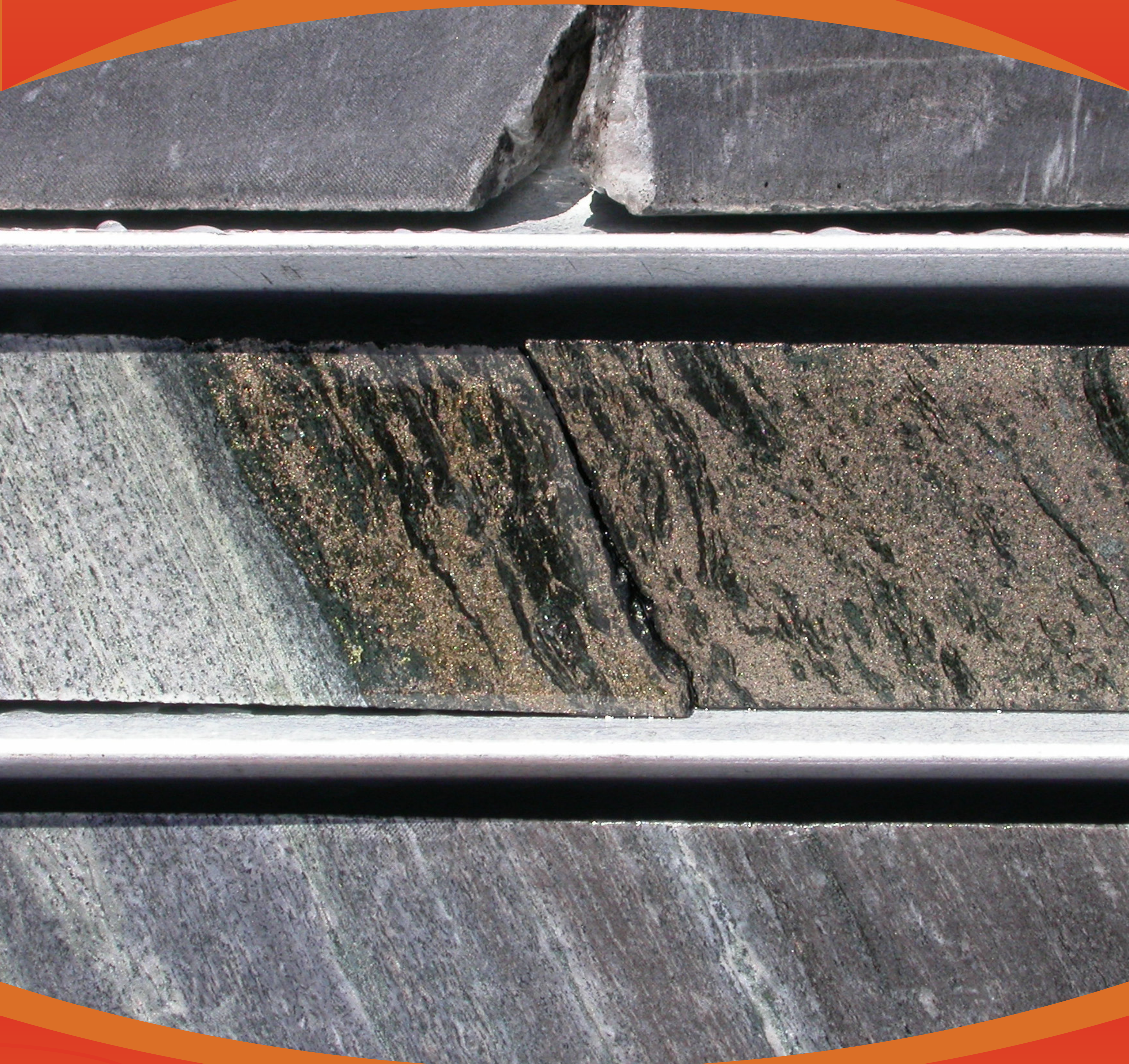
Department of Energy, Mines, Industry Regulation and Safety
GOVERNMENT OF WESTERN AUSTRALIA
Geological Survey of Western Australia

REPORT 253



DEFORMED NI–CU–(PGE) DEPOSITS: STRUCTURES, REMOBILIZATION, AND EXPLORATION IMPLICATIONS

P DUURING

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The Department of Energy, Mines, Industry Regulation and Safety (DEMIRS) respectfully acknowledges Aboriginal peoples as being the traditional custodians of Western Australia. We acknowledge the enduring connection Aboriginal people continue to share with the land, sea and sky through both their ancestral ties and custodianship to Country. We pay our respect to Elders both past and present, and acknowledge the value brought to our department through the collective contribution of Aboriginal and Torres Strait Islander peoples across Western Australia.

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Cover image: Drillcore examples of deformed pyrrhotite–pentlandite massive sulfides from the Perseverance deposit, Leinster, Western Australia

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Deformed Ni–Cu–(PGE) deposits: structures, remobilization, and exploration implications

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Scientific abstract

This study investigates the mineralogical and geochemical characteristics of remobilized massive sulfide orebodies, emphasizing their distribution, structural deformation and metamorphic transformation, and the influence of hydrothermal processes within terranes hosting primary Ni–Cu–(PGE) deposits. The research provides critical insights for refining exploration models by identifying key controls on orebody remobilization and predicting their locations in structurally complex terranes. Primary massive sulfides, predominantly composed of pyrrhotite and pentlandite with minor pyrite, chalcopyrite, and magnetite, commonly occur along footwall contacts of ultramafic rocks. In contrast, remobilized massive sulfides are often found in structurally complex settings, within faults, shear zones, and folds, and can be associated with various host rocks. These remobilized sulfides exhibit distinctive features, including foliation defined by flattened pentlandite porphyroblasts formed due to partial sulfide recrystallization under stress. Structural elements, such as elongated, folded massive sulfides and boudinage, significantly influence ore redistribution. Boudinage and durchbewegung structures arise from competency differences between host rocks, matrix sulfide-bearing rocks, and massive sulfides, influencing orebody geometry and providing important structural markers for exploration. Shear zones, piercement cusps, and veins frequently host remobilized ore, further emphasizing the role of deformation in redistributing sulfides. Metamorphism modifies sulfide textures and compositions through recrystallization and coarsening, with temperature being the primary control over these changes. Additionally, alteration and hydrothermal transport contribute significantly to chemical remobilization, where fluids infiltrate sulfide-bearing rocks, dissolving and reprecipitating minerals such as chalcopyrite and pentlandite. This process not only redistributes metals over greater distances but can also enhance ore grades by concentrating metals in structurally favourable zones. Insights from experimental studies on sulfide minerals and hydrothermal systems provide a framework for interpreting remobilization distances and the effects of metamorphic and hydrothermal conditions. Analysis of compiled data from naturally occurring massive sulfide ores shows that remobilization distances are typically within 50 m of primary ore positions but can extend to 500 m or, in highly deformed terranes, up to 1 km. This range underscores the importance of integrating structural, geochemical and hydrothermal data when prioritizing exploration targets. Variations in Ni tenor and Ni/Cu ratios with remobilization distance are attributed to contrasting rheological and chemical behaviours of sulfides, with softer minerals like pyrrhotite and chalcopyrite being transported farther than pentlandite. These findings enhance our understanding of remobilization, metamorphic effects, and hydrothermal contributions in komatiitic Ni–Cu–(PGE) deposits and provide valuable insights for exploration strategies in structurally complex terranes.

KEYWORDS: deformation (structural geology), exploration, komatiite, nickel

Lay abstract

This study explores how nickel-rich sulfide ores, essential for industrial metals, are affected by geological processes such as deformation and metamorphism in ancient rock formations. These sulfide deposits often form along the edges of ultramafic rocks but can move to new locations through natural forces like faulting and folding. By studying their mineral makeup and how they change under heat and pressure, scientists can better predict where to find these valuable resources. This research shows that remobilized ores are often located within 50 m of their original position but can sometimes be displaced by up to 1 km. These findings help improve strategies for locating nickel deposits in complex geological terrains.

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Introduction

Ultramafic-hosted Ni–Cu–(PGE) deposits result from magmatic processes that concentrate Ni-rich sulfides at the base of crystallizing high-temperature, low-viscosity magmas (Watkinson and Irvine, 1964; Naldrett and Cabri, 1976; Campbell and Naldrett, 1979; Naldrett, 1997, 1999, 2004; Barnes et al., 2016). Exploration strategies in nickel sulfide camps, such as those at Kambalda and the Agnew–Wiluna greenstone belt in Western Australia, as well as the Superior Craton in Canada, primarily focus on the stratigraphic footwall positions of komatiites. These locations have consistently proven to be promising exploration targets. However, these deposits are often found in Archean terranes that have undergone significant metamorphism, deformation, and hydrothermal alteration, leading to the overprinting of post-magmatic processes, which result in the redistribution of nickel sulfides to exotic positions relative to their primary footwall contacts. Since the late-1960s, there has been an increasing awareness of the role of secondary processes in modifying the textural, mineralogical, and chemical properties of ultramafic-hosted Ni–Cu–(PGE) deposits (e.g. Vokes, 1969; Marshall and Gilligan, 1987; Bleeker, 1990; Stone, 2003; Duuring et al., 2007; Gonzalez-Alvarez et al., 2013; Le Vaillant et al., 2015).

Despite the comprehensive literature on the deformation and metamorphism of Ni–Cu–(PGE) deposits, several important questions remain that have implications for exploration: (i) how far massive sulfide ores can migrate from their primary footwall contacts; (ii) whether high-temperature metamorphism significantly reduces sulfide viscosity, allowing greater ore displacement; and (iii) whether systematic mappable changes exist in ore texture and chemistry with increasing distance from footwall locations.

This study addresses these questions through the compilation of a database (Appendix 1) that documents the physical and chemical characteristics of 75 massive sulfide-bearing, komatiite-hosted Ni–Cu–(PGE) deposits located in Western Australia, Canada, Russia, Zimbabwe, Brazil, and Vietnam. The study compares mineralogical and structural features to infer metamorphic grade, ore redistribution distances, and compositions, all documented in the database. An understanding of these secondary processes presents additional opportunities for the exploration and mining of magmatic-related Ni–Cu–(PGE) deposits.

Experimental studies on sulfide minerals, combined with natural observations, provide critical insights into their behaviour under deformation and metamorphism, essential for understanding Archean amphibolite-facies terranes. For example, an understanding of knowledge gained from experimental studies on sulfide minerals (i.e. pyrite, galena, chalcopyrite, pyrrhotite, and pentlandite), followed by experiments on naturally-occurring, pyrrhotite–pentlandite massive sulfide ores from the Yilgarn Craton, provides vital insight into the expected behaviour of these minerals during increasing deformation and prograde metamorphism, as present in Archean amphibolite-facies terranes that typically contain these deposits.

Characteristics of deformed and metamorphosed Ni–Cu–(PGE) deposits

Primary massive sulfides

Primary, or 'contact,' massive sulfides are located in their original magmatic position along basal footwall contacts of ultramafic rocks (Fig. 1). They exhibit undisturbed, gradational contacts with overlying matrix and/or disseminated sulfide ores. Primary massive sulfides are primarily composed of pyrrhotite and pentlandite, with lesser amounts of pyrite and chalcopyrite, and minor inclusions of magnetite, chromite, hematite, sphalerite, galena, PGE, millerite, and violarite (Appendix 1). Their texture is generally massive. However, when subjected to deformation and metamorphism, primary massive sulfides may develop coarser-grained textures, pentlandite–pyrrhotite±chalcopyrite banding, aligned asymmetric pentlandite porphyroblasts, annealed grains, kink bands, recrystallized pyrite, and foliation. These secondary textures form essentially in situ, contrasting with the remobilized massive sulfides described below.

Remobilized massive sulfides

In this study, the term 'remobilization' refers to the processes affecting existing orebodies, while 'mobilization' describes the movement of metallic constituents initially dispersed in ordinary rocks (cf. Marshall et al., 1998; Vokes et al., 1998). Remobilized massive sulfides are identified by their migration within the parent komatiite or into surrounding footwall and hangingwall units (Fig.1), such as metamorphosed basalt, sedimentary and volcaniclastic rocks, or felsic intrusions. Footwall units more commonly host remobilized ore compared to hangingwall units due to their proximity to primary massive sulfides concentrated along basal contacts (Fig.1).

Remobilized ore is often found in post-magmatic faults, shear zones, piercement structures, and fold hinges and may incorporate brecciated wallrock clasts (Fig. 2). Ore textures can vary widely and they may include massive, coarser-grained sulfides, brecciated wallrock inclusions, pentlandite–pyrrhotite banding, aligned asymmetric pentlandite porphyroblasts, annealed grains, kink bands, recrystallized pyrite, chalcopyrite bands, and weak foliation (Appendix 1).

Distinguishing between deformed primary massive sulfides and remobilized ores is often challenging, especially without a clear structural context. Many textural features, such as recrystallized sulfide minerals and banding, are commonly observed in both types. Brecciated wallrock clasts, while more frequently associated with remobilized ores due to mechanical incorporation during ore migration through post-magmatic faults and shear zones, are not unique and can occasionally form within primary ores. This overlap, combined with gaps in the existing literature, makes quantifying remobilization parameters difficult.To address these complexities, this study examines 75 deposits (Appendix 1) that provide detailed documentation of both primary and remobilized sulfide characteristics.

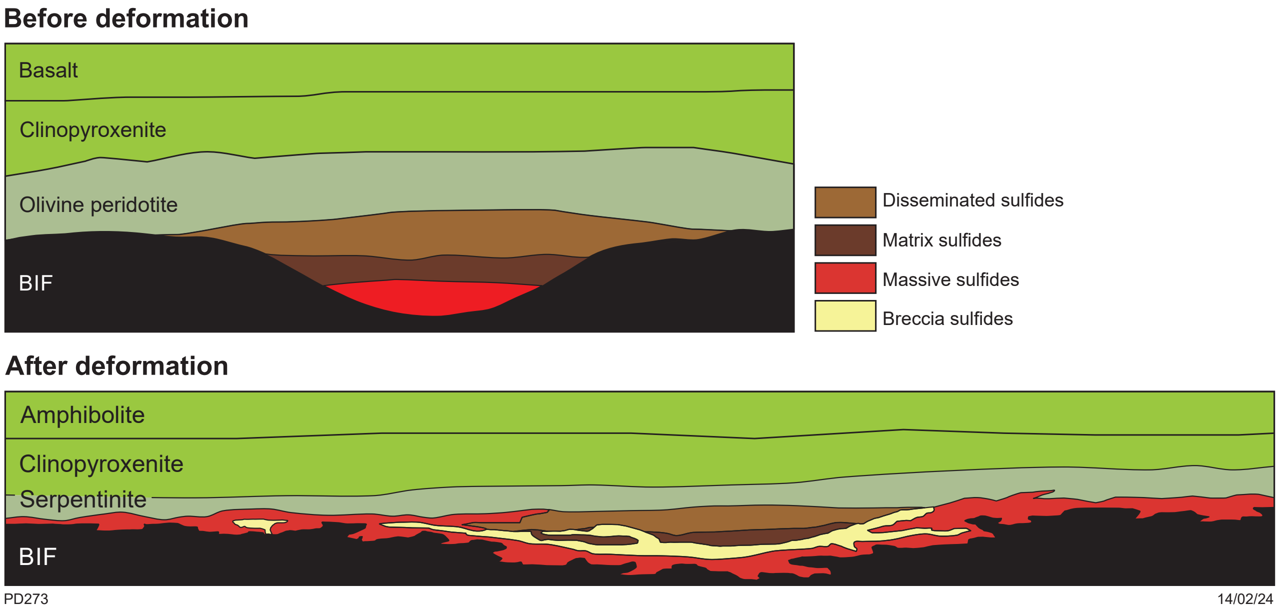

Figure 1. Massive sulfide injection into banded iron-formation (BIF) footwall and overlying metakomatiite hangingwall at the O'Toole Ni deposit, Morro do Ferro greenstone belt, Brazil (from Brenner et al., 1990)

Understanding the characteristics of primary and remobilized massive sulfides provides the foundation for interpreting their current geometry and distribution. Structural deformation and metamorphism, discussed in the following sections, play a critical role in modifying these ores, influencing their texture, composition, and spatial relationships.

Folds and elongated orebodies

Thin massive sulfide layers may thicken passively by the duplication of ore layers (Fig. 2a) or by the active remobilization of massive sulfides from fold limbs to hinge areas (Fig. 2b; Martin, 1966; Zachrisson, 1971; Davis, 1972; Marshall and Gilligan, 1987; Duuring et al., 2007). In these cases, orebodies tend to be elongated parallel to fold axial surfaces or mineral stretching lineation directions (Gilligan, 1984; Plimer, 1987 Fig. 3). Subsequent deformation episodes may result in multiple fold generations, which complicate the overall plunge of the orebodies and may also lead to the disruption of folded ores by the thinning and rupture of the fold limbs or by movement along axial planes (Fig. 4), causing the segmentation and en echelon displacement of the massive sulfide orebodies (Gilligan, 1984; Plimer, 1987).

Boudinage, attenuation, and durchbewegung structures

Boudinage and attenuation of massive sulfide orebodies arise from the competency contrast between an incompetent massive sulfide-rich host and surrounding more competent host rocks. During deformation, massive sulfides are remobilized and flow towards low mean stress zones that develop at boudin necks (Fig. 2c, 5). Simple shearing along a ductile sulfide layer causes durchbewegung (Vokes, 1973) or 'ball' texture.

During shearing, the more competent wallrock material is detached from the margins and incorporated into the ductile massive sulfide layer (Fig. 2d). Rolling of wallrock fragments in the highly ductile massive sulfide matrix causes rounding of the fragments, rootless folds, and pressure shadows of plastic sulfides that develop around more competent phases, such as pyrite and wallrock clasts.

Shear zones, piercement cusps, and veins

Tectonism accompanying metamorphism may cause massive sulfides to be remobilized within shear zones (Fig. 2e; up to 1 km from their original position; Barnes and Hill, 1998) or along deformed lithological contacts, axial planar foliation of folds, or structures that transgress footwall and hangingwall contacts, including piercement cusps and piercement veins (Fig. 2f). The margins of intrusions that cut the primary basal contact can also be sites for thickened massive sulfide ore (e.g. Flying Fox; Collins et al., 2012b). The deformation of massive sulfides during remobilization is strongly influenced by the deformation regime and crustal depth. In ductile regimes at deeper crustal levels, massive sulfides are more likely to deform within shear zones and other ductile structures, whereas, in brittle regimes at shallower depths, massive sulfides are typically affected by localized fracturing and faulting. Deposits that experienced multiple episodes of deformation may contain massive sulfides within structures formed under both ductile and brittle regimes (e.g. Rocky's Reward, Harmony, Edwards, Otter–Juan deposits).

Metamorphic recrystallization and coarsening of sulfides

The effect of prograde metamorphism on Ni–Cu–(PGE) ores through amphibolite-facies grades is that ores revert to mixtures of monosulfide solid solution, intermediate solid solution, pentlandite, and/or pyrite, with relict spinels during peak metamorphism (McQueen, 1979).

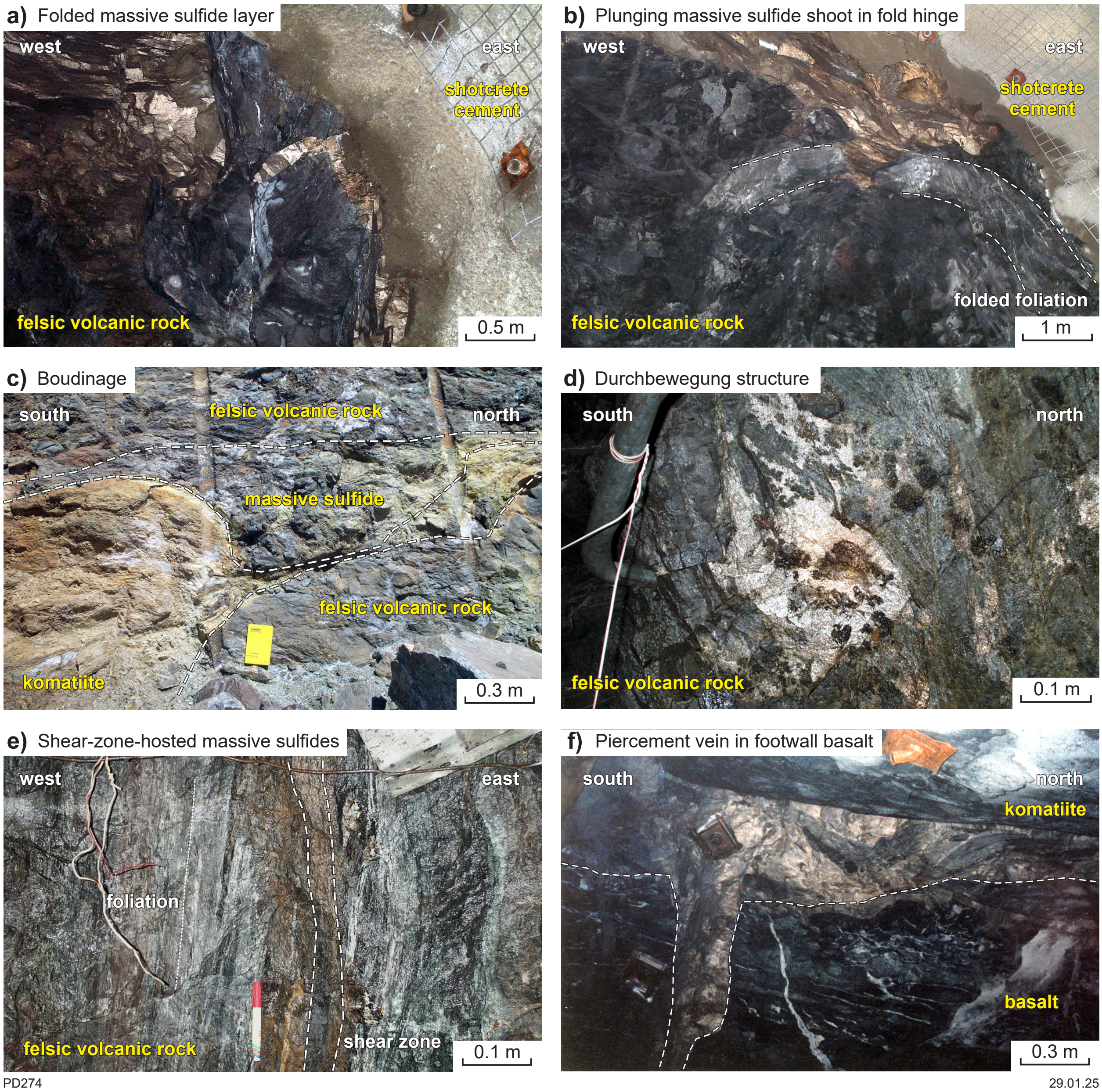

Figure 2. Photoplate showing common massive sulfide remobilization structures: a) folded footwall rocks, bedding-parallel schistosity, and a massive sulfide vein in the F2 shoot at Perseverance; b) remobilized massive sulfides concentrated in the hinge zone of an upright fold in the Felsic Nose area, Perseverance; c) massive sulfides are concentrated in a boudin neck area of deformed komatiite and surrounding footwall rocks at Harmony; d) brecciation and inclusion of footwall rocks in massive sulfides within 2 m of the 1A massive sulfide shoot, Perseverance; e) massive sulfides hosted by a northwest striking subvertical shear zone in footwall rock in the F2 access drive, 9780mRL, Perseverance; f) massive sulfide piercement structure from the footwall contact into metabasalt, Wannaway (from Seat, 2002)

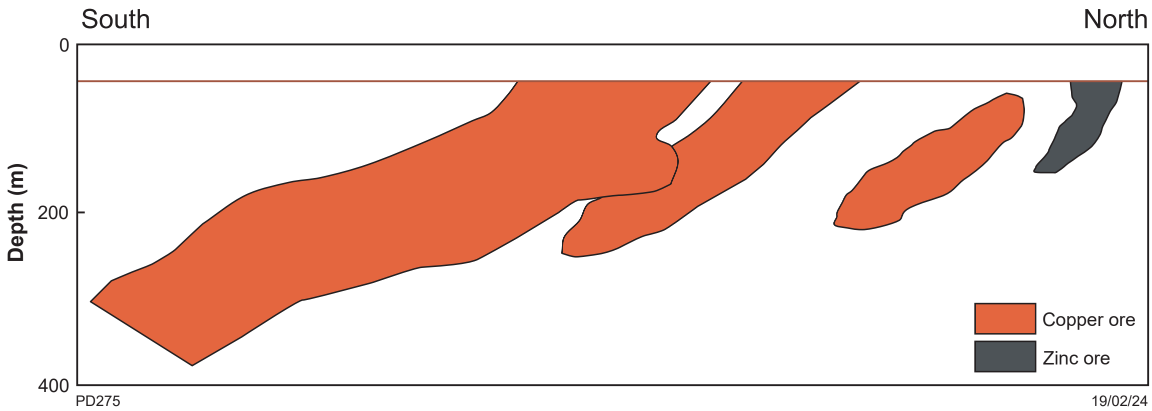

Figure 3. A long-section of the Vihanti and Hammaslahti Zn–Cu deposits, Norway (after Gaál, 1977). The plunge of the massive sulfide shoots is parallel to that of S-plunging folds and regional stretching directions

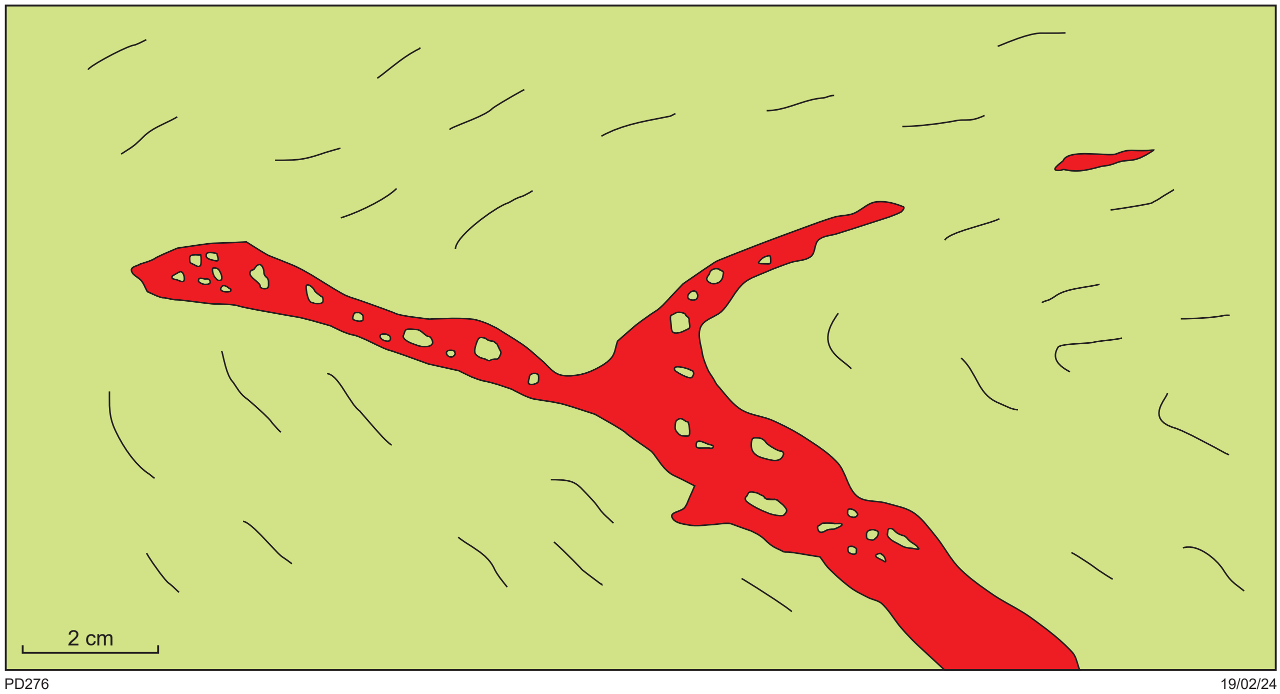

Figure 4. Pyrrhotite injection along the axial planar schistosity to a fold hinge in a schist from the New Consort deposit, Barberton district (from Pedersen, 1980)

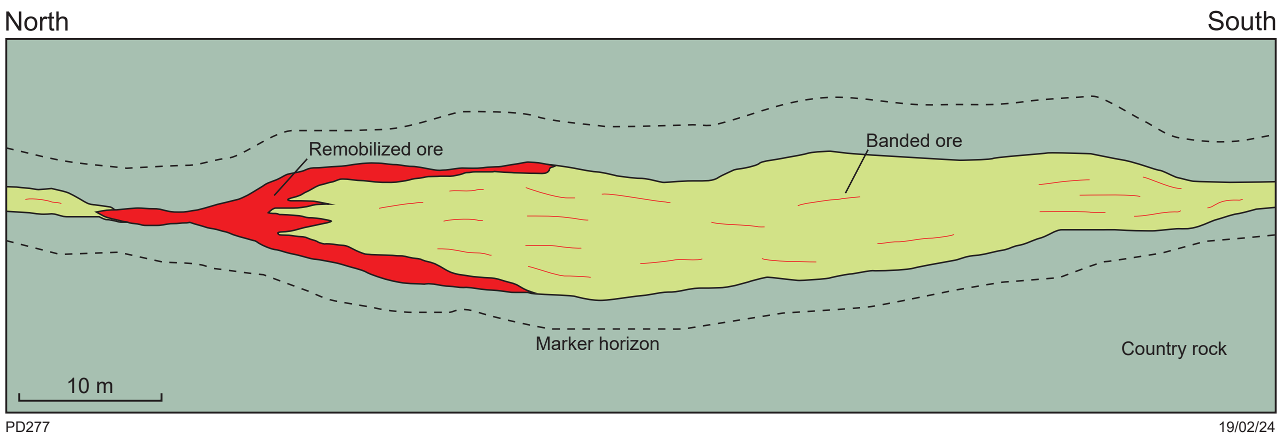

Figure 5. Remobilized galena, tennantite, sphalerite, and chalcopyrite concentrated in a boudin neck area of a deformed horizon of evaporite-bearing marbles at the Black Angel deposit, Greenland (from Pedersen, 1980)

The precise assemblage depends on temperature and the initial composition, including Fe–Ni–S–Cu content (Hill, 1984). Metamorphism results in fine-grained, strained sulfide textures becoming coarser grained and unstrained through recrystallization (Fig. 6). Metamorphism may also lead to: (i) the conversion of pyrite to pyrrhotite and the generation of pyrrhotite through sulfidation of Fe in other minerals (more common above the upper-greenschist metamorphic boundary (Vokes, 1969); (ii) the release of trace elements (e.g. gold from pyrite); (iii) partitioning of trace elements between equilibrium sulfide pairs; and (iv) the release of metamorphic fluids from hydrous silicate phases in host rocks (Marshall et al., 1998). Metamorphism of disseminated Ni–Cu–(PGE) komatiite-hosted deposits can cause the diffusion of nickel from silicates into sulfide minerals, thereby increasing the tenor of a disseminated sulfide orebody (Barnes and Hill, 1998) (where 'tenor' is the amount of Ni contained in 100 % sulfides).

Metamorphism accompanied by tectonism may result in flattened sulfides in disseminated and massive sulfide ores, plus pentlandite–pyrrhotite banding in massive sulfides (Cowden, 1985). Contrasting relative strengths between pyrrhotite (more ductile) and pentlandite (less ductile) in massive sulfide ores may cause pyrrhotite-rich ores to have well-developed tectonic banding, whereas pentlandite-rich ores are weakly banded (Cowden and Archibald, 1987). During peak metamorphic conditions—such as 500–550 °C at the Redross Ni deposit (McQueen, 1979)—the Ni-poor monosulfide solid solution is more ductile than the Ni-rich fraction and can be preferentially remobilized during deformation. By this method, high-tenor remobilized massive sulfides are fringed by their low-tenor counterparts at the Wannaway nickel deposit, Widgiemooltha (Seat, 2002).

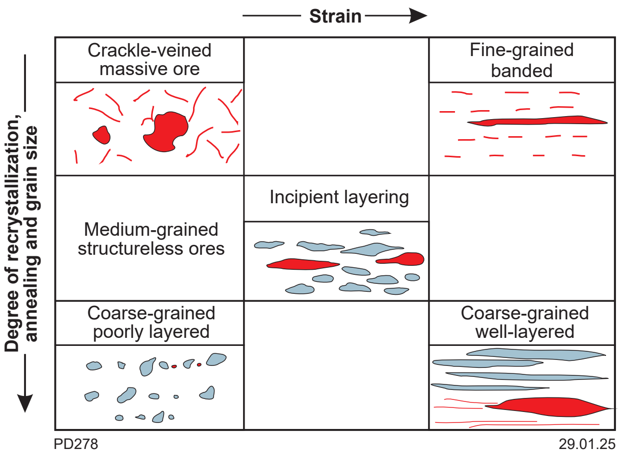

Figure 6. Textural changes in massive sulfides with changes in strain intensity and degree of recrystallization. Massive sulfides become banded with increasing strain, and undergo grain size increase with recrystallization (after Cowden and Archibald, 1987)

Examples of deformed Ni–Cu–(PGE) deposits in the Yilgarn Craton

The Yilgarn Craton hosts several well-documented examples of deformed and metamorphosed ultramafic-hosted Ni–Cu–(PGE) deposits, each illustrating the interplay between magmatic, structural, and metamorphic processes. These examples, located in the Kambalda, Agnew–Wiluna, Forrestania, and Widgiemooltha greenstone belts, provide critical insights into the effects of deformation on ore geometry and composition.

Kambalda

At Kambalda, peridotite-associated nickel sulfide deposits (e.g. Hunt, Fisher, Otter–Juan) underwent polyphase deformation (Cowden and Archibald, 1987; Cowden and Archibald, 1991; Stone, 2003) and are affected by amphibolite-facies peak metamorphism (510° ± 20 °C and 1.0 to 2.5 kbar confining pressure; Bavinton, 1979). Within the deposits, massive, disseminated, and matrix sulfide ores are commonly spatially related to secondary embayment features, which exhibit footwall irregularities, such as graben-like structures and massive sulfide±quartz–carbonate veins (Stone, 2003). In some areas, massive sulfides are remobilized along the basalt–ultramafic contact and into pillow interstices in the footwall basalt.

The massive sulfides may exhibit banding with gneissic and mylonitic textures, characterized by monomineralic layering of pentlandite and pyrrhotite (Cowden and Archibald, 1987; Fig. 7). As the banding approaches the footwall contact, it becomes mylonitic, while clasts of wallrock and quartz–carbonate veins are commonly found within the massive sulfides. Fractures and open synclines in the footwall basalt serve as hosts for these massive sulfides. The discordant relationship between embayment features and interpreted channels suggests that the embayment features formed as parasitic fold–thrusts that developed on the flanks of the Kambalda anticline (Cowden and Roberts, 1990; Stone, 2003).

Agnew–Wiluna

Massive and disseminated sulfides in the Perseverance, Rocky's Reward, and Harmony deposits in the Leinster nickel camp primarily occur in their original magmatic position, along the steeply west-dipping, overturned, stratigraphic footwall contact to komatiite (Barnes et al.,1988; Duuring et al., 2007; Duuring et al., 2010). However, in each deposit, massive sulfides have been remobilized along respective footwall contacts into several generations of fold hinge areas, as well as within shear zones that cut both komatiite and footwall country rock units. Massive sulfides within these structures display deformational banding of pyrrhotite and pentlandite and host fragments of wallrock and quartz–carbonate veins.

The presence of massive sulfides in early-formed fold hinges and late, brittle faults suggests that the sulfides were progressively remobilized during an extended deformation interval, coinciding with a range of metamorphic grades (probably from peak lower-amphibolite to lower-greenschist facies). The Perseverance 1A massive sulfide shoot extends for about a kilometre to the north of the dunite lens that hosts the main disseminated sulfide Perseverance orebody (Fig. 8).

The 1A shoot was previously interpreted as a direct product of magmatism (Barnes et al., 1988), but it has more recently been seen as a flattened pod of massive sulfides that accumulated in an isoclinal fold hinge during folding of the lower komatiite units of the Perseverance ultramafic complex (Fig. 9; Duuring et al., 2010).

Figure 7. Layering of pentlandite and pyrrhotite in a massive sulfide ore zone at the Wannaway deposit, Kambalda (photo courtesy Zoran Seat)

Moving northwards, the Rocky's Reward deposit hosts a multiply-folded komatiite unit with massive sulfides mainly located along the folded footwall contact. Sulfides are preferentially concentrated in fold hinge areas and along the sheared western margin of the komatiite (Fig. 9; Duuring et al., 2012). Further north at the Harmony deposit, massive sulfides are primarily situated along the footwall contact, but they are also present along the hangingwall margin and internally within the komatiite. Pods of massive sulfides in komatiite probably indicate remnant fold hinge positions; however, subsequent intense flattening, shearing, and attenuation of fold limbs have resulted in rootless fold hinges with thin, discontinuous fold limbs (Fig. 10; Duuring et al., 2007).

The Cosmos Deeps orebody consists of zones of massive sulfides hosted within a shear zone, found in felsic volcanic, sedimentary, and porphyry units that form the stratigraphic footwall to the Cosmos komatiite-hosted massive sulfide deposit (Rovira, 2003). Regional metamorphism caused the recrystallization and growth of pentlandite grains within pyrrhotite in the massive sulfide. Banding in massive sulfides is locally observed. In contrast to the disseminated Cosmos orebody, the Cosmos Deeps massive sulfide ore zones contain large euhedral pyrite grains, abundant wallrock clasts, and zones of massive sphalerite and galena.

Cosmos is interpreted to be a Type 1 deposit that has undergone the removal of matrix and disseminated mineralization above the massive sulfides through structural processes and tectonic remobilization of massive sulfides (Rovira, 2003). The evidence supporting this interpretation includes similar geochemistry between the primary and remobilized massive sulfide bodies, presence of wallrock clasts within the Cosmos Deeps massive sulfides, recrystallized textures, and the location of massive sulfides within structures in the felsic footwall unit (Rovira, 2003).

The Waterloo and Amorac deposits are situated 40 km southeast of Leinster. The Waterloo orebody consists of matrix and disseminated nickel sulfides located at the lower contact of a serpentinized olivine cumulate-textured unit (Bennett, 2003). The matrix and disseminated sulfides form a metamorphic fabric, suggesting centimetre-scale recrystallization and remobilization. The massive sulfide zones in Waterloo are banded and contain wallrock clasts. On the other hand, Amorac is briefly described as being structurally hosted within an undulating shear zone and is not obviously associated with an ultramafic host (Bennett, 2003).

Forrestania

The Flying Fox komatiite-hosted nickel sulfide deposit is situated within an amphibolite facies volcano–sedimentary succession. Deformation has played a crucial role, resulting in the shearing and fragmentation of the orebody, giving rise to several distinct ore shoots. These ore shoots encompass massive, stringer vein, and breccia sulfides, comprising minerals such as pyrrhotite, pentlandite, chalcopyrite, and pyrite (Collins et al., 2012b).

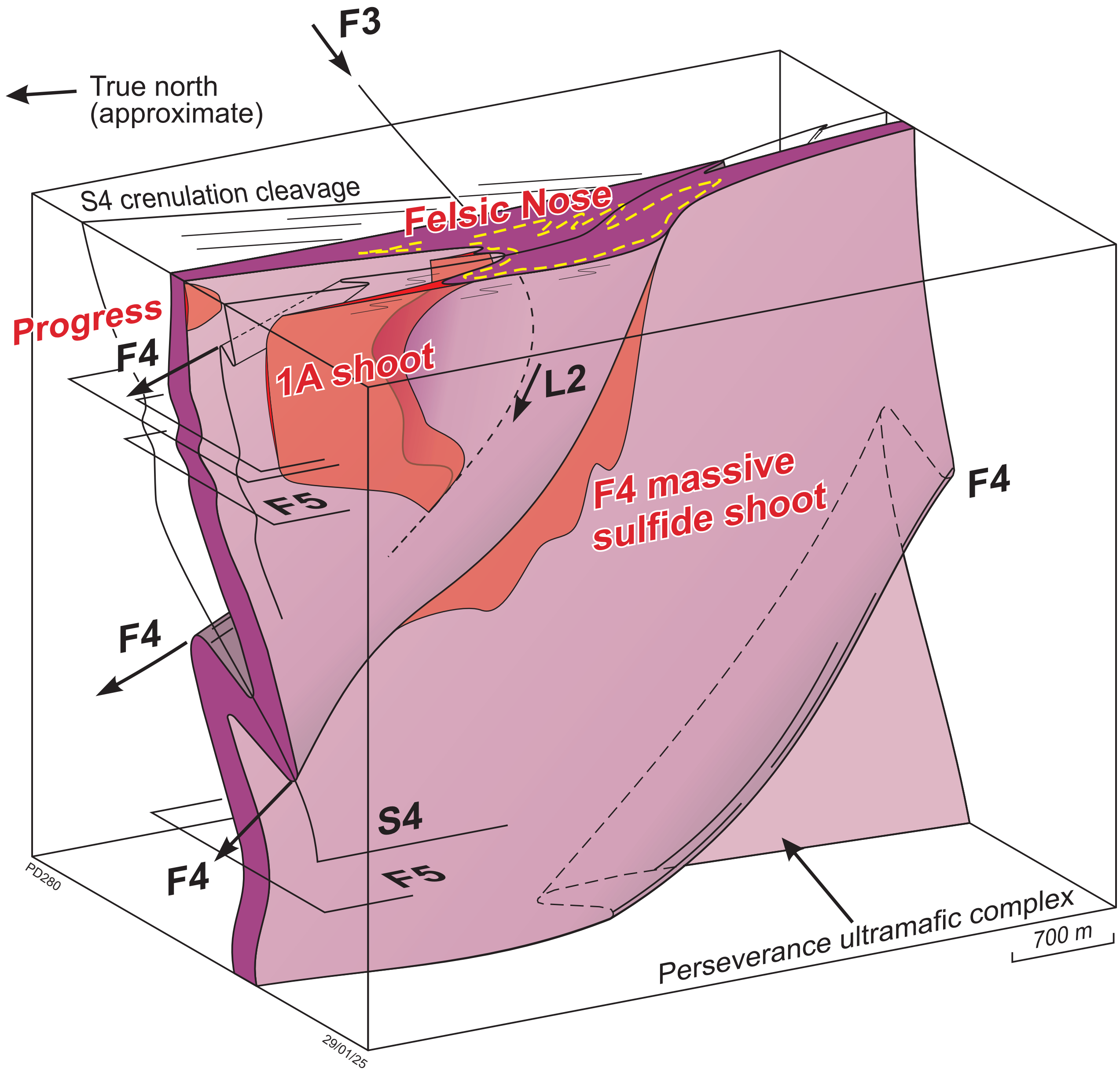

Figure 8. Block diagram of the Perseverance deposit in the Agnew–Wiluna greenstone belt, showing the concentration of massive sulfides in major fold hinges (from Duuring et al., 2010)

Figure 9. Weathered massive sulfides in folded felsic volcanic country rock, exposed in the southern wall of the Rocky's Reward pit

The ore shoots are located at the base of a komatiite sequence, which structurally overlies deformed metasedimentary rocks. Successive deformation events caused: (i) tilting of the stratigraphy and orebody; (ii) coaxial flattening along the footwall contact during peak metamorphism; (iii) non-coaxial shearing leading to the remobilization of sulfides into fold hinges; (iv) emplacement of granitic intrusions along the deformed footwall contact; and (v) the later intrusion of a dolerite dyke (Collins et al., 2012b).

Nickel sulfides were physically remobilized up to 5 m away from the ultramafic rocks along the footwall sedimentary rock — komatiite contact, into footwall sedimentary rocks. They were also entrained in the granitic magma, leading to the formation of atypical granite-hosted sulfides. Additionally, flat-lying brittle faults resulted in the displacement of the original orebody into separate ore shoots with offsets of up to 300 m (Collins et al., 2012b). The addition of pyrite via post-magmatic hydrothermal fluids containing Fe, S, Cu, and As has resulted in significant variation in the Ni tenor and chemistry among the various massive sulfide ore types (Collins et al., 2012b; Collins, 2013).

Widgiemooltha

The Widgiemooltha nickel camp includes the Redross, Mariners, Miitel, Mt Edwards, and Wannaway deposits (Appendix 1).

These deposits are situated near the base of the Widgiemooltha Dome sequence, which comprises Archean metamorphosed ultramafic, mafic, felsic volcanic rocks, and sedimentary rocks intruded by granitic rocks and Proterozoic dolerite dikes (McQueen, 1981; Marston, 1984; Seat, 2002). The deposits contain massive sulfides located at the contact between the Mount Edwards tholeiitic basalt and the overlying Widgiemooltha komatiites (Willett et al., 1978).

Peak metamorphic conditions affecting the Widgiemooltha Dome are estimated to have reached mid-amphibolite facies, with temperatures of 550–620 °C and pressures of 3.2 – 4.0 kbar, increasing to the southwest across the dome (Archibald et al., 1978). Extensive talc–carbonate alteration of the komatiites most likely represents retrograde carbonate metasomatism of these rocks (McQueen, 1979, 1981).

The present-day deposit-scale geological relationships observed in the Widgiemooltha nickel deposits closely resemble those of the Kambalda Dome. Massive sulfides hosted by komatiites occur on both limbs of an anticlinal structure, positioned directly on the footwall basalts or sulfidic sedimentary rocks. The massive sulfides, which are 1–2 m thick, are overlain by matrix or net-textured ores, followed by disseminated nickel sulfides (Marston, 1984).

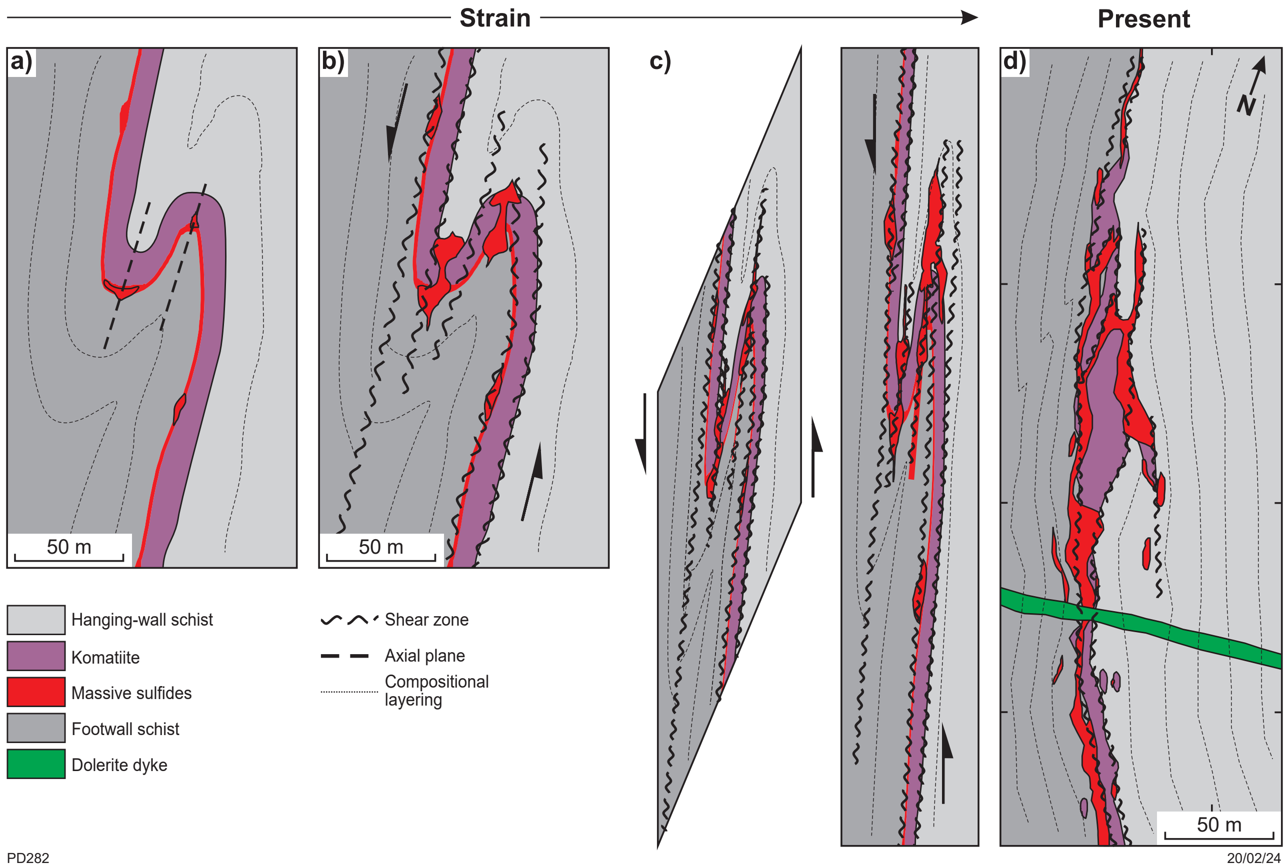

Figure 10. Schematic deformation model for the Harmony deposit, demonstrating the progressive flattening and shearing of the komatiite-hosted orebody. Massive sulfides are remobilized from the western footwall contact and are now positioned within the komatiite and along the hanging wall margin (from Duuring et al., 2007)

These massive sulfides form numerous plunging, lens-shaped bodies that commonly follow the plunge of embayments in the basalt footwall contact, as seen at the Wannaway and Miitel deposits (Seat, 2002; Le Vaillant et al., 2015).

Post-magmatic deformation is evident at all documented Widgiemooltha deposits. For example, at Miitel and Redross, massive sulfides are locally hosted entirely within the footwall basalt due to the thrusting of basalt along the sulfide contacts (Barrett et al., 1977; McQueen, 1981; Stone and Archibald, 2004).

This interpretation is supported by the occurrence of massive sulfides that contain metabasalt breccia fragments and are bordered by shear zones, suggesting sulfide movement over tens of metres (Barrett et al., 1977). Additionally, the presence of massive sulfide piercement veins in the footwall basalt has been observed at several deposits, including Redross, Widgiemooltha, Mariners, and Mt Edwards (McQueen, 1981). Remobilized ore shoots exhibit brecciated wallrock fragments and display deformation features, such as partially annealed twinning and kink banding in pyrrhotite. Minor chalcopyrite is frequently associated with footwall sulfide stringers (McQueen, 1979).

At Miitel, anomalous hydrothermally remobilized nickel, gold, and PGE are found in the footwall basalt up to 1 m from the contact with the Widgiemooltha mineralized komatiites. These mineralized komatiites extend up to 250 m from the basal footwall contact of the massive sulfide Miitel deposit. This mineralization is associated with the presence of gersdorffite and minor nickeline, which are concentrated within quartz–carbonate veinlets. It is associated with an alteration assemblage dominated by actinolite and chlorite, with locally occurring biotite, hornblende, and serpentine. These features are interpreted to have formed during the circulation of arsenic-rich hydrothermal fluids along shear zones (Cairns et al., 2003; Le Vaillant et al., 2015).

Significance

Collectively, these examples demonstrate that deformation and metamorphism significantly alter the distribution and texture of massive sulfides. Recognizing the structural and compositional changes documented in these deposits is essential for refining exploration strategies and predicting orebody geometries in similar terranes.

Key mechanisms driving sulfide remobilization

Physical and chemical processes are the two primary mechanisms responsible for the remobilization of sulfide minerals. Physical remobilization, also referred to as 'mechanical' remobilization, involves the solid-state redistribution of primary Ni–Cu–(PGE) massive sulfides during deformation (Marshall and Gilligan, 1987).

In contrast, chemical remobilization entails the dissolution of metals and sulfur by hydrothermal fluids, followed by their subsequent precipitation in new locations.

It is reasonable to propose that physical and chemical processes may act independently or in combination during massive sulfide remobilization. Both styles of remobilization may have operated at different times during the deformation and alteration of a single deposit. Although this interplay is supported by features observed in natural systems (e.g. Thompson nickel belt, Bleeker, 1990; Sudbury, Hanley and Bray, 2009; Widgiemooltha, Le Vaillant et al., 2015), further detailed studies are required to quantify the relative contributions of each mechanism under varying geological conditions.

This section focuses on describing each process. Physical remobilization is comparatively better constrained due to the availability of experimental studies on individual sulfide minerals and naturally occurring pyrrhotite–pentlandite massive sulfide ores from the Yilgarn Craton.

Chemical processes

Chemical remobilization of nickel sulfides via dissolution, transport, and reprecipitation remains less understood than physical processes (Gilligan, 1984; Gilligan and Marshall, 1987). A key challenge lies in isolating examples of chemical remobilization where physical remobilization and metamorphism are minimal or absent, which would allow clearer inferences about its independent influence. Additionally, rare standalone hydrothermal nickel deposits are enigmatic, with few constraints on the solubility of Ni under low-temperature conditions, the diversity of potential ligands, and the extent to which fluids can transport Ni away from its source (González-Álvarez et al., 2013). Addressing these uncertainties requires further study of such deposits and their distinct geochemical signatures.

Some of the best-documented examples of chemical remobilization include Ni–Cu–(PGE) massive sulfides in footwall and hangingwall rocks at Kambalda (Lesher and Keays, 1984) and in the adjacent wallrock of the Sudbury Igneous Complex in Canada (Farrow and Watkinson, 1996, 1997; Molnar et al., 1997; Farrow and Watkinson, 1999; Mukwakwami et al., 2014a; Mukwakwami et al., 2014b). Evidence of chemical remobilization includes: (i) the presence of hydrothermal quartz, albite, and carbonate at the tips of piercement structures in footwall lithologies (Lesher and Keays, 1984; Gilligan and Marshall, 1987); (ii) close spatial relationships between sulfide mineralization and hydrothermal alteration (Farrow and Watkinson, 1997; Hanley and Bray, 2009; Le Vaillant et al., 2015); (iii) Cu–Pt–Pd-rich massive sulfides with very low Ir contents and high Pd/Ir ratios, which contrast with primary magmatic sulfides (Lesher and Keays, 1984; Farrow and Watkinson, 1999; Mukwakwami et al., 2014b); and (iv) enrichment of Cu, Au, Pd, REE, Sn, Mo, and W in Ni sulfides hosted in ophiolites, as seen at the Avebury Ni deposit in Tasmania (Keays and Jowitt, 2013).

Another notable example is Sarah's Find in the Agnew–Wiluna greenstone belt, Yilgarn Craton, which provides valuable insights into the interplay between physical and hydrothermal remobilization processes. Le Vaillant et al. (2016) documented a Ni–Co–Pd–As halo surrounding massive nickel sulfides at this deposit.

The halo resulted from the combined effects of physical remobilization, observed up to 150 m from the sulfide body within the footwall dacite along the contact with the Mount Keith ultramafic unit, and hydrothermal remobilization facilitated by syn deformation As-rich fluids.

These fluids extracted Ni, Co, and Pd from the primary massive sulfides and redeposited them as gersdorffite within the sheared footwall dacite, creating a geochemical halo that extends up to 1780 m along the shearing direction. This example underscores the critical role of structural pathways and hydrothermal processes in the redistribution of Ni–Cu–(PGE) ores. Variations in Ni/Cu ratios and PGE ratios between primary ores and re-precipitated massive sulfides are believed to result from differences in the solubility of individual sulfide phases (Bavinton and Keays, 1978; Lesher and Keays, 1984; Farrow and Watkinson, 1999). For example, Cu is more soluble than Ni, while Pt and Pd are more soluble than Ru, Ir, and Os (Bavinton and Keays, 1978). As a result, chemically remobilized massive sulfides typically exhibit elevated Pd/ Ir and Pt+Pd/Ru+Ir+Os ratios compared to primary ores. Deposits such as Lunnon, Langmuir, Donaldson West, Garson, and Zapolyarninskoe (Pechenga) provide notable examples of these patterns.

Although the pressure–temperature–chemical conditions of hydrothermal fluids in these settings are poorly constrained, fluid inclusion studies at Sudbury, Canada, suggest that Ni and S were likely transported by high-salinity fluids enriched in $NaCl–KCl–CaCl_2–H_2O$ at temperatures of 200–450º C (Molnar et al., 1997). The Cl- and S-rich hydrothermal fluids may have also transported Pt and Pd as aqueous PtS_2 and PdS complexes (Gammons et al., 1992).

Physical processes

Common evidence for physical remobilization includes: (i) the presence of pentlandite–pyrrhotite banding; (ii) mechanically granulated country rock clasts (e.g. durchbewegung textures); (iii) sulfide mineral fractionation in remobilized ore shoots; and (iv) the ductile warping of pentlandite–pyrrhotite bands into piercement cusps in footwall rocks (e.g. at the Harmony and Otter–Juan deposits).

Sulfide minerals undergo various deformation mechanisms, including brittle failure, solution–precipitation creep, dislocation creep, and diffusion creep (Cox, 1984). The dominant mechanism in a given set of conditions depends on the material and environmental parameters (as discussed below in the sulfide experimental section). Among these mechanisms, dislocation creep is the most common, causing kink bands (Fig. 11), translation gliding, and twin gliding (Clark and Kelly, 1976).

Experimental studies (see below) show that under most geological stress conditions, pyrrhotite and chalcopyrite are more ductile than pentlandite and can be remobilized over greater distances, resulting in a decrease in Ni tenor and Ni/ Cu ratios in remobilized massive sulfides with distance from primary ore shoots (e.g. the Edwards lode and Wannaway deposit at Kambalda, Heath et al., 2001; Seat, 2002).

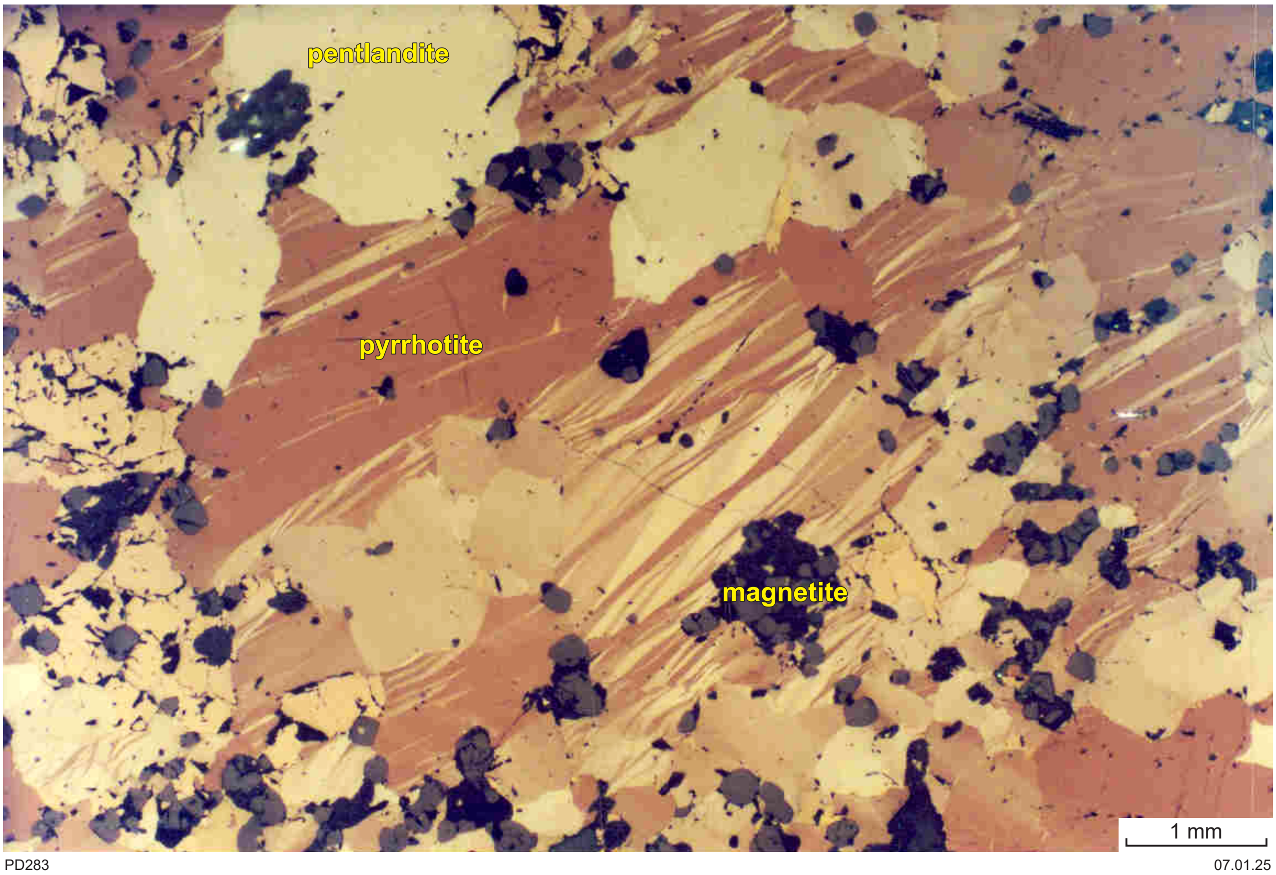

Figure 11. Kink banding in physically deformed massive sulfides from the Wannaway deposit, Kambalda (photo courtesy Zoran Seat)

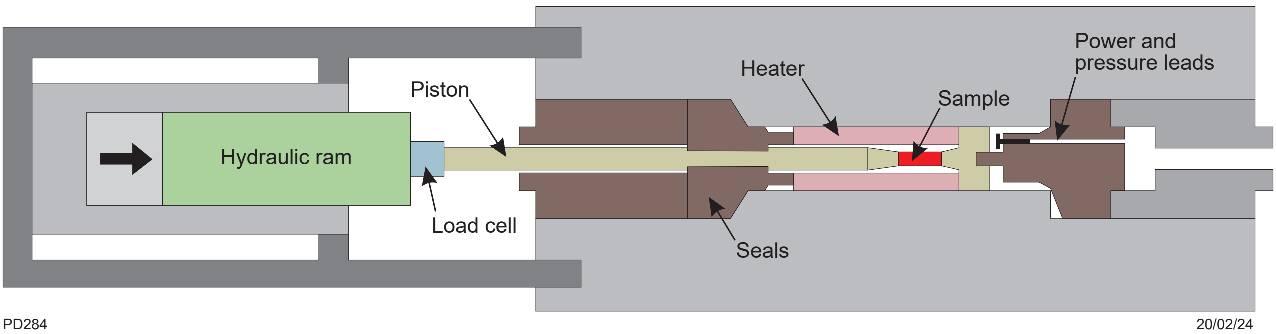

Figure 12. A long-sectional view through a typical deformation chamber used for the experimental deformation of sulfides (after Clark and Kelly, 1973)

Table 1. Deformation properties of some naturally occurring sulfides

Sulfide mineral	*Experimental conditions*	*Observed deformation*	*References*
Pyrite	<700 °C at 1 to 3 kbar	Cataclasis and pressure solution occur below 300 °C; followed by ductile dislocation above 300 °C	McClay and Ellis (1984), Cox et al. (1981)
Chalcopyrite	<700 °C at 0.5 to 2 kbar and 7.2 x 10^{-5}/sec	Cataclasis and minor translation gliding below 100 °C; followed by polysynthetic deformation twinning and minor cataclasis above 100 °C	Atkinson (1974), Kelly and Clark (1975)
Sphalerite	<500 °C at <2 kbar and 7.2 x 10^{-5}/sec	Fracturing, twinning, slip, and minor kinking	Clark and Kelly (1973)
Galena	<400 °C at 0.5 to 2 kbar and 7.2 x 10^{-5}/sec	Cataclasis at low temperatures and pressures; localized translation gliding and kinking at all conditions, whereas recrystallization occurs above 200 °C	Salmon et al. (1974)
Pyrrhotite	<700 °C at <1 kbar and 7.2 x 10^{-5}/sec	Brittle fracture at lower temperatures, whereas slip, kinking, and twin gliding occur at higher temperatures	Clark and Kelly (1973)

Experimental insights into sulfide deformation

Experimental studies provide valuable insights into the deformation behaviour of sulfide minerals and massive sulfides under varying geological conditions (e.g. temperatures of 200–800 °C and differential stresses of several tens of kilobars; Fig. 12). These studies encompass single sulfide minerals and naturally occurring massive sulfides, revealing significant variability in ductility, strength, and deformation mechanisms (Table 1).

Single sulfide minerals

Deformation experiments on individual sulfide minerals reveal significant variability in their mechanical properties:

(i) **Pyrite**: Exhibits brittle behaviour under low temperatures (<300 °C) but becomes ductile at elevated temperatures and pressures. Mechanisms include cataclasis, dislocation creep, and pressure solution, with brittle fracturing dominating near-surface conditions (Vokes, 1969; Atkinson, 1975; Cox et al., 1981; McClay and Ellis, 1984).

(ii) **Chalcopyrite**: Displays moderate ductility compared to pyrite (Vokes, 1969), transitioning from brittle to ductile deformation at ~200 °C and 0.5 kbar, facilitated by translation gliding and deformation twinning (Atkinson, 1974; Kelly and Clark, 1975).

(iii) **Pyrrhotite**: Highly ductile above 250 °C and 1.5 kbar, governed by twin gliding and dislocation creep. Ductility under most crustal metamorphism except zeolite or low-temperature facies (Clark and Kelly, 1973).

(iv) **Sphalerite**: Stronger than pyrrhotite and chalcopyrite (Fig. 13), deforming through fracturing, slip, and minor kinking (Clark and Kelly, 1973).

(v) **Galena**: Among the most ductile sulfides, deforms easily under experimental conditions (24–400 °C; 0.5 – 2.0 kbar), showing physical injection into fractures and preferential concentration in low-pressure zones (Salmon et al., 1974).

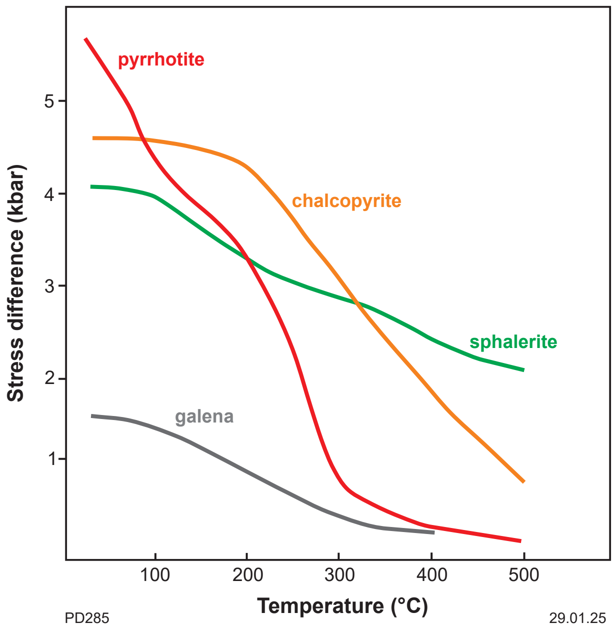

Figure 13. Comparative deformation strengths of chalcopyrite, pyrrhotite, sphalerite, and galena in response to changes in temperature at a constant 1 kbar confining pressure (after Kelly and Clark, 1975)

These experiments demonstrate that the relative plasticity of sulfides influences remobilization during deformation, with more ductile sulfides like galena and pyrrhotite migrating farther than harder minerals like pyrite.

Naturally occurring massive sulfides

Nickel sulfide ores originate from the segregation of an immiscible sulfide liquid, which crystallizes into monosulfide solid solution and undergoes exsolution during cooling, forming various sulfide phases governed by phase equilibria in the Fe–Ni–Cu–S–(O) system (Naldrett et al., 1967).

This crystallization sequence can reverse during metamorphism, especially under conditions that enable diffusion-driven homogenization of coarse-grained, layered sulfide aggregates (McQueen, 1979). Such reversion can influence the deformation response of these ores and determine their post-metamorphic textures and mineralogy.

Laboratory experiments using massive nickel sulfide ore samples from Redross (McQueen, 1979) and Kambalda (McDonald and Paterson, 1980) simulate the amphibolite-facies metamorphism experienced by these deposits. Under these conditions, massive sulfides deform in a ductile manner, while footwall basalts exhibit brittle failure. Talc–carbonate-altered ultramafic units and matrix sulfide samples display a brittle-ductile deformation response through the development of a foliation. Deformation of the talc–carbonate-altered ultramafic rock is further complicated by dehydration reactions and micro shear zone failure (Table 2).

Key findings from these deformation experiments (Table 3) demonstrate that massive sulfides exhibit low shear strength and high ductility compared to silicate rocks, undergoing plastic deformation under significantly lower stresses (McDonald and Paterson, 1980). At temperatures as low as 200 °C, sulfides develop slip planes and twins, while higher temperatures (>300 °C) promote diffusion-driven recrystallization, obliterating primary foliation and facilitating grain growth. Above 400 °C, pentlandite transitions to monosulfide solid solution, equilibrating with pyrrhotite-derived monosulfide solid solution, and temperatures exceeding 600 °C led to partial resorption of chalcopyrite, pyrite, and spinel phases. Sulfide grains align orthogonal to the maximum principal stress during deformation, reflecting their ductile behaviour. In pyrrhotite-rich, medium tenor ores, pyrrhotite deforms plastically, while pentlandite resists deformation, maintaining structural integrity and enabling differential creep (Cowden, 1986). These processes contribute to recrystallization and compositional banding, creating localized Ni enrichment.

Deformation-induced remobilization is evident in the migration of sulfides along shear zones and low-stress regions, with observations from Redross and Kambalda showing movement over tens to hundreds of metres (McQueen, 1979; McDonald and Paterson, 1980).

Limitations

Experimental studies provide a valuable framework for understanding sulfide deformation but are constrained by faster strain rates used in laboratories (e.g. 7.2 x 10^{-5}/ sec) compared to natural geological processes (10^{-13} to 10^{-14}/ sec; Clark and Kelly, 1973; Gilligan, 1984; Marshall et al., 1998). Slower strain rates in natural settings reduce mineral strength and enhance ductile behaviour. The presence of fluids further lowers sulfide strengths, facilitating remobilization. Consequently, experimental results represent the upper limits of strength and temperature–pressure conditions for brittle-ductile transitions (Clark and Kelly,1973; Kelly and Clark, 1975).

Simple heating and compressional experiments have been performed on pyrite, sphalerite, chalcopyrite, pyrrhotite, and galena, as well as naturally occurring Ni–Cu–(PGE) massive sulfides at Redross and Kambalda. However, pentlandite's strength needs to be experimentally tested under conditions similar to those used for the other sulfide phases to allow for a direct comparison.

Furthermore, existing experiments do not model the effect of volatiles (e.g. H_2O, Cl, and CO_2) during the mechanical remobilization of Ni–Cu–(PGE) massive sulfides. It is predicted that the presence of volatiles will lower the strengths of pentlandite and pyrrhotite. To make these sulfide deformation experiments more geologically relevant, it is suggested that volatiles be included as a variable in future experiments on natural and synthetic massive sulfides. However, it is acknowledged that the inclusion of volatiles may introduce difficulties in these experiments (e.g.due to the corrosive nature of chlorine at high temperatures).

Table 2. Rock type responses to deformation at Kambalda (after McDonald and Paterson, 1980)

Sample type	*Observed response to increasing deformation*
Massive sulfide	200–250 °C: rapid change from brittle fracture to twin and kink formation 500–600 °C: diffusion-dominated mechanisms, with only minor work hardening above 400 °C
Footwall metabasalt	A very strong unit that fails by brittle fracture in all tests
Talc–carbonate-altered ultramafic rock	Dehydration mineral reactions cause brittle failure above 300 °C Brittle failure occurs along conjugate sets
Matrix sulfide unit	Displays deformation features that are between talc–carbonate-altered ultramafic and massive sulfide units

Table 3. Summary results from the experimental deformation of massive sulfide samples from Kambalda (after McDonald and Paterson, 1980)

Changes in massive sulfide properties	*Detailed observations*
Minerals	At 300 °C: first evidence of the conversion of pentlandite to monosulfide solid solution (mss) equivalent. At 400 °C: remnant pentlandite grains are completely replaced by mss as pseudomorphs. Chalcopyrite and pyrite are stable at higher temperatures; chalcopyrite undergoes exsolution, forming a darker, Fe-rich chalcopyrite phase, which is resorbed at 700 °C. Spinel-group minerals with internal gangue inclusions are most resistant to mineralogical modification, apparently unaffected up to 600 °C, whereupon ferrichromite rims on cumulate chromite become sulfidized and new grains of magnetite form. Gangue inclusions alter to mss and magnetite at 700 °C.
Textures	Below 400 °C: local granulation and brittle fractures. Above 400 °C: alteration to mss is complete. As reaction time and temperature increase to 400 °C, grain size increases, but textures are unstable. Recrystallization and grain growth of mss produce texturally stable assemblages above 700 °C. At room temperature, pyrrhotite has strong foliation. Below 400 °C: foliation is preserved, with kinks and twins becoming more common. At 500°–600 °C: foliation is mostly destroyed. Above 600 °C: recrystallization, grain growth, with grain alignment perpendicular to the compressional direction.
Structures	Structures include fractures, kinks, and twins in all massive ore. Fractures are common below 400 °C. A prominent set occurs parallel to σ1. A second set occurs <45° to σ1. A third minor set occurs perpendicular to kink axes. Kink surfaces occur up to 250 °C, concentrated around grain irregularities and inclusions within pyrrhotite. Twins developed at 200 °C are short and blocky. At 400 °C: twins are long. At 400 – 500 °C: the maximum twin frequency and twin to kink ratio are reached; however, both decrease at higher temperatures.
Composition	Below 400 °C: no change in pentlandite composition. At 500 – 600 °C: former pentlandite and pyrrhotite masses begin to approach a common value. At 700 °C: diffusion occurs to homogenize the former two sulfides (although textural dissimilarity persists).
Strain-induced exsolution	At 700 °C: local areas of strain-induced exsolution.
Stress–strain behaviours	Specimens deformed at 10^{-5}/sec are weaker than those deformed at 10^{-4}/sec at equivalent temperatures.

Evaluating factors that may influence remobilization distances and compositional variations of deformed massive sulfides

Database compilation

A database was compiled from available literature, encompassing physical and chemical characteristics of komatiite-hosted Ni–Cu–(PGE) deposits worldwide (details provided in Appendix 1). The primary objective of this compilation was to document well-studied deformed deposits and use the tabulation to assess the factors influencing remobilization distances and to identify any systematic compositional variations in remobilized massive sulfide ore shoots compared to their primary counterparts (also detailed in Appendix 1). The database includes estimates of values such as: (i) reported maximum remobilization distances from primary magmatic positions; (ii) the estimated regional metamorphic grade affecting the orebody; and (iii) textural or chemical variations in massive sulfide ores. A common method for estimating remobilization distances involves determining the extent to which massive sulfides penetrate footwall units, such as their occurrence within piercement veins (e.g. the McMahon deposit, Kambalda; Marston, 1984).

Hypothesis 1: The probability of discovering remobilized massive sulfides decreases significantly with distance from komatiite-hosted Ni–Cu–(PGE) deposits in deformed terranes

This hypothesis posits that the likelihood of finding remobilized massive sulfides decreases as the distance from primary komatiite-hosted Ni–Cu–(PGE) deposits increases in deformed terranes. Data analysis shows a clear spatial relationship, with the probability of discovering economically significant ore sharply declining beyond a threshold distance (e.g. 50–1000 m; Fig. 14). Deformation, remobilization, and geochemical dispersion contribute to this pattern, making localized enrichment less likely at greater distances.

The data strongly support this hypothesis and provide key insights into the spatial distribution of remobilized massive sulfides. On average, physical remobilization appears to expand the exploration footprint of many deposits by a factor of approximately two. This observation underscores the significant role that physical remobilization plays in enhancing the size and accessibility of mineralized zones in deformed terranes.

Additionally, the analysis identifies a remobilization limit of roughly 1000 m, indicating that remobilized massive sulfides within this range serve as reliable indicators of a nearby primary magmatic deposit. These findings have practical implications for exploration, as they emphasize the importance of targeting areas within this critical distance to maximize the likelihood of discovery.

Another important observation is the apparent scarcity of examples where remobilization occurs over distances of less than 5 m. This discrepancy between theoretical expectations from sulfide deformation experiments and reported field data is probably due to under-reporting in published studies. Distinguishing remobilized ore from deformed in situ primary ore is often challenging, and the perceived significance of reporting such cases may be low. Addressing this reporting gap could provide valuable insights into short-distance remobilization processes.

Hypothesis 2: Massive sulfide ores are remobilized greater distances in higher-grade metamorphic terranes

Experimental deformation studies on sulfide minerals suggest that the higher temperatures, pressures, and fluid concentrations associated with high-grade metamorphic facies enhance the ductility of massive sulfides.This increased ductility is hypothesized to facilitate the remobilization of massive sulfides over greater distances in higher-grade metamorphic terranes. To test this hypothesis, maximum remobilization distances cited in the literature were plotted against their respective peak metamorphic temperatures (Fig. 15).

A weak positive correlation ($r = 0.29$) was identified between maximum remobilization distances and peak metamorphic temperatures. However, the strength of this correlation may be limited by the scarcity of data for deposits in low-grade metamorphic facies terranes. Additionally, maximum remobilization distances are likely influenced not only by peak metamorphic conditions but also by the duration and intensity of deformation experienced by a deposit. For instance, both Mt Windarra and Maggie Hays experienced peak amphibolite facies metamorphism, yet their remobilization distances differ significantly, with Mt Windarra exhibiting approximately 2 m and Maggie Hays reaching 800 m.

To refine the test of this hypothesis and address potential sampling biases, more examples of low-grade metamorphic deposits are needed, alongside additional data from deposits with remobilization distances of less than 1 m. Expanding the dataset in this way would provide a more balanced and comprehensive understanding of the relationship between metamorphic grade and sulfide remobilization distances.

Hypothesis 3: Remobilized massive sulfide ores have lower Ni tenor and Ni/Cu ratios compared to primary ores

Based on sulfide mineral deformation experiments, it is hypothesized that during the physical remobilization of massive sulfides, lower-strength sulfides (e.g. pyrrhotite and chalcopyrite) migrate farther from higher-strength sulfides (e.g. pentlandite and pyrite). As a result, this migration is expected to lead to lower nickel tenor and Ni/Cu ratios in the distal parts of remobilized massive sulfide ores.

The compiled Ni tenor data supports this hypothesis for 13 out of the 20 deposits analysed (Fig. 16). Examples include the Juan, Ken, Lunnon, and Jan deposits from the Kambalda nickel camp, where this trend is evident.

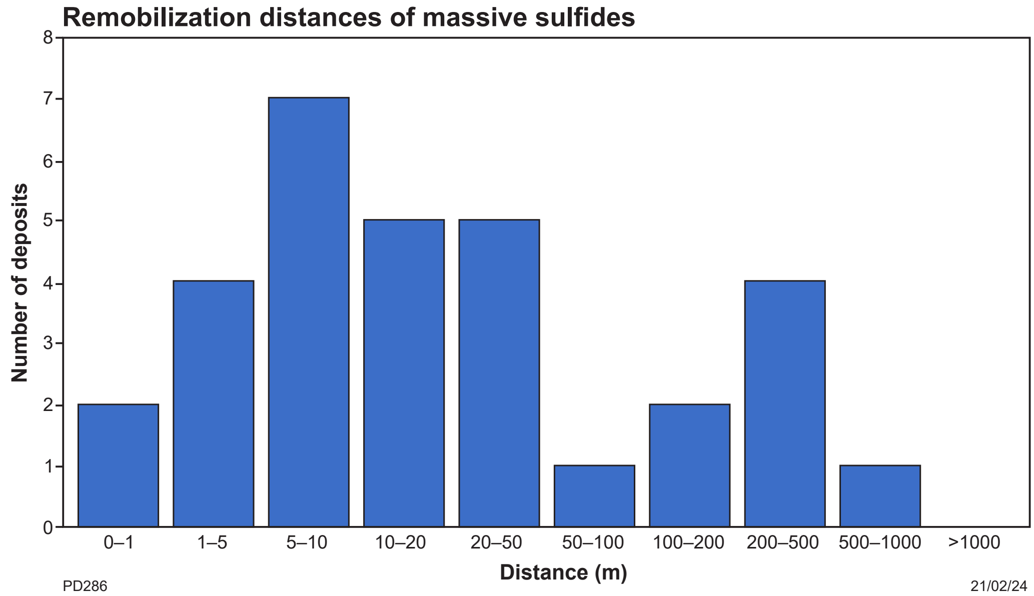

Figure 14. Frequency of maximum remobilization distances for massive sulfides in komatiite-hosted Ni–Cu–(PGE) deposits (number of deposits = 27). Massive sulfides are most commonly remobilized up to 50 m from their primary magmatic position, with decreasing likelihood of remobilization occurring beyond 50 m. Distances of up to 5 m are probably under-represented by the data due to the lack of reporting of these minor remobilization distances in the literature

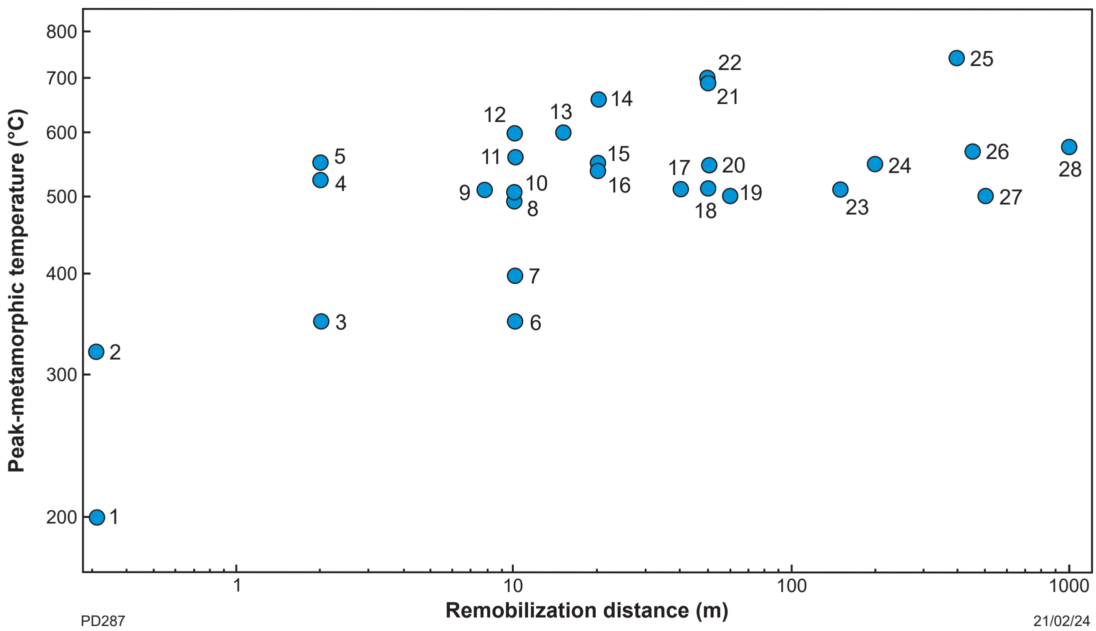

Figure 15. Massive sulfide remobilization distances plotted against peak metamorphic temperatures. A weak positive correlation exists between distance and temperature (correlation coefficient of 0.29), indicating that higher temperatures promote the ductile remobilization of massive sulfides over greater distances. Note that peak metamorphic facies temperature data estimates were obtained from existing geothermometry studies or were extrapolated from metamorphic facies conditions. Deposit abbreviations: 1, Dee's Flow; 2, Silver Swan; 3, Shangani; 4, Mt Windarra; 5, Marbridge; 6, Damba–Silwane; 7, Donaldson West; 8, Widgiemooltha; 9, Otter-Juan; 10, McMahon; 11, Rocky's Reward; 12, Trojan; 13, Wannaway; 14, South Endeavour; 15, Redross; 16, Jan; 17, Ken; 18, Edwards; 19, Cosmos; 20, Perseverance; 21, New Morning; 22, Nepean; 23, Lunnon; 24, O'Toole; 25, Thompson; 26, Garson; 27, Maggie Hays; 28, Zapolyarninskoe

However, some deposits show negligible differences in Ni tenor between primary and remobilized massive sulfides, such as Perseverance and Waterloo.

Conversely, inverse compositional trends are observed at Spargoville, Donaldson West, Minibridge, Cosmos, and Nepean (Fig. 16). Similarly, Ni/Cu ratios predominantly decrease in distal ores but also exhibit negligible differences and sometimes inverse trends (Fig. 17).

In more structurally complex Ni–Cu–(PGE) deposits, deviations from this hypothesis can occur due to additional factors. At the Pechenga deposit, for instance, the inclusion of pyrite-rich sedimentary fragments in massive sulfide ores dilutes the chalcophile elements, reducing Ni tenor and Ni/Cu ratios while increasing As, Sb, and Zn (Barnes et al., 2001). Further studies by Lightfoot et al. (2017) highlight similar variability in Ni tenor at deposits such as Kambalda (Heath et al., 2001; Stone et al., 2004), Flying Fox (Collins et al., 2012a, b), and the Thompson nickel belt (Lightfoot et al., 2017). This chemical variability reflects the combined effects of primary magmatic processes and post-formational deformation and hydrothermal activity.

Hypothesis 4: Higher metamorphic conditions lessen compositional differences between primary and remobilized massive sulfide ores

Deformation studies on Ni–Cu–(PGE) massive sulfides at Redross and Kambalda (McQueen, 1979; McDonald and Paterson, 1980) suggest that elevated metamorphic conditions may promote the reversion of massive sulfides into a more homogeneous monosulfide solid solution. Consequently, it is hypothesized that the rheological strength contrasts between pentlandite and pyrrhotite diminish at higher peak metamorphic temperatures. This reduction in strength contrasts would be expected to result in less pronounced variations in nickel tenor and Ni/Cu ratios between primary and remobilized massive sulfides, compared to those subjected to lower-grade metamorphic conditions during a prograde metamorphic cycle. An example of this phenomenon may be observed in the Lunnon Shoot, where remobilized massive sulfides concentrated in fold hinge areas exhibit nickel tenor values comparable to those in massive sulfides along fold limbs (McDonald and Paterson, 1980).

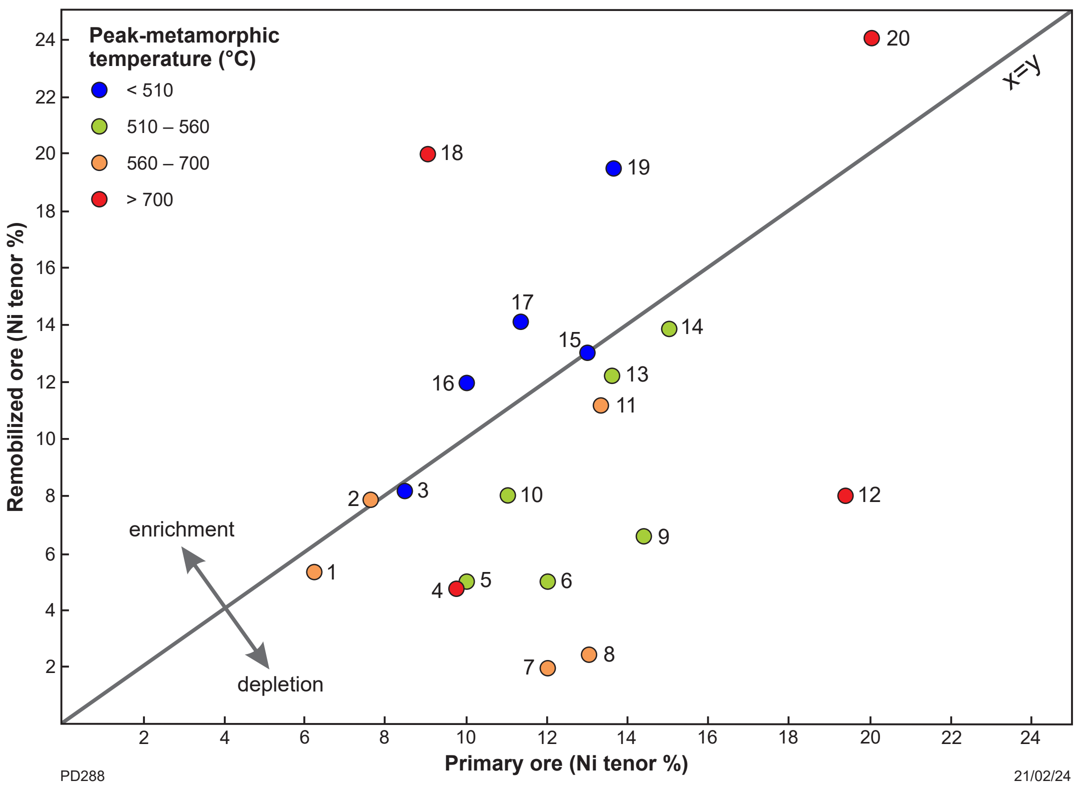

Figure 16. Nickel tenor variations between primary and remobilized massive sulfides in individual komatiite-hosted Ni–Cu–(PGE) deposits. Remobilized ore mainly has a lower nickel tenor than primary ore, although some deposits show no difference or inverse nickel tenor relationships. Deposit abbreviations: 1, Rocky's Reward; 2, Perseverance; 3, Shangani; 4, Zapolyarninskoe; 5, McMahon; 6, Gelatelly; 7, Mt Edwards; 8, Mt Windarra; 9, Fisher; 10, Thayer Lindsley; 11, Garson; 12, Wannaway; 13, Otter–Juan; 14, Edwards; 15, Waterloo; 16, Cosmos; 17, Donaldson; 18, Spargoville; 19, Manibridge; 20, Nepean

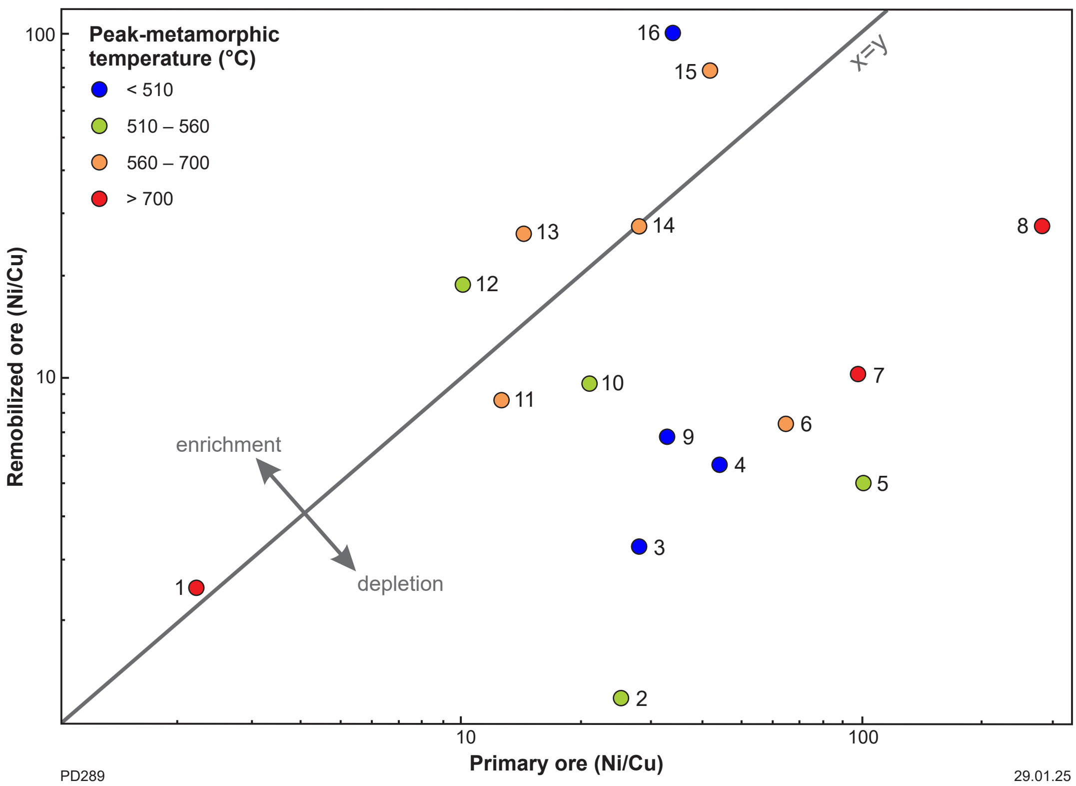

Figure 17. Nickel versus copper variations between primary and remobilized massive sulfides in individual komatiite-hosted Ni–Cu–(PGE) deposits. The data show that remobilized ore mainly has lower Ni/Cu ratios than primary ore, although some deposits show no difference or inverse Ni/Cu relationships. Deposit abbreviations: 1, Zapolyarninskoe; 2, Fisher; 3, Shangani; 4, Donaldson; 5, Lunnon; 6, Mt Windarra; 7, Nepean; 8, Wannaway; 9, Langmuir; 10, Otter– Juan;11, Garson; 12, Gelatelly; 13, Bucko Lake; 14, Rocky's Reward; 15, Perseverance; 16, Manibridge

However, testing this hypothesis by comparing peak metamorphic temperature data with Ni tenor (Fig.16) and Ni/Cu (Fig. 17) for specific komatiite-hosted Ni–Cu–(PGE) deposits reveals a random distribution. This lack of a clear trend could partly be attributed to the limited representation of low-temperature metamorphic data within the dataset.

Additionally, deposits such as Nepean (Marston, 1984) and Thompson (Lightfoot et al., 2017) demonstrate prolonged remobilization histories spanning a range of metamorphic conditions. These examples highlight that remobilization distances and compositional differences are not solely determined by a single peak metamorphic temperature but are also influenced by the cumulative effects of deformation and thermal history.

Implications for nickel exploration

This data compilation confirms that remobilized massive sulfide orebodies are a prominent feature in deformed and metamorphosed terranes hosting primary Ni–Cu–(PGE) deposits. Understanding the deformation and remobilization processes is essential, particularly due to the strong structural controls typically exhibited by Archean komatiite-hosted deposits on orebody distribution and geometry. These insights provide significant opportunities for advancing exploration strategies.

A review of the existing literature shows that massive sulfide remobilization distances in komatiite-hosted Ni–Cu–(PGE) deposits are most commonly within 50 m of primary magmatic ore positions. While remobilization distances of 50–500 m are less frequent, they remain important targets, especially in highly deformed and metamorphosed terranes. Structural factors such as faulting, folding, and geochemical dispersion processes can create localized enrichment zones even at these less common distances. Additionally, the weak positive correlation between metamorphic grade and maximum remobilization distances observed in this study suggests that higher-grade metamorphic terranes are more likely to exhibit extended remobilization distances.

In many cases, remobilized massive sulfide ores show decreasing nickel tenor and Ni/Cu ratios with increasing distance from primary ore positions. Furthermore, the orientation of asymmetric pentlandite grains in pyrrhotite offers valuable insights, as these grains define the stretching direction and plane of movement for remobilized massive sulfides (e.g. Perseverance; Eisenlohr, 1989).These observations can aid in determining the ductile flow direction of massive sulfides, potentially serving as mappable indices for predicting the locations of primary massive sulfide ores. Incorporating these indices into exploration planning would allow geologists to better interpret structural fabrics and deformation patterns, guiding drilling campaigns and geophysical surveys towards higher-probability target zones.

Conclusions and recommendations

This study highlights the critical role of understanding remobilized massive sulfide orebodies in deformed and metamorphosed terranes hosting primary Ni–Cu–(PGE) deposits. Primary massive sulfides, predominantly composed of pyrrhotite and pentlandite with minor pyrite and chalcopyrite, are typically confined to footwall contacts of ultramafic rocks. In contrast, remobilized massive sulfides are often found in structurally controlled settings, far removed from primary magmatic sources.

Distinct textures and structural features, such as foliation, flattened pentlandite porphyroblasts, and competency contrasts, are key to identifying remobilized deposits. Structural elements like elongated folded orebodies, boudinage, and shear zones significantly influence the redistribution of these ores. Metamorphism further modifies sulfide textures and compositions through recrystallization and coarsening, with temperature being the primary driver of these changes.

Experimental studies on sulfide minerals provide a robust framework for interpreting remobilization distances and the impact of metamorphic conditions. Analysis of the compiled database indicates that remobilization distances are commonly within 50 m of primary ore positions but can extend to 500 m or, in highly deformed terranes, up to 1 km. Variations in Ni tenor and Ni/Cu ratios with remobilization distance are attributed to the differing rheological behaviours of sulfides, with pyrrhotite and chalcopyrite traveling farther than pentlandite due to their lower strength.

Future research should address current limitations by incorporating data from non-komatiite-hosted Ni–Cu–(PGE) deposits to reduce sampling biases. Additionally, collecting new massive sulfide samples across a range of metamorphic grades would improve understanding of nickel tenor and compositional variations. These efforts should aim to correlate remobilization timing with incremental deformation and metamorphic events, enabling the development of a comprehensive model for orebody evolution and enhancing exploration strategies.

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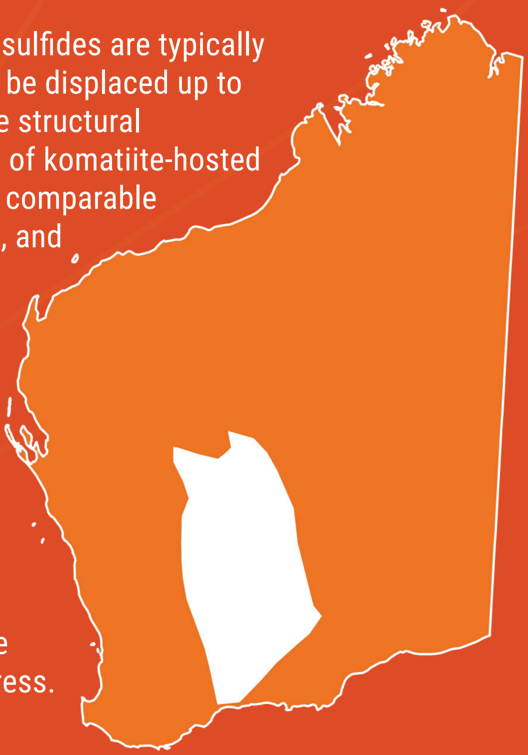
REPORT 253

DEFORMED NI–CU–(PGE) DEPOSITS: STRUCTURES, REMOBILIZATION, AND EXPLORATION IMPLICATIONS

P DUURING



This Report examines how remobilized massive sulfides are typically found within 50 m of primary orebodies but may be displaced up to 1 km in highly deformed regions. It describes the structural deformation, metamorphism, and remobilization of komatiite-hosted Ni–Cu–(PGE) deposits in the Yilgarn Craton and comparable terranes. By integrating geological, geochemical, and structural analyses, it outlines the mechanisms governing massive sulfide redistribution and their implications for mineral exploration.

The study compiles data from over 75 deposits worldwide, analysing how deformation structures — such as folds, shear zones, boudinage, and durchbewegung structures — control sulfide migration. It also demonstrates that nickel tenor and Ni/Cu ratios decline with increasing remobilization distance, reflecting the differential mobility of sulfide minerals under stress.

By evaluating both physical and chemical remobilization processes, including hydrothermal influences, the report refines exploration models for structurally complex terranes.

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