**T.G. Schultz**
The Project Blue Group Limited, 71-75 Shelton Street, Covent Garden, London, WC2H 9JQ, United Kingdom
e-mail: tanisha.schultz@projectblue.com

**C. Djeutchou**
African Rainbow Minerals Chair in Geometallurgy, Department of Earth Sciences, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa
e-mail: djeutchoucdric@gmail.com



## Abstract

Manganese (Mn) is a crucial metal for steelmaking and is increasingly being sought after for its use in the battery and clean-energy sectors. Through discovery of the Kalahari Manganese Field (KMF), the world's largest land-based Mn resource, South Africa has positioned itself as a major player in the global Mn supply chain. However, only a fraction of this total Mn resource is currently being exploited, and opportunities for further exploitation in the KMF and at several other Mn deposits and occurrences throughout South Africa remain to be realised. To consolidate scientific and industrial interest in the entire South African Mn resource base, the present contribution provides a holistic overview of (1) global Mn mineral economics, (2) the processes that give rise to enrichment of Mn in crustal rocks, (3) the palaeoenvironmental implications of Mn enrichments, (4) the geology of domestic Mn deposits and occurrences, and (5) the geometallurgical and mineral processing paradigms applicable to full value realisation from these diverse ore types. South African Mn deposits are broadly subdivided into those formed from chemical sedimentary processes and subsequent diagenesis (e.g., the KMF, deep-sea Mn nodules and crusts); those formed as residual enrichments after chemical weathering of Mn-bearing protolith (e.g., North West Manganese Fields); and those formed through mobilisation by hydrothermal fluids and groundwater (e.g., vein and breccia-hosted deposits in fractured lithologies in the Cape Supergroup, Waterberg Group, etc.). Because of these differences in the mechanisms of Mn deposit formation, and because of the various valence and ligand bonding interactions associated with Mn, the resultant mineralogy of the individual deposit groups is widely varied. Primary chemical sediments typically comprise $Mn^{2+}$ carbonates, braunite and occasionally $Mn^{2+}$ silicates, which may be locally upgraded to $Mn^{2+/3+}$ oxide minerals by subsequent hypogene enrichment. Low temperature deposits, including Mn nodules, groundwater-associated deposits, and residual accumulations are marked by $Mn^{4+}$ mineral parageneses, which may subsequently be modified by regional metamorphism. Inasmuch as Mn grade is a primary variable governing economic Mn extraction, a growing body of geometallurgical work highlights that full value realisation will only be achieved through targeted exploitation of the Mn mineralogical diversity. This includes the realisation that Mn valence and ligand coordination impact the energy consumption and reagent utilisation during down-stream processing.

## Introduction

Manganese (Mn) is a vital metal used in the production of essentially every tonne of steel, and as a key cathode material for the manufacture of modern lithium (Li) ion batteries. It is mainly produced in the Republic of South Africa (RSA; 36%), along with Gabon (23%), Australia (15%), Ghana (4.2%), China (3.7%), India (3.6%), and Brazil (3.1%) (Ziemann et al., 2013; Singh et al., 2020; USGS, 2024). There is a significant increase in demand for Mn alloys driven by the manufacturing industry which is, in turn, driven by rapid industrialisation of certain countries and by population growth. However, rapid depletion of high-grade Mn ore resources imposes challenges for Mn-based industries. These challenges are similar to those experienced in other commodity spaces and include the unavailability of high-grade raw materials, techno-economic difficulties associated with beneficiation of low-grade ores, and environmental restriction on ore processing technologies (e.g., $CO_2$ emission and toxic waste disposal; Lund, 2013; Aasly and Ellefmo, 2014; Ortiz, 2019; Singh et al., 2020; Gholami et al., 2022; Chetty et al., 2023). Manganese is increasingly listed on governments' critical materials lists, appearing in over half of the lists evaluated in a review by McNulty and Jowitt (2021). These lists highlight the economic importance of a metal in a context of the intrinsic risks associated with its supply chain.

Because of these issues, and because of South Africa's positioning as a major supplier to global mining outputs and as a major resource and reserve base (USGS, 2024), a review of the local Mn geology and its geometallurgy is both timely and geographically relevant. Scientific understanding of South Africa's world-class endowment of this critical metal is well-advanced, with comprehensive reviews provided by Cairncross et al. (1997), Astrup and Tsikos (1998), Cairncross and Beukes (2013), and Beukes et al. (2016). Renewed interest in Mn,