is not known in most cases due to the lack of data, with the exception of the pinchout described in the next section. One example is shown from the central part of McLeay where drill hole MDU-710 intersected a typical profile through the interspinifex ore-hosting part of the orebody (Figs. 4, 5) on an open contact (i.e. on the flat floor of the orebody away from the marginal pinchouts). The basal sulfide contact is a melting-infiltration front (Barnes et al. 2018) characterized by igneous textures such as melt plumes and skeletal chromite clusters originating from thermomechanical erosion (Fig. 4a; Staude et al. 2016, 2017a). The upper sulfide contact contains skeletal chromite (Fig. 4b) and an irregularly developed zone of interspinifex ore (random spinifex). This is overlain by 80 cm of komatiite, which includes patchy zones of interspinifex ore and irregular sulfide aggregates, mostly concentrated on its lower and upper contact. The sulfide-poor komatiite is overlain by net-textured sulfides (Figs. 4, 5). The contact between them contains patchy massive sulfides and frequent spherical sulfide-free areas. The net-textured sulfides are overlain by barren komatiite, which is partly vesicular. Another open contact interspinifex ore is shown in Fig. 2c; however, due to limited underground exposure, the position or distance to the potential net-textured sulfides above is not known.

The best exposed interspinifex ore was intersected in the pinchout of McLeay (Figs. 3, 5, 6). This pinchout is primary magmatic as opposed to a tectonically formed pinchout (e.g. eastern pinchout in Fig. 3c). This pinchout shows all the characteristics of igneous pinchouts reported by Staude et al. (2016) including a “scum layer” of remolten basalt floating on the top of the sulfides; this location is indicated in Fig. 3b between the interspinifex ore occurrences. This interspinifex ore unit forms ribbon-like sub-parallel bodies of 10–30 m width and 20–50 m length (Fig. 3b). This part of the pinchout was displaced about 25 m above the main deposit due to younger tectonic events (Fig. 3c), but the sulfides and their contacts were not modified in the pinchout itself. The contact between the upper massive sulfides and the overlying interspinifex ore is sharp but undulating (Fig. 6c). The lower portion of the spinifex is usually free of interstitial silicate material, whereas the upper part frequently hosts patchy

sulfide-free areas (Fig. 6). These patches contain coarse platy and/or random spinifex. Parallel coarse platy spinifex between sulfides occurs in randomly oriented patches (Fig. 6b, d; compared with homogeneous downwards-growing spinifex at Lunnon; Fig. 2). Occasionally, irregular aggregates of skeletal chromite occur in the interspinifex ore (Fig. 6a, f). Spinifex plates are locally broken and crumpled (Fig. 6f). Frequently, coarse parallel spinifex plates are situated next to fine-grained sulfide-silicate intergrowths and emulsion textures (Barnes et al. 2018), where sulfide grains are chaotically intermixed at a mm scale with silicate material (Figs. 6e, f).

Sulfide-poor komatiite immediately overlies the interspinifex ore. This komatiite is composed of random spinifex crystals with similar grain size and random orientation as the spinifex grains in the sulfide ore. It hosts abundant irregular patches of silicate-free sulfides. The combined interspinifex ore and associated komatiite layer in the pinchout is up to 3 m in thickness and is capped by the older Lunnon Basalt, forming the roof of the pinchout, with biotite alteration on the contact.

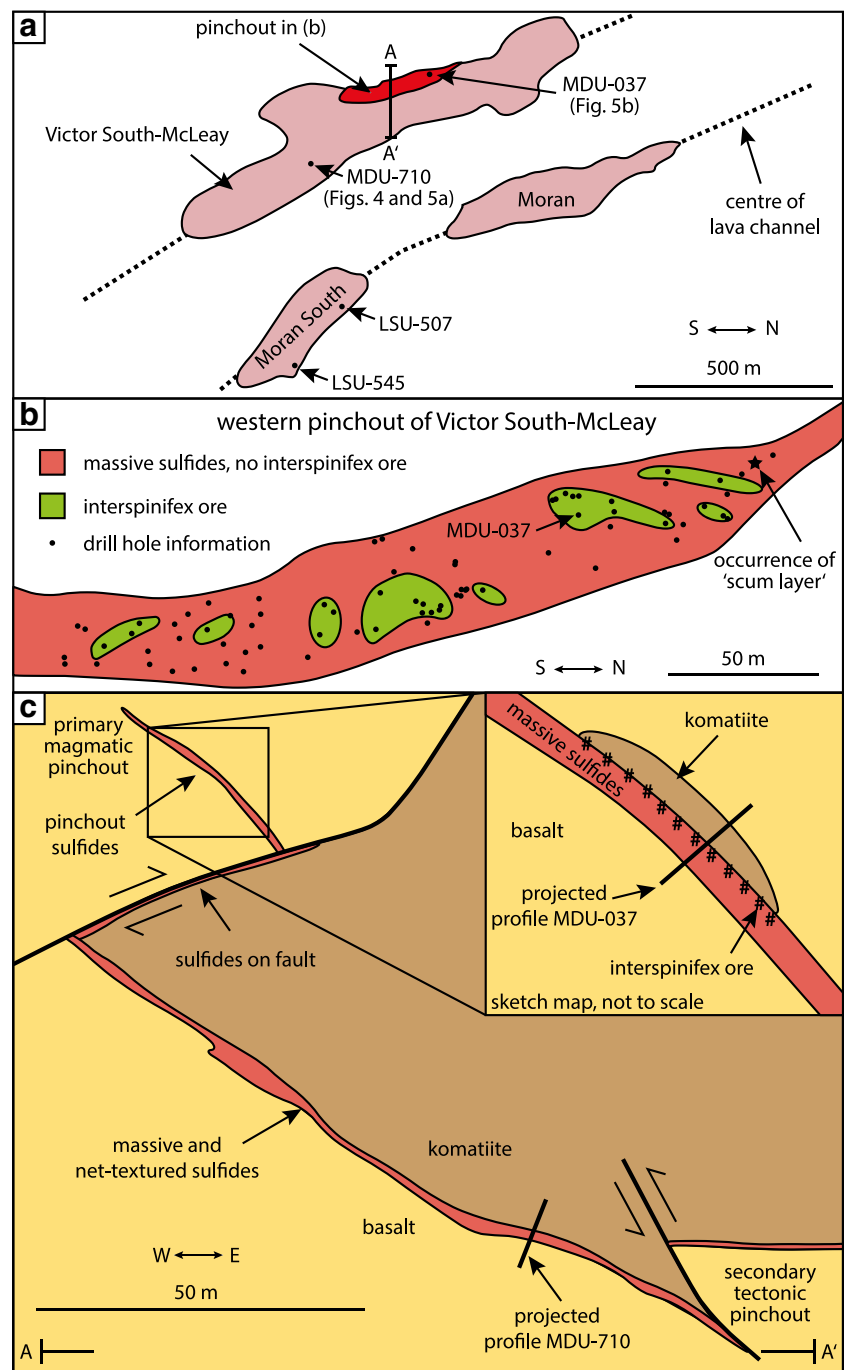
Interspinifex ore in Moran South (Fig. 7) was intersected only in two holes in an area of sparse drilling. The textures are similar to interspinifex ore from McLeay. One intersection displays only a thin interspinifex texture overlain by komatiite with large irregular patchy sulfides as well as small spherical sulfide globules (Fig. 7b). Several other massive sulfides in Moran South are overlain by barren komatiite hosting minor patches of blebby or disseminated sulfides. Up to 10 cm of skeletal magnetite occurs along the contact between sulfides and komatiite (Fig. 7c). Net-textured sulfides have only been intersected rarely at this locality as centimetre- to decimetre-sized aggregates in barren komatiite.

Samples were collected from the komatiite above the interspinifex ore to compare their petrography and chemistry to published data of the Kambalda Komatiite as well as interspinifex ore from all described occurrences above, for petrography and textural observations.

Analytical methods

Major and trace elements were determined at ALS (Perth, Western Australia), and analytical results are listed in the electronic supplementary material (ESM) 1. Samples were digested using 4-acid digestion, lithium borate fusion, aqua regia digestion or by fire assay, respectively (see ESM 2 for individual elements). Parts of the samples were decomposed using a Leco furnace for S- and C-analysis by infrared spectroscopy. Analysis was carried out using ICP-AES or ICP-MS, respectively (see ESM 2 for individual elements). Multiple standards and blanks were dispatched to check for precision and accuracy. The laboratories' accuracy and precision tests are listed in ESM 2.

Fig. 3 **a** Location of the pinchout hosting interspinifex ore at McLeay and the drill holes mentioned in the text and other figures. **b** Occurrence of interspinifex ore in the pinchout of McLeay. Shown is also the location of the drill hole shown in Fig. 5 and the “scum layer” between massive sulfides and the Lunnon Basalt on top which originated from remolten basalt floating on top of the sulfide melt (Staude et al. 2016, 2017a). **c** Profile across McLeay showing the location of the interspinifex ore hosting pinchout. The inlet sketch shows the patchy ribbon-like occurrence of interspinifex ore in the pinchout



The spinel main element chemistry was determined using a JEOL 8900 electron microprobe at the University of Tübingen (Germany). Analyses were carried out in wavelength-dispersive (WD) mode using an acceleration voltage of 20 kV, a probe current of 20 nA with a focused beam and PRZ correction. Counting times on the peak position (all $K\alpha$) were 15 s for main elements (Al, Cr, Fe) and 30 s for trace elements (V, Ti, Mn, Co, Ni, Zn, Mg, Si). Peak overlap corrections were applied for Mn interfering with Cr with a correction factor of 0.00455,

V interfering with Ti with a factor of 0.00649 and Al interfering with Cr with a factor of 0.00089. Results of all spinel analyses are presented in ESM 3.

Microbeam XRF maps were collected using the Bruker Tornado instrument at CSIRO, Perth, with a spot size of 40 μm , pixel size 40 μm and a dwell time of 10 ms per pixel. Element maps are shown as 8 bit per channel false colour images with the indicated elements in red, green and blue channels scaled between minimum and maximum counts per pixel.

Fig. 4 **a** Drill hole MDU-710 from the central parts of McLeay showing a typical profile of Lunnon Basalt followed by massive sulfides, komatiite with minor irregular sulfide patches, net-textured sulfides and barren komatiite. **b** Close-up of (a) to show the contact of massive sulfides to komatiite which hosts the interspinifex ore. **c** Close-up of (a) to show the upper contact of the komatiite with patchy sulfides to the net-textured sulfides above.



Results

Petrography of interspinifex ore and of komatiite associated with the interspinifex ore

On a microscopic scale, many of the textures are overprinted and somewhat obscured by the metamorphic silicate assemblage (ESM 4) of tremolite, serpentine, chlorite and minor talc, although the general outlines are preserved (e.g. folding of spinifex; ESM 5). Along the silicate-sulfide interface, magnetite is common where the spinifex plates reach several centimetres in length (ESM 5). Where the spinifex is on the sub-centimetre scale, magnetite is hosted by sulfides (ESM 5). These sulfides also host abundant silicate inclusions (ESM 5). At McLeay the silicate portion always hosts some sulfides, and magnetite is always present in large quantities (ESM 5), especially along the sulfide-silicate interface. In contrast, at the Coronet locality, Cr-magnetite is developed along sulfide-silicate contacts only within the upper few cm of the interspinifex ore and disappears progressively away from the base of the pure massive sulfide (Barnes et al. 2016).

The komatiite above the interspinifex ore is composed entirely of secondary minerals: tremolite, chlorite and minor serpentine in McLeay and serpentine, chlorite and minor talc in Moran South. At both localities, euhedral chromite (which always is surrounded by euhedral magnetite) and euhedral magnetite without a chromite core occur. Sulfide globules in Moran South are all surrounded by magnetite.

The irregular distribution of chromite in all interspinifex ore (besides the macroscopically visible chromite aggregates of Fig. 6a and f) is best displayed by XRF maps of polished hand specimens (Fig. 8). Contrasting relationships between sulfide, komatiite and chromite can be seen in Fig. 8. They show the gradational contact between interspinifex ore below and sulfide-poor komatiite above. The komatiite in contact with sulfide contains spinifex plates of identical size and shape to those in the sulfide and an upper contact with fine-grained komatiites containing disseminated sulfide and minor equant chromite grains. The image in Fig. 8 shows interspinifex ore with abundant-associated sub-skeletal chromite within sulfide; the chromite shows very similar morphologies to that developed at thermal erosion contacts between silicate and sulfide melts (Staude et al. 2016, 2017a). Another polished specimen shows a higher chromite content around the spinifex (Fig. 8c), but with relative little chromite where the spinifex is intact and more chromite where the silicates are positioned more irregularly.

Komatiite and spinel geochemistry

Major elements of the komatiite associated with interspinifex ore are similar to spinifex-textured samples of the Kambalda Komatiite (Arndt and Jenner 1986; Leshner and Arndt 1995; Staude and Markl 2019) but in general display higher FeO contents (ESM 1, ESM 6), which is in line with the high magnetite content found

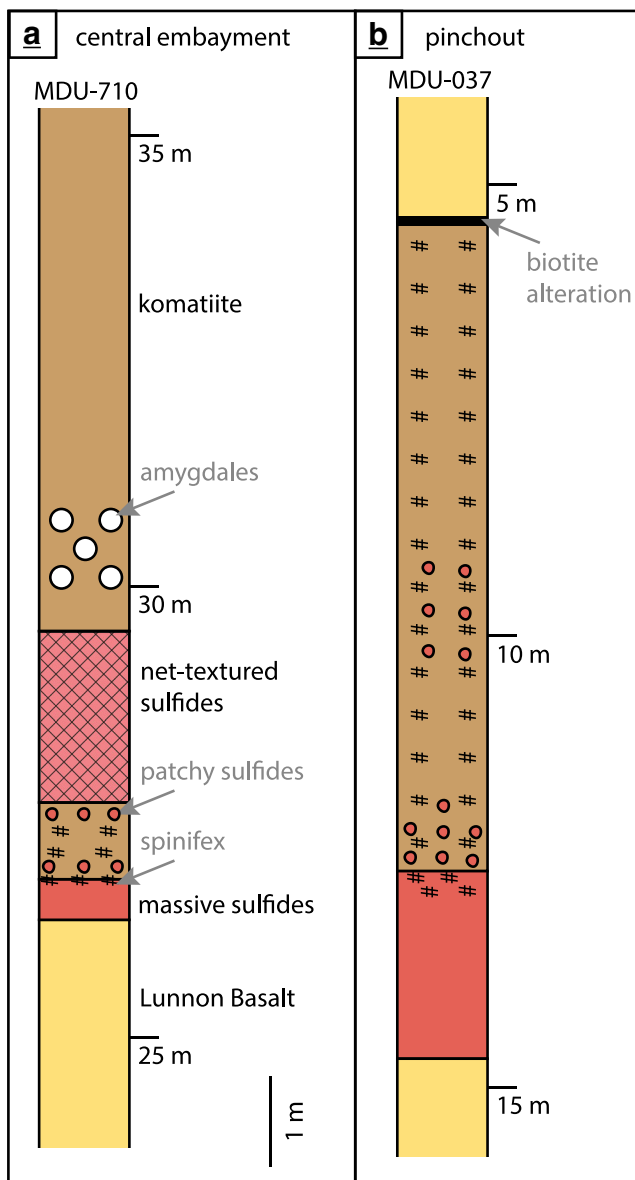


Fig. 5 Typical drill hole profiles hosting interspinifex ore. **a** MDU-710 is from the central part of McLeay whereas **b** MDU-037 is from the pinchout. Note that the typical stratigraphy (basalt-massive ore-net-textured ore in the centre and basalt-massive ore-basalt) is in both interspinifex ore occurrences changed by komatiite situated on top of massive ore

in polished sections. Trace elements are also similar, but Ni, S, Pd and Pt are higher (ESM 1, Fig. 9). Light REEs are lower than in the Kambalda Komatiite sequence, with La/Sm ratios between 0.3 and 1.1 (Kambalda komatiite: 0.7–1.2, Staude and Markl 2019).

The geochemistry of spinel from Kambalda reflects primary magmatic signatures (recorded by proportions of the trivalent ions) as well as secondary signatures from the metamorphic overprint (Barnes 2000) that primarily modifies only the divalent components under greenschist facies conditions; therefore, only the trivalent ions are

shown and discussed. Three types of spinel are observed in the interspinifex ore and the komatiite above which partly overlap with compositional fields defined by Barnes and Roeder (2001): (1) komatiite-hosted chromite composition, (2) sulfide-hosted chromite composition and (3) magnetite rims (ESM 3, Fig. 10). Type (1) chromite occurs always as cores surrounded in some cases by type (2) spinel and always by type (3) magnetite in all investigated samples. Type (2) chromite occurs surrounding type (1) chromite or as euhedral crystals, both surrounded by type (3) magnetite. Magnetite (3) also occurs commonly in euhedral crystals in the former olivine plates of the spinifex and throughout the komatiite above the interspinifex ore.

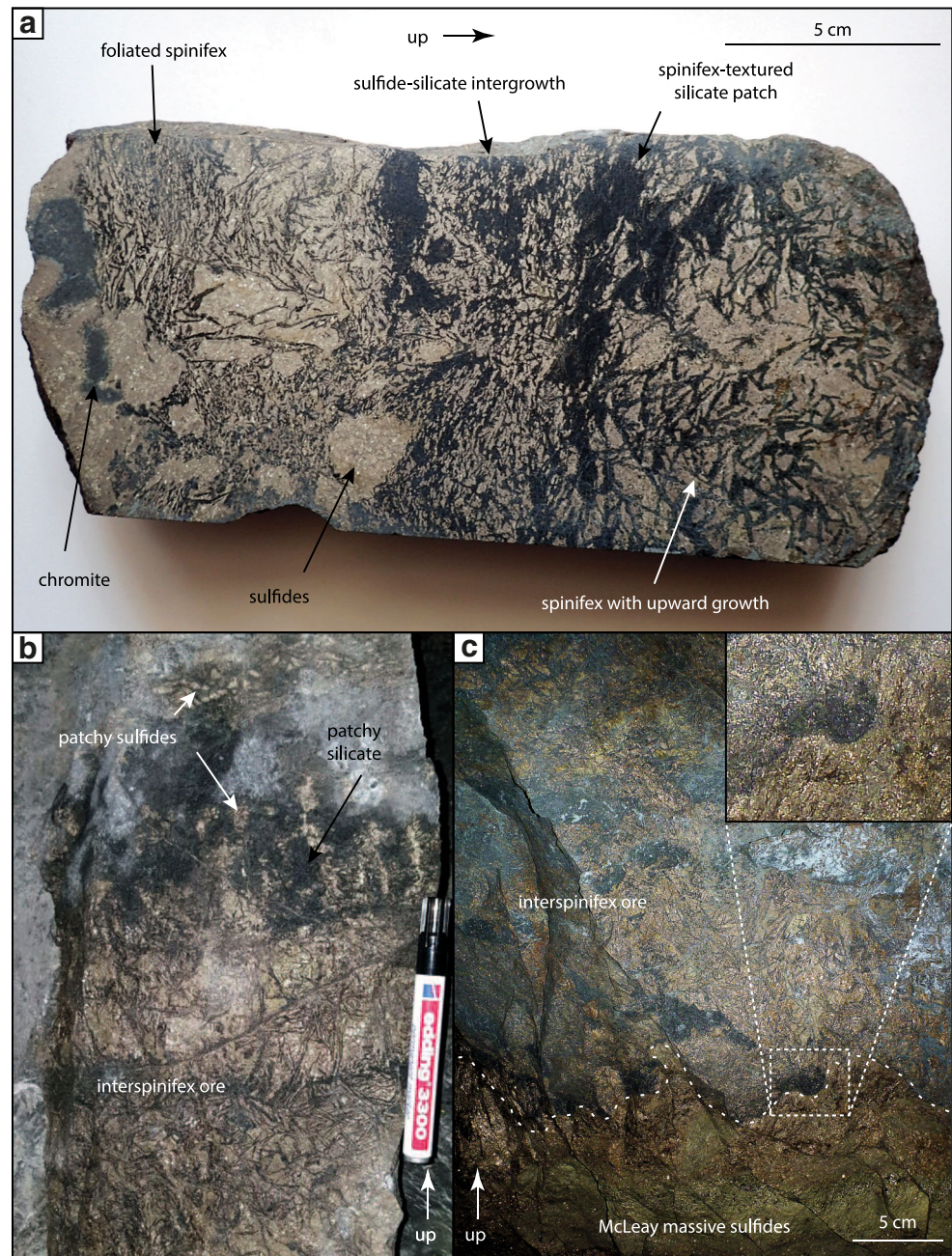
Discussion

Effect of alteration

The Kambalda sulfide deposits have been overprinted by sea floor alteration, metamorphism and hydrothermal events; additionally, younger felsic to mafic dykes and sills cross-cut them and caused limited contact metamorphism (Gresham and Loftus-Hills 1981; Arndt et al. 2008). Hence, the impact of these various processes on the igneous textures and geochemistry needs to and will be addressed in the following paragraph.

From previous studies on Kambalda rocks, it has been inferred that Mg, Cr, Al, Fe, Mn, Ni, Co, Y, Ti, Zr, Nb and REEs were relatively immobile in these events, whereas Ca, Cs, Rb, K, Na, Ba, Sr and Eu^{2+} were (partly) mobilized (Leshner and Arndt 1995; Said et al. 2010). Additionally, altered rocks usually contain a high proportion of carbonates (Leshner and Arndt 1995), and primary textures are destroyed due to recrystallization (Arndt et al. 2008). Bladed metamorphic olivine is observed in some komatiite-hosted sulfide deposits metamorphosed under amphibolite facies (Barnes et al. 1988; Barnes 2006). The metamorphic blades, however, are randomly oriented, contain a high proportion of sulfide inclusions and do not form parallel spinifex plates. For this reason, and in the absence of evidence for metamorphic olivine in this part of the Kambalda Dome, we are confident in interpreting the observed interspinifex ore as an igneous texture. The random spinifex of the associated komatiite above is in direct contact with the interspinifex ore, in some cases as in Fig. 8a and b having identical appearance and therefore most likely also represents an igneous texture. The low metamorphic overprint is also indicated by the low carbon content of <0.7 wt% of the samples (ESM 1).

Fig. 6 Photos displaying textural variations of interspinifex ore from McLeay. **a** Hand specimen with aggregates of skeletal chromite, patches of silicate-free sulfides and patches of sulfide-free silicates in-between spinifex. The orientation of individual sub-parallel plates is patchy, and in the central part, plates are smaller and change to a sulfide-silicate intergrowth without preferred orientations. **b** Hand specimen of interspinifex ore with patches of parallel plates of different orientation. On the upper contact of interspinifex ore and komatiite, irregular silicate and sulfide patches occur. This photo was provided by Tom Járóka (Freiberg, Germany). **c** Underground exposure of interspinifex ore showing an undulating contact to massive sulfides. Partly patches of sulfide-free areas occur on the contact (inlet). **d** Hand specimen of the contact of massive sulfides and interspinifex ore. Aggregates of parallel plates are oriented differently. **e** Enlargement of (d) to show an area where spinifex plates are intergrown with silicates hosting little sulfide blebs and sulfide-silicate intergrowths with emulsion texture. **f** Polished specimen where spinifex plates change into aggregates of emulsion texture. Note the bending of some spinifex plates and aggregates of skeletal chromite



Geochemical characteristics of the interspinifex ore

Whole-rock geochemistry

The major and trace element chemistry of komatiite associated with the interspinifex ore are similar to other spinifex-textured komatiites of the Kambalda Dome and, hence, do not represent olivine cumulates which usually overlay the sulfides. This is in line with the observed spinifex textures in some samples. Due to the geochemical similarity to other spinifex-textured komatiites of the

Kambalda sequence, it is impossible to estimate whether there is a genetic link between the komatiite associated with the interspinifex ore to one of the lava flows of the Silver Lake or Tripod Hill komatiites and to the komatiitic dykes observed in close vicinity (Staudé and Markl 2019). Globular sulfides in the komatiite associated with the interspinifex ore show that sulfides were present prior to komatiite emplacement and that the komatiite interacted with the older sulfides (globular sulfides usually represent entrained sulfides from a larger sulfide accumulation rather than newly segregated sulfides from the silicate

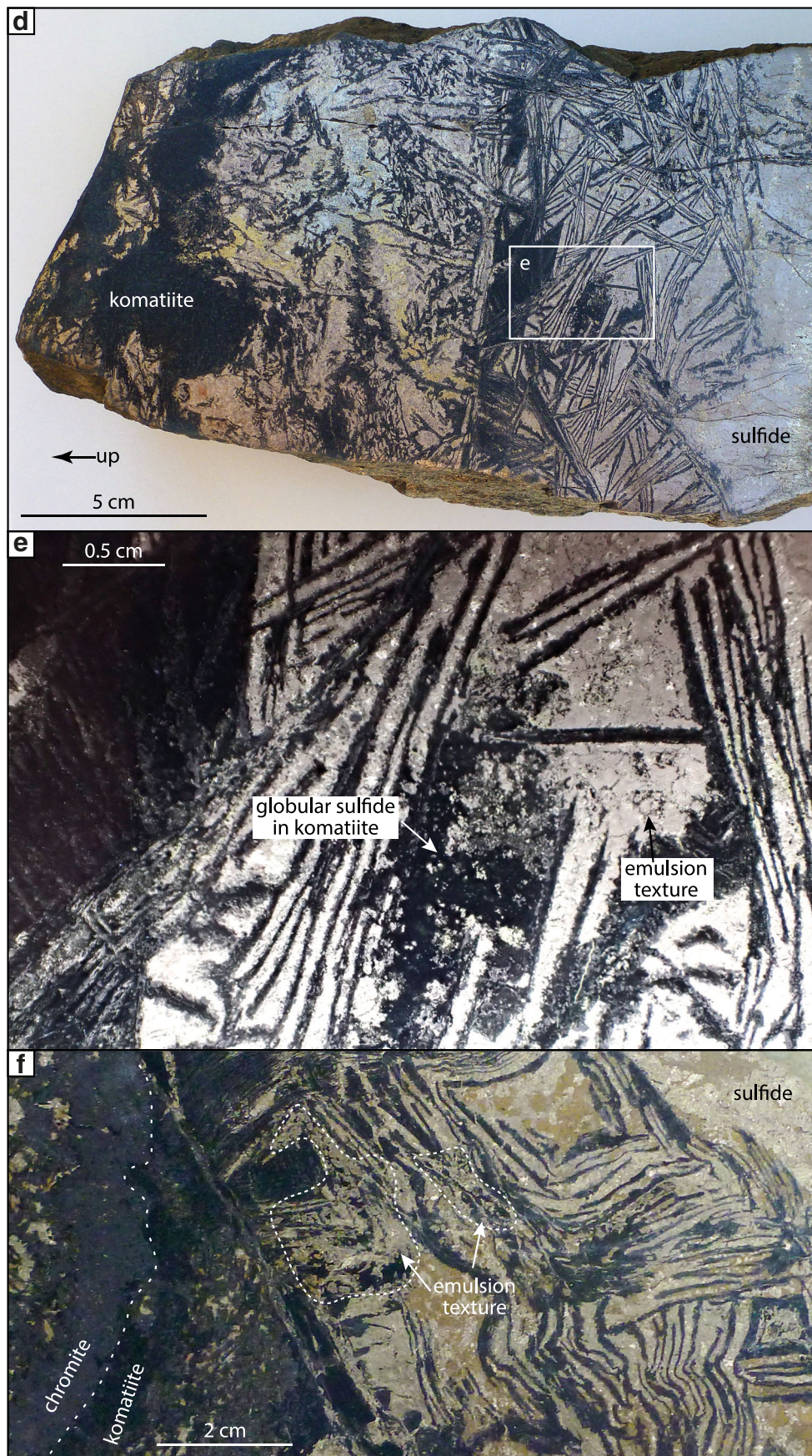


Fig. 6 (continued)

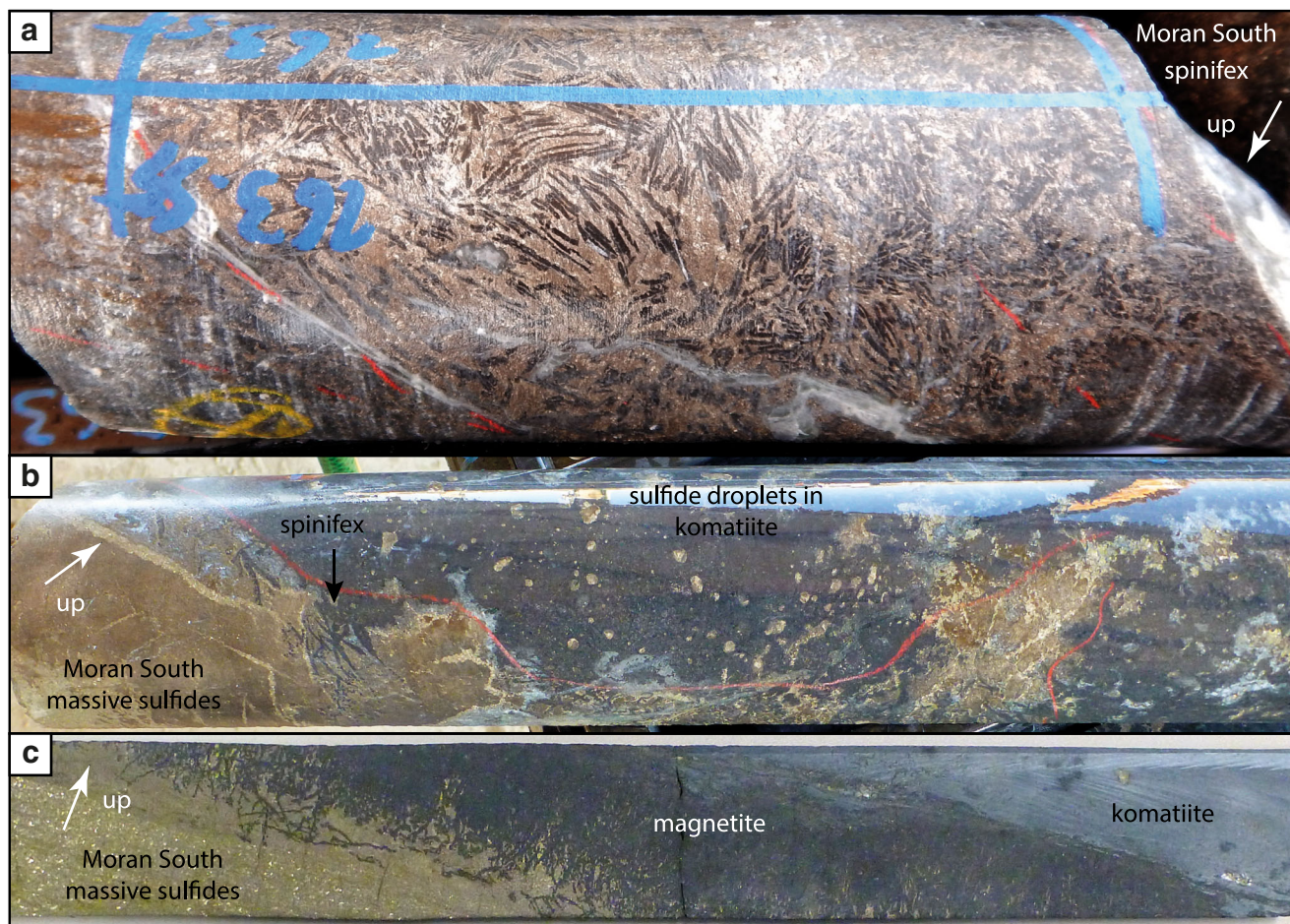


Fig. 7 Drill core intersects of interspinifex from Moran South. **a** Patches with spinifex plates (partly crumpled) which become smaller towards the right (LSU-507). **b** Contact of massive sulfides to komatiite with sulfide droplets with minor spinifex in-between. Note the preserved loop texture

in the sulfide aggregate to the right (LSU-507). **c** Contact of massive sulfides to barren komatiite with skeletal magnetite aggregates on the contact (LSU-545)

melt; Robertson et al. 2016). Possible formation models of komatiite and sulfide emplacement will be discussed below.

The higher Fe content in some komatiites associated with the interspinifex ore could be from dissolution of sulfides. The drill holes in Fig. 7 show the interaction of komatiite with older sulfides in the form of sulfides becoming entrained (Fig. 7b) and forming large sulfide droplets (indicative for this process; Robertson et al. 2016). Furthermore, dendritic magnetite forms on the contact and grows towards and inside the sulfides (Fig. 7c). The possibility of sulfide dissolution by younger magma batches was proposed by Kerr and Leitch (2005) and is thought to be responsible for Ni-rich olivine in Huanshanan (China) by scavenging Ni from a previously formed sulfide melt (Zhao et al. 2016). Magnetite is also a common metamorphic mineral in komatiites, and thus a definitive conclusion cannot be drawn whether the high magnetite content originates from sulfide dissolution or from metamorphism.

Spinel occurrence and geochemistry

Three types of spinel were observed in the interspinifex ore and komatiite associated with the interspinifex ore which overlap with the komatiite and massive sulfide fields or the magnetite rims (after Barnes and Roeder 2001). Interestingly, chromite of the komatiite and massive sulfide fields occurs both in interspinifex ore and in the komatiite associated with the interspinifex ore. An example is shown in Fig. 10, where the sulfide-hosted chromite cluster of Fig. 6a is composed of a chromite core, reflecting its origin from the komatiite, surrounded by a growth zone, which reflects growth in the sulfide melt, and an outer magnetite rim, likely of metamorphic origin (Barnes 2000). This also shows that the komatiite and sulfide melts interacted with each other and give important clues for the formation mechanism discussed below.

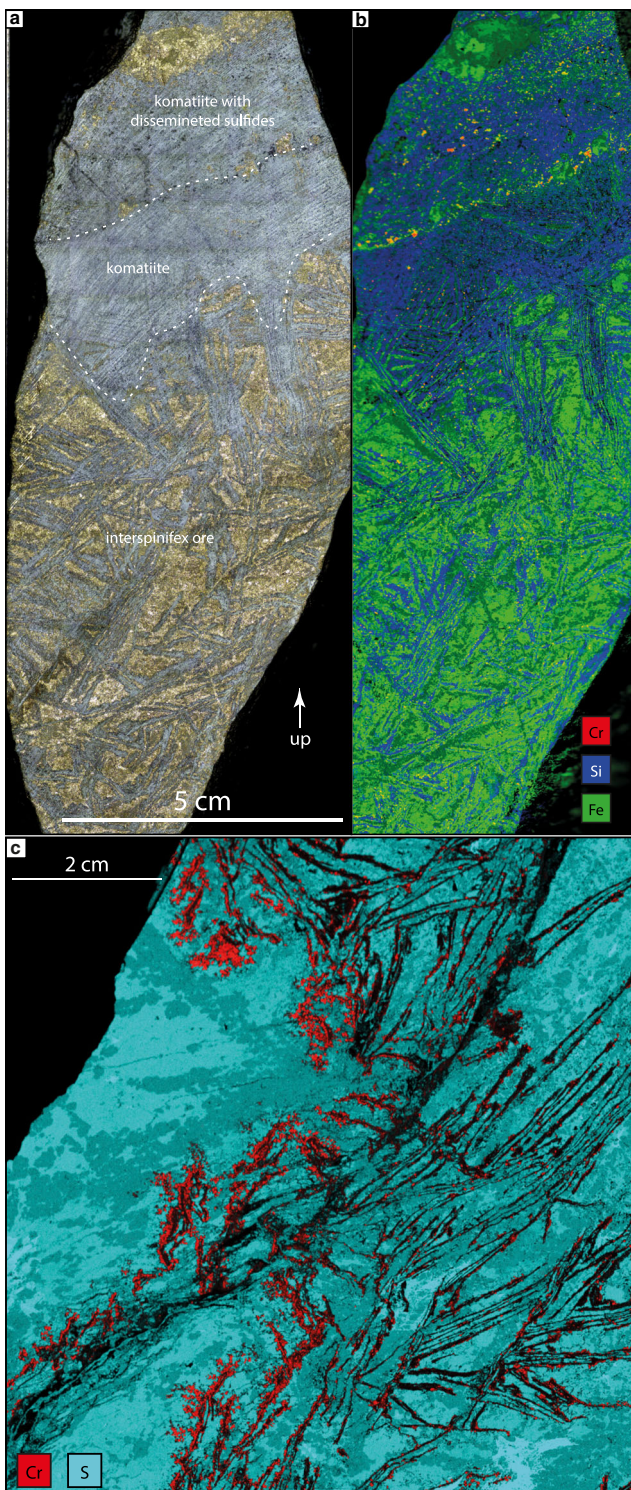


Fig. 8 **a** Photo of hand specimen where interspinifex ore is associated with komatiite and a fine-grained sulfide-silicate mixture. **b** Microbeam X-ray fluorescence image of (a) showing that the spinifex continues into the komatiite. The contact of the komatiite to the sulfide-silicate mixture is sharp. **c** Microbeam X-ray fluorescence image of a hand specimen containing a higher chromite amount. Note the lower amount of chromite where spinifex occurs and the higher amount where the silicate forms more irregular schlieren-like aggregates

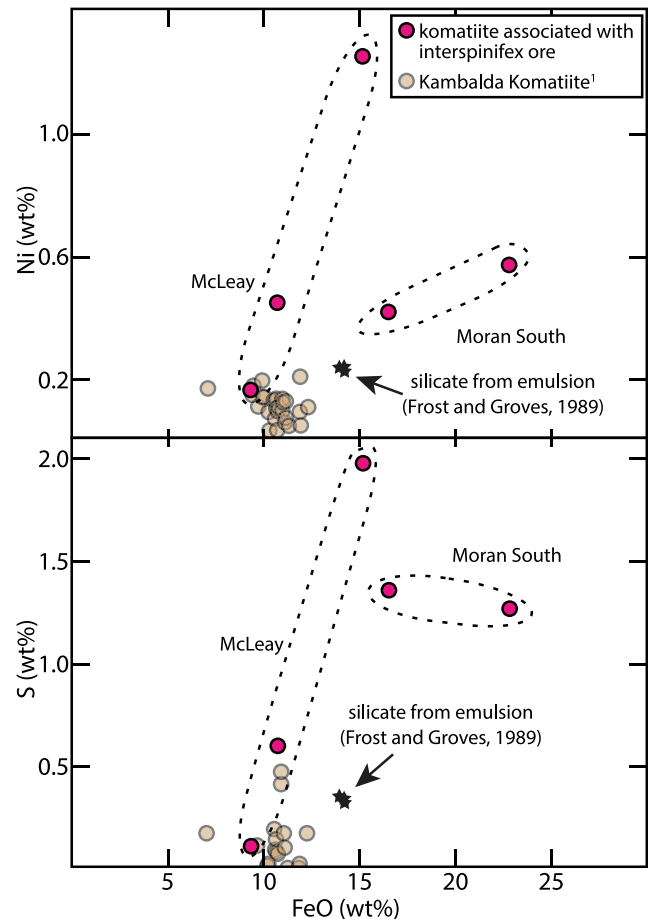
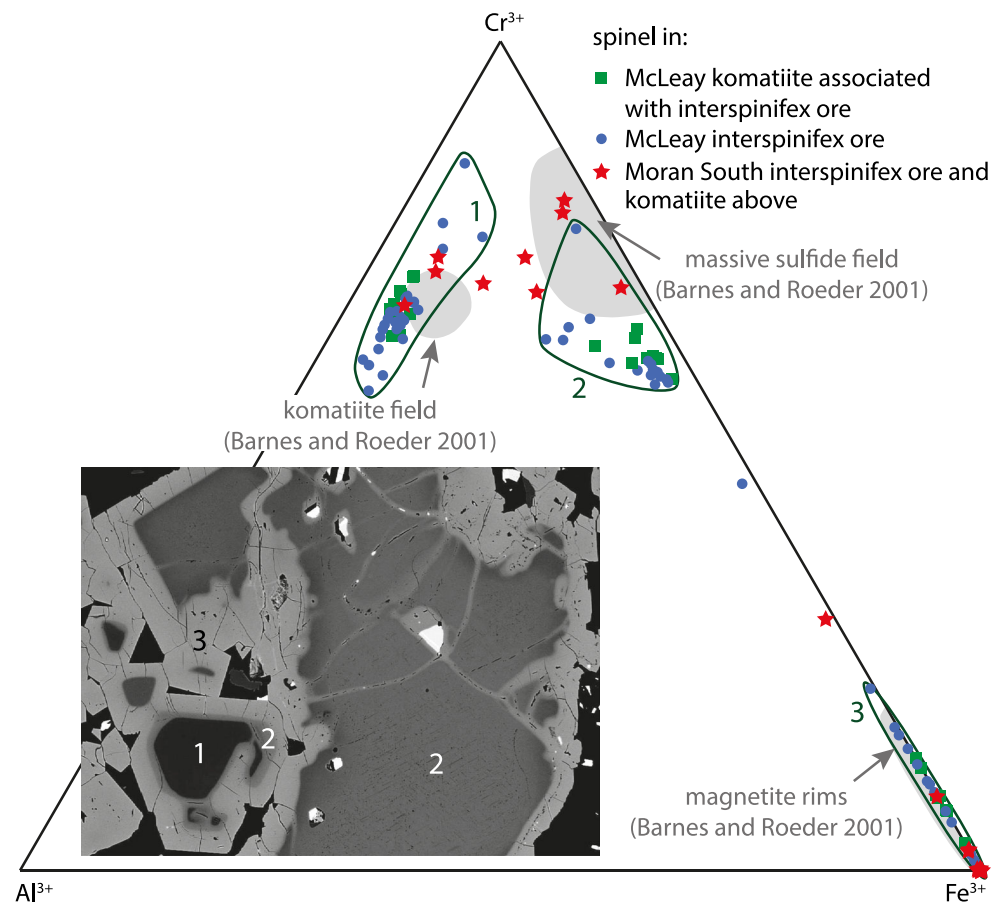


Fig. 9 Whole rock Ni **(a)** and S **(b)** versus FeO of Kambalda Komatiite (brown; Arndt and Jenner 1986; Leshner and Arndt 1995; Staude and Markl 2019), the komatiite above interspinifex ore (red) from McLeay and Moran South and silicate data from an emulsion from the Foster deposit. Data are not corrected for LOI or sulfide content. Note the higher Fe content of komatiite above interspinifex ore which cannot be explained by entrained sulfides

Comparison to similar textures in other komatiite-hosted sulfide deposits

In other deposits of the Kambalda Dome, lithologies have been described that could have a similar origin to the komatiite associated with the interspinifex ore described above. Beresford and Cas (2001) showed profiles from the flank of the Coronet deposit where ore-bearing random spinifex-textured komatiite is hosted by sediments forming a shallow intrusion. These textures were interpreted to originate from a komatiite intruding into unconsolidated sediments due to the higher density of the komatiite (Beresford and Cas 2001). Similar to the Coronet flank, the komatiite unit described here forms random spinifex. However, the reason for a possible burial into the denser cumulate pile of McLeay and Moran South remains unclear.

Fig. 10 Plot of the trivalent ions of spinel of interspinifex ore and the komatiite above. The inset shows a BSE image of a clustered chromite aggregate (from Fig. 6a) with all 3 types of spinel found in the interspinifex ore and the komatiite above



A section from the Foster deposit is presented by Frost and Groves (1989) and displays an unusual profile with the basal flow sulfides being overlain by a komatiite, hosting sulfide blebs, which is overlain by net-textured sulfides. This profile is similar to profile MDU-710 (Fig. 5a) of McLeay, although interspinifex ore is not mentioned. Frost and Groves (1989) report komatiite-sulfide emulsions on the upper sulfide contact which they argue originate from the interaction of a turbulent komatiite flow with sulfide melt. This could be a similar scenario to the observations described from McLeay/Moran South, but they report the upper net-textured sulfides on a faulted contact without further explanation where the net-textured ore comes from. If the example from Foster is similar to McLeay/Moran South, then it represents an early stage of the komatiite deposition or a lower komatiite volume, where the melt is frozen in prior to spinifex formation. Similar to the McLeay example, Frost and Groves (1989) report chromite in the silicate portion of the emulsion with a chemistry reflecting a sulfide origin.

Comparison with other interspinifex ore occurrences

The stratigraphic position and textures of interspinifex ore from Lunnon and Coronet have been interpreted as the result of downward infiltration of sulfide melt into older spinifex-textured komatiite, melting and displacing the original interspinifex liquid component (Groves et al. 1986; Barnes et al. 2016). These ores are developed as so-called hanging wall ores in open contact positions (i.e. outside pinchouts), where massive sulfide overlies the top of older internally differentiated flows. In both cases, the sulfide in the interspinifex ore can clearly be identified as having percolated down from an overlying massive sulfide pool. Interspinifex ore from McLeay and Moran South, on the other hand, differs significantly in the following respects:

- Part of the interspinifex ore occurrence is found in the pinchout of McLeay.
- McLeay/Moran South interspinifex ore occurs on top of the basal sulfides rather than at the base of hanging-wall sulfides associated with a subsequent flow.

- A sulfide-poor and magnetite-rich komatiite occurs on top of the interspinifex ore in McLeay/Moran South.
- The komatiite above the interspinifex ore contains globular sulfides that are concentrated near the interspinifex ore and near the net-textured ore above.
- Interspinifex ore from McLeay/Moran South is composed of randomly oriented patches of parallel spinifex plates rather than a single aggregate of parallel plates as in Lunnon and partly in Coronet (Barnes et al. 2016).
- Plumes of interstitial melt on top of the interspinifex ore from Lunnon and Coronet are lined by chromite, a texture which is not observed in McLeay/Moran South.
- Chromite in McLeay occurs irregularly and partly in clusters of skeletal crystals internally disposed within the interspinifex ore, not at the contacts.
- Fine-grained sulfide-silicate intergrowths and emulsion textures occur within large aggregates of spinifex plates in McLeay, a feature which is not observed at Lunnon or Coronet.

Despite detailed textural observations, the stratigraphic position of interspinifex ore and numerous whole-rock and chromite chemical compositions, a single model explaining every aspect is currently not available. A dynamic evolution of a large-scale lava flow systems with multiple separate ore deposits (especially in Archean rocks which are metamorphically overprinted and lack younger equivalents) excludes the classical explanation that all observations can fit one model. More likely, there are several end-member models with the real formation mechanism being a mixture of them. Thus, two potential formation models are presented in the following sections to account for the observations, followed by an assessment of the pros and cons of each. We believe this is the scientifically most honest way to deal with such a case.

Formation model 1 for the interspinifex ore

Some critical evidence bearing on the origin of the McLeay interspinifex ore comes from the drill hole shown in Fig. 4. The komatiite above the interspinifex ore appears to interact with massive sulfides underneath and also with the net-textured sulfides above (Fig. 4) to form the sulfide aggregates in the komatiite and spherical komatiite in the lower net-textured ore. Both ore types usually form a continuous sequence in undeformed contact ore in Kambalda (Gresham and Loftus-Hills 1981; Marston 1984), and therefore, it can be postulated that the komatiite in between intruded as a sill.

The sulfides need to be liquid during sill emplacement to form coarse plate spinifex in sulfides, spherical komatiite in sulfides, spherical sulfides in komatiite and emulsion textures

(Figs. 4, 6). Therefore, we propose that the komatiite melt injected into the sulfide melt pool, floating on its top and creating a barrier between massive and net-textured sulfides above (Fig. 11). The interpretation that both melts interacted with each other and komatiite melt assimilated and oxidized sulfides is also consistent with the observed textures and the geochemical data (e.g. sulfide blebs in komatiite, magnetite formation). Stirring during the injection formed an emulsion between the two immiscible melts, of which remnants are still visible in some samples (Fig. 6a, c) and in polished sections (e.g. frequent sulfide inclusions in the silicate portion of interspinifex ore and vice versa). As the net-textured sulfides were already present during the time of komatiite injection (e.g. large amounts of olivine are present) and the sulfides were still liquid, it can be assumed that the sulfide melt temperature was well below the komatiite eruption temperature (> 1500 °C; Arndt et al. 2008) and close to its solidus temperature (1190 °C; Naldrett 2004, and references therein). Therefore, during the initial contact between the two melts, a strong temperature gradient occurred, allowing for the formation of skeletal crystals of the liquidus phase (olivine) on the emulsified contact. The crystal growth was probably enhanced by the movement of the emulsion, i.e. small moving komatiite droplets constantly provided new material for crystal growth (Fig. 11c).

A possible analogue to this situation is a series of pharmaceutical-related experiments on organic crystal growth from an emulsion between viscous and less viscous water-based solutions performed by Wang et al. (2006). They found that needles and skeletal crystals were formed in the host liquid (analogous to the sulfide melt) outside the solvent drop (analogous to the silicate melt) by contact of the solvent with the growing crystal (equivalent to olivine). A frozen example of this process is seen in Fig. 6e and f where sulfide-silicate intergrowth and emulsion textures are situated immediately next to interspinifex ore and resemble an emulsion between the two melts. Once the crystals formed, the movement of the emulsion slowed down, allowing the two melts to separate again. The lighter komatiite melt floated upwards resulting in the inflow of sulfide melt between the olivine skeletons, forming the interspinifex ore observed in McLeay and Moran South (Fig. 11). Trapped silicate or sulfide melts between the crystals are now represented by the spheres observed (Fig. 6).

The downward growth of A-zone plate spinifex in komatiite lava flows is caused by the temperature gradient between the komatiite lava flow and the water above (Faure et al. 2006) creating the uniformly oriented parallel plates observed in the Lunnon and Coronet interspinifex ore. The patchy distribution of parallel plates in McLeay indicates a

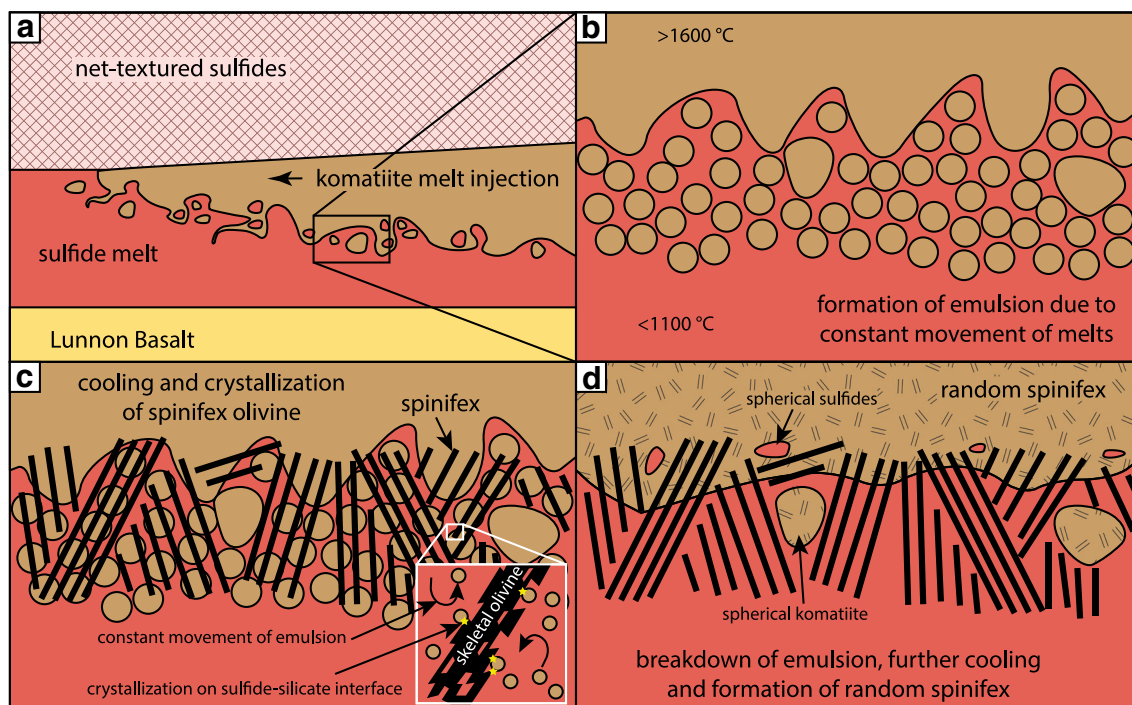


Fig. 11 Formation model (1) of interspinifex ore from McLeay and Moran South. **a** Komatiite melt injects into the liquid sulfide melt pool after the formation of net-textured ore but prior to sulfide crystallization. **b** At the sulfide-silicate melt interface, an emulsion is forming due to the movement. There is a strong temperature gradient of the komatiite melt to the sulfide melt and therefore skeletal olivine forms **c**. The crystal is growing due to constant stirring of the emulsion and therefore the silicate droplet coming in contact with a crystal nucleus (see inlet), increasing its

size to form the spinifex. **d** Due to the formation of large skeletal crystals, the movement of the melts slows down and the emulsion breaks down. Thus, the silicate portion of the emulsion floats up leaving the spinifex-textured plates in the sulfide melt behind. Where trapped between plates sulfides form aggregates in the komatiite portion and where komatiite is trapped between plates, it can form aggregates in the sulfide portion of the interspinifex ore

different and more complex cooling history. Variable flow velocity and cooling rate of the injecting komatiite melt are caused by the turbulent mixture of both melts resulting in various patches or adjacent cells with different droplet size and distribution. Thus, a temperature gradient is formed not only between sulfide and komatiite melt but also between the patches of the different types of emulsion. This can explain why there are patches with different growth direction of the spinifex but also the different size of the spinifex plates.

Chromite in the Lunnon interspinifex ore occurs on the contact of the interstitial silicate melt and the sulfide melt and represents the frozen melting front. In the emulsion scenario of McLeay/Moran South, both melts interact more dynamically, and, as noted above, chromite shows growth zonation originating from both silicate and sulfide melt. This can be explained by chromite growing in the injecting komatiite melt, continued growth in the sulfide-silicate emulsion, and re-deposition into the komatiite melt for the chromites found above the interspinifex ore. That can also explain the heterogeneous distribution of chromite in the McLeay interspinifex ore. The movement of the melts and emulsion prevents chromite from settling and could

concentrate it in eddies or areas of lower flow velocity, forming the chromite clusters as seen in Fig. 6a and f.

Formation model 2 for the interspinifex ore

Model 1 potentially explains many of the geometrical relationships but raises a number of other difficulties, as summarized in the following section. We therefore propose an alternative model involving multiple pulses of phenocryst-poor komatiite and sulfide liquid. The model illustrated in Fig. 12 refers specifically to the formation of spinifex ore in the pinchout position. Here, we envisage that the pinchout was initially formed by lateral thermal erosion by sulfide liquid as proposed by Staude et al. (2016). The pinchout then served as an undercut lateral flank of a continuously active flow channel, such that subsequent flows of sulfide-poor komatiite down the channel flushes out the original sulfide liquid that eroded the pinchout, replacing it with a thin komatiite unit consisting entirely of spinifex-textured A-zone with no corresponding cumulate B-zone. Subsequently, a second pulse of sulfide liquid flowed down the channel and through the pinchout,

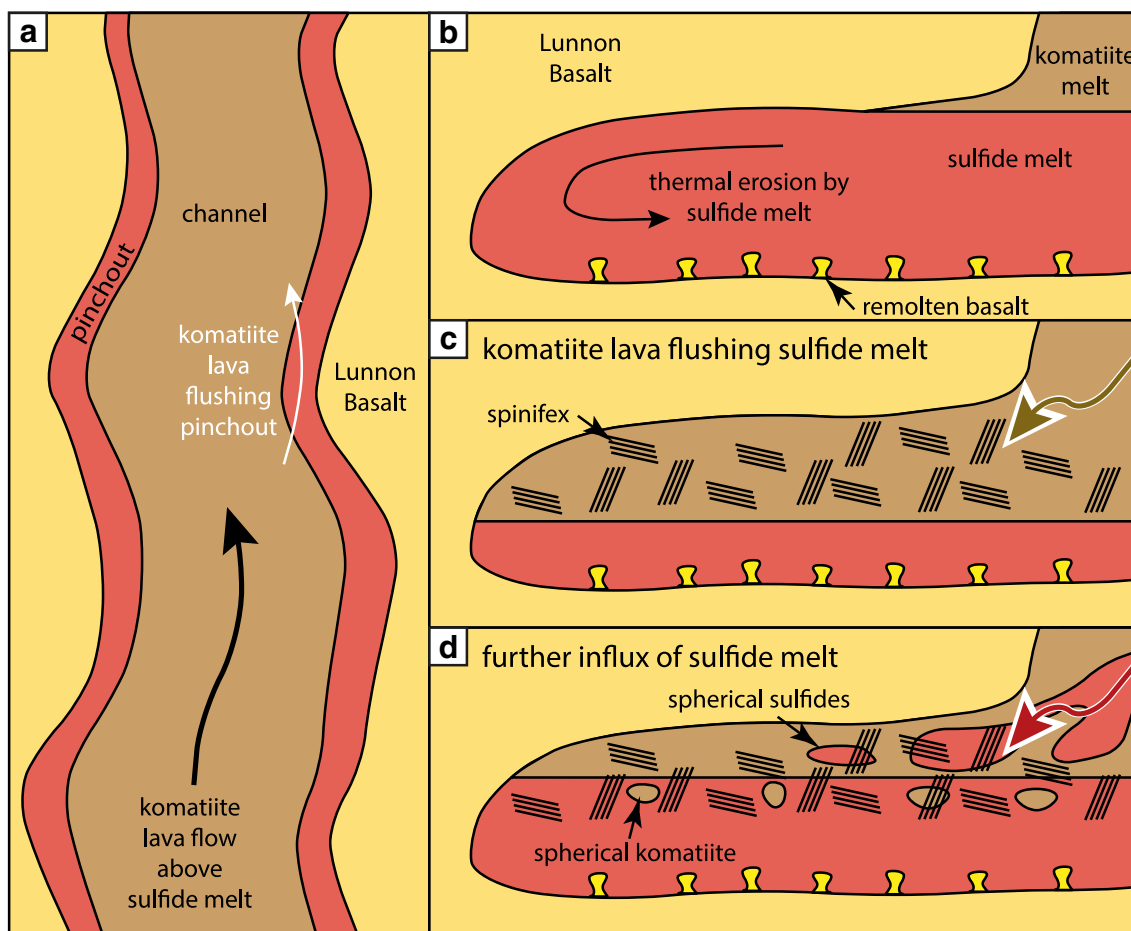


Fig. 12 Formation model (2) of interspinifex ore from McLeay and Moran South. **a** Plan view of channel showing pinchouts as multi-stage, dynamic features initially excavated by sulfide and/or komatiite lava, flushed out by komatiite, then by more sulfide. **b** Section view, excavation of pinchout by sulfide beneath flowing komatiite lava—note major component of the flow vector is into the page (parallel to channel). **c**

Continuing flow of lava flushes out most of sulfide—pinchout occupied by partially crystalline komatiite with spinifex (random and plates). **d** Further influx of sulfide displacing molten komatiite and generating spinifex ore—followed by further erosion and filling of pinchout by more komatiite lava

invading the komatiite flow (possibly still partially liquid) and flushing out the interspinifex liquid in the same way that interspinifex ore at Lunnon and Coronet have been thought to form (Barnes et al. 2016). Successive pulses of komatiite and sulfide in different parts of the channel potentially give rise to the various different configurations observed between sulfide, barren komatiite, interspinifex ore and net-textured ore.

Discussion of pro and con arguments for the two formation models

Model 1 of a younger komatiite melt intruding between the still liquid sulfides and the net-textured sulfides above can not only explain the observed textures (emulsion-like sulfide-silicate intergrowth immediately next to interspinifex ore) but also the observed stratigraphy in

the centre of the channel and in the pinchout, which forms by sulfides thermally eroding sideways in the final stages of embayment formation (Staude et al. 2016). Injecting komatiite melt would float on top of the sulfides underneath the older basalt (where there is a topographic height to form ribbon-like bodies) as is observed. Model 2 can also explain the pinchout geometry but requires a more complicated process by a further influx of sulfides after the komatiite melt flushed the pinchout and crystallized spinifex. Model 2 also requires the formation of net-textured sulfides without massive sulfides, after a barren komatiite flush, e.g. the initial sulfide melt on the base gets flushed out by komatiite. This komatiite is then followed by sulfides to displace the interstitial komatiite melt to form interspinifex ore. This needs to be followed by another barren komatiite and that is then followed by net-textured sulfides. Therefore, from a stratigraphic point

of view, model 1 is supported best by the observations, but model 2 is also able to explain them.

The high content of magnetite in the komatiite associated with interspinifex ore, together with the komatiite's high Ni, S, Pd and Pt content, could be explained by both models, i.e. by komatiite-sulfide interaction. The lack of large volumes of dispersed chromite in McLeay is in favour of model 2 if assumed that the upper portion of the texture, where a large volume of chromite is found in interspinifex ore from Coronet (Barnes et al. 2016), is missing by subsequent erosion of younger komatiite. If the texture is formed by an emulsion (model 1), more dispersed chromite would be expected due to the sulfide-silicate intersection. For model 1, chromite would need to be physically moved out of the texture and found elsewhere, which could explain the observed chromite cluster (Fig. 6a, f). The movement of the chromite can also explain their unusual growth zonation, reflecting alternating growth in sulfide and komatiite melts.

The main physical difficulty with model 1 is that it requires a relatively light komatiite liquid to inject as a sill into denser, still partially molten sulfidic material above (net-textured sulfides) and below (massive sulfides). It is a radically different mechanism than that proposed for interspinifex ores elsewhere. The main difference, besides the stratigraphic position, is that the interspinifex ores described here mostly show coarse random A2-zone textures rather than parallel plate A3 spinifex; otherwise, the essential relationship is the same. The injection of komatiite into its substrate has been reported in Kambalda (Beresford and Cas 2001) but into less dense sediments. An explanation could be the rupture (from seismicity) and dislocation of the cumulate pile; the lava flowing above is then blocked and forced to inject downwards. An alternative explanation in model 1 could be the injection from nearby faults from deeper reservoirs by syn-eruption tectonism. In this case, the liquid sulfide to solid net-textured contact can act as a barrier for the ascending komatiite melt. Komatiitic dykes have been observed in the immediate vicinity to McLeay and Moran South; however, they are probably younger than the basal komatiite flow (Staude and Markl 2019). Additionally, the new komatiite flow model by Gole and Barnes (2020) shows that there is the possibility of additional vents through all komatiite facies. From the physical process, it is easier to explain multiple sulfides and komatiite melts flushing the channel, but it is then difficult to explain why this easier process is not observed elsewhere.

An observation in favour of the “conventional” melt-displacement model 2 is that the interspinifex ore interval contains irregular sulfide-poor patches of spinifex-textured komatiite, wherein the form and grain size of the spinifex olivine is identical to that within the

immediately adjacent interspinifex sulfide ore (Fig. 8a, b). This is the same relationship observed in the more “conventional” interspinifex ores at Coronet, which tends to favour a commonality of process rather than a radically different mechanism for the Moran-McLeay interspinifex ores. In model 1, this texture could be realized, assuming that the emulsion breaks down and the komatiite floats up and is trapped in some places between the olivine plates.

Given these various objections to both models, it is unlikely that either is exactly correct, and some component of both processes may well be operating. It is also possible that some of the complexity may arise from fluidization and transport of more conventional spinifex ore developed initially upstream of the final site of deposition. Fragments of spinifex ore and partially remelted komatiite flow top may have been incorporated into a flowing sulfide-dominated mush flowing under a thin skin of komatiite lava, since removed by erosion by subsequent flows. Such a mechanism of transport and redeposition is consistent with our knowledge of sulfide melts as being very dense, very inviscid and highly corrosive fluids with remarkable capability of infiltrating and melting solid silicates (Barnes et al. 2018).

Summary and conclusion

Interspinifex ore from Victor South-McLeay and Moran South in Kambalda is found in the upper portion of basal massive sulfides and is overlain by a sulfide-free magnetite-rich komatiite. This is in contrast to interspinifex ores described from the nearby Lunnon and Coronet deposits which are found on the base of massive sulfides of the second lava flow. The Lunnon and Coronet occurrences are in central channel, open contact positions and formed from sulfide melt infiltrating the underlying spinifex zone of the basal flow (Barnes et al. 2016). The interspinifex ore described in here also is found in the centre of a channel at an open contact, but more significantly, the McLeay example is developed within a pinchout position. Such pinchouts are usually completely occupied by massive sulfides without underlying komatiite flows.

The observations preclude a definite textbook-like formation model, and thus, two formation mechanisms are presented: (1) a younger komatiite melt batch intrudes into its own cumulate pile to float on the still liquid sulfide melt. The komatiite melt is above its liquidus temperature ($> 1500\text{ }^{\circ}\text{C}$) whereas the sulfide melt is initially well below that temperature. During this injection process, a sulfide-silicate emulsion is formed with the immediate crystallization of skeletal olivine due to the temperature gradient. The skeletal crystals within the emulsion prevent further mingling of both melts and the

emulsion separates. The silicate portion floats upwards leaving skeletal olivine crystals in a sulfide matrix. (2) The interspinifex ore forms as result of sulfide melt invading and infiltrating a pre-existing thin komatiite flow lacking a cumulate B-zone, the entire sequence representing a dynamic sequence of multiple pulses of sulfide liquid and komatiite along a channel with undercut margins. Both of these models have substantial drawbacks, and additional factors such as downstream mobilization and redeposition of a sulfide melt-komatiite-olivine slurry may have played a role. Regardless of the precise mechanism, the complexity of the McLeay and Moran South occurrences shows that the dynamics of komatiite ore-forming environments are more complex than classical textbook models or all current models for magmatic sulfide deposits suggest. The McLeay and Moran interspinifex ores are examples of the complex textural relationships that can develop between flowing and crystallizing immiscible magmas.

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References

- Arndt NT (1986) Thermal erosion by komatiite at Kambalda. *Nat* 324: 600
- Arndt NT, Jenner GA (1986) Crustally contaminated komatiites and basalts from Kambalda, Western Australia. *Chem Geol* 56:229–255
- Arndt NT, Leshner CM, Barnes SJ (2008) Komatiite. Cambridge University Press
- Barnes SJ (2000) Chromite in komatiites, II modification during greenschist to mid-amphibolite facies metamorphism. *J Petrol* 41: 387–409
- Barnes SJ, Roeder PL (2001) The range of spinel compositions in terrestrial mafic and ultramafic rocks. *J Petrol* 42:2279–2302
- Barnes SJ (2006) Komatiites: petrology, volcanology, metamorphism, and geochemistry. *Soc Econ Geol Spec Publ* 13:13–49
- Barnes SJ, Gole MJ, Hill RET (1988) The Agnew nickel deposit, Western Australia: part I. stratigraphy and structure. *Econ Geol* 83:524–536
- Barnes SJ, Beresford SW, Le Vaillant M (2016) Interspinifex Ni sulfide ore from the coronet shoot, Kambalda: characterization using microbeam X-ray fluorescence mapping and 3-D X-ray computed tomography. *Econ Geol* 111:1509–1517
- Barnes SJ, Mungall JE, Le Vaillant M, Godel B, Leshner CM, Holwell DA, Lightfoot PC, Krivolutskaia NA, Wei B (2017) Sulfide-silicate textures in magmatic Ni-Cu-PGE sulfide ore deposits. Disseminated and net-textured ores. *Am Mineral* 102:473–506
- Barnes SJ, Stauda S, Le Vaillant M, Pina R, Lightfoot PC (2018) Sulfide-silicate textures in magmatic Ni-Cu-PGE sulfide ore deposits: massive, semi-massive and sulfide-matrix breccia ores. *Ore Geol Rev* 101:629–651
- Bavinton OA (1981) The nature of sulfidic metasediments at Kambalda and their broad relationship with associated ultramafic rocks and nickel ores. *Econ Geol* 76:1606–1628
- Beresford SW, Cas RAF (2001) Komatiitic invasive lava flows, Kambalda, Western Australia. *Can Mineral* 39:525–535
- Cowden A (1988) Emplacement of komatiite lava flows and associated nickel sulfides at Kambalda, Western Australia. *Econ Geol* 83: 436–442
- Faure F, Arndt NT, Libourel G (2006) Formation of spinifex texture in komatiites: an experimental study. *J Petrol* 47:1591–1610
- Frost KM, Groves DI (1989) Magmatic contacts between immiscible sulfide and komatiite melts: implications for genesis of Kambalda sulfide ores. *Econ Geol* 84:1697–1704
- Gole MJ, Barnes SJ (2020) The association between Ni-Cu-PGE sulfide and Ni-Co lateritic ores and volcanic facies within the komatiites of the 2.7 Ga East Yilgarn Craton Large Igneous Province, Western Australia. *Ore Geol Rev* 103231
- Goscombe B, Blewett RS, Czarnota K, Groenwald PB, Maas R (2009) Metamorphic evolution and integrated terrane analysis of the eastern Yilgarn Craton: rationale, methods, outcomes and interpretation. *Geosci Aust Rec* 2009(23)
- Green AH, Naldrett AJ (1981) The Langmuir volcanic peridotite-associated nickel deposits: Canadian equivalents of the Western Australian occurrences. *Econ Geol* 76:1503–1523
- Gresham JJ, Loftus-Hills GD (1981) The geology of the Kambalda nickel field, Western Australia. *Econ Geol* 76:1373–1416
- Groves DI, Korhonen EA, McNaughton NJ, Leshner CM, Cowden A (1986) Thermal erosion by komatiites at Kambalda, Western Australia and the genesis of nickel ore. *Nat* 319:136–139
- Houlé MG, Leshner CM (2011) Komatiite-associated Ni-Cu-PGE deposits, Abitibi greenstone belt, Superior Province, Canada. *Rev Econ Geol* 17:89–121
- Houlé MG, Leshner CM, Davis PC (2012) Thermomechanical erosion at the Alexo Mine, Abitibi greenstone belt, Ontario: implications for the genesis of komatiite-associated Ni-Cu-PGE mineralization. *Mineral Deposita* 47:105–128
- Kerr A, Leitch AM (2005) Self-destructive sulfide segregation systems and the formation of high-grade magmatic ore deposits. *Econ Geol* 100:311–332
- Kress V, Greene LE, Ortiz MD, Mioduszecki L (2008) Thermochemistry of sulfide liquids IV; density measurements and the thermodynamics of O-S-Fe-Ni-Cu liquids at low to moderate pressures. *Contrib Mineral Petrol* 156:785–797
- Leshner CM, Arndt NT, Groves DI (1984) Genesis of komatiite-associated nickel sulphide deposits at Kambalda Western Australia: a distal

- volcanic model. In: Buchanan DL, Jones MJ (eds) Sulphide deposits mafic ultramafic rocks. Institute of Mining and Metallurgy, London, pp 70–80
- Leshner CM, Arndt NT (1995) REE and Nd isotope geochemistry, petrogenesis and volcanic evolution of contaminated komatiites at Kambalda, Western Australia. *Lithos* 34:127–157
- Marston RJ (1984) Nickel mineralization in Western Australia. Geological Survey of Western Australia, Mineral Res Bull 14
- Naldrett AJ (2004) Magmatic sulfide deposits. Springer
- Robertson JC, Barnes SJ, Le Vaillant M (2016) Dynamics of magmatic sulphide droplets during transport in silicate melts and implications for magmatic sulphide ore formation. *J Petrol* 56:2445–2472
- Said N, Kerrich R, Groves DI (2010) Geochemical systematics of basalts of the lower basalt unit, 2.7 Ga Kambalda sequence, Yilgarn Craton, Australia: plume impingement as a rifted craton margin. *Lithos* 115: 82–100
- Staude S, Barnes SJ, Le Vaillant M (2016) Evidence of lateral thermomechanical erosion of basalt by Fe-Ni-Cu sulfide melt at Kambalda, Western Australia. *Geol* 44:1047–1050
- Staude S, Barnes SJ, Le Vaillant M (2017a) Thermomechanical erosion of ore-hosting embayments beneath komatiite lava channels: textural evidence from Kambalda, Western Australia. *Ore Geol Rev* 90:446–464
- Staude S, Sheppard S, Parker P, Paggi J (2017b) Long-Victor nickel sulfide complex, Kambalda, Western Australia. In: Philips N (ed) Australian ore deposits monograph 32. Australian Institute of Mining and Metallurgy, Melbourne, pp 107–112
- Staude S, Markl G (2019) Remnant lenses of komatiitic dykes in Kambalda (Western Australia): occurrences, textural variations, emplacement model, and implications for other komatiite provinces. *Lithos* 342–343:206–222
- Staude S, Jones TJ, Markl G (2020) The textures, formation and dynamics of rare high-MgO komatiite pillow lavas. *Precambrian Research* 343:105729
- Stone WE, Archibald NJ (2004) Structural controls on nickel sulphide ore shoots in Archaean komatiite, Kambalda, WA: the volcanic trough controversy revisited. *J Struct Geol* 26:1173–1194
- Wang X, Gillian JM, Kirwan DJ (2006) Quasi-emulsion precipitation of pharmaceuticals. 1. Conditions for formation and crystal nucleation and growth behaviour. *Cryst Growth Design* 6:2214–2227
- Williams DA, Kerr RC, Leshner CM (1998) Emplacement and erosion by Archean komatiite lava flows at Kambalda: revisited. *J Geophys Res* 103:27533–27549
- Zhao Y, Xue C, Zhao X, Yang Y, Ke J, Zu B, Zhang G (2016) Origin of anomalously Ni-rich parental magmas and genesis of the Huangshannan Ni-Cu sulfide deposit, Central Asian Orogenic Belt, Northwestern China. *Ore Geol Rev* 77:57–71

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