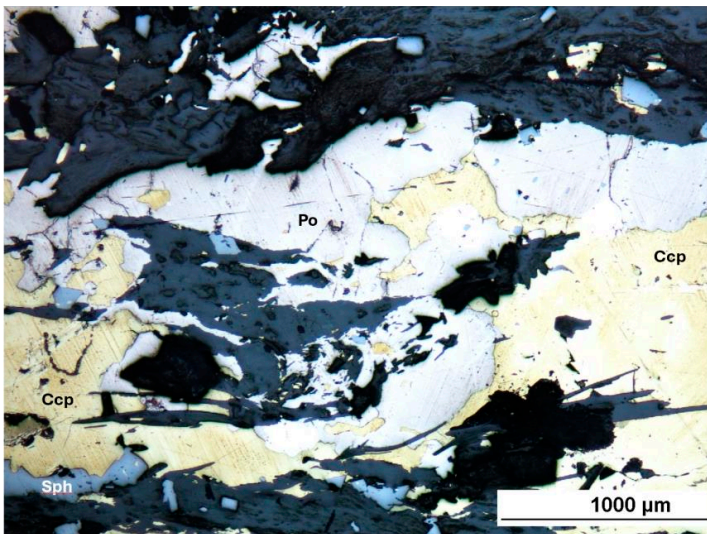
DOCTORAL THESIS

Geology, Magmatic Evolution, and Cu–Au Sulfide Genesis of the Mundonguara Deposit, Manica Greenstone Belt, Mozambique



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Ore Geology

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Front page: Reflected light microphotograph of a sulfide-bearing vein in komatiite, featuring chalcopyrite (Ccp), pyrrhotite (Po), and sphalerite (Sph).

To my children, Adaeze, Bhonghani, and Jabulani,
my inspiration and strength every step of the way.

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Abstract

This thesis presents an integrated geological study of the Mundonguara Cu-Au deposit, located within the Archean Manica Greenstone Belt of western Mozambique, which forms part of the eastern Zimbabwe Craton. The research combines petrography, lithogeochemistry, U-Pb geochronology, mineralogy, mineral chemistry, and stable isotope analysis (S, C, and O isotopes) to develop a comprehensive genetic model and contribute to the understanding of metallogenic processes in Archean greenstone terranes.

Fieldwork and geochemical analyses reveal that the Macequece Formation, which hosts the Mundonguara Cu-Au deposit, comprises Al-undepleted peridotitic komatiites, pyroxenitic komatiites, ultramafic cumulates, and intrusive mafic to felsic rocks. These units show evidence of a mantle plume origin and were emplaced in a continental rift setting. U-Pb zircon ages from intrusive and extrusive units constrain the timing of a major magmatic event to 2.94-2.91 Ga, placing the Macequece Formation within the Lower Greenstones of the Bulawayan Supergroup. A major unconformity separates it from the overlying M'Beza-Vengo Formation, recording a temporal gap of ca. 170 Ma and indicating a craton-wide tectonic transition. Additional Neoproterozoic ages (578-846 Ma) reveal overprinting by later tectono-thermal events, including those associated with the Rodinia breakup and the Pan-African orogeny.

Sulfur isotope compositions of sulfides ($\delta^{34}S$: -0.40‰ to +4.02‰) support a dominantly magmatic source, with minor crustal input. Carbon and oxygen isotope ratios in gangue carbonates ($\delta^{13}C$: -9.61‰ to -4.32‰; $\delta^{18}O$: +4.93‰ to +13.05‰) define multiple stages of fluid-rock interaction, from early carbonate alteration of komatiites to later Cu-Au mineralization. These isotope signatures reflect the involvement of hybrid fluids of predominantly magmatic-hydrothermal character and with minor crustal contributions.

Mineral chemistry data further support this model. Chalcopyrite trace element patterns are consistent with medium-temperature hydrothermal systems (e.g., IOCG, skarn), while Ni enrichment indicates interaction with komatiitic host rocks. Pyrite compositions define two groups with contrasting Co/Ni ratio, pointing to mixing between magmatic and metamorphic fluid sources. Sphalerite Fe content yields ore formation temperatures between 280 and 335 °C, consistent with low- to medium-temperature hydrothermal systems and overlapping with orogenic gold deposits.

Altogether, the data supports a hybrid genetic model for the Mundonguara deposit, involving dominantly magmatic-hydrothermal fluids, minor metamorphic contributions, and metal input from both mantle-derived and local ultramafic rocks. The system differs from classical IOCG- and orogenic gold deposits and is best interpreted as an orogenic gold deposit with atypical metal association hosted in komatiitic rocks.

Acknowledgments

This PhD research was generously funded by the Swedish International Development Cooperation Agency (SIDA) through a bilateral cooperation program between Mozambique and Sweden. This support was instrumental in enabling the successful completion of this study, fostering academic exchange and collaboration between the two countries.

I also extend my gratitude to the Geology Department at Eduardo Mondlane University for their support during fieldwork, and to the Geosciences and Environmental Engineering Department of Civil, Environmental and Natural Resources Engineering at Luleå University of Technology for their academic and logistical support.

To my mother and father, Maria Alice Lourenço and Norberto José da Conceição *(in loving memory)*, I express my deepest gratitude for giving me the opportunity to study and for instilling in me the value of knowledge. This doctorate is also the fruit of your efforts.

To my supervisors, Christina, Olof, and Jamal, I am sincerely grateful for your continuous support, academic guidance, and trust throughout this process. Your dedication was essential to the completion of this work.

To my colleagues and friends from the Ore Geology Research Group: Glenn, Cheche, Amir, Jonathan, Tobias, Edward, Filip, Emilie, Emily, Ervin, Iris, Joel, Nils, Leslie, Lidia, Francisca, Mathis and John, thank you for your companionship, enriching scientific discussions, and the joyful moments we shared throughout my studies.

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To my siblings, Vovoty, Zito, Lulú, Paulina, and Nilton, and to my brothers- and sisters-in-law, José, Igma, Luzia, and Yolanda, thank you for your unconditional love and strength when it mattered most. To my cousin Lawrence, a special thank you for always being by my side. Your support truly made a difference.

List of papers

The following scientific papers are included in this doctoral thesis:

Paper I **Mendes, L.N.**, Martinsson, O., Jamal, D.L., Azim Zadeh, A.M., Wanhainen, C. (2024). Lithogeochemistry and origin of the komatiites from Mundonguara mine in the Manica greenstone belt, Mozambique. *Journal of African Earth Sciences*, 223, 20p. https://doi.org/10.1016/j.jafrearsci.2024.105494

Paper II **Mendes, L.N.**, Martinsson, O., Jamal, D.L., Wanhainen, C. (2025). Geochronology of mafic and felsic rocks at the Mundonguara Mine: Insights into the chronostratigraphy of Archean greenstones within the Zimbabwe Craton. *Journal of African Earth Sciences*, 232, 11p. https://doi.org/10.1016/j.jafrearsci.2025.105821

Paper III **Mendes, L.N.**, Martinsson, O., Jamal, D.L., Wanhainen, C. (submitted to Geoenergy) Sulfur, carbon and oxygen isotope constraints on the origin of the Mundonguara Cu–Au deposit, Manica, Mozambique.

Paper IV **Mendes, L.N.**, Martinsson, O., Jamal, D.L., Azim Zadeh, A.M., Nopeia, M., Wanhainen, C. (manuscript) Mineral chemistry constraints on a hybrid magmatic-hydrothermal and metamorphic fluid origin for the Mundonguara Cu-Au deposit, Manica Greenstone Belt, Mozambique.

Reprints have been made with the permission of the publisher. The following scientific papers are not included in this doctoral thesis:

Mendes, L. N., Martinsson, O., Jamal, D. L., & Wanhainen, C. (2022). Mineralogy and geochemistry of komatiites associated with Cu-Au deposits: An example from the Mundonguara mine in Manica Greenstone Belt, Mozambique (Conference paper). GF150 – Geological Society of Sweden 150th Anniversary Conference, Uppsala, Sweden.

Nhamutole, N., Bamford, M. K., Souza, P. A., Felix, C. M., Pereira, E., Bastos, L., **Mendes, L.**, Deus, O., Nopeia, M., & Carmo, D. A. (2025). Reconstructing the late Permian–early Triassic environment of a coal-bearing succession in the Maniamba Basin, Mozambique (Central Gondwana): A multiproxy palynological and geochemical approach. *International Journal of Coal Geology, 304*, Article 104755. https://doi.org/10.1016/j.coal.2025.104755

Assessment of contribution

Prof. Salvador Mondlane Jr., Prof. Thorkild M Rasmussen, Prof. Christina Wanhainen, Assoc. prof. Daud Jamal, and Dr. Olof Martinsson were responsible for setting up this thesis project, organizing funding, and establishing the initial project goals. The PhD candidate (LM), Prof. Wanhainen (CW), Dr. Martinsson (OM), and Assoc. prof. Jamal (DJ) developed the research study and experimental design at the start of the thesis project.

Paper I: LM, OM, and DJ conducted fieldwork, including sampling and drill core logging. LM prepared samples for thin sections and ICP-MS analyses, performed petrographic analysis, interpreted the data with guidance from OM and DJ, visualized the results, and wrote the original manuscript. The manuscript was critically reviewed and edited by OM, DJ, Amir Azim Zadeh (AZ), and CW, with revisions led by LM. ICP-MS analyses were conducted by ALS Lab in South Africa.

Paper II: LM and DJ carried out fieldwork and sampling. LM prepared the samples for U–Pb (SHRIMP) analyses, performed petrographic analysis, interpreted the data, visualized the results, and wrote the original manuscript. The manuscript was critically reviewed and edited by OM, DJ, and CW, and revised by LM. U–Pb analyses were performed by Dr. Sato at the Centro de Pesquisas Geológicas (CPGeo) at University of São Paulo, Brazil.

Paper III: LM conducted petrographic analysis, interpreted the data with guidance from OM, visualized the results, and wrote the original manuscript. The manuscript was critically reviewed and edited by OM, DJ, and CW, and revised by LM. Sulfur, carbon, and oxygen isotope analyses were carried out by Prof. Martin Whitehouse and Dr. Heejin Jeon at the NordSIMS laboratory (Swedish Museum of Natural History, Stockholm), with LM assisting in the analytical process.

Paper IV: LM conducted petrographic analysis, interpreted the data with guidance from OM, CW and AZ, visualized the results with help from AZ and colleagues, and wrote the original manuscript. Critical review and editing of the manuscript were done by OM, CW, AZ, and DJ, with revisions by LM. EPMA analyses were performed by Manuel Nopeia (MN) at Akita University Lab in Japan, and LA-ICP-MS analyses were conducted by AZ at Luleå University of Technology with LM assisting in the analytical process.

1. Introduction

Archean greenstone belts contain a wide variety of mineral deposits and are critical for the global supply of base and precious metals. These belts commonly host volcanogenic massive sulfide (VMS) deposits, orogenic gold deposits, and komatiite-hosted Ni-Cu-(PGE) deposits, among others. Within the Zimbabwe Craton, (Fig. 1) Archean greenstone belts are widespread and host significant gold deposits and komatiite-hosted Cu-Ni occurrences (Förster et al., 1996; Prendergast, 2003; Mondlane, 2005). On the Mozambican side of the craton, the greenstone belts are largely restricted to the Manica Greenstone Belt (MGB), where mining activity has primarily focused on alluvial gold, minor orogenic gold occurrences, and the historically significant Mundonguara deposit (D'Orey, 1992; Förster et al., 1996). This deposit preserves multiple generations of sulfide mineralization, making it an ideal natural laboratory for studying magmatic-hydrothermal systems in Archean komatiitic environments.

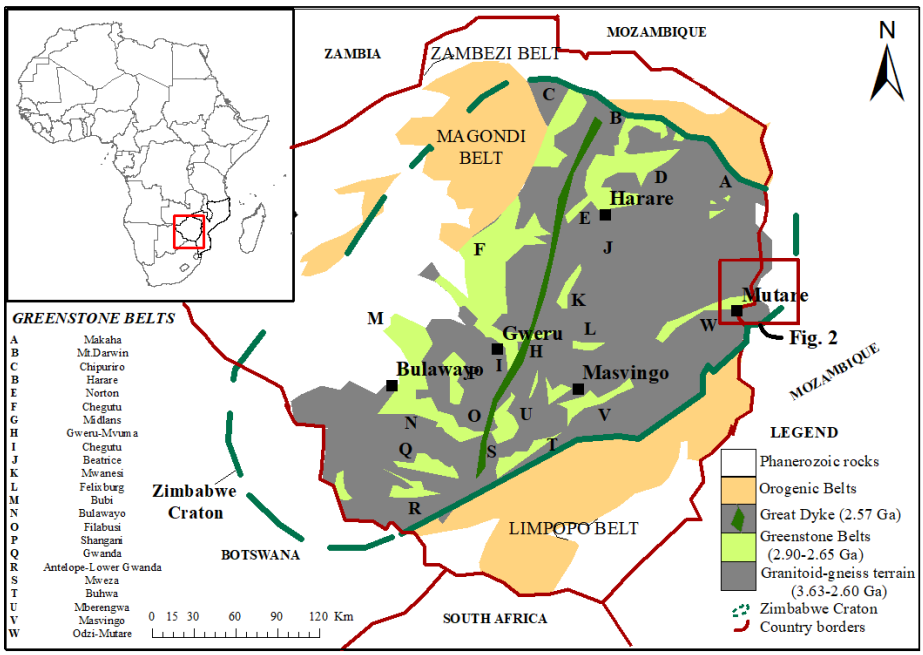

Figure 1- Map of the Zimbabwe Craton, illustrating age divisions of the cratonic units and its greenstone belts. The red square marks the location of the Odzi-Mutare-Manica Greenstone Belt, extending eastward into Mozambique (Modified from Hoffman et al., 2024).

The Mundonguara deposit (Fig. 2), located in west-central Mozambique, was intermittently mined between 1902 and 1990, producing approximately 15,000 tonnes of copper and 150 kilograms of gold from an estimated 0.5 Mt of ore (Förster et al., 1996). The remaining resources are estimated at 0.323 Mt with grades of 3.12% Cu, 0.58 g/t Au, and 25.04 g/t Ag (Baobab Resources, 2007). The deposit is hosted by komatiitic rocks and exhibits an elevated nickel content and traces of PGE minerals, raising debates about its genesis, particularly regarding the relative contributions of syngenetic and epigenetic processes (D'Orey, 1992). The unusual presence of both copper and gold as main commodities in a komatiite-hosted setting makes the deposit of significant interest for understanding the metallogeny of Archean greenstone belts in the region.

Several studies have investigated the geology and mineralization of the Manica Greenstone Belt and the Mundonguara area (D'Orey, 1992; Manuel, 1992; Förster et al., 1996; Manhiça, 1998; GTK, 2006; Sumburane, 2011; Mendes et al., 2024), focusing on petrography, geochemistry, structural geology, and lithostratigraphy. However, the genesis of the Mundonguara deposit remains debated, especially the possible genetic relation between syn- and epigenetic mineralization.

Archean deposits often record complex histories involving multiple stages of magmatism, fluid circulation, and tectonic overprinting (Anhaeusser, 2014; Crépon et al., 2024). Distinguishing magmatic from post-magmatic hydrothermal processes remains a fundamental challenge in Archean terranes (Poulsen et al., 2000). In this context, stable isotope geochemistry, particularly sulfur ($\delta^{34}S$), carbon ($\delta^{13}C$), and oxygen ($\delta^{18}O$), is a powerful tool to identify fluid sources and constrain ore-forming processes (Ohmoto & Rye, 1979; Wei et al., 2019). While sulfur isotope studies are commonly applied to sulfide minerals, recent advances show that carbon and oxygen isotope data from calcite can be used to trace hydrothermal fluid evolution and help distinguish between early and later generations of mineralizing events (Morishita, 2022; Mustafa et al., 2023).

This thesis presents an integrated study of lithology, mineralization, and fluid evolution at the Mundonguara deposit, combining petrographic, geochemical, geochronological, mineralogical, and isotopic data to develop a comprehensive genetic model and analyze its implications for regional mineral exploration.

The research aims to improve the understanding of metallogenic processes associated with the Archean Mundonguara deposit. By integrating petrography, lithogeochemistry, ore microscopy, mineral chemistry, and stable isotope geochemistry (S, C, O), this study investigates the origin and evolution of the mineralizing system, its host rocks, and the related alteration processes.

To examine the lithological, geochemical, and isotopic characteristics of the Mundonguara Cu-Au deposit and to clarify its origin, fluid sources, and implications for Archean greenstone belt metallogeny, the following research questions are addressed:

- What are the lithological and geochemical characteristics of the host komatiites, and how are they related to regional Archean magmatism?
- What is the timing of magmatic and mineralizing events in relation to the regional geodynamic evolution of the Zimbabwe Craton?
- What mineralization styles and sulfide assemblages are present at Mundonguara, and what do they reveal about the ore-forming processes?
- What are the sources of hydrothermal fluids involved in sulfide mineralization?
- How does the Mundonguara deposit compare with other Archean komatiite-hosted or Cu-Au systems in terms of genesis and exploration potential?

1.1 Approach to the study

To address the above research questions and develop an integrated genetic model for the Mundonguara deposit, this study combines field-based observations with several laboratory analyses. The approach integrates lithological, petrographic, mineralogical, geochemical and isotopic data from both drill core- and outcrop samples.

The study begins with a detailed petrographic description of host rocks, gabbro-diorite intrusions, and sulfide-bearing mineralized zones to establish lithological frameworks and alteration patterns. Whole rock lithogeochemical analyses were used to characterize the host komatiites and identify magmatic signatures and alteration trends. Ore microscopy, Scanning Electron Microscope (SEM), Electron Probe Microanalysis (EPMA) and Laser Ablation ICP-MS (LA-ICP-MS) techniques provide mineralogical and chemical data on sulfide assemblages, contributing to the understanding of mineral paragenesis and ore forming processes.

To constrain the timing of magmatic and hydrothermal events, U-Pb zircon geochronology was applied to selected rock units. Stable isotope analyses ($\delta^{34}S$, $\delta^{13}C$, $\delta^{18}O$) were performed on sulfide and carbonate minerals to determine fluid sources, fluid-rock interactions, and post-magmatic overprints.

By integrating these datasets, the study aims to unravel the evolution of the mineralizing system and its relationship to Archean tectono-magmatic processes. The results are evaluated in the context of greenstone belt metallogeny and compared with other komatiite-hosted and Cu-Au systems.

2. Regional geology

The Zimbabwe Craton, forming the Archean nucleus of the Kalahari Craton (Fig. 1) evolved primarily during two major Meso- to Neoarchean events characterized by crustal growth, volcanism, plutonism, and tectonic accretion processes (Wilson et al., 1995; Horstwood, 1999). This evolution led to the formation of typical Archean tonalite-trondhjemite-granodiorite (TTG) suites and associated greenstone belts. The oldest components include gneiss terrains such as the Tokwe, Sebakwe, and Shabani Gneisses, which dates between 3.6 and 3.4 Ga (Kusky, 1998; Jelsma et al., 2021).

The greenstone sequences of the Zimbabwe Craton have historically been classified into three distinct supergroups: the Belingwean (ca. 2.9 Ga), the Bulawayan (2.8–2.7 Ga), and the Shamvaian (ca. 2.65 Ga) Supergroups (Wilson et al., 1995). These represent successive volcanic and sedimentary episodes during the late Archean. However, more recent stratigraphic interpretations have revised this framework. Jelsma et al. (2021) propose a simplified classification in which all greenstone belts older than 2.65 Ga are grouped into a single Bulawayan Supergroup, informally subdivided into a Lower Greenstone Sequence (ca. 3.0–2.8 Ga) and an Upper Greenstone Sequence (ca. 2.75–2.68 Ga). These sequences consist of thick packages of tholeiitic basalt, komatiite, and felsic to intermediate volcanic rocks, overlain by clastic sedimentary rocks assigned to the Shamvaian Supergroup (~2.65 Ga). Volcanic and sedimentary units have been further subdivided into Eastern and Western Successions based on lithostratigraphy and geochemistry (Wilson, 1979). The Eastern Succession, developed in a continental rift setting, includes the Reliance Formation komatiites and Zeederbergs Formation basalts (Prendergast & Wingate, 2013; Hofmann et al., 2004). The Western Succession, by contrast, is marked by calc-alkaline intermediate to felsic volcanics and associated TTG

intrusions from the Wedza and Sesombi Suites (Wilson et al., 1995; Jelsma & Dirks, 2002) formed in an arc environment.

Geodynamically, the Zimbabwe Craton has been interpreted as an accreted terrane formed by successive arc-related events between 3.23 and 2.65 Ga (McCourt et al., 2004; Zeh et al., 2009). Alternative models propose rift-related deposition followed by arc accretion (Kusky, 1998), or lateral accretion involving oceanic fragments (Dirks & Jelsma, 1998).

In western-central Mozambique, the Manica Greenstone Belt (MGB) represents the eastern continuation of the Odzi-Mutare Greenstone Belt in Zimbabwe (D'Orey, 1978; Förster et al., 1996). The Manica Group forms part of the MGB and is divided into two main lithostratigraphic units: the older Macequece Formation and the younger M'Beza-Vengo Formation (Fig. 2a). These units are equivalent to the lower Bulawayan and upper Shamvaian groups in Zimbabwe, respectively (Sumburane, 2011; Mendes et al., 2025).

The Macequece Formation consists predominantly of peridotitic komatiites, pyroxenitic komatiites, ultramafic cumulates, and intrusive mafic to felsic rocks interpreted to have formed in a plume-related continental rift setting (Mendes et al., 2024). These rocks are intruded by mafic dykes and granitic plutons dated at around 2.94–2.92 Ga (Mendes et al., 2025). The overlying M'Beza-Vengo Formation is primarily composed of metasedimentary rocks (greywackes, quartzites, marbles, and schists) and includes polymictic conglomerates with TTG clasts. It is estimated to be ~170 Ma younger than the Macequece Formation (Mendes et al., 2025).

3. Local geology

The Mundonguara Cu-Au deposit (Fig. 2b) is situated in the central part of the Manica Greenstone Belt and is hosted within the lower unit of the Macequece Formation (Förster et al., 1996; Sumburane, 2011; Mendes et al., 2024). This unit, dated between 3.0 and 2.8 Ga (Mendes et al., 2025), comprises predominantly ultramafic to mafic metavolcanic rocks, including peridotitic and pyroxenitic komatiites, olivine cumulates, and serpentinites derived from komatiites. Despite having undergone regional greenschist facies metamorphism (400–500 °C, <4 kbar), primary volcanic textures and structures such as cumulate and spinifex textures, and amygdaloidal structures, are locally preserved (Manhiça, 2001; GTK, 2006; Sumburane, 2011).

Olivine-rich rocks are strongly serpentinized, while peridotitic and pyroxenitic komatiites are characterized by assemblages of serpentine, chlorite, tremolite, and plagioclase. In more strongly deformed zones, these rocks are transformed into talc-chlorite schists with no preservation of primary textures (GTK, 2006; Mendes et al., 2024).

Carbonate alteration is pervasive in parts of the deposit, with calcite, dolomite, and locally magnesite forming both disseminated porphyroblasts and veins. This alteration is attributed to hydrothermal processes associated with mineralization. The volcanic sequence is intruded by several generations of mafic dykes, ranging in composition from gabbronorite to diorite. Mafic dykes, some reaching tens of meters in thickness, are observed to follow the strike of the komatiitic units. To the south of the deposit, a monzogranitic intrusion dated at 2.92 Ga intrudes the greenstone sequence. This rock shows contact metamorphic effects and is locally enriched in chlorite near the contact zone, indicating chemical exchange of the adjacent ultramafic units (Mendes et al., 2024).

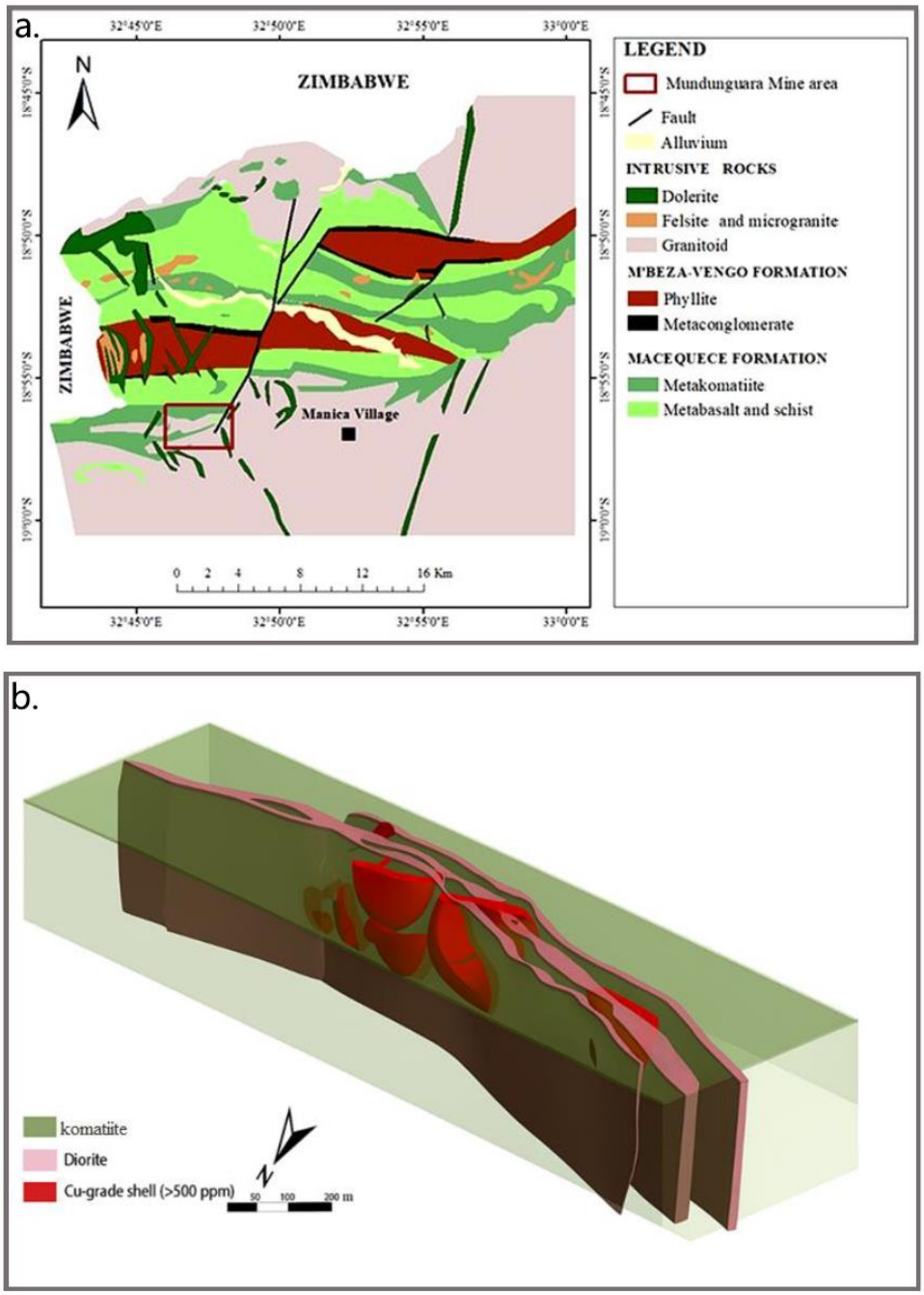

Figure 2. (a) Map of the study area showing the Mundonguara mine area (in red) and the division of the Manica Group. Modified from Sumburane (2004). (b) 3D E–W cross section illustrating the subsurface geology of the Mundonguara mine, view from NW.

4. Methodology

The research presented in this thesis integrates multiple analytical methods to investigate the geological and metallogenic evolution of the Manica Greenstone Belt in western Mozambique, with a particular focus on the Mundonguara Cu-Au deposit. The methodologies applied span from field-based sample collection and petrographic observations to advanced mineralogical, geochemical, geochronological, and isotopic analyses. These methods were employed across four independent but complementary studies, which collectively form the core of this compilation thesis.

4.1. Petrographic and geochemical analyses

Rock samples were collected from outcrops in the Manica Province during field seasons in 2019, 2021, and 2022 and from drill cores obtained from the Mozambique geological warehouse (originally drilled by Baobab Resources in 2007). A total of 60 samples were selected for petrographic and lithogeochemical studies. Thin sections were prepared by Precision Petrographics Ltd. (Canada) and examined at the Microscopy Laboratory at Luleå University of Technology using a Nikon Eclipse petrographic microscope. Geochemical analyses were conducted by ALS Geochemistry (South Africa) using lithium metaborate/tetraborate fusion followed by ICP-AES for major, trace, and rare earth element (REE) concentrations. For sulfide-rich samples, Na_2O_2 fusion was employed. Geochemical data were processed and visualized using IOgas 7.3 software.

4.2. Geochronology (U–Pb SHRIMP dating)

Zircon grains from four rock samples were extracted and analyzed using the Sensitive High-Resolution Ion Microprobe (SHRIMP) at the Geochronological Research Center (CPGeo), University of São Paulo, Brazil. Standard heavy liquid and magnetic separation techniques were applied to isolate non-magnetic zircon grains. These were cleaned, mounted in epoxy, and polished for cathodoluminescence (CL) imaging. U–Pb isotopic analyses were conducted using a SHRIMP IIe instrument under high mass resolution (5,000–5,500) to ensure accuracy and precision.

4.3. Mineralogical characterization and ore petrography

Additional mineralogical characterization focused on sulfide-bearing samples from four drill cores (MUD 007, 009, 011, and 014) along the mineralized zone. Ten polished thin sections were analyzed using a Zeiss Sigma 300 VP SEM (equipped with EDS and BSE detectors) and a JEOL JXA-8230 EPMA at Akita University, Japan. Analytical conditions included an accelerating voltage of 15 kV, probe current of 20 nA, beam diameter of 3–5 µm, detection limit of 0.02 wt.%, and counting time of 20 seconds per point. Trace element analyses were performed by LA-ICP-MS at LTU, using a New Wave Research NWR193 laser ablation system coupled to a Thermo Scientific iCAP-Q quadrupole ICP-MS. Analyses were conducted on pyrite (5 spots), chalcopyrite (49 spots), and pyrrhotite (22 spots), using a laser spot size of 35 µm, repetition rate of 5 Hz, and fluence of approximately 2.5 J/cm². Each acquisition included 20 seconds of background, 30 seconds of ablation, and 10 seconds of washout.

4.4. Stable isotope geochemistry (S, C, and O)

Sulfur isotope compositions ($\delta^{34}S$) of pyrite and chalcopyrite were measured using a CAMECA IMS 1280 ion microprobe at the NordSIMS laboratory (Swedish Museum of Natural History, Stockholm). A $^{133}Cs^+$ primary beam was used to generate secondary ions ^{32}S and ^{34}S, measured by Faraday cups. Results were calibrated using matrix-matched reference standards: S0302A pyrite ($\delta^{34}S$ = 0.0 ± 0.2‰, 2σ; Liseroudi et al., 2021) Nifty-B chalcopyrite ($\delta^{34}S$ = -3.58 ± 0.44‰, 2σ; LaFlamme et al., 2016) and are reported relative to V-CDT. Carbon and oxygen isotope ratios ($\delta^{13}C$ and $\delta^{18}O$) from calcite were determined using a Kiel IV carbonate device coupled to a ThermoFinnigan MAT 253 mass spectrometer at the same facility. Micro-drilled carbonate powders were reacted with phosphoric acid at 70°C to release CO_2, and results were reported relative to the VPDB standard. Precision for isotope measurements was better than ±0.1‰ for $\delta^{13}C$ and ±0.2‰ for $\delta^{18}O$.

By integrating these diverse but complementary methodologies, the thesis aims to provide a robust framework for interpreting the tectono-magmatic evolution and ore-forming processes in an Archean greenstone belt, with specific implications for metallogeny within the Zimbabwe Craton. The overall research workflow is summarized in the flowchart below, which outlines the sequential and interrelated steps taken throughout the study.

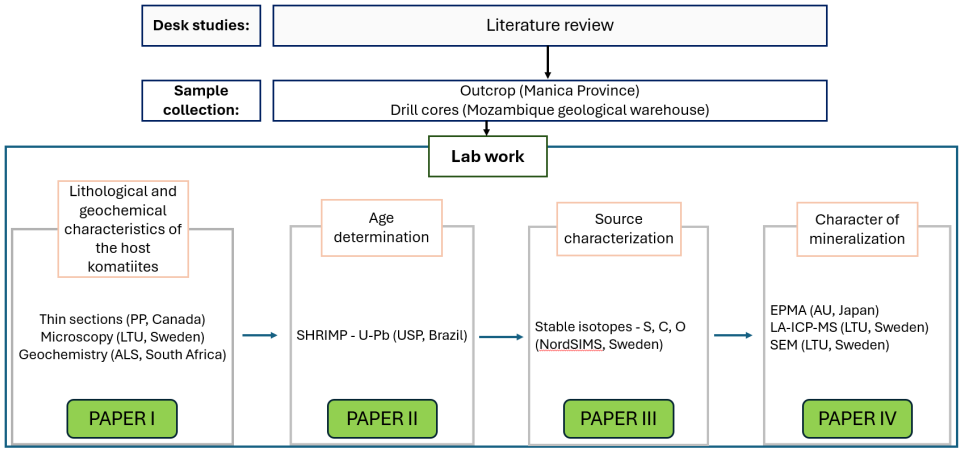

Figure 3. Methods and objectives flowchart showing each step until completion of the four scientific papers included in the PhD thesis. PP – Precision Petrographics Ltd, LTU – Luleå University of Technology, USP - University of São Paolo, AU -Akita University.

5. Summary of papers

Paper I: *Lithogeochemistry and origin of the komatiites from Mundonguara mine in the Manica Greenstone Belt, Mozambique*

This study presents new lithogeochemical and petrographic data from the Mundonguara area in the Manica Greenstone Belt, Mozambique, aimed at elucidating the origin and tectono-magmatic evolution of komatiitic and associated mafic-felsic rocks. Komatiites are classified as Al-undepleted (AUK) peridotitic and pyroxenitic komatiites, preserving primary textures such as cumulate layering and rare spinifex. Their geochemistry, characterized by high MgO (25-45 wt%) and low TiO_2 (<0.9 wt%), indicates derivation of magma from high-degree partial melting of a mantle source, with some pyroxenitic komatiites displaying boninitic affinities.

Metamorphic overprint under greenschist facies conditions modified mineralogy but preserved immobile trace element signatures. The komatiites and mafic intrusions show geochemical signatures transitional between N-MORB and OIB sources, yet negative Nb anomalies and Th enrichment suggest crustal contamination. Felsic units, including rhyolites and the Isitaca monzogranite, appear genetically unrelated to komatiites, with trace element patterns pointing to crustal contributions during emplacement.

Tectonic discrimination diagrams support a possibly plume-related continental rift setting, for komatiite formation, with affinities to older greenstone sequences like the Hokonui Formation from the Mtshingwe Group in the Belingwe Greenstone Belt (Jelsma et al., 2021; Hoffman et al, 2024). These findings contribute to the understanding of the magmatic and tectonic evolution of the Manica Greenstone Belt within the eastern Zimbabwe Craton, emphasizing a complex interplay of mantle sources and crustal melting.

Paper II: ***Geochronology of mafic and felsic rocks at the Mundonguara mine: Insights into the chronostratigraphy of Archean greenstones within the Zimbabwe Craton***

This study presents new U-Pb zircon geochronological data from mafic and felsic rocks in the Manica Greenstone Belt, aimed at constraining the timing of magmatic activity and subsequent tectonothermal events in the Mundonguara area. The results identify a narrow time span from 2.92 to 2.94 Ga for magmatic activity, including emplacement of gabbronoritic dykes, rhyolitic units, and the Isitaca granodiorite, which intrude the komatiitic units of the Macequece Formation. The age of the host komatiites remains undetermined, but stratigraphic relationships and geochemical features indicate they may predate the felsic units and potentially reflect older mantle melting events (Sumburane, 2011).

Lower intercept ages ranging from ca. 578 to 846 Ma suggest that the eastern margin of the Zimbabwe Craton was affected by multiple Neoproterozoic tectonothermal events. These include thermal overprinting linked to the Pan-African orogeny (ca. 650–500 Ma) and isotopic disturbance potentially related to extensional magmatism during the breakup of Rodinia (Gumsley et al., 2024; Chaúque et al., 2017). The identification of a ~170 Ma stratigraphic gap between the volcanic Macequece Formation and the overlying sedimentary M'Beza-Vengo Formation, points to a major unconformity, not recorded in other greenstone belts within the Zimbabwe Craton.

The results clarify the temporal framework of magmatism in the Manica area and support a multiphase tectono-magmatic evolution extending from late Archean to the Neoproterozoic. These findings also contribute to ongoing efforts to refine the chronostratigraphy of the Zimbabwe Craton, placing the upper part of the Macequece Formation within the 3.0–2.8 Ga Lower Greenstones of the Bulawayan Supergroup.

Paper III: ***Sulfur, carbon and oxygen isotope constraints on the origin of the Mundonguara Cu-Au deposit, Manica, Mozambique***

This study investigates the Mundonguara Cu-Au deposit, previously classified as a Cu-Ni deposit (Manuel, 1992; D'Orey, 1992; Förster et al., 1996). Petrographic and mineralogical analyses reveal that chalcopyrite, pyrrhotite, and pyrite are the dominant sulfide phases, with accessory minerals such as pentlandite, cobaltite, sphalerite, galena, and scheelite. The gangue mineral assemblage includes chlorite, talc, amphibole, and various carbonates (calcite, dolomite, magnesite). Ore-related alteration is limited and dominated by talc, chlorite, amphibole, carbonates, and albite, confined to narrow zones around mineralization.

Sulfur isotope compositions ($\delta^{34}S$ -0.4‰ to +4.0‰) of chalcopyrite and pyrite support a predominantly magmatic sulfur source consistent with magmatic-hydrothermal systems (Ohmoto, 1972; Keet et al., 2021). Carbon and oxygen isotopes from gangue calcite ($\delta^{13}C$ -8.5‰ to -4.3‰; $\delta^{18}O$ +6.5‰ to +8.5‰) also suggest a magmatic-hydrothermal fluid origin with minor crustal contributions, consistent with isotopic signatures found in IOCG systems and distinct from the heavier $\delta^{18}O$ compositions common in orogenic gold system (Wang et al., 2014; Rieger et al., 2011; Quesnel et al., 2023).

Regional carbonate alteration in komatiites, common in many other Archean greenstone belts and related to serpentinization and rodingite formation, is pervasive but with more negative carbon isotope composition values indicative of magmatic-hydrothermal and possible organic carbon influence (Albai et al., 2023).

Genetically, the Mundonguara deposit shares some features with both IOCG and orogenic gold systems but differs in several of the most typical characteristics of these. It lacks potassic alteration and iron oxides typical of IOCG deposits, and green carbonate alteration (carbonate-fuchsite association) characteristic of orogenic gold deposits in komatiites (Moritz & Crocket, 1991; Schandl & Wicks, 1993) and having copper as the main commodity. Instead, its mineralogy, metal associations, and isotopic data align it more closely with orogenic gold systems with hybrid magmatic-hydrothermal and metamorphic fluid signatures (Goldfarb et al., 2001; Holma & Keinänen, 2007; Hector et al., 2023). The elevated Ni and Co contents are likely inherited from the komatiitic host rock, while Cu, Au, and other elements were introduced by magmatic-hydrothermal fluids (Förster et al., 1996; Hector et al., 2023).

The Mundonguara deposit is best interpreted as a structurally controlled, epigenetic Cu-Au system, formed during late Archean tectono-metamorphic events (~2.6–2.7 Ga), possibly related to felsic magmatism and shear zone fluid flow as suggested for other epigenetic deposits within the Zimbabwe Craton (Vinyu et al., 1996).

Paper IV: ***Mineral chemistry constrains on a hybrid magmatic-hydrothermal and metamorphic fluid source for the Mundonguara Cu-Au deposit, Manica Greenstone Belt, Mozambique***

This study investigates the origin of the Mundonguara Cu-Au deposit using the chemistry of its sulfide minerals. Previous interpretations suggest that the deposit represents either remobilized syngenetic sulfides from the komatiitic host rock (D'Orey, 1992; Manuel, 1992) or an epigenetic magmatic-hydrothermal origin (Förster et al., 1996; Baobab Resources, 2007). Our mineralogical observations and mineral chemistry data provide new constraints supporting a hybrid genesis involving both magmatic-hydrothermal and metamorphic fluid contributions.

The deposit is structurally controlled and mainly hosted by gabbro-dioritic dykes intruding komatiitic units of the Macequece Formation. Sulfide minerals (chalcopyrite and pyrrhotite with minor pyrite, cobaltite, pentlandite, and sphalerite) occur predominantly as aggregates, schlieren, and carbonate-quartz sulfide veins. Geochemical data indicate that Ni concentrations in the host rocks are lithology-dependent, being highest in komatiitic rocks (750–1500 ppm) and lower but variable in gabbro-dioritic intrusions (<80 to >400 ppm), while Cu, Co, and Au in the mineralization are significantly enriched relative to host rocks (Förster et al., 1996). This suggests an external source for Cu, Co, and Au, incompatible with an origin from remobilized magmatic sulfides hosted by the komatiites.

Trace element compositions of chalcopyrite, compared with global datasets, reveal a geochemical signature for most elements consistent with hydrothermal deposits such as VMS, IOCG, and skarn deposits, with a few elements (e.g. Ag) conform with chalcopyrite from orogenic gold mineralization. The Ni signature suggests contribution from komatiitic host rocks. Pyrite chemistry shows dual populations with contrasting Co/Ni ratios, reflecting a transition from metamorphic to magmatic-hydrothermal fluids (Yan et al., 2012), supported by isotopic data (Mendes et al., submitted).

Temperature estimates derived from the Fe content of sphalerite indicate ore formation temperatures between 280 and 335 °C, consistent with low- to medium-temperature hydrothermal systems and overlapping with the range of orogenic gold deposits (Hutchinson & Scott, 1982; Lusk & Calder, 2004; Zhu et al., 2011; Fontboté et al., 2017).

The study demonstrates that the Mundonguara Cu-Au deposit represents a structurally controlled, epigenetic mineralization with a hybrid fluid origin involving predominantly magmatic-hydrothermal fluids and subordinate metamorphic contributions. The elevated Ni contents are linked to fluid interaction with komatiitic rocks.

6. Conclusions

This thesis provides a comprehensive contribution to the understanding of the magmatic, tectonic, and metallogenic evolution of the southern part of the Manica Greenstone Belt, located along the eastern margin of the Zimbabwe Craton. Through integrated lithogeochemical, geochronological, isotopic, and mineralogical data, it constrains the character and origin of the komatiitic to felsic rocks and reevaluates the origin of the Mundonguara Cu-Au deposit.

The detailed characterization of komatiites from the Mundonguara deposit, based on new petrographic and geochemical data, identifies Al-undepleted (AUK) peridotitic and pyroxenitic varieties. Their high MgO contents reflect derivation from high-degree partial melting of a depleted mantle source. Geochemical signatures, including negative Nb anomalies and Th enrichment, point to crustal contamination and support emplacement in a continental rift setting, possibly plume-related, with similarities to the Hokonui Formation in the Belingwe Greenstone Belt.

U-Pb zircon geochronology reveals a major magmatic event between ca. 2.92 and 2.94 Ga, involving the emplacement of mafic intrusions and felsic units such as the Isitaca granodiorite. While the exact age of the komatiites remains uncertain, stratigraphic and geochemical evidence suggests they may record an older magmatic episode. A major stratigraphic hiatus of ~170 Ma, coupled with younger Neoproterozoic ages (~578-846 Ma), indicates overprinting by Pan-African tectonothermal events and crustal reactivation during the breakup of Rodinia. These findings emphasis the multiphase tectono-magmatic evolution of the Manica Greenstone Belt.

The reclassification of the Mundonguara Cu-Au deposit as a structurally controlled, epigenetic mineralization system, rather than remobilization of magmatic sulfides, has significant implications. The ore occurs in veins, schlieren, and shear zones hosted in komatiitic and mafic rocks. Sulfur, carbon, and oxygen isotope data, together with sulfide mineral chemistry, point to a hybrid fluid origin, dominated by magmatic-hydrothermal inputs with minor metamorphic contributions. Chalcopyrite and pyrite trace element signatures, along with ore formation temperatures estimated between 280 and 335 °C, align with medium-temperature hydrothermal systems and suggest genetic affinities to both IOCG deposits and orogenic gold deposits with atypical metal association.

The Mundonguara deposit is interpreted to represent a hybrid deposit formed through the interplay of metamorphic processes and fluid flow with a major contribution of magmatic-hydrothermal fluid that become enriched in Ni from the local komatiitic protoliths. This integrated genetic model contributes to the metallogenic framework of the Manica Greenstone Belt and has important implications for exploration strategies targeting Cu-Au mineralization within the Zimbabwe Craton and possibly other Archean greenstone belts worldwide.

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