Mineralium Deposita
https://doi.org/10.1007/s00126-024-01345-5

PREFACE

Thematic Issue on Magmatic PGE-(Ni-Cu-Cr-V) deposits: petrology, geochemistry and exploration tools

Wolfgang D. Maier[1] · Eduardo Mansur[2] · Vesa Nykänen[3]

Received: 15 December 2024 / Accepted: 20 December 2024

The 14th Platinum Symposium, held in July 2023 at Cardiff University, UK, was attended by 170 delegates from 20 countries who presented talks and posters on the geology, mineralogy, geochemistry, beneficiation and petrogenesis of platinum-group element mineralisation as well as associated metals such as Ni, Cu, Cr, Ti, and V. Delegates had the option to attend online but most decided to attend in person. For most delegates it was the first in-person experience of an international conference after the pandemic. It made us realise (again) that discussions and social interactions during breaks, poster sessions and at breakfast and dinner are crucial to develop and test ideas and build new collaborations. For the younger scientists, these activities are essential to advance their careers.

The symposium ran back-to-back with the Wager and Brown Workshop on layered intrusions. We also organised three fully subscribed field trips to the St David's layered intrusion in Wales, the Rum layered igneous complex in Scotland, and the Palaeoproterozoic Ni-Cu-PGE-Ti-V-Cr mineralised intrusions in Finnish Lapland.

This thematic issue contains contributions on topics presented at the Platinum Symposium, including PGE, Ni, Cu, Cr and Ti-V deposits at Bushveld, Stillwater, Duluth, Lac des Iles, Sudbury, Lac Fabien, Gondpipri and several Norwegian intrusions. In addition, the issue contains contributions on trace element- and isotope geochemistry of mafic-ultramafic systems, the description and origin of nano PGM, chemical mapping using microXRF, and experimental petrology.

The first group of contributions addresses different aspects of the world's largest layered intrusion and magmatic ore belt, the Bushveld Complex of South Africa and associated mineral deposits. The paper by **Hayes et al.** investigates the significance of coarse-grained and pegmatoidal textures in the Merensky Reef along 10 km of strike in the western Bushveld Complex. Based on textural and in-situ geochemical data the authors argue that the Merensky Reef did not form at the base of a large magma chamber, but instead formed in response to lateral melt infiltration into a pre-existing crystal pile. The paper by **Brits et al.** provides a comprehensive study of the structural context of the Flatreef in the Northern Limb of the Bushveld Complex. The authors combine results and observations from geophysical investigations, exploration drill cores and recent underground exposures to assess the effects of deformation on the mineralisation. They argue that the architecture of the host rocks controlled the emplacement of the intrusion while syn-magmatic deformation led to strata thickening driven by subsidence. The authors conclude that structures influenced the metal endowment of the Flatreef. The paper by **Latypov and Chistyakova** explores the paradox that the PGE-rich layers of the Bushveld Complex are widely argued to have formed through multiple magma injections, however, no feeder conduits have so far been identified. The authors suggest that following magma emplacement, the feeder channels in layered intrusions tend to be obliterated by the adjacent elastically deformed cumulate pile. The paper by **Otto et al.** investigates the possibility that the chromitite seams of the Bushveld Complex result from the entrainment of mantle source components in the Bushveld parent magmas. Based on thermodynamic modelling the authors postulate a domain in the sub-cratonic mantle within which Cr-bearing orthopyroxene forms as a product

Editorial handling: B. Lehmann

✉ Wolfgang D. Maier
MaierW@cardiff.ac.uk

Eduardo Mansur
Eduardo.Teixeira.Mansur@ngu.no

Vesa Nykänen
vesa.nykanen@gtk.fi

1 Cardiff University, Cardiff, UK

2 Geological Survey of Norway (NGU), Trondheim, Norway

3 Geological Survey of Finland (GTK), Rovaniemi, Finland

Published online: 25 January 2025

of incongruent melting. Entrainment of this orthopyroxene produces magmas that crystallise peritectic olivine and chromite on ascent, due to the consumption of orthopyroxene by melt. The chromite- and olivine-bearing magmas intrude as sills and can produce chromitite seams.

Several contributions of the thematic issue deal with other mineralised layered intrusions, including Duluth and Stillwater in the USA, Lac des Iles and Sudbury in Canada, Gondpipri in India and the Etoile Suite of Quebec, Canada. **Virtanen et al.** studied copper-nickel(-PGE) sulfide mineralisation of the Duluth Complex, Minnesota, believed to have formed by assimilation of sulfur from the Virginia Formation black shale. Using Raman spectroscopy, the authors show that carbonaceous material within the regionally metamorphosed Normal Black Shale (NBS) represents graphitized biogenic material. In contrast, the Bedded Pyrrhotite Unit (BPU) contains pyrobitumen representing residues of oil that accumulated to porous horizons which formed due to dissolution of precursor sedimentary clasts. Sulfur mobilization in the NBS occurred during the subsolidus devolatilization stage of the black shale, while partial melting was required to release sulfur from the BPU to the magma. **RP Maier et al.** investigated the petrogenesis of the Etoile Suite of the Grenville Province in Quebec, Canada. The intrusion has been dated at 1149 ± 11 Ma, i.e. broadly coeval to the Lac St Jean and other anorthosites in the Greenville Province. The main mafic intrusion of the Etoile Suite contains an approximately 1-km-thick wehrlitic interval in its central portion hosting disseminated and semi-massive ilmenite and titanomagnetite, the latter with up to 1.85 wt% V_2O_5. The authors argue that the intrusion formed via fractional crystallisation of a high-Al basalt derived from a depleted mantle source. The magma solidified in an open system recording minimal contamination and moderate fO_2 (~FMQ 1.1 ± 0.3). **Gupta and Boudreau** used several lines of evidence to suggest that the reappearance of olivine and PGE-rich sulfide in the J-M Reef of the Stillwater Complex, Montana is due to fluid infiltration and hydration melting. MELTS modelling suggests that incongruent hydration melting results in up to 37% olivine (Fo76-86, overlapping with natural compositions). Modelling with the PELE program suggests that to explain the ores, CO_2-rich fluids need to have metal concentrations on the order of 25 ppm Pt, 75 ppm Pd, 0.03 wt% Cu, and 0.20 wt% Ni, at a fuid/rock mass ratio of ~0.25. Sulfide and ore metals are readily remobilized by more H_2O-rich fuids, consistent with the heterogeneous distribution of sulfide and regionally variable ore grades. **Smith et al.** studied feldspathic lherzolite and harzburgite in the southern Lac des Iles Complex, Canada, an ~2.69-Ga arcuate mafic intrusion that hosts world-class Pd mineralisation within varitextured and brecciated gabbronoritic rocks. The authors used detailed petrographic studies in combination with whole-rock and mineral compositions to model batch crystallization of a hydrous andesitic magma that has interacted with antecedent feldspathic cumulates. They conclude that the parent magma was likely at or close to sulfde saturation upon emplacement and may have co-existed with a volatile-rich phase. The Lac des Iles Complex may serve as a type-example of Archean continental arc-related magmatic sulfide deposits, fed by fertile andesitic parent magmas formed through the diferentiation of primitive sub-arc mantle melts in the juvenile crust. **Genereux and Lafrance** investigated PGE mineralisation within brecciated footwall rocks at the Crean Hill and Vermilion deposits of the Sudbury Igneous Complex (SIC), Canada. They suggest that PGE deposition involved three stages. During the magmatic stage, fractionating sulfide melts infiltrated the footwall rocks to form sulfide (-PGE) breccias and disseminated PGE mineralisation (at Crean Hill), and sulfide-PGE veins (at Vermilion). During a syn-tectonic remobilization stage, PGE and Au were remobilized via fluids into shear zones in the footwall rocks of both deposits. A late metasomatic stage at < 300 °C is observed at Vermilion only, where it caused epidote-albite-quartz-calcite alteration of the SIC rocks and deposition of low-temperature sulfides and precious metals in veins crosscutting shear zones. **Dora et al.** studied the Gondpipri layered mafic–ultramafic intrusion in the Bastar Craton in Central India. The intrusion hosts both magmatic and hydrothermal Ni-PGE mineralisation, the latter formed some 700 Ma after the ca. 3.3–3.2 Ga crystallisation of the mafic-ultramafic host rocks. It is proposed that an immiscible Bi-Te melt collected primary PGMs, which were later redistributed and reprecipitated to form Pd tellurides, tsumoite, melonite, and hessite, due to deformation, metamorphism and the late-stage cooling of high-temperature hydrothermal fluids. Selenium geothermometry of pyrite indicates that hydrothermal mineralisation occurred within a temperature range of 200 to 475 °C.

Three contributions deal with the petrogenesis of magmatic nickel deposits. **Mansur et al.** constrained the origin of Ni-Cu-Co sulfides in the Proterozoic Espedalen anorthosite Complex of Norway. The mineralisation occurs as primary, undeformed sulfides and as deformed sulfides hosted within shear zones. Both types have Ni tenors ranging from 3 to 10%, but relatively low concentrations of PGE, indicating PGE-depleted parent magmas. The authors further show a positive correlation between Se concentrations in pentlandite and whole-rock Ni tenors for Espedalen and magmatic Ni-Cu-Co sulfde deposits worldwide. They argue that Se concentrations in pentlandite remain largely undisturbed during post-cumulus processes as opposed to other trace elements. Consequently, Se concentrations in pentlandite may serve as a proxy for metal enrichment in magmatic sulfde deposits. **WD Maier et al.** studied magmatic

Ni-sulfides within the ~3.0 Ga Maniitsoq belt in Western Greenland. The sulfides form disseminations and sulfide matrix breccia veins within pipe-like bodies of orthopyroxenite and gabbronorite interpreted to represent magma conduits. Sulfide segregation was likely triggered by assimilation of crustal sulfur, as suggested by whole rock S/Se ratios of 7000–9000. The sulfide melt underwent extensive fractionation after final emplacement, caused by downward percolation of Cu-rich sulfide melt through incompletely solidified cumulates. The authors suggest that the exposed Maniitsoq intrusions represent the Ni-rich upper portions of magma conduits implying that there is potential for Cu-rich sulfides in unexposed deeper portions of the belt. **Caruso et al.** showed that in sulfide-matrix breccias at Voisey's Bay, hydrous silicate rims are commonly present at the interface between the sulfide matrix and the silicate framework. Through the integration of compositional maps with major and trace element analyses of the main accessory minerals, the authors propose that the hydrous silicate rims originated from an immiscible Fe-Ti-P melt. Distinct textural and compositional features of apatite, hercynite, ilmenite and magnetite support the presence of small amounts of Fe-Ti-P melt in the sulfide melt. This Fe-Ti-P melt likely formed through melt immiscibility in the early stages of the development of the Voisey's Bay complex and was transported in magma conduits together with the sulfide melt.

The paper by **Schoneveld et al.** presents spectacular chemical maps of Cr-zoning patterns in orthopyroxenes from the Nova-Bollinger (Australia) and Kevitsa (Finland) Ni-Cu deposits. The authors propose that the zonation resulted from growth of the pyroxenes within dynamic magma conduits that are multiply recharged by new magma pulses. Therefore, such zonation could be used as an indicator of favourable conditions for metal enrichment in magmatic sulfide ores.

Finally, the issue contains three contributions focussed on in-situ mineral characterization aiming to better understand the formation of magmatic sulfide deposits. **Milani et al.** investigated the major- and trace-element composition of magnetite from mafic–ultramafic intrusions peripheral to the Kunene Complex of Angola and Namibia. The authors identified different types of magnetite ranging from magmatic to secondary hydrothermal magnetite and discuss the application of the mineral chemistry as a proxy for metallogenetic processes. They argue that highly serpentinized ultramafic rocks in the Kunene Complex may constitute possible targets for magmatic Ni-Cu mineralisation. The contribution by **González-Jiménez et al.** reports on nanoscale analysis of Cu-Ni-Fe sulfide inclusions in laurite from the Taitao ophiolite (Chile) and the Kevitsa intrusion (Finland). The authors highlight the importance of nanoscale studies in reaching a better understanding of the formation of magmatic sulfide deposits. The morphologies of sulfide inclusions and their interfaces with the laurite host are interpreted via the complex solidification history of Cu-Ni-Fe sulfides, involving the coexistence of nano-sized volatile-rich melts and crystalline phases. The authors also argue that arsenide and sulfide melts may coexist during the early stages of chromitite formation. **Cherdantseva et al.** study the formation of volatile-rich phases in magmatic sulfide systems, based on isotopic signatures and trace element distributions of sulfides, calcite, apatite and zircon. They conclude that both mantle and crustal sources play a role in the formation of volatile- and incompatible element-rich halos around sulfide globules. In the authors' view, this confirms the common origin of sulfides, carbonate and fluids during ore-forming processes, while ruling out a secondary origin of volatile-rich phases. Specifically, the authors propose that volatile- and incompatible element-rich halos could have formed due to the interaction of immiscible sulfide, carbonate, and silicate melts.

We thank the reviewers of this special issue and chief editor Bernd Lehmann for his careful editing. We also thank the sponsors of the symposium and field trips, including SGA, IAGOD, Stillwater Critical Minerals, Rio Tinto and Cardiff University.

Declarations

Conflict of interest No funding was received for this work. The authors declare they have no financial interests. WDM is on the editorial board of Mineralium Deposita.