AEGC2019
Data to Discovery
Australasian Exploration Geoscience Conference
2-5 September 2019 • Perth, Western Australia
Incorporating the AIG, ASEG, PESA and WABS

Nova-Bollinger Ni-Cu sulfide ore deposits, Fraser Zone, Western Australia: Petrology of the host intrusions sulfide-silicate textures and emplacement mechanisms of the ores

Valentina Taranovic*
CSIRO Mineral Resources
Perth, Australia
valentina.taranovic@csiro.au

Stephen J. Barnes
CSIRO Mineral Resources
Perth, Australia
steve.barnes@csiro.au

Steve Beresford
IGO NL
Perth, Australia
steve.beresford@igo.com.au

John Miller*
CSIRO Mineral Resources
Perth, Australia
*(*present address UWA-CET, Perth)*

Steven Rennick
IGO NL
Perth, Australia
steven.rennick@igo.com.au

SUMMARY

The Nova-Bollinger Ni-Cu sulfide ore deposits are hosted within a suite of mafic-ultramafic intrusive cumulate bodies. The Lower Intrusion is a thin semi-conformable chonolith comprising unlayered mafic to ultramafic orthocumulates, hosting the bulk of the mineralisation. The much thicker overlying Upper Intrusion is bowl-shaped and modally layered with alternating peridotite and norite mesocumulate layers. A distinctive rock-type containing both orthopyroxene and olivine as cumulus phases is a characteristic of the Lower Intrusion. The intrusions differ in olivine and spinel chemistry, and in the volume of sulfides. Sector zoning in Cr content of pyroxenes is observed in the Lower Intrusion, and in the lower marginal zone of the Upper, and is attributed to crystallisation under supercooled conditions. Symplectite orthopyroxene-spinel-amphibole coronas at olivine-plagioclase contacts are attributed to near-solidus peritectic reaction between olivine, plagioclase and liquid during high pressure emplacement (>6 Kb), consistent with high Al contents in igneous pyroxenes and estimates of the peak regional metamorphism. The Upper and Lower Intrusion rocks represent cumulates from a similar parental magma, derived via multiple magma pulses, variably fractionated and undergoing sulfide saturation prior to emplacement into the deep crust at pressures of 6-10 Kb during the peak of regional metamorphism under extremely low cooling rates. The ores show a remarkable assemblage of textures indicative of emplacement into hot, soft country rocks at a large-scale melting-infiltration front. Sulfide infiltration was accompanied by partial melting of the country rock producing felsic leucosomes, some of them strongly enriched in garnet, showing close spatial association with sulfide infiltrations and veins. Coarse grained pentlandite – chalcopyrite – pyrrhotite "loop textures" are characteristic of all ore types, down to the scale of the infiltrating sulfides within the gneisses, and are regarded to be diagnostically magmatic textures generated by sulfide liquid fractionation and growth of high-T pentlandite by peritectic reaction between fractionated sulfide melt and early crystallised MSS.

Key words: layered intrusion, chonolith, Ni sulfides, symplectite, loop texture, melting-infiltration front.

INTRODUCTION

The Nova-Bollinger Ni sulfide ore deposits are hosted in a suite of cumulate mafic and ultramafic intrusive rocks of the Mesoproterozoic Fraser Zone, located about 160km east-northeast of Norseman, Western Australia. The Fraser Zone is the innermost of the three geographical, structural and fault-bound zones produced during ca. 1345–1260 Ma Albany-Fraser Orogen (Spaggiari et al., 2009; Smithies et al., 2013; Maier et al., 2016). Nova-Bollinger occurs within a prominent fold interference feature called an "eye" structure (Parker et al., 2017). The regional metamorphic grade is granulite, with peak conditions up to 850C at 7-9 Kb (Clark et al., 2014).

The mineralization is hosted by the lower of a pair of stacked intrusions: an Upper Intrusion, a thick, layered ultramafic-mafic body with a dominantly mafic lower zone, and the Lower Intrusion, a thin mafic/ultramafic chonolith hosting the bulk of the mineralization (Figure. 1) in the form of the Nova and Bollinger orebodies. These are two distinct ore deposits with a combined resource estimate of 13.1Mt at about 2% Ni, 0.8% Cu and 0.1% Co (Independence Group, 2019).

Sulfide-silicate ores display a spectacular array of textures largely attributed to magmatic processes. However, the strongly deformed nature and lower granulite metamorphic grade of the country rocks, coupled with the presence of a large proportion of the sulfide-rich ores within the country rock immediately adjacent to the host intrusions, give the initial impression that the ores have been subjected to tectonic remobilization. In this contribution, we address the geochemistry, internal structure, mineralogy and petrogenesis of the two intrusions, and we evaluate ore emplacement mechanisms in the light of recent findings by Barnes et al. (2017a,b; 2018a,b) on the tendency of magmatic sulfides to develop melting-infiltration fronts at interfaces with less-refractory country rocks, and to migrate through partially solidified crystal mushes.

LOCAL GEOLOGY

The two main intrusive packages of the Nova-Bollinger intrusive suite are (1) the Upper Intrusion consisting of interlayered mafic and ultramafic cumulate rocks with localised disseminated mineralization and (2) the Lower Intrusion consisting of mafic and ultramafic cumulate rocks hosting the bulk of the disseminated, net-textured and massive sulfide

mineralization comprising the Nova and Bollinger deposits (Figure. 1).

The Upper Intrusion is a bowl-shaped, internally layered body extending about 2.4 km NS and about 1.2 km EW across the Nova mine lease (Figure. 1) and up to 450 m in thickness. Cumulate ultramafic rocks, primarily lherzolite and feldspathic lherzolite, are interlayered with predominately mafic rock compositions ranging from norite to gabbronorite. The ultramafic layers vary in thickness from about 20 cm to 100 m, show complicated interdigitation with mafic layers (Figure. 1) and comprise predominately poikilitic textured heteradcumulate lherzolites. These rocks are primarily composed of medium to coarse-grained olivines with occasional fine-grained olivine clumps, chromian Mg-Fe-Al spinel inclusions in olivines, and both orthopyroxene and clinopyroxene oikocrysts zoned from Cr-rich cores to Cr-poor rims.

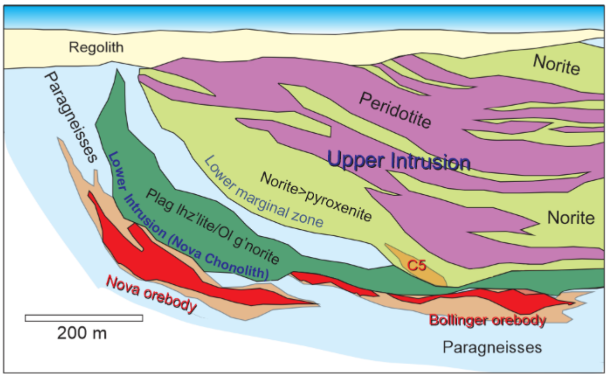

Figure 1. Nova-Bollinger East-West schematic long section, looking north, modified from Parker et al., 2017.

A lower heterogenous marginal zone up to 100 m thick contains predominantly orthocumulate norite, olivine orthopyroxenite and feldspathic lherzolite, and hosts the disseminated C5 sulfide resource. Orthopyroxenites have resorbed olivine inclusions in coarse interlocking orthopyroxene oikocrysts comprising ~90% of the rock. Vari-textured rocks (with heterogeneous grainsize on a cm scale) are present in this zone. Unevenly distributed patches of variably sized clusters of pyroxene, spinel, plagioclase and carbonate are evident in this unit but not elsewhere in the Upper Intrusion.

The lower Intrusion has a maximum thickness of about 100 m thick, 300-500 m wide and at least 1500 m long, significantly thinner than the Upper Intrusion, having a characteristic flattened tube (chonolith) morphology with broadly lenticular cross section. Lithologies are predominantly orthocumulates, ranging from a feldspathic lherzolite to poikilitic melagabbro, with generally coarse to medium-grained pyroxene and fine-grained olivine clumps. A distinctive lithology in the Lower Intrusion is a poikilitic olivine-orthopyroxene orthocumulate with intercumulus plagioclase, poikilitic clinopyroxene, locally branching olivine grains and pronounced sector zoning of Cr in the pyroxenes. Orthopyroxene-spinel-hornblende symplectites are extensively developed at olivine-plagioclase contacts as reaction coronas. Less abundant lithologies include olivine clinopyroxenites with globular disseminated sulfides, and mixed lithologies with irregular clumps of orthopyroxenite within melagabbro. The Lower Intrusion is host to disseminated and net-textured sulfide mineralization of variable thickness. Massive sulfide lenses and veins are extensively developed below this intrusion forming the bulk of the Nova and Bollinger orebodies.

The Nova-Bollinger ores are emplaced into a tightly folded sequence of granulite facies gneisses, comprising a mixture of intermediate to felsic garnetiferous meta-sediments and mafic gneisses with minor marble layers.

Ni-Cu sulfide ores are found in a wide variety of textural types, both within the host intrusion, and within country rocks to a distance of approximately ~20 m from the basal contact. The intrusion hosted ores are dominated by net-textured (matrix) ores with subordinate globular disseminated ores (Barnes et al., 2017b), the latter mainly found in Bollinger, as discordant massive sulfide veins and (uncommonly) as massive segregations along the basal contact. Exo-contact ores are found as a spectacular variety of sulfide-matrix ore breccias, as heavily disseminated sulfide within the country rock gneissosity, and as close-spaced vein arrays, with mutual gradation between all these types.

PETROLOGY AND GEOCHEMISTRY

Geochemistry of all the intrusive lithologies in the system is consistent with cumulates with variable trapped liquid content forming from related but variably evolved magmas. Two dominant mineral accumulation trends have been observed: one corresponding to the predominant accumulation of olivine in both the Upper and Lower Intrusions and the other for the accumulation of orthopyroxene + plagioclase with or without olivine for the Lower Intrusion and for the lower marginal zone of the Upper Intrusion. A proportion (>50%) of rocks in both Upper and Lower Intrusions have MgO contents greater than 20% and fall on olivine control lines, representing mixtures of cumulus olivine and parental liquid. Trends of MgO vs FeO for these rocks can be used to estimate the MgO and FeO contents of the liquid and olivine end members. The Upper Intrusion trend indicates an average cumulus olivine of Fo85 + 1 and a parent liquid of 8 + 1% MgO, while the Lower Intrusion trend indicates Fo83 + 1 and 7 + 1% MgO.

Higher abundances of trace elements in the Lower Intrusion are consistent with greater amounts of trapped intercumulus liquid, but the relative proportions of mildly to strongly incompatible elements (REE, Nb, Th, Zr, Ti) vary very little between the Lower and Upper Intrusions, or within either intrusion.

Trends of V vs Ti are distinct between the two intrusions; a vanadiferous chromian Mg-Al spinel appears to have been a cumulus phase in the Lower Intrusion, consistent with the inferred high pressure of emplacement. This conclusion from geochemical trends is borne out by the presence of spinel as chadacrysts within orthopyroxene oikocrysts and inclusions in olivines in Lower Intrusion cumulates.

Sector zoning in Cr content has been identified in the cumulus and poikilitic pyroxenes, particularly in cumulus orthopyroxene, from the Lower Intrusion and the lower marginal zone of the Upper Intrusion (Figure. 2). This type of trace element zoning is a hallmark of several other ore-bearing small intrusions worldwide including Ntaka Hill (Tanzania), (Barnes et al 2016). Sector zoning is significant as an indicator of crystallisation under supercooled conditions.

Complex assemblages of symplectite textures have been observed at Nova-Bollinger suite, in all lithologies, including silicate – silicate, silicate – sulfide, and rarely silicate – oxide

mineral intergrowths. Green spinel – orthopyroxene – hornblende (Figures 3A and 3B), developed as coronas at original olivine-plagioclase contacts or olivine – sulfide (pyrrhotite or chalcopyrite most common) (Figures 3C and 3D) are the typical assemblages at Nova.

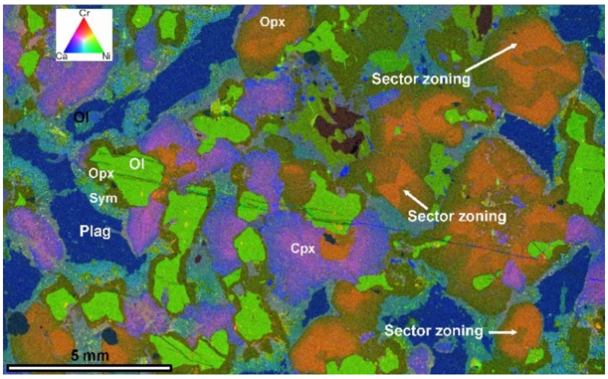

Figure 2. Ca – Ni – Cr elemental map (Cr and Ni are log transformed) obtained via XFM beamline on the Australian Synchrotron. Cpx – clinopyroxene; Ol – olivine; Opx – Orthopyroxene; Plag – plagioclase; Sym – symplectite.

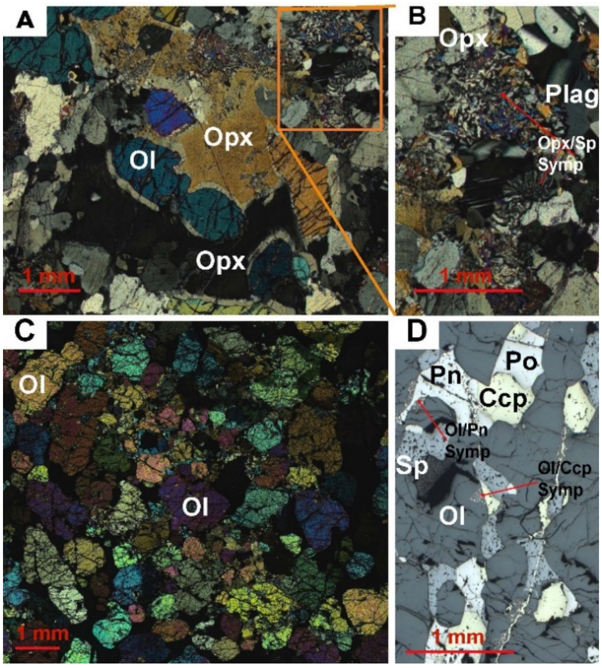

Figure 3. Symplectite textures in the Nova-Bollinger intrusions: A. Meta-norite/gabbronorite with remnant Opx and a few large fresh Ol grains; abundant symplectites, spindle twinning, bent exsolution patterns in pyroxene, annealed grain boundaries, and fresh Ol with Opx coronas. B. Opx - green spinel –hornblende symplectites on a microscopic scale in the same sample. C. Lherzolite with disseminated sulfides: Fresh Ol/Px pyroxene coronas around Ol and sulfides; D. Lherzolite with disseminated sulfides (same as C.): Primary, undifferentiated sulfide assemblage (Po-Pn-Ccp + Mag), Ccp-rich veinlets/patches vs. Po-Pn (spinel + Mag) domains; veinlets of sulfides (Ccp and Pn) forming symplectites. Ol – olivine, Opx – orthopyroxene, Plag – plagioclase, Sulf – sulfide, Pn – pentlandite, Po – pyrrhotite, Ccp – chalcopyrite, Sp – spinel, Symp - symplectite.

Olivine Fo content ranges from 84 to 78 with Ni content for the highest Fo of 1800ppm for the Upper Intrusion, and from 82 to 67 with Ni content of 1400ppm for the Lower Intrusion. These compositions are slightly more magnesian than the average cumulus olivine compositions estimated from whole-rock FeO-MgO trends; this is due to reaction of cumulus olivine with trapped intercumulus liquid. The Upper Intrusion shows a normal Ni-depletion trend (i.e. positively correlated Ni and Fo) whereas the Lower Intrusion shows evidence for sulfide equilibration with olivine during trapped liquid crystallisation, giving rise to a weak negative Fo-Ni correlation. Vanadium in olivine is very low, indicating redox conditions around the QFM buffer or above. Orthopyroxenes have high Al_2O_3 contents, typically 2.5-3.5% in plagioclase-poor rocks and ranging as high as 5%, indicative of crystallisation at pressures of at least 5 Kb.

SULFIDE-RICH ORES AT NOVA

Sulfide-rich mineralisation extends to distances of at least 20 metres from the host intrusion, as well as within the intrusion itself. The bulk of the ore falls on a spectrum between two gradational types: sulfides within mainly sharp-walled extensional vein arrays within the footwall gneisses, containing abundant inclusions of the immediate wall rock as well as rare inclusions of host intrusion; and “infiltrating sulfides” ranging from soft-walled irregular veins within paragneiss to heavy disseminations of sulfide permeating at grain-scale within the gneisses that form the vein walls (Figure. 4). In many cases sulfides selectively infiltrate particular layers. The gneisses within the infiltrating sulfide zone typically show chaotic rootless folds and appear to have been folded during emplacement of the sulfides. The sulfide rich veins within the infiltrating sulfide zones commonly contain bodies of coarse felsic material interpreted as leucosomes formed by partial melting of the immediately adjacent gneisses. These felsic bodies typically occupy the margins of the sulfide veins and have mineralogy varying widely from coarse grained tonalite with minor garnet to almost pure garnetites with interstitial quartz.

The sulfides themselves show spectacular coarse-grained “loop textures” (Figure. 5) where both pentlandite and chalcopyrite form semi-continuous rims to large (~1 cm) single pyrrhotite grains, interpreted as original MSS. Such textures have hitherto been regarded as the result of MSS exsolution, but this interpretation cannot explain the close association of pentlandite and chalcopyrite in the “loops” or the characteristic (relatively) high Pd content of the pentlandite. Recent work (Mansur et al., 2019) has solved this problem by interpreting coarse grain-boundary (as opposed to flame exsolution) pentlandite as the result of peritectic reaction between residual sulfide liquid and early-formed solid MSS. On this interpretation, loop texture is diagnostically magmatic. The widespread presence of loop textures in the Nova-Bollinger ores, in almost all settings from massive sulfide pools, veins, tension gashes and permeations into gneiss (e.g. Figure. 4) is therefore further strong evidence for high-P, high-T emplacement into granulite country at or just post the main metamorphism and deformation. Conditions were such that the country rock was able to fail either by folding or by semi-brittle fracturing depending on local lithology and strain rate.

GLOBULAR AND MATRIX ORES AT BOLLINGER

The Bollinger orebody contains a similar assemblage of disseminated, matrix, infiltrating massive and vein-hosted massive ore to Nova, but differs in that infiltrating sulfide is less abundant (probably due to the more mafic and hence more refractory nature of the immediate footwall) and matrix ores show characteristically layered leopard-textures defined by cm-scale sulfide-poor olivine-clinopyroxene clusters within typical olivine-sulfide matrix ore (Figure. 6). The clinopyroxene typically forms single or clustered oikocrysts with a shape-preferred orientation imparting a planar magmatic fabric to the rock. This is a variant of poikilitic leopard-textured ore (Barnes et al., 2017b) formed by percolation of sulfide liquid through a partially consolidated orthocumulate with early-formed oikocrysts. Some of these clinopyroxene clusters or clots have autolithic or xenolithic cores.

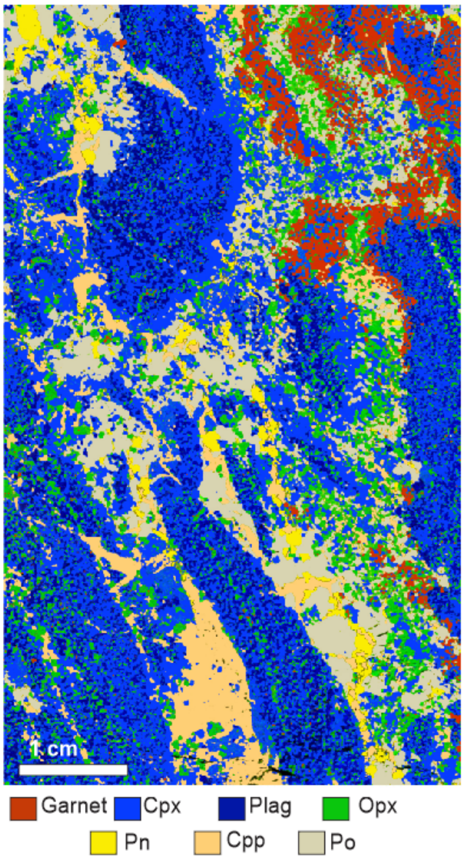

Figure 4. Phase map based on Tornado x-ray element map of cut slab showing permeation of sulfide into disaggregating garnet granulite, typical of sulfide infiltration zone in Nova orebody.

Globular ores also define a weak magmatic fabric, and in some cases (Figure. 6B) consist of convex sulfide globules rimmed by clots of Cr-poor clinopyroxene, intermixed at cm scale with patches of fine-grained olivine-sulfide matrix ore.

DISCUSSION

The Upper Intrusion itself is interpreted as the result of multiple pulses of variably fractionated magma of common parentage, to account for the alternation of peridotite and norite mesocumulate layers with similar incompatible trace element ratios. The Lower Intrusion appears to be a distinct unit, much thinner and lacking distinct internal variations, though with more extensive accumulation of orthopyroxene together with olivine. The lower marginal zone of the Upper Intrusion overlaps with the Lower Intrusion in several aspects of its whole rock and mineral chemistry. Abundant sector zoning in the pyroxenes in the Lower Intrusion is indicative of growth of these pyroxenes under mildly supercooled conditions. Addition of silica during assimilation of country rocks is a likely explanation for the abundance of cumulus orthopyroxene.

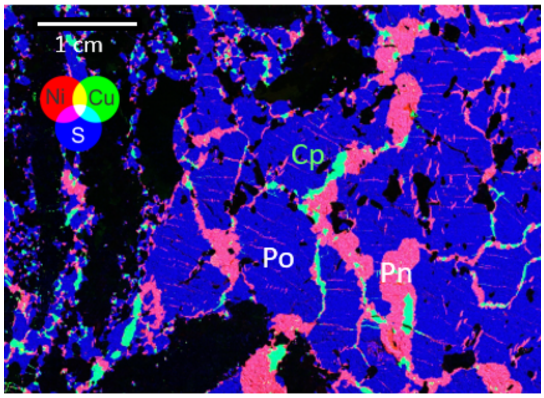

Figure 5. Tornado x-ray element map showing characteristic sulfide loop texture, with "chicken wire" loops of pentlandite and chalcopyrite developed around large single crystal pyrrhotite grains. Also note fine pentlandite exsolution in cores of pyrrhotite.

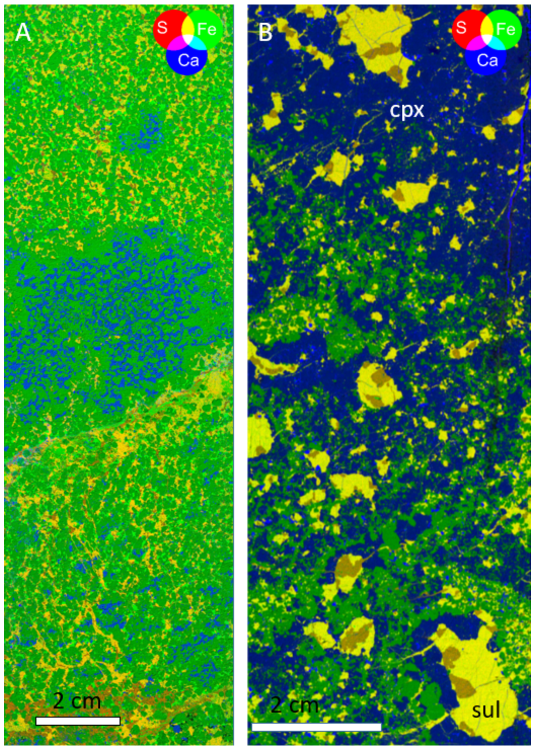

Figure 6. Tornado x-ray element maps (S, Fe, Ca) showing sulfides in yellow-orange, olivine (green) and cpx (blue) of drill core of matrix (A) and globular disseminated (B) ore from Bollinger. A: note absence of sulfide in cpx oikocrysts, occurring as single grains and one large cluster of grains. B: sulfide globules are associated with clumps of Cr-poor diopsidic augite (dark blue) and patches of fine-grained olivine-sulfide matrix ore.

The cumulate rocks of both intrusions preserve primary igneous cumulus textures with only minor evidence of post-solidification deformation.

Parent magmas to the intrusions were typical tholeiitic basalts in composition, with ~6-8% MgO, having major and trace element characteristics similar to typical island arc and back-arc basalts. Trace element patterns between Lower and the Upper Intrusion are essentially identical and do not provide unequivocal evidence of crustal contamination.

The origin of the symplectite coronas developed between olivine and plagioclase is a significant question given that they are found in a granulite facies metamorphic terrane. Either they were related to late stage mineral reactions during final solidification of trapped liquid at high pressure, where olivine and plagioclase are not stable together, or to metamorphism of initially low-pressure cumulus assemblages. However, the presence of cumulus low-Cr Mg-Al spinel coupled with high-Al pyroxenes strongly indicates high pressure crystallization, consistent with the independent evidence that sulfides were forming an infiltration-melting front into the underlying gneisses, implying emplacement into granulite facies country rocks already close to the onset of partial melting. The symplectites therefore probably record near-solidus late magmatic reaction, a consequence of the expanded stability field of low-Cr spinel at high pressures.

Olivine chemistry data is consistent with multiple magma pulses, variably fractionated and experiencing sulfide saturation at different stages of their evolution history with a significant postcumulus sulfide liquid equilibration trend evident for the Lower Intrusion.

The Nova-Bollinger mafic-ultramafic suite was formed from multiple pulses of magmas derived by varying degrees of fractionation of a common parental magma. The intrusions were emplaced into the deep crust contemporaneously with the regional metamorphic peak.

Mesoscopic and outcrop-scale features of the massive and semi-massive ores at Nova indicate emplacement in an extensive infiltration-melting front, under conditions where the country rocks were at or above their solidus temperatures within the thermal aureole of the intrusions.

Infiltration of sulfide served to effectively carry heat into the country rock gneisses, facilitating melting and infiltration of sulfide into the less refractory (garnet-bearing) layers. Partial melting produced felsic leucosomes that segregated by counter-flow into the sulfide-bearing veins. In some cases, these leucosomes may have been crystallising as they flowed, leaving behind “cumulates” of quartz, garnet and/or feldspar as vein linings and selvages (Figure. 4). Where country rocks were more mafic and hence less refractory, as in the footwall of Bollinger, partial melting was less extensive and sulfides tended to form sharp-walled vein arrays.

Coarse grained pn-ccp-po loop textures are ubiquitous within the massive ores, regardless of micro-scale setting, to the extent of being developed within narrow veins and broken fold-hinges. These textures are now regarded as diagnostically magmatic. This implies that sulfide vein emplacement took place under conditions where country rock deformation was either ductile or semi-brittle, despite the high temperatures of emplacement within the sulfide liquid melting range (~800°C). It is possible that much of the characteristic local deformation of the country rocks was a response to the emplacement of a large body of dense cumulate rocks and sulfide liquid, under conditions of very slow cooling.

Coupled with the clear evidence for high-P crystallisation of the host intrusions (cumulus Mg-Al spinel, symplectic coronas forming from trapped liquid reaction, high-Al pyroxenes) these observations attest to deep emplacement of the Nova-Bollinger ores at mid to lower crustal depths during the peak of regional metamorphism. Aside from some local post-emplacement shearing, the Nova-Bollinger ores and host rocks retain primary magmatic features and have not been penetratively deformed post magmatic emplacement.

ACKNOWLEDGEMENTS

We thank IGO NL for financial support, access to drill core and underground workings and permission to present data, and IGO geologists and staff for helping organize Nova mine site visits and assistance in various phases of the project. We acknowledge the contributions of IGO mine geological staff, particularly Sebastien Staude, Kyle Hodges and Paul Hetherington. The image in Figure. 2 was collected on the XFM Beamline of the Australian Synchrotron, Clayton, Victoria, operated by ANSTO.

REFERENCES

Barnes SJ, et al., 2016, Poikilitic Textures, Heteradcumulates and Zoned Orthopyroxenes in the Ntaka Ultramafic Complex, Tanzania: Implications for Crystallization Mechanisms of Oikocrysts: Journal of Petrology, 57/6, 1171-1198.

Barnes, S.J., et al., 2017a, Textural development in sulfide-matrix ore breccias and associated rocks in the Voisey's Bay Ni-Cu-Co deposit, Labrador, Canada: Ore Geology Reviews, 90, 414-438.

Barnes, S.J., et al., 2017b, Sulfide-silicate textures in magmatic Ni-Cu-PGE sulfide ore deposits: Disseminated and net-textured ores: American Mineralogist, 102, 473-506.

Barnes, S.J., et al., 2018, Sulfide-silicate textures in magmatic Ni-Cu-PGE sulfide ore deposits: massive, semi-massive and sulfide-matrix breccia ores: Ore Geology Reviews, 101, 629-65.

Clark, C., et al., 2014, Proterozoic granulite formation driven by mafic magmatism; an example from the Fraser Range Metamorphics, Western Australia: Precambrian Research, 240, 1-21.

Independence Group, 2019, CY18 Annual update of exploration results, mineral resources and ore reserves, CY18 Mineral Resource and Ore Reserve Statement

Maier, W.D., et al., 2016, Petrogenesis and Ni–Cu sulphide potential of mafic–ultramafic rocks in the Mesoproterozoic Fraser Zone within the Albany–Fraser Orogen, Western Australia: Precambrian Research, 281, 27-46.

Mansur, E.T., et al., 2019, Textural and compositional evidence for the formation of pentlandite via peritectic reaction: Implications for the distribution of highly siderophile elements: Geology, 47 (4), 351-354.

Parker, P., et al., 2017, Nova-Bollinger Ni-Cu-Co sulfide deposit In: Phillips GN (ed) Australian Ore Deposits: The Australasian Institute of Mining and Metallurgy, Melbourne, 139-142.

Smithies, R.H., et al., 2013, Petrogenesis of Gabbros of the Mesoproterozoic Fraser Zone: Constraints on the Tectonic Evolution of the Albany–Fraser Orogen: Geological Survey of Western Australia, Record 2013/5, 29.

Spaggiari, C.V., et al., 2009, Interpreted bedrock geology of the south Yilgarn and central Albany–Fraser Orogen, Western Australia: Geological Survey of Western Australia, Record 2009/10, 84.