

Volcanology and geochemistry of selected kimberlites from the Lulo kimberlite field, Angola

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Abstract

The area under study is the Lulo Kimberlite Field in the province of Lunda Norte, Angola, which is located 630 km east of the capital, Luanda. This 3000 km² concession is one of the world's most abundant alluvial diamond fields, producing high value Type IIa diamonds, as well as hosting a significant number of kimberlite pipes. Within Angola, there are hundreds of known kimberlite bodies of which, it is estimated, far fewer than 50% have been studied and fewer than 5% have economic diamond grades (Pereira et al., 2003). With ongoing exploitation of predominantly high-grade alluvial deposits, depletion of the diamond reserves demands continual and improved exploration of primary sources. Alluvial diamond mining within the Lulo Field has yielded large, high-value diamonds along the Caculo River. These diamonds are anhedral in morphology and show sharp edges with little abrasive signs of travel, indicating that their primary kimberlite source is likely nearby.

With more than 560 geophysical anomalies having been identified in the Lulo Field, 164 have been drilled, with 141 shown to be kimberlitic (Lucapa Diamond Company, 2024). This study aims to conduct a reconnaissance survey of volcanoclastic kimberlites within these pipes to classify eruptive styles, providing insights into the internal geology of pipes with implications for diamond grade bulk sampling. A total of 52 kimberlite targets were sampled, yielding 83 thin sections for petrographic analysis and eight representative hypabyssal kimberlites for bulk rock geochemistry, through collaboration with Lucapa diamonds. Each one of the 83 thin sections were described using a petrographic microscope and classified following the scheme of Scott Smith et al. (2018) and Webb & Hetman (2021), with 22 chosen as representative samples. Petrographic analyses of the thin sections allowed for the classification of the kimberlites, at the most primary form of subdivision, as either coherent or magmaclastic (Webb & Hetman, 2021). Within the magmaclastic subsection, pyroclastic kimberlites are classified as Fort à la Corne-type pyroclastic kimberlites (FPK) and abundant resedimented volcanoclastic kimberlites (RVK) are also observed interbedded with the FPKs.

The classification of the Lulo kimberlites as FPKs is based on their clast-supported texture, olivine-dominated magmaclasts, and ultra-fine serpentine and carbonate cement. The magmaclasts display varied morphologies and include cored and uncored

varieties, with a wide range of olivine macrocrysts abundances and low proportion of crustal xenoliths further supporting the classification. Furthermore, the presence of RVKs is confirmed due to the predominant clastic texture, abundant quartz and commonly seen broken grains. The identification of kimberlites as predominantly FPK and RVK indicates an explosive eruptive style that led to pipe excavation and post-eruptive reworking. Comparisons with other kimberlite fields, such as the Voorspoed mine in South Africa and the Lac de Gras kimberlite field in Canada, reveals similarities in internal pipe geology to those in the Lulo field and thus are comparable to kimberlite pipes within Diavik and Ekati mines alike. Thus, the Lulo field kimberlites pipes are classified as Class 3 pipes following the scheme of Skinner and Marsh (2004) or Lac de Gras type following the scheme of Scott Smith (2008).

Geochemical analysis shows the Lulo kimberlites share characteristics with South African Group I kimberlites, known for their diamondiferous nature. However, certain deviations, such as depleted MgO and enriched Al₂O₃ and Nb concentrations, suggest crustal contamination that is further supported by a contamination index > 1.0 for all bulk-rock samples.

Exploration initiatives, including drilling and bulk sampling, are directed at determining diamond grade and identifying the primary source of the high-value, Type IIa alluvial deposits. Kimberlite pipes within the Lulo field, classified as Class 3 pipes, consist of multiple volcanoclastic units (FPK and RVK) within individual pipes, indicative of considerable variability in diamond content. This heterogeneity underscores the importance of detailed stratigraphic analysis to enhance the accuracy of grade estimation. Olivine macrocrysts, which serve as key indicators of diamond-bearing potential, range from 25 to 53 vol.% in FPKs, reflecting mantle-derived material with varying degrees of sorting (ranging from poorly to well sorted) across different pipes. As a comprehensive assessment across the full length of boreholes has not yet been conducted, olivine macrocryst abundance and sorting remains speculative. A thorough understanding of internal pipe geology and olivine distribution is essential for refining diamond exploration and sampling strategies. Moreover, for the RVKs, the proportion of externally derived material may dilute grades and should therefore be considered.

Due to the favourable geological setting of the Lulo Mine and its geological and geochemical similarity to other diamond-rich kimberlite occurrences, it can be inferred

that Lulo kimberlites hold significant potential for high-grade diamond deposits. However, current bulk sampling for diamond grades is primarily conducted at the surface for each pipe. Accurate diamond grade estimation requires understanding the internal geological variation within a kimberlite, as surface sampling alone may not represent the true diamond potential of deeper units. Therefore, understanding the internal geology of each pipe is essential, as it significantly influences diamond grades during bulk sampling campaigns aimed at discovering high-value stones. This study highlights the importance of integrating detailed petrographic, geochemical, and geological analyses to fully understand the factors controlling diamond grade, providing valuable insight for the future exploration of Angola's primary diamond sources.

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List of abbreviations

Ap	- Apatite
FPK	- Fort à la Corne type pyroclastic kimberlite
HREE	- Heavy rare earth elements
HK	- Hypabyssal kimberlite
ICP-MS	- Inductively Coupled Plasma Mass Spectrometry
KPK	- Kimberley type pyroclastic kimberlite
LILE	- Large-ion lithophile elements
LOI	- Loss on ignition
LLD	- Lower limits of detection
LREE	- Light rare earth elements
MC-ICP-MS	- Multicollector Inductively Coupled Plasma Mass Spectrometry
MVK	- Massive volcanoclastic kimberlite
Nd	- Neodymium
Ol	- Olivine
Phl	- Phlogopite
PPL	- Plane polarised light
ppb	- parts per billion
ppm	- Parts per million
Prv	- Perovskite
REE	- Rare earth elements
RVK	- Resedimented volcanoclastic kimberlite
SCLM	- Sub-continental lithospheric mantle
Sp	- Spinel
Sr	- Strontium
TK	- Tuffisitic kimberlite

Xen	- Xenolith
XPL	- Cross polarised light
XRF	- X-ray fluorescence
wt.%	- Weight percentage

Chapter 1: Introduction

Diamonds have long held cultural and economic significance, symbolizing status and driving regional economies. While synthetic diamonds have become viable alternatives for industrial applications and jewellery, large, high-quality natural diamonds remain central to the luxury jewellery market, which reached an estimated \$84 billion in sales in 2021. Although global rough diamond production exceeded 136 million carats in 2013, it is expected to remain stable until post-2025, in which mine closures are projected to cause a decline in production (Goodman et al., 2014). Angola stands out as a promising region for diamond exploration, highlighted by the discovery of exceptionally large diamonds in its alluvial deposits, including a 404-carat diamond in 2016 (Lucapa Diamond Company, 2024). Exploration efforts in Angola aim to locate the kimberlite pipes that serve as the primary sources of these alluvial diamonds. The work presented in this study is crucial not only for advancing the understanding of diamondiferous kimberlite formation but also for addressing broader industry challenges, such as plateauing production, rising mining costs, and increasing demand for high-value diamonds in emerging markets like China and India (Goodman et al., 2014). Discovering Angola's kimberlite pipes is therefore vital for both academic research and the sustainable future of the diamond industry.

1.1 Kimberlites

Kimberlites are ultramafic, volatile-rich (H_2O ~5 wt.% and CO_2 ~10 wt.%) olivine-phyric (~50 modal %), silica-undersaturated igneous rocks that form from mantle-derived magma originating at depths of 150 - 450km (Mitchell et al., 2019). They commonly occur within Archaean cratons as post-tectonic, intra-continental magmas (Scott Smith et al., 2018). Kimberlites show two primary modes of emplacement. 1) Hypabyssal settings that can take the form of dikes and sills and in the root zones of pipes. These rocks are referred to as 'coherent' textured rocks. 2) Volcaniclastic rocks, which can be in-vent Kimberley-type pyroclastic kimberlites (KPK) or subaerial Fort à la Corne-type pyroclastic kimberlites (FPK) as well as resedimented volcaniclastic kimberlite (RVK) formed through re-working tuff ring material back into volcanic craters.

Kimberlites were first described and named by Professor Henry Carvil Lewis in 1887 and following the type-locality nomenclature after the town of Kimberley, South Africa. A further sub-division into two groups, namely, Group 1 and Group 2 was then proposed by C. B. Smith (1983) based on Sr, Nd and Pb isotopic studies. Present day studies have

found that Group 1 and Group 2 kimberlites originate from genetically distinct parental magma types and have been reclassified using ‘kimberlite’ for Group 1 kimberlites and ‘olivine lamproite or Kaapvaal lamproite’ for Group 2 kimberlites (Scott Smith et al., 2018; Pearson et al., 2019).

The characteristic features of kimberlites include: (1) Macrocrysts of predominantly olivine with anhedral- to- round morphology with a variety of sizes ranging from ~ 0.50mm – 10.0 mm (rarely up to 20.0 mm). These olivine macrocrysts can have (a) fine-grained neoblasts (from recrystallization) and (b) overgrowths of olivine (crystallized from the kimberlitic melt). (2) Matrix to the macrocrysts consisting of primary microphenocrysts (predominantly olivine and less commonly phlogopite and spinels) and a fine-grained groundmass forming a result of kimberlitic melt crystallization. (3) Fine-grained interstitial groundmass to the macrocrysts and microphenocrysts containing most commonly; monticellite, perovskite, spinel, apatite, carbonate, and serpentine. (4) Xenoliths including (a) mantle-derived peridotite/eclogite (b) rare lower crust rocks, and (c) abundant upper crust rocks (Scott Smith et al., 2018).

1.2 Kimberlites and their association with diamonds

Diamond formation typically occurs at depths of 140-190 km and temperatures ranging from 1040 - 1250 °C within the sub-continental lithospheric mantle (SCLM) (e.g., Stachel & Luth, 2015). The relatively cool geothermal gradients characteristic of Archean cratons, with their stable, thick crustal sections and deep lithospheric keels, create the necessary pressures at relatively low temperature conditions for diamond formation and survival over geological time. Kimberlitic magmas entrain diamonds in varying concentrations as they ascend through the SCLM toward the surface (Figure 1).

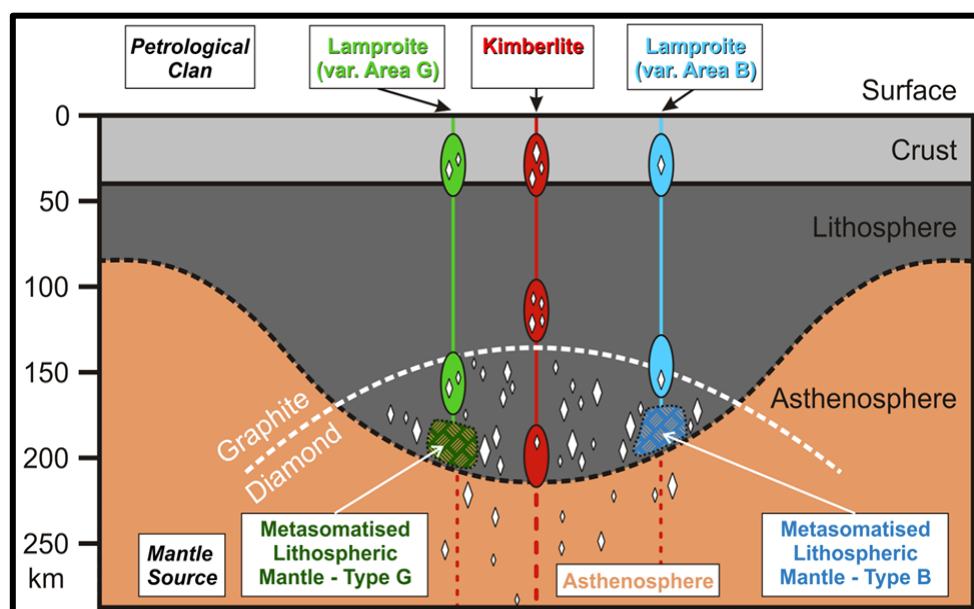


Figure 1: Schematic illustration of the two primary diamond sources: kimberlite and lamproite. White diamonds reflect the uneven distribution of diamonds within the mantle. For emphasis in this study, red ovals: indicate varying diamond concentrations within three distinct batches of kimberlite melt ascending to the surface. Green and blue ovals: illustrate different types of metasomatized lithospheric mantle - which produce varying lamproite melts, such as lamproite from areas G or B. Adapted from Scott Smith (2017).

For a considerable period, the belief that diamonds were phenocrysts within kimberlites prevailed (Richardson, 1986). However, the understanding of diamond genesis underwent a significant transformation upon the discovery that diamonds predate their host rocks (Richardson, 1986). This finding helps one understand that, despite a rock being classified as a kimberlite, this does not ensure the presence of economically significant amounts of diamonds. This is due to (1) diamonds being xenocrystic in nature and the heterogeneous diamond distribution in the SCLM and (2) magmatic processes may result in the diamond resorption (Fedortchouk, 2019) and/or removal of entrained diamonds through subsequent infilling/reworking of kimberlite pipes (Scott Smith, 2008). This emphasizes the importance of understanding the geological processes involved in kimberlite formation, as these aforementioned processes can heavily influence diamond grade.

Diamonds can be found in two main deposit types: primary and secondary. Primary deposits occur as sparse diamond xenocrysts within pyroclastic, volcanoclastic, resedimented volcanoclastic, and hypabyssal rocks (i.e., kimberlite-hosted deposits). Secondary deposits form from the weathering of these primary deposits and are found in both unconsolidated and consolidated sediments, including placers, paleo-placers, and alluvial deposits (Kjarsgaard, 2007).

1.3 Significance of this study

In 2019, the global diamond industry achieved a production volume of 135.8 million carats and a market size of \$89.18 billion (Sun et al., 2024; Bain & Company, 2014). In 2021, revenue in the diamond mining segment grew by 62%, surpassing pre-pandemic levels by 13% (Bain & Company, 2021). The industry, in the next 10 years, is projected to grow at a compound annual growth rate of 3.0%. This growth is largely driven by the increasing demand for jewellery in emerging markets, especially in Asia-Pacific regions like China and India (Sun et al., 2024; Pereira et al., 2019).

Kimberlite-hosted diamond mines, both active and historical, are found in various regions around the world, including southern Africa (South Africa, Botswana, Zimbabwe, Lesotho), south-central Africa (Tanzania, Democratic Republic of Congo, Angola), western Africa (Sierra Leone), Russia (Yakutia), China, Canada, and the United States (Kjarsgaard, 2007). Within Angola, there are hundreds of known kimberlite bodies of which, it is estimated, less than 50% have been studied and fewer than 5% have economic diamond grades (Pereira et al., 2003). With ongoing exploitation of predominantly high-grade alluvial deposits in Angola, depletion of the alluvial diamond reserves demands continual and improved exploration of primary diamonds sources. Alluvial diamond mining within the Lulo Field has yielded large, high-value diamonds along the Caculo River. These diamonds have sharp edges with little abrasive signs of travel, indicating that their primary kimberlite source is likely nearby (Lucapa Diamond Company, 2024). With more than 560 geophysical anomalies having been identified in the Lulo Field, 164 have been drilled, with 141 shown to be kimberlites (Lucapa Diamond Company, 2024). The area is therefore considered highly prospective for potential economic diamond deposits and the likely source of the alluvial diamonds.

1.4 Aims and objectives

This study investigates kimberlites within the Lulo Kimberlite Field, Angola, and has three main aims and associated objectives.

Aim and objective #1: To describe and classify the volcanoclastic kimberlites within 52 kimberlite pipes of the Lulo Field. This will be accomplished through a petrographic study of 83 thin sections (ranging from 1 - 10 thin sections per pipe, with 25 of the 52 pipes having one thin section), in which 22 representative samples are chosen for in-depth classification. The drilling, initial core logging, and sampling were carried out by Lucapa Diamonds in the field and the samples were sent to UCT for this study. Detailed petrographic descriptions of these representative volcanoclastic and coherent textured kimberlites will support classification and broader contextualization within global kimberlite frameworks.

Aim and objective #2: Analyse and characterize the bulk-rock geochemistry of representative coherent-textured kimberlites of the Lulo Field. This will be achieved

through bulk rock XRF majors, ICP-MS trace elements and MC-ICP-MS Sr-Nd isotopes analyses to evaluate compositional signatures and relate findings to global kimberlite trends.

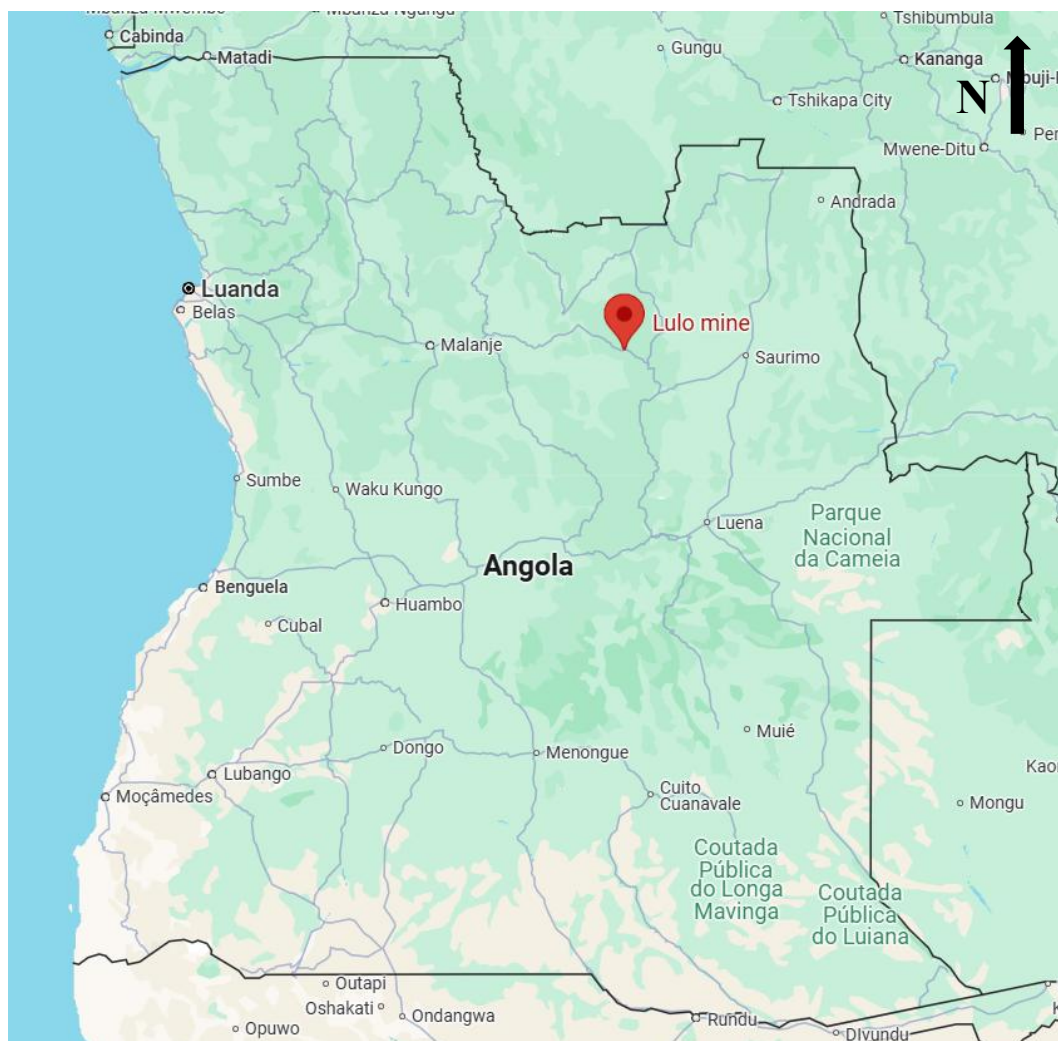
Aim and objective #3: Evaluate the variation in internal geology across the Lulo Field kimberlite pipes and assess its implications for diamond grade estimations through a comparative analysis with global kimberlite occurrences. This contributes contextually to Lucapa's ongoing bulk-sampling of high-interest kimberlite pipes for diamond grade evaluation.

The primary purpose of this study is to provide a reconnaissance survey of volcanoclastic kimberlites within the pipes of the Lulo Field, aiming to understand their eruptive styles and assess the consequent implications for diamond grade. It is important to note that most kimberlite pipes in the Lulo Field have been sampled by only a single drill core, with some represented by just one sample (ranging from 1 to 10 samples per pipe). This underscores the preliminary nature of this study and limits the current understanding of the pipes' internal geology. Additional boreholes would enable a more detailed investigation into the internal geology. Furthermore, there is no publicly available literature on the geology of Lulo Field kimberlites and, thus, this study provides the first glimpse into the kimberlite geology of this highly prospective region.

Chapter 2: Geological setting and kimberlite classification

2.1 Background to diamond mining in Angola

The area under study is the Lulo Field in the province of Lunda Norte (Figure 2a), Angola which is located 630 km east of the capital, Luanda. This 3000 km² concession is one of the world's most abundant alluvial diamond fields producing high value Type IIa diamonds.



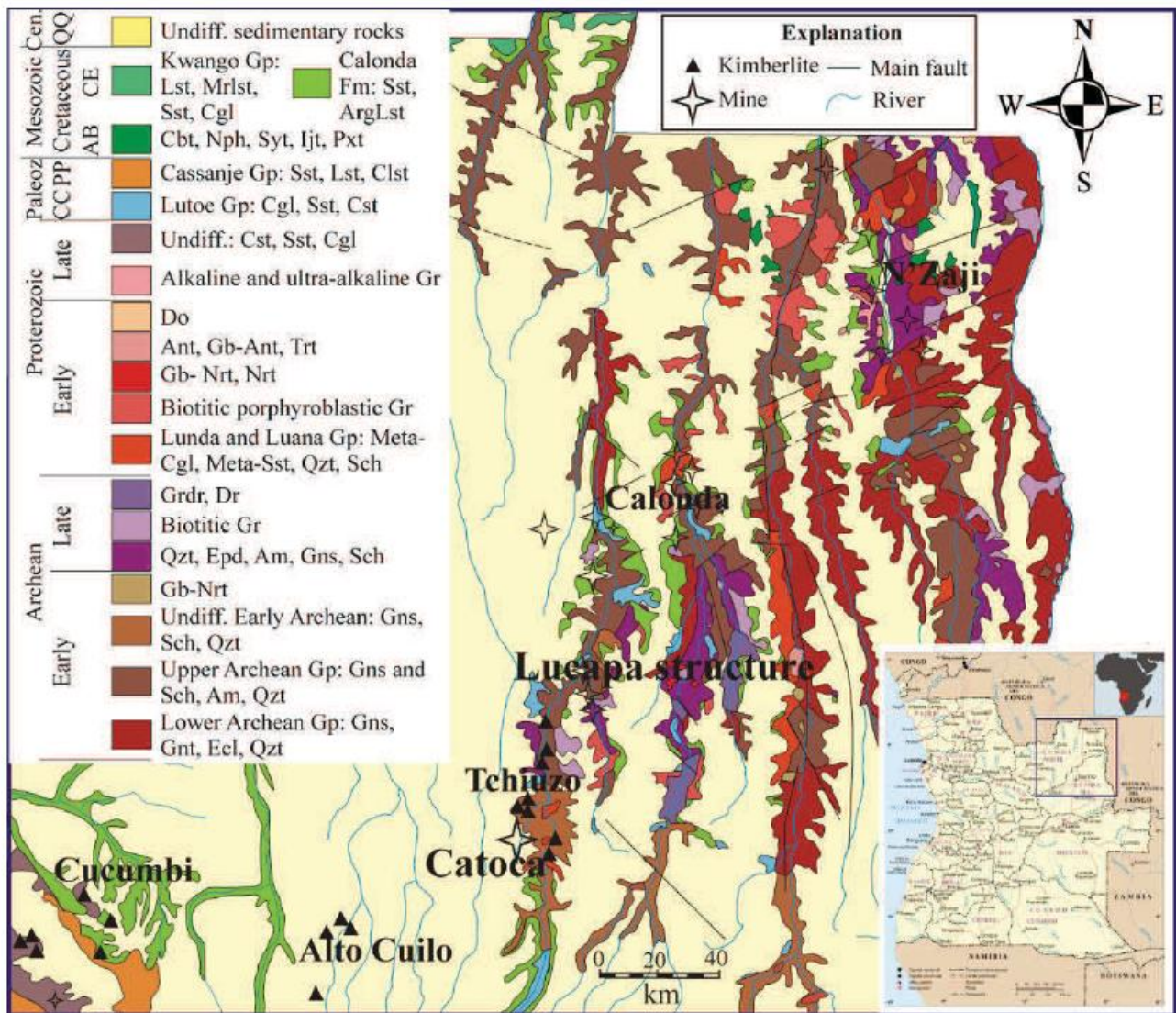


Figure 2: (a) Satellite image of Lulo alluvial diamond mine captured from (Google, 2025). Google Maps. Retrieved 02/02/2025, from <https://www.google.com/maps>. (b) Geological map of northeastern Angola (modified from Elvira and Cruz, 2012 after De Araujo et al., 1988; De Araujo and Perevalov, 1998; De Carvalho et al., 2000; Egorov et al., 2007). Geological time units: Quaternary (QQ), Cenomanian (CE), Albian (AB), Permian (PP), Carboniferous (CC), Undifferentiated (Undiff.). Stratigraphic terms: Group (Gp), Formation (Fm). Lithologies: Sandstone (Sst), Conglomerate (Cgl), Limestone (Lst), Marlstone (Mrls), Argillaceous Limestone (ArgLst), Claystone (Clst), Granite (Gr), Gabbro (Gb), Quartzite (Qzt), Schist (Sch), Granodiorite (Grdr), Dolerite (Do), Amphibolite (Am), Gneiss (Gns), Carbonatites (Cbt), Nephelinite (Nph), Syenite (Syt), Ijolite (Ijt), Pyroxenite (Pxt), Anorthosite (Ant), Troctolite (Trt), Norite (Nrt), Epidotite (Epd), Granulite (Gnt), Eclogite (Ecl).

Diamond exploration commenced in 1912 within the Lunda province, whereby diamonds were found in the Mussalala River (Pereira et al. 2003). This was followed by diamond exploration in 1913, which resulted in the introduction of the first open cast mines on alluvial deposits in 1919. In 1952, the first kimberlite pipe, named Camafuca,

was discovered within the Chicapa River drainage region (Real, 1959 as cited in Janse & Sheahan, 1995) and many others have been discovered since. Within the Lulo Field alone, 164 targets have been drilled, 141 kimberlites discovered, 35 kimberlites processed and 16 proved to be diamondiferous (Lucapa Diamond Company, 2024).

The Lulo Alluvial Mine commenced commercial production in January 2015, and to date, has recovered more than 35 +100 carat diamonds (Lucapa Diamond Company, 2024). The alluvial mining process involves the utilization of excavators and haul trucks to extract surface deposits of gravel, sand, and clay, which are subsequently screened to recover diamonds. Current mining has two primary focuses, the floodplains (Leziria) and terrace deposits along the Cacuilo River, which occurs along a 50 kilometre stretch that flows through the Lulo concession (Lucapa Diamond Company, 2024). For more than 15 years, Lucapa Diamond Company has been exploring in Angola with the goal of finding the primary kimberlite source to the alluvial diamonds. While some potential sources of alluvial diamonds have been identified, such as the discovery of large Type II diamonds from pipe L164, the primary, high-grade sources remain elusive.

2.2 Geology of northeastern Angola

The geological history of Angola (Figure 2b) can be described as having three main stages (De Carvalho, Tassinari, Alves, et al., 2000; Guiraud et al., 2005; Robles-Cruz et al., 2012): (1) An Archean orogeny, documented by the Central Shield, Cuango Shield, and Lunda Shield, predominantly composed of gabbro, norite, and charnockitic complexes, forms the Angolan basement. (2) Three primary Proterozoic cycles, namely the Eburnean-Paleoproterozoic, Kibaran-Mesoproterozoic, and Pan-African-Neoproterozoic, are identified, with the Eburnean cycle being the most significant. This period is marked by volcanosedimentary formations, gneisses, and migmatites as well as granites and syenites. Following this Paleoproterozoic event, the Kibaran cycle ensued, characterized by extensional events along the periphery of the Congo craton, resulting in clastic-carbonate sequences and localized basic magmatism. The Pan-African orogeny, associated with the formation of Gondwana, led to the creation of fold belts and granitic intrusions. The activation of zones of lithospheric weakness, particularly major fault zones, facilitated the subsequent fragmentation of Gondwana. (3) The deposition of Phanerozoic sedimentary sequences on previously eroded surfaces. The subsequent fragmentation of Gondwana during the Jurassic to Cretaceous period, spanning between 190 and 60 million years ago, triggered the formation of

basins linked to deep fault systems in Angola. These fault systems played a crucial role in the emplacement of alkaline, carbonatitic, and kimberlitic magmas.

The Lulo field is situated in an ideal tectonic and stratigraphic location, where the Lucapa Graben intersects Angola's diamond-rich Cuango basin. The Lucapa Graben forms part of the NE-SW-oriented Lucapa corridor, a graben structure exceeding 1000 km in length, characterized by a complex history of magmatic and tectonic activity (Giuliani et al., 2017). The corridor preserves evidence of magmatic activity (including kimberlites and intrusive carbonatites) and records tectonic events spanning the Neoproterozoic, Permo-Triassic, and Cretaceous periods (145 - 100 Ma) (Allsopp & Hargraves, 1985; Jelsma et al., 2009; 2013). It is underlain by a notably thinned lithosphere (≤ 140 km), which contrasts with the thicker lithosphere of inland Angola (>160 km) (Globig et al., 2016). The corridor is located on the Bié Dome, a vast plateau approximately 1000 km in diameter and ~ 2500 m in elevation, this region experienced significant uplift during the Oligocene and Pleistocene that is presumed to triggered and supported by mantle upwelling (Al-Hajri et al., 2009; Walker et al., 2016). Furthermore, ongoing tectonism in the corridor is indicated by recorded earthquakes with magnitudes up to 5.1 M (highlighted in Giuliani et al., 2017) suggest ongoing tectonism in the corridor and could be a contributing factor in the formation of the Lulo kimberlite field.

The local geology within the Lulo fields is made up of predominantly upper Karoo sediments, with beds comprised of mudstone, shale, siltstone and sandstone. Lulo Field kimberlites are estimated to be 114 - 140 Ma with an average age of 125 Ma (Lucapa Diamond Company, 2024).

2.3 Classification of kimberlite pipes and pyroclastic kimberlite types

In Canada, over a period of 1000 Ma, ~ 770 kimberlites were emplaced in a range of different local geological settings. It has been proposed that due to the nature of the surrounding country rock, three distinctive kimberlite pipe types can form, depicted in Figure 3 (Scott Smith, 2008a), highlighting a correlation between pipe morphology and local geology. This classification of kimberlite pipes into three types was initially proposed by Field and Scott Smith (1999). All the pipes show distinct differences in the size, shape and infill of the pipe and can be described as (a) large, shallow, bowl-shaped

pipes primarily filled with Fort a la Corne-type pyroclastic kimberlite (FPK); (b) small, steep-sided pipes mainly filled with resedimented volcanoclastic kimberlite (RVK); (c) small, steep-sided pipes containing Kimberley-type pyroclastic kimberlite (KPK) and hypabyssal kimberlite (HK). It was then suggested by Skinner and Marsh (2004) to use the terms, Class 1, 2 and 3 to describe the three types of kimberlites. Class 1 - South Africa type kimberlites equivalent of (c) described above; Class 2 - Fort a la Corne type equivalent to (a); and Class 3 - for steep-sided pipes infilled with FPK and RVK equivalent to (b) (Figure 3).

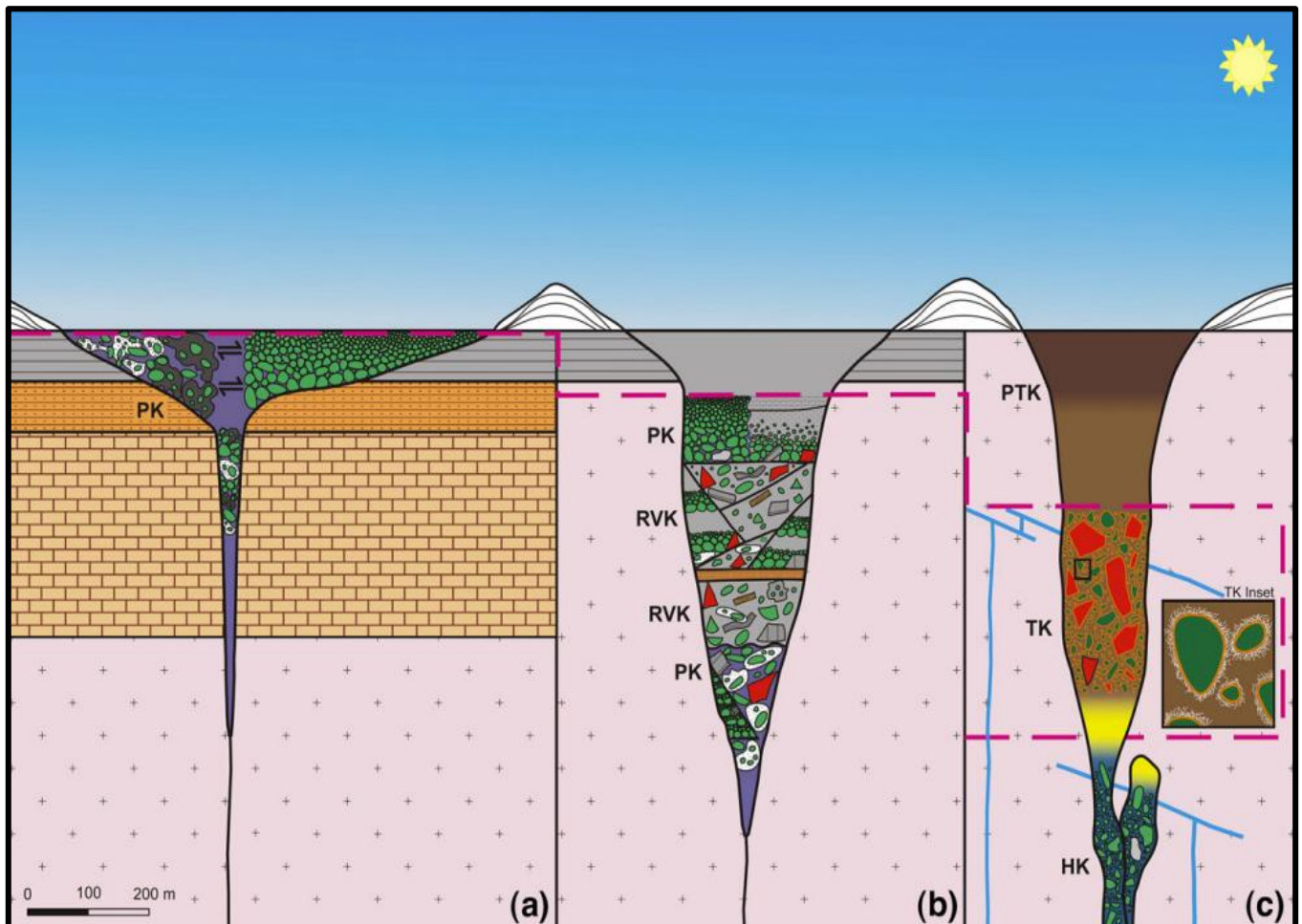


Figure 3: Diagram depicting the three main types of kimberlites (a) Class 2 (represented by Prairies kimberlites) - main pipe infill of Fort à la Corne-type pyroclastic kimberlites (b) Class 3 (represented by Lac de Gras kimberlites) - main pipe infill of Fort à la Corne-type pyroclastic and resedimented volcanoclastic kimberlite (c) Class 1 (represented by Gahcho Kue kimberlites) - main pipe infill of Kimberley-type pyroclastic kimberlite. Pink dashed line = present day surface. With: PK = pyroclastic kimberlite; RVK = resedimented volcanoclastic kimberlite; TK = tuffitic kimberlite; HK = hypabyssal kimberlite; PTK = pyroclastic equivalent of TK & with the country rock: pink = basement; cream = Palaeozoic carbonates; orange = Cretaceous siltstone and grey = Cretaceous shale. Adapted from (Scott Smith, 2008a)

2.3.1 Kimberley-type pyroclastic kimberlites (KPK)

Kimberley-type pyroclastic kimberlites (KPKs) are the primary infill material within the diatreme zone of Class 1 pipes, a feature unique to this class of pipe (Figure 3c). Kimberlite pipes in southern Africa are predominantly Class 1, with few exceptions. KPKs originate as a product of in-vent magmatic fluidisation processes and tend to be, in part, intrusive in nature (Scott Smith, 2008). Characteristic features of KPKs include, but are not limited to (Scott Smith et al., 2018): (1) massive texture and absence of bedding; (2) unsorted; (3) matrix-to-clast supported; (4) olivine macrocryst size distribution similar to that in coherent kimberlites, representing the magma pre-eruption; (5) contain many pseudomorphed olivine macrocrysts (anhedral) and phenocrysts (euhedral) but can have lower olivine abundance than coherent kimberlites due to crustal xenolith dilution; (6) melt-bearing pyroclasts are commonly subspherical-to-ovoid in shape and display a thin rim comprising crystallised kimberlitic melt; (7) fine-grained kimberlite groundmass (similar to coherent kimberlites) within melt-bearing pyroclasts consists of predominantly olivine crystals and can include perovskite, spinel, phlogopite and serpentine; (8) broken olivine is absent/rare; (9) contains abundant crustal xenoliths (~15-90 vol.%) that vary widely in size (10's of metres to mm); (10) fine-grained interclast matrix is comprised of serpentine and microlitic diopside in variable amounts. Microlitic diopside is a characteristic feature of these pyroclastic kimberlites. It is important to note that primary calcite is absent in KPKs (Scott Smith et al., 2018).

Within KPKs, the Figure 3c depicts a simple internal distribution of rock types, with KPK (previously TK) forming the main diatreme zone. It is assumed that fluidization leads to the homogenization of the pipe infill, which in turn results in a consistent diamond grade. This means that large vertical intervals exhibit uniform grades. This assumption has been questioned by Kjarsgaard (2007) who argues that this is an oversimplification and although these Class 1 pipes are primarily composed of KPK, they contain multiple intrusive and extrusive phases, each with potentially different diamond grades. Thus, thorough geological mapping, sampling, and analysis of the different phases within the pipe is crucial. A study by Field et al. (2008) presents examples of this approach from several southern African kimberlite mines, including Dutoitspan, Finsch, and Orapa, where detailed investigations revealed a complex internal architecture with multiple kimberlite phases and highly variable diamond grades.

2.3.2 Fort à la Corne-type pyroclastic kimberlite (FPK)

Fort à la Corne type pyroclastic kimberlites (FPKs) constitute the PKs (pyroclastic kimberlites) in Class 2 and 3 pipes (Figure 3a and b). FPKs originate as a product of pipe excavation and subsequent infill, thus are extrusive (i.e., pyroclastic) in nature (Scott Smith, 2008a). Characteristic features of FPKs include, but are not limited to (Scott Smith et al., 2018): (1) massive to sharply bedded; (2) evidence of sorting; (3) clast-supported nature; (4) variable abundance and size distribution of olivine not comparable to that of original kimberlite magma; (5) highly abundant olivine-dominated pyrocrysts reflecting the extensive separation of solids during eruption; (6) amoeboidal - curvilinear morphology of magmaclasts with sharp outlines/margins representing fragmentation during eruptions from original kimberlite magma; (7) cryptocrystalline groundmass within melt-bearing pyroclasts consists of predominantly serpentine and/or carbonate that can contain phlogopite, perovskite, spinel and apatite. Larger melt-bearing pyroclasts varieties contain abundant macrocrystic and phenocrystic olivine; (8) central kernels within magmaclasts of olivine and/or xenoliths commonly 10-20 mm in size, and up to 30.0 mm; (9) crustal xenoliths are seen in varying abundances, although generally low abundance (<5 vol.%), and could have been residing in the kimberlite magma (will have kimberlitic rim) or be incorporated from the crater wall during eruption; (10) interclast material consists of predominantly serpentine and/or carbonate. It is important to note that calcite is a common component of the interclast material and is a characteristic feature of FPK's (Scott Smith et al., 2018).

In the case of FPKs, the diamond grade is contingent upon factors such as potential sorting due to the removal of fine material from kimberlites, a product of their extrusive nature. This results in sorting of diamonds and consequently increase the diamond grade of the resultant deposit (Scott Smith, 2008). This, in combination with layering, as seen in Class 3 pipe types, can result in sharp changes in diamond grade within the pipe over short intervals. It is important to note that these pipes are complex, with multiple phases of kimberlite formed from various eruptive and resedimentation processes (B. Kjarsgaard, 2007). Kimberlite phases can be distinguished based on their macroscopic appearance, mineralogy, and geochemistry (Kjarsgaard, 2007; Grunsky & Kjarsgaard, 2008). Thus, the implication of diamond grade is linked to the sorting, layering of these distinct individual eruptive phases.

2.3.3 Resedimented volcanoclastic kimberlites

Resedimented volcanoclastic kimberlites (RVKs) constitute sedimentary infill from weathering and erosion and form as a product of two main stages of development: excavation of the pipe followed by infill into open craters (Scott Smith, 2008a). RVKs can contain varying amounts of kimberlitic material but commonly contains xenocrystic quartz. Characteristic features of RVKs include but are not limited to (Scott Smith et al., 2018): (1) breakage/rounding of pyroclasts; (2) melt-bearing pyroclasts from different magma batches; (3) high proportions of extrinsic material, including most commonly quartz, other non-kimberlitic material and xenoliths/crysts; (4) interclast material consists of predominantly fine-grained clastic material (Scott Smith et al., 2018).

Factors influencing diamond grade in RVKs include considerations such as the original volcanoclastic material from which it formed and internal pipe complexity. Processes such as slumping, grain flows, and deposition in crater lakes, which form RVK, could potentially concentrate or disperse diamonds, further impacting the final grade (B. Kjarsgaard, 2007).

2.3.4 Massive volcanoclastic kimberlites

The term Massive volcanoclastic kimberlites (MVKs) in this study is used to describe a volcanoclastic kimberlite with a homogeneous structure and texture in which classification as FPK or KPK is not possible. This is commonly the result of high degrees of post-emplacement alteration that obscures primary textures.

Chapter 3: Samples, methodology, and analytical techniques

3.1 Sample selection and analysis

Within the Lulo Field, there are 141 confirmed kimberlite targets, of which drill cores from 52 pipes are included in this study in which one, or multiple drill cores, have been drilled within a single pipe. Figure 5 shows the broader distribution of kimberlites of the Lulo Field. Table 13 in Appendix A shows a list of all pipes, depths and number of thin sections obtained. Lucapa Diamond Company conducted the drilling and core logging on-site in Angola and is referenced throughout this study. Representative samples of lithologies from each pipe were then sent to Remote Exploration Services (RES) for petrographic analysis. This study aims to use these observations in addition to providing a comprehensive petrographic analysis of selected representative samples to understand the distribution of kimberlites within the Lulo Field. In addition, borehole logs provided by Lucapa Diamond Company were used to inform the overall pipe architecture and geological characteristics across the field.

These drill cores were sampled for this study and thin sections ($n=83$) were obtained for petrographic classification, in which representative samples ($n=22$) were chosen for detailed petrographic classification. Bulk rock samples of coherent kimberlite ($n=7$) were collected from 4/5 different pipes containing coherent kimberlites for bulk-rock geochemistry analysis, namely, L050, L254, L125, and L026.

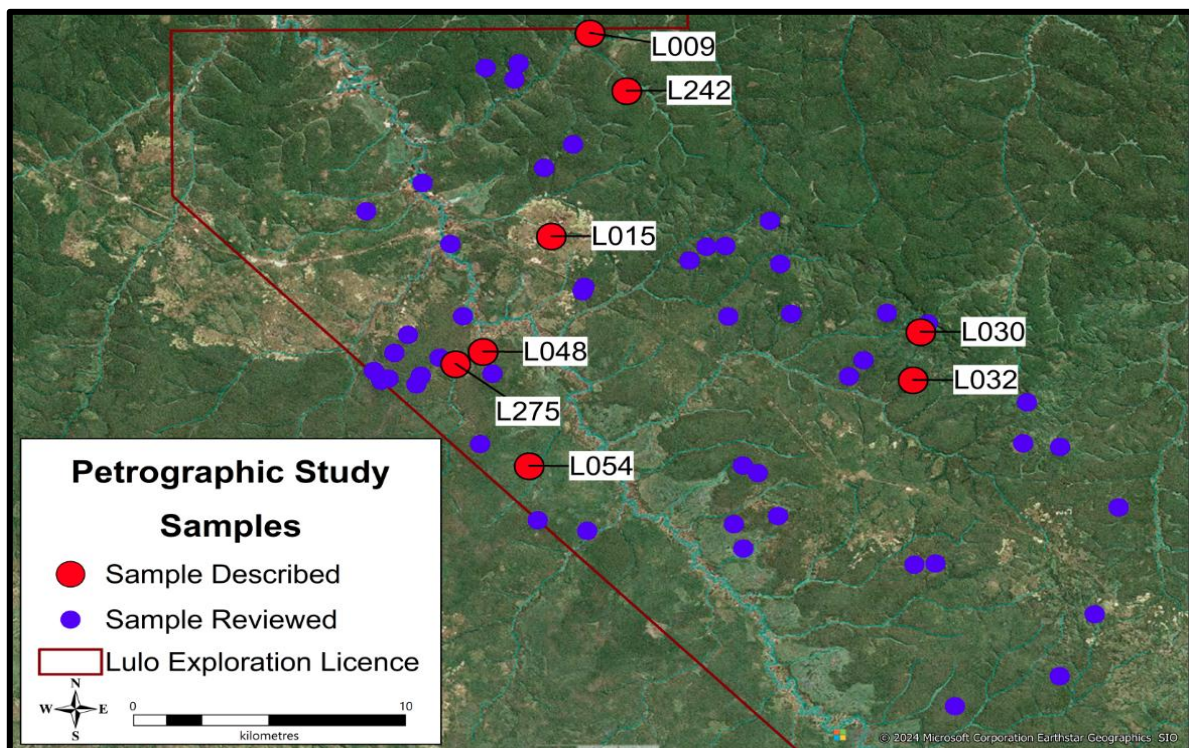


Figure 4: Map illustrating the locations of eight samples currently being described on-site, marked in red, with previously reviewed samples indicated in blue. Supplied by (Lucapa Diamond Company, 2024)

3.1.1 Petrographic approach/methodology

Each one of the 83 thin sections were analysed and petrographically classified. A subset of 22 samples were then chosen for detailed petrographic analysis as representative of the volcanoclastic kimberlites of the region. The description and subsequent classification of samples is done using the description classification suggested by Scott Smith et al., (2018). This staged progressive interpretation scheme is displayed in Table 1 and outlines a classification scheme for kimberlites, divided into five progressive stages: Rock Description, Petrogenetic Classification, Textural-Genetic Classification, Intrusive/Volcanic Spatial Context, and Genetic/Process Interpretation. Each stage progressively refines the classification, ultimately providing a comprehensive framework for describing kimberlites based on their physical and genetic characteristics. Within this classification scheme, under the rock description stage, magmaclasts are described using the scheme suggested by Webb & Hetman (2021), depicted in Figure 6 “Descriptive terminology for magmaclasts in Kimberlites” with a focus on the chosen representative samples. The selection of representative samples was based on the preservation of primary textures and their ability to illustrate the main types of kimberlites found within the Lulo Field, namely FPK and RVK. Several additional samples were included to highlight textural variation and notable features. They were specifically selected to represent the range of textures observed. These samples have been grouped accordingly in the Results section. The descriptions provided are based on the abundance and size classifications outlined in Table 2.

Thin sections were analysed at the University of Cape Town using a Zeiss Imaging Microscope, using Zen 2 lite Version 2.014283.302 software, with a N-Achroplan 2.5x and 5x objectives for transmitted light, under PPL and XPL. A Swift Model F point counter was used to determine the vol % of minerals in thin section samples. This instrument utilizes a systematic sampling method to count discrete mineral particles under a microscope, providing a quantitative analysis of mineral composition. In this case, a 200-sample target was set for the analysis, meaning the counter would collect data from 200 distinct sampling points across the thin section.

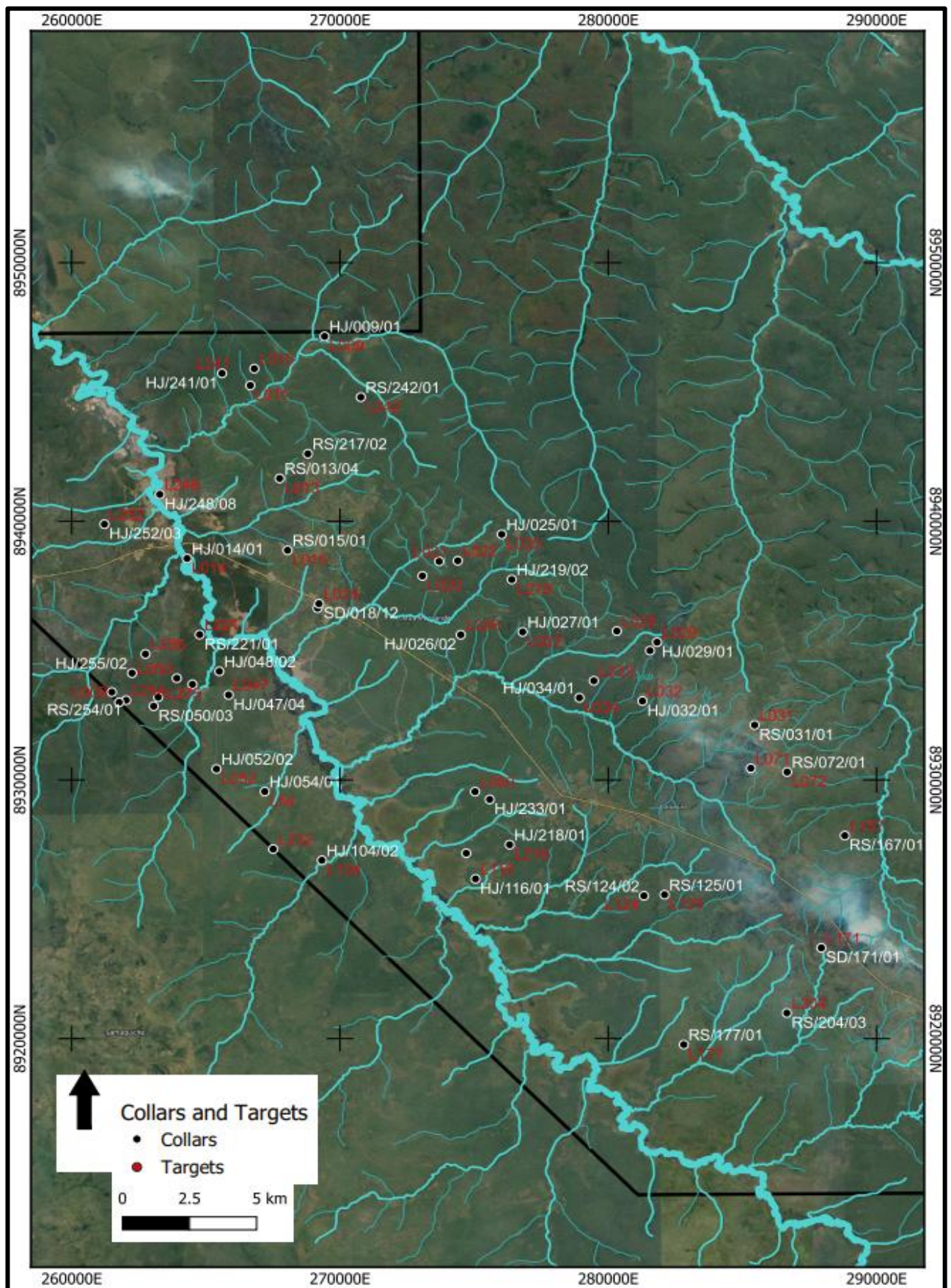


Figure 5: Map illustrating the broad distribution of kimberlite occurrences across the Lulo Field. Refer to Chapter 4, Section 4.1 for an explanation of naming conventions. Supplied by Lucapa Diamond Company (2024)

Stage 1	Stage 2	Stage 3a	Stage 3b	Stage 4	Stage 5
PROGRESSIVE INTERPRETATION					
Rock Description	Petrogenetic Classification	Textural-Genetic Classification		Intrusive / Volcanic Spatial Context	Genetic / Process Interpretation
Alteration: intensity; distribution; mineralogy; imposed textures; preservation; timing; xenolith reaction Structure: e.g. massive; inhomogeneous; layered; flow zoned; laminated; cross-bedded; jointed Texture: component distribution; shape; size distribution (e.g. well sorted; inequigranular); packing; support (e.g. clast or matrix supported) Components: compound clasts (e.g. xenoliths, magmaclasts, autoliths, accretionary clasts); crystals (e.g. olivine macrocrysts, crustal xenocrysts); interstitial matrix	Parental Magma Type: e.g. kimberlite; lamproite; melniotte; alnoite; olivine mellilite Mineralogical Classification: e.g. monticellite; phlogopite; carbonate	Coherent: [descriptors] coherent kimberlite (CK) Volcaniclastic: [descriptors] volcaniclastic kimberlite (VK)	Intrusive: [descriptors] intrusive coherent kimberlite (ICK) or hypabyssal kimberlite (HK) Extrusive: [descriptors] extrusive coherent kimberlite (ECK) Pyroclastic: [descriptors] pyroclastic kimberlite (PK) or [descriptors] kimberlitic [standard pyroclastic rock name] Resedimented Volcaniclastic: [descriptors] resedimented volcaniclastic kimberlite (RVK) or [descriptors] resedimented kimberlitic [standard sedimentary rock name] Epilastic Volcanic: [descriptors] epilastic volcanic kimberlite (EVK) or [descriptors] epilastic kimberlitic [standard sedimentary rock name]	e.g. intra-crater ICK sheet; non-volcanic HK plug; sub- volcanic root zone-fill e.g. intra-crater ECK; extra-crater ECK e.g. pipe-fill KPK; subsurface diatreme-fill KPK; crater-fill KPK e.g. vent-proximal FPK, intra-crater FPK; crater rim FPK; distal extra-crater FPK e.g. pipe-fill RVK; intra- crater kimberlitic sediments; distal extra-crater RVK e.g. pipe-proximal EVK; epilastic volcanic kimberlitic sediment	e.g. composite flow- differentiated hypabyssal sheet; intrusive plug e.g. fountain-fed clastogenic lava lake; effusive lava flow e.g. fluidised; column collapse e.g. spatter; fallout; base surge; pyroclastic flow e.g. grain flow; debris flow; mass flow; lacustrine; reworked crater rim; alluvial fan; turbidite e.g. lithified crater rim scarp slope mass wasting
Example names: uniform, xenolith-poor, medium-grained, olivine macrocryst-rich rock; massive, xenolith-rich, fine to medium-grained, olivine-poor rock; cross-bedded microcrystic rock	Example names: olivine macrocryst-rich carbonate phlogopite monticellite kimberlite; leucite lamproite; olivine macrocryst-poor phlogopite orangite	Example names: xenolith-poor, flow zoned, variably macrocrystic CK; xenolith-rich, well bedded VK	Example names: macrocryst-poor ICK; uniform macrocrystic HK; flow banded crystal-poor ECK; thickly bedded PK; massive unsorted very macroxenolith-rich KPK; graded xenolith-poor olivine pyrocryst-rich FPK; cross-bedded very fine-grained crystal-dominated RVK; well sorted resedimented kimberlitic sandstone; poorly sorted EVK; bedded kimberlitic lapilli tuff	Example names: steep discordant HK sheet; diatreme-fill massive xenolith-rich KPK; crater-fill mega-graded olivine pyrocryst-dominated FPK	Example names: graded, olivine pyrocryst-rich FPK fallout deposit; kimberlitic lacustrine mudstone; clast supported, very xenolith-rich RVK mass flow deposit

Table 1: Schematic showing staged progressive interpretation scheme outlining a classification scheme for kimberlites, divided into five progressive stages: Rock Description, Petrogenetic Classification, Textural-Genetic Classification, Intrusive/Volcanic Spatial Context, and Genetic/Process Interpretation. Adapted from Scott Smith et al. (2018).

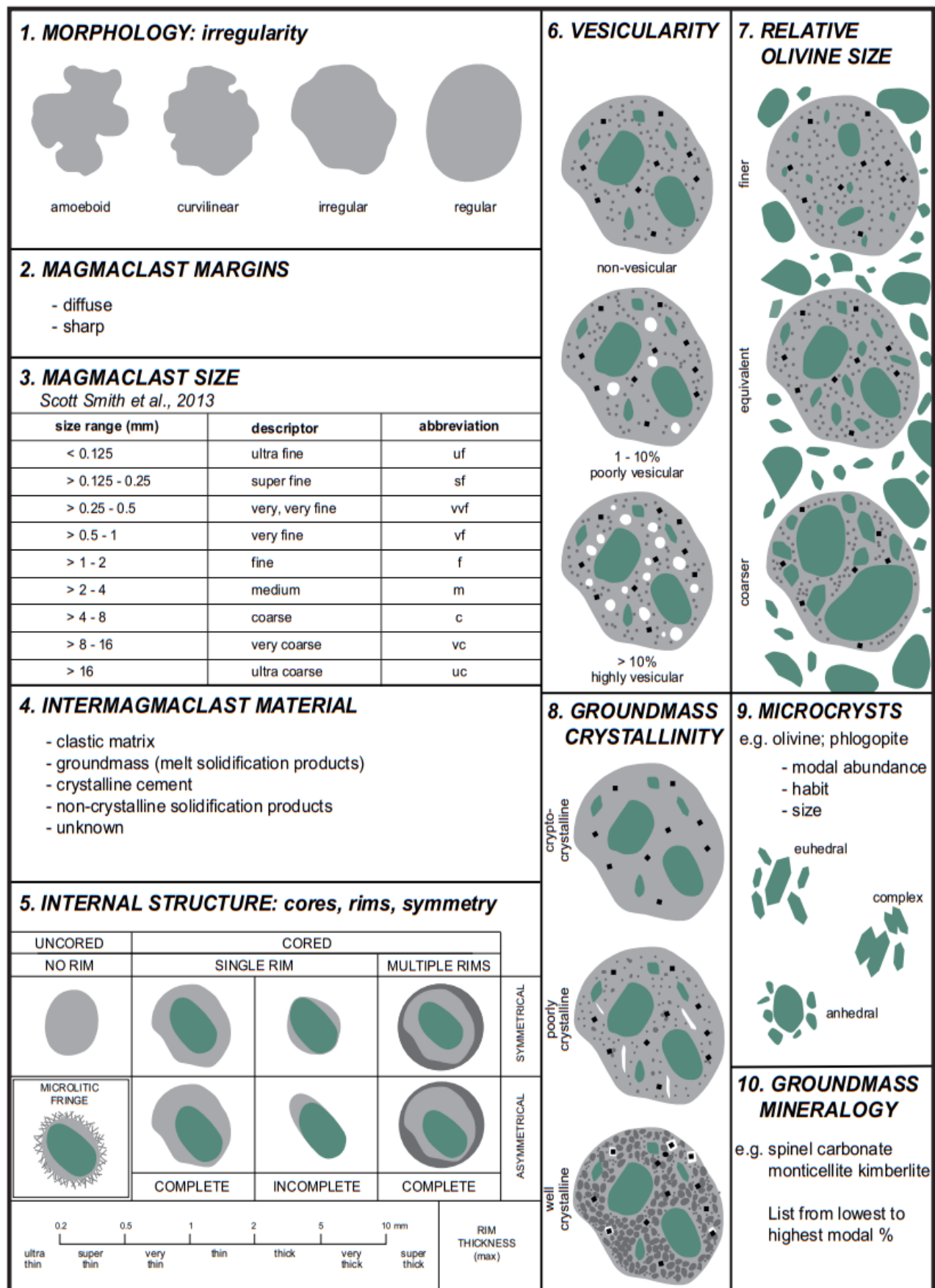


Figure 6: Visualization of magmaclast classification scheme. Adapted from Webb & Hetman (2021)

(a)

Percentage range	Descriptor
0	[crystal]-free
> 0 – 5	very [crystal]-poor
> 5 – 15	[crystal]-poor
> 15 – 50	[crystal]-rich
> 50 – 75	very [crystal]-rich
> 75	[crystal]-dominated

(b)

Size range (mm)	Descriptor	Abbreviation
< 0.125	ultra fine	uf
> 0.125 – 0.25	super fine	sf
> 0.25 – 0.5	very very fine	vvf
> 0.5 – 1	very fine	vf
> 1 – 2	fine	f
> 2 – 4	medium	m
> 4 – 8	coarse	c
> 8 – 16	very coarse	vc
> 16	ultra coarse	uc

(c)

Percentage range	Descriptor	Abbreviation
0	xenolith-free	x-free
> 0 – 5	very xenolith-poor	v-x-poor
> 5 – 15	xenolith-poor	x-poor
> 15 – 50	xenolith-rich	x-rich (or Kx)
> 50 – 75	very xenolith-rich	v-x-rich (or Kxx)
> 75	xenolith-dominated	x-dominated (or Kxxx)

Table 2: Overview of abundance and size descriptors for (a) crystals, (b) magmaclasts and (c) xenoliths. Adapted from Scott Smith et al. (2018)

3.1.2 Bulk-rock geochemistry

Selected coherent kimberlites were analysed for their bulk-rock chemistry. XRF, ICP-MS, and MC-ICP-MS Sr-Nd isotope analyses were performed.

3.1.2.1 X-ray fluorescence (XRF)

In this study, X-ray fluorescence (XRF) analysis was conducted to measure both major oxides and trace elements in bulk rock samples at the Department of Geological Sciences, University of Cape Town. Major oxides, reported in weight percent (wt.%), were analysed on fused disks prepared from ignited powders, while trace elements (in parts per million, ppm) were measured on pressed, unignited powder pellets. To

calculate adsorbed water content (H_2O^-), 2 grams of powder were weighed, dried at 110°C overnight, and reweighed. The powder was then heated at 900°C for at least four hours to remove structural volatiles (e.g., H_2O and CO_2) and oxidize ferrous iron to ferric iron oxide (Fe_2O_3), then weighed again to determine Loss on Ignition (LOI).

Fused disks were prepared by combining 0.7 grams of ignited powder with 6 grams of Claisse XRF flux (57% lithium tetraborate, 43% lithium metaborate) and melting the mixture in platinum crucibles using an automated Claisse M4 Fluxer. This produced a homogeneous melt, which was then poured into a platinum mold to cool into a disk. For trace elements, pressed powder pellets were prepared by mixing 10 grams of rock powder with 2.5 grams of Hoescht tableting wax, compacted at 10 tons pressure. Major oxide and trace element concentrations were determined using a Panalytical Axios XRF spectrometer, calibrated using standard reference materials made of natural rock powders, issued by MINTEK, the USGS, the Geological Survey of Japan and other agencies. Analyte intensities were corrected for mass attenuation, peak overlap and background following techniques as outlined by Rousseau et al. (1996).

The lower limit of detection (LLD) was 0.01 wt.% for major oxides, with values below this marked as “b.d.” (below detection) or as less than the LLD threshold. Trace elements exceeding the calibrated range are marked in red, indicating approximate values.

3.1.2.2 Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

The concentrations of rare earth element (REE) and several other trace elements for ten of the kimberlite samples, plus standard SARM-39 (a kimberlite standard issued by MINTEK) were determined by solution inductively coupled plasma mass spectrometry using the Thermo iCAP-RQ quadrupole ICP-MS instrument within the Department of Geological Sciences. The sample preparation involved weighing out 0.05g of sample powder, to which 2 ml of a mixture of 3:1 concentrated hydrofluoric (HF) and nitric (HNO_3) acids were added in a 3 ml teflon vial. The vial was sealed and placed inside the teflon capsule of a steel-jacketed Parr digestion vessel. Two ml of ultrapure water was added to the outer vessel to help minimise the pressure differential between the inner and outer teflon vials. The vessels were tightly closed and placed in an oven for 24 hours at 200°C for complete digestion. The small vial was removed from the capsule, the cap carefully removed and placed on a hot plate at 100°C to allow evaporation of

the acid mixture. This followed by adding 2 ml of concentrated HNO_3 (nitric acid) and evaporating to complete dryness. The samples were diluted 20,000-fold with a 5% nitric acid solution containing 10 parts per billion (ppb) of the internal standard elements Rh, In, Re and Bi. The samples were then placed in 15 ml centrifuge tubes for analysis.

Data acquisition for the ICP-MS trace element measurements was performed in peak-jumping mode, where each sample was scanned in three replicates of 100 sweeps across the mass spectrum, using a peak dwell time of 40 milliseconds on each atomic mass selection of analytes, interferences, and internal standards. The subsequent ion intensities were converted to concentrations through a series of four synthetic calibration standards. The standards were prepared from a certified multi-element standard solutions that spanned ranges of concentration of nearly three orders of magnitude, to guarantee that all sample analytes were within the calibrated range. The repeated analyses of the kimberlite standard SARM-39 precision and accuracy with relative errors better than 3% for most elements with detection limits in the lower ppb range.

3.1.2.3 MC-ICP-MS Sr-Nd isotope analyses

Isotope analyses were performed on Nu Instruments NuPlasma HR in the MC-ICP-MS facility at the Department of Geological Sciences, University of Cape Town. Sample preparation begins with concentrated $HF:HNO_3$ digestion of rock, mineral, or ash samples at 140°C for 48 hours in sealed Teflon beakers, followed by drying and conversion to nitrate form, while enamel samples undergo a 1-hour HNO_3 digestion at 140°C. Isotopic separation of Strontium (Sr) and Neodymium (Nd) is achieved through sequential extraction chromatography, following the method by Pin et al. (2014). Sr isotopes are analysed as a 200 ppb solution in 0.2% HNO_3 using NIST SRM987 as a reference standard, normalized to an Sr^{87}/Sr^{86} value of 0.710255 (Waight et al., 2002). For Nd isotopes, a 50 ppb solution in 2% HNO_3 is used, analysed with the Nu Instruments DSN-100 desolvating nebuliser and JNdi-1 as a reference, normalized to $Nd^{143}/Nd^{144} = 0.512115$ (Tanaka et al., 2000).

Chapter 4: Results

4.1 Petrography

A comprehensive list of all samples discussed in this study, including sample name, pipe number, depths, classification, and key features, is provided in Table 14 in Appendix B. Samples showing a high degree of alteration where primary textures have been lost (n=3), are not recorded in the table to avoid inaccurate classification.

The nomenclature for thin sections follows a standardized format across all samples. For instance, in "HJ-054-01-96P," "HJ/RS" designates the drilling rig used, while "054" identifies the target, anomaly, or deposit, with "L" under 'Pipe number' indicating a confirmed kimberlite target. The subsequent "01" specifies the sequence of drilling, where "01" denotes the initial or 'discovery hole.' Finally, "96P" indicates the depth from which the sample was taken - in this case, 96m.

Detailed petrographic descriptions of representative samples are conducted with a focus on detailing essential magmaclast characteristics for use in the Webb and Hetman (2021) classification scheme with the overarching aim to describe the samples using the classification scheme suggested by Scott Smith et al. (2018). In addition, key notable features of interstitial material and textural variations are included. Selected representative samples are given in Table 3.

It is important to note that the grouping of samples presented in the following results section reflects a preliminary classification based on macroscopic features observed prior to detailed petrographic analysis which allowed for an initial assignment of samples to one of the three main kimberlite types: FPK, RVK and CK. This pre-grouping approach provided a framework for organizing and comparing representative samples across the different kimberlite pipes.

4.1.1 Overview

Within the Lulo Field, olivine grains are completely serpentized in most instances, except for Pipe L026, where some fresh olivine remains. It is important to note that while the olivine grains contained in magmaclasts are fully serpentized, the magmatic

groundmass surrounding these grains often remain fresh, allowing for the observation of the primary mineralogy to be observed. Furthermore, late-stage alteration has led to varying degrees of serpentine formation in the interclast material, with varying degrees of serpentine formation with the interclast material.

Table 3: Summary table of representative samples, including pipe number, depth and type

<i>Sample name</i>	<i>Pipe number</i>	<i>Depth (m)</i>	<i>Type</i>
HJ-054-01-96P	L054	96.7	FPK
HJ-054-01-46P	L054	46.6	FPK
RS-008-02-65P	L008	65.5	FPK
RS-008-02-16P	L008	16.0	FPK
HJ-030-01-76P	L030	76.4	FPK
RS-221-01-56P	L221	56.4	FPK
HJ-219-02-35P	L219	35.7	FPK
HJ-032-01-86P	L032	86.7	FPK
HJ-060-01-69P	L060	69.6	FPK
HJ-048-02-43P	L048	43.7	FPK
HJ-048-02-180P	L048	180.0	FPK
HJ-009-01-23P	L009	23.7	RVK
HJ-009-01-96P-B	L009	96.6	RVK
HJ-033-01-78P	L033	78.6	RVK
HJ-011-01-91P	L011	91.4	RVK
RS-167-01-52P	L167	52.1	RVK
HJ-026-02-102P	L026	102	Coherent sill
HJ-026-02-55P	L026	55.5	Coherent sill
RS-050-03-32P	L050	30.0	Coherent sill
HJ-050-01-45P	L050	45.0	Coherent sill
RS-254-01-19P	L254	19.0	Coherent sill
RS-254-01-53P	L254	53.0	Coherent sill
RS-125-01-63P	L125	63.1	Coherent sill

4.2 Fort à la Corne-type pyroclastic kimberlite (FPK)

4.2.1 Staged progressive interpretation scheme

Stage 1 - Rock description

Alteration

Representative samples of FPKs within the Lulo Field display a fragmental, volcanoclastic texture whereby the primary volcanoclastic textures have been preserved. Representative samples with relatively low degrees of alteration have been selected to ensure primary features can be recognized. Notably, late-stage alteration has resulted in extensive serpentine formation in the interclast material seen most notable in pipes L008, L221 and L048 which show a higher serpentine abundance and higher degrees of olivine alteration (Figure 7a) while pipes L054, L219, L030, L060 and L032 displays less serpentinization by comparison (Figure 7d). In addition, apatite is altered in all cases, as seen exclusively in L221, with altered apatite laths consisting of calcite within the kimberlitic groundmass of magmaclasts. Phlogopite is relatively fresh as seen in pipes L048 and L060, with relatively little serpentinization.

Structure and texture

The overall structure visible in thin sections is massive and homogeneous in nature with no signs of layering.

The components of the volcanoclastic kimberlite are either matrix-supported, as seen in L008, L030, and L221 (Figure 7a), or clast-supported, as observed in pipes L054, L219, L060, and L048 (Figure 7d). Pipe L032 exhibits a mixed clast-matrix-supported structure. These components are embedded in an ultra-fine-grained crystalline cement primarily composed of serpentine and calcite. Clast sizes range from ultra-fine to very coarse (~0.10-15.0 mm). Ultra fine to very fine-grained examples such as in pipe L048 (Figure 7c), consist of clasts measuring between 0.125-1.00 mm. Pipe L032 and L030 (Figure 7a) shows a large abundance of very very fine grains, though occasionally showing coarse grains up to 8.00 mm, with L060 showing similar features, but with fewer coarse grains up to 6.00 mm (Figure 7e). Pipe L054 (Figure 7b) and L008 contains abundant very fine-grained clasts (~0.50 mm) but also commonly feature coarser magmaclasts, ranging up to 6.00 mm (Figure 7d) and 15.0 mm (Figure 7f) respectively. L219 and L221 show a wide range of sizes with equal amounts of very very fine to coarse grains.

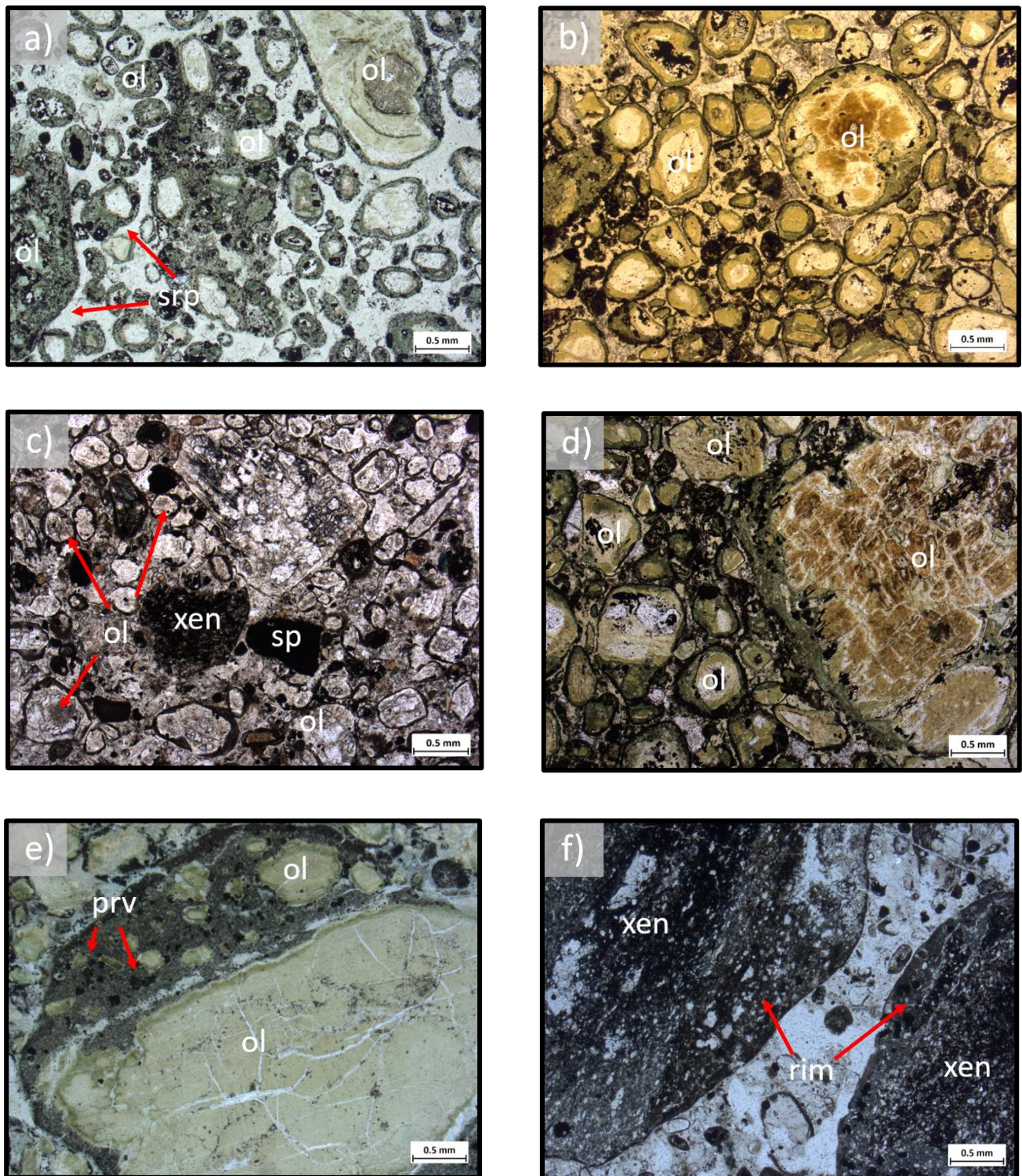


Figure 7: Photomicrographs in PPL of olivine (ol) and xenolith (xen) cored magmaclasts with varying textures and sizes. All samples display a large abundance of very fine to very very fine grained clasts, with differences in matrix support, clast morphology, and magmaclast size: (a) HJ-030-01-76P - Altered olivine-cored magmaclasts in a matrix-supported framework, with a very very fine-grained texture (b) HJ-054-01-96P - Olivine-cored magmaclasts with regular to irregular morphologies, within a clast-supported matrix, also showing very fine-grained clasts (c) HJ-048-02-180P - Very very fine-grained overall texture (d) HJ-054-01-96P - Olivine-cored magmaclasts up to 6.00 mm in size (e)

HJ-060-01-69P - Olivine-cored magmaclasts up to 8.00 mm in size (f) RS-008-02-65P - Xenolith (xen)-cored magmaclasts up to 15.0 mm in size.

Sorting within the kimberlite pipes is not distinctly observable on a microscopic scale, as component packing shows minimal variation with depth (Figure 8). Core logging reveals poor sorting in pipe L048 over a depth of 187 m, moderate sorting in pipe L030 over 94.0 m and pipe L032 over 61.0 m, and a moderate to well-sorted structure in pipe L054 over 96.0 m.

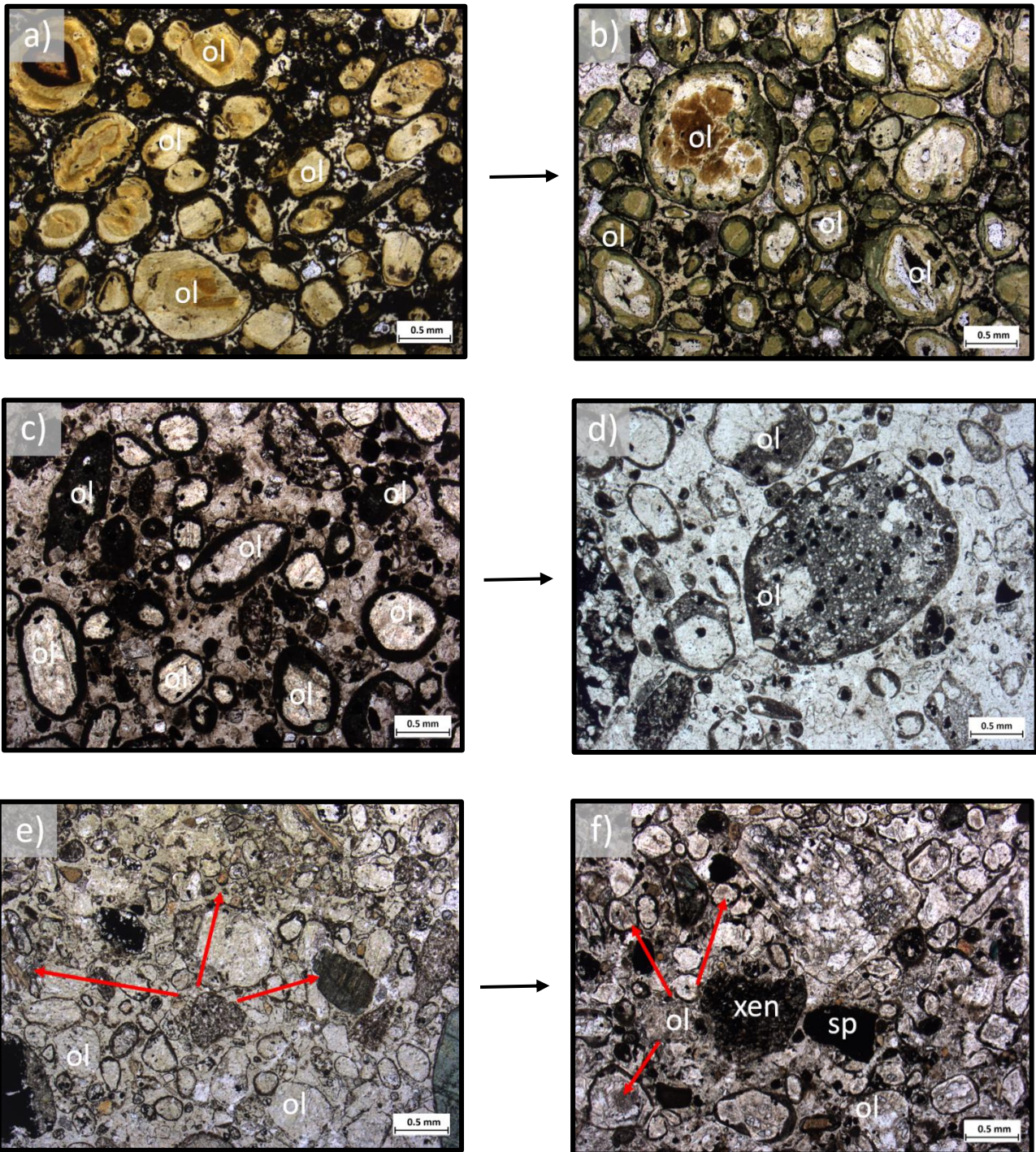
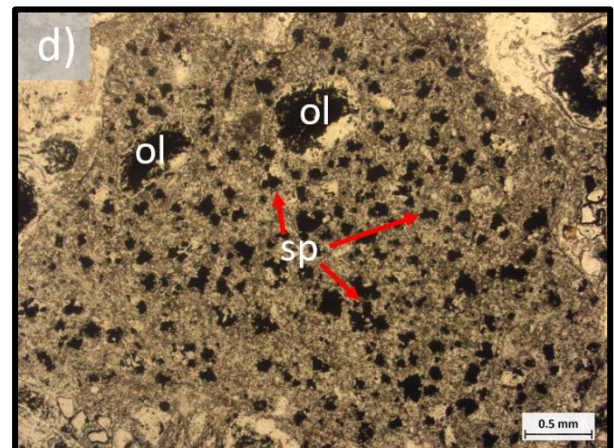
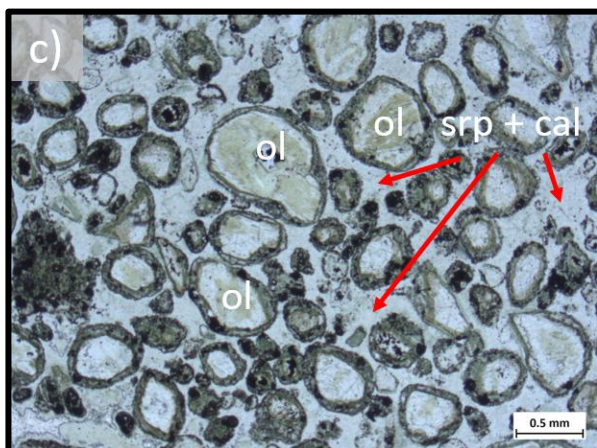
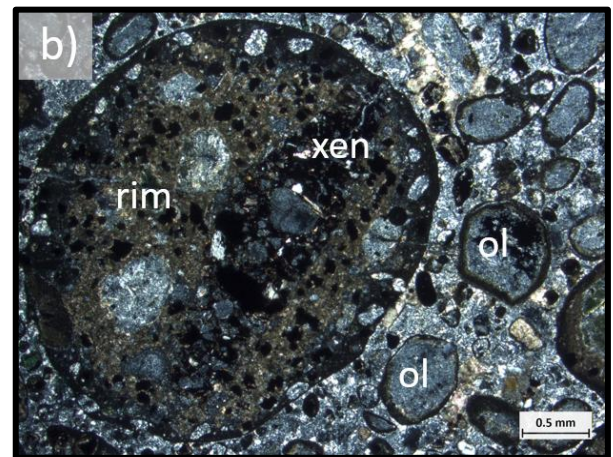
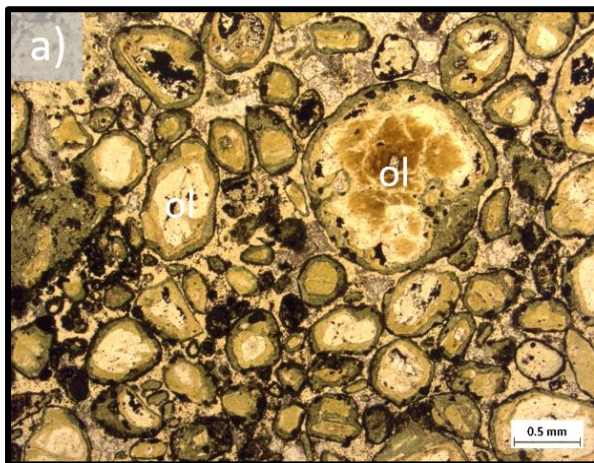


Figure 8: Photomicrographs in PPL illustrating grain sorting variations across three different pipes at varying depths: (a) HJ-054-01-46P at depth 46 m (b) HJ-054-01-96P at depth 96.0 m (c) RS-008-02-16P at depth 16.0 m (d) RS-008-02-65P at depth 65 m (e) HJ-048-02-43P at 43.0 m (f) HJ-048-02-180P at 180 m

Components

Magmaclasts

Magmaclast morphologies vary from regular/rounded in pipes L054, L008, L030, and L032 (Figure 9a, 9b and 9c) to curvilinear/curved edges in pipes L219, L221, L060, and L048 (Figure 9d and 9e). Additionally, broken olivine grains are common in pipes L032, L219, L030, and L221 (Figures 9f, 9g and 9h). With all magmaclasts showing sharp, defined margins and are non-vesicular in nature.



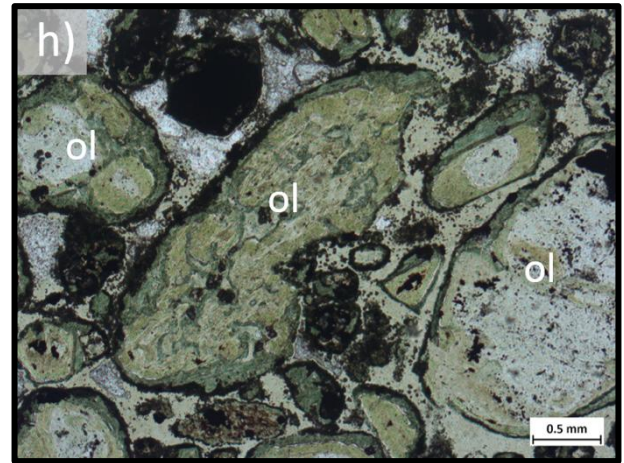
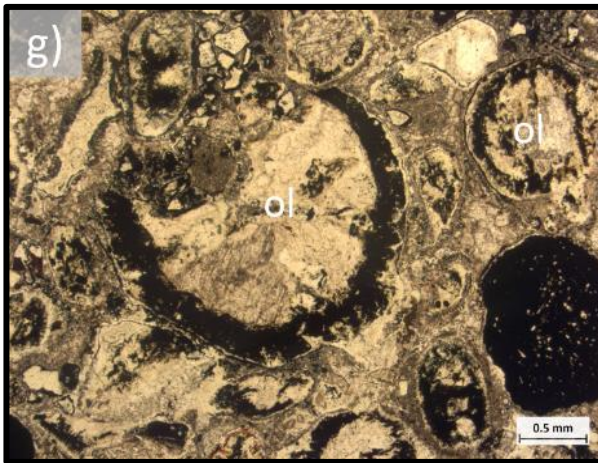
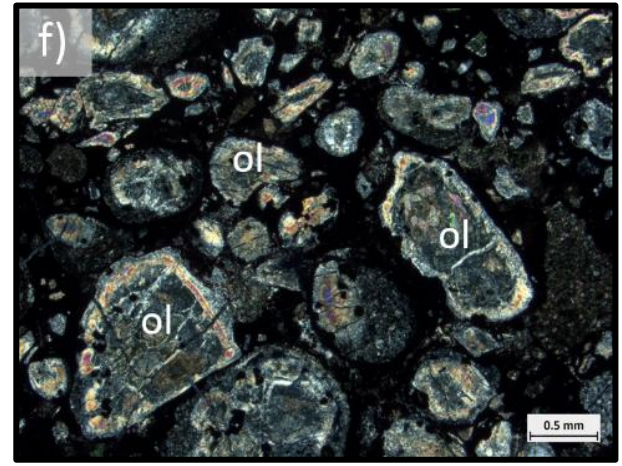
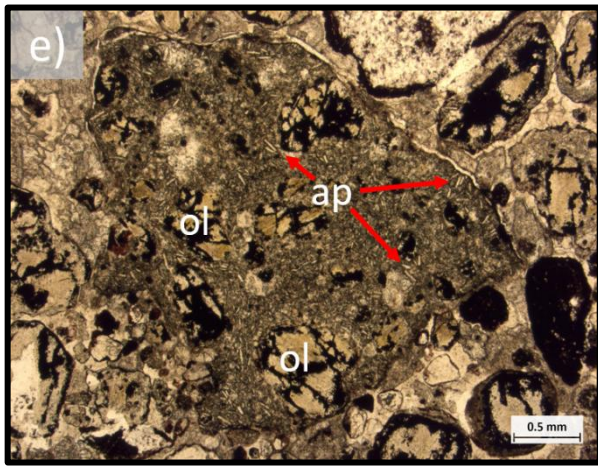


Figure 9: Photomicrographs in PPL of various magmaclast containing samples. All samples exhibit regular/rounded or curvilinear/curved-edged morphologies, with some displaying cored magmaclast varieties and altered apatite (ap). Distinct characteristics include: (a) HJ-054-01-96P, a cored magmaclast variety with regular/rounded morphology; (b) RS-008-02-65P, an uncored magmaclast variety with regular/rounded morphology; (c) HJ-030-01-76P, a cored magmaclast variety with regular/rounded morphology; (d) HJ-219-02-35P, an uncored magmaclast variety with curvilinear/curved-edged morphology; (e) RS-221-01-56P, an uncored magmaclast variety with altered apatite (ap) laths and curvilinear/curved-edged morphology. Photomicrographs in XPL show: (f) HJ-032-01-86P, olivine (ol)-cored magmaclast varieties with broken edges and a matrix-supported nature. Photomicrographs in PPL also show: (g) HJ-219-02-35P, a broken macrocrystic olivine (ol) grain with euhedral morphology; (h) HJ-030-01-76P, olivine (ol)-cored magmaclast varieties with broken olivine (ol) grains in a matrix-supported nature.

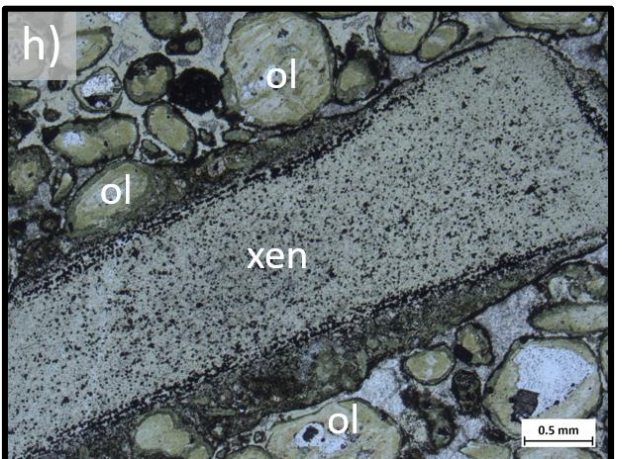
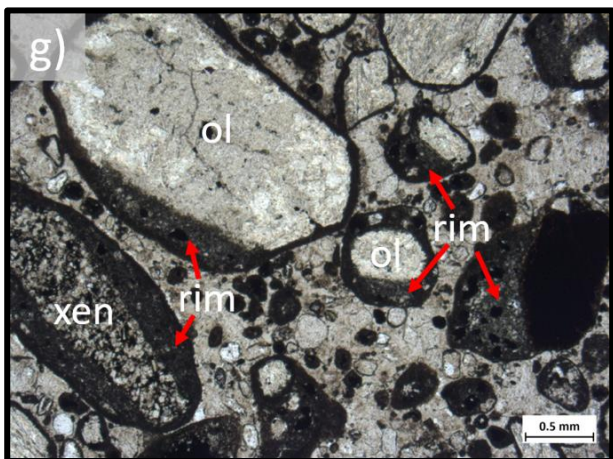
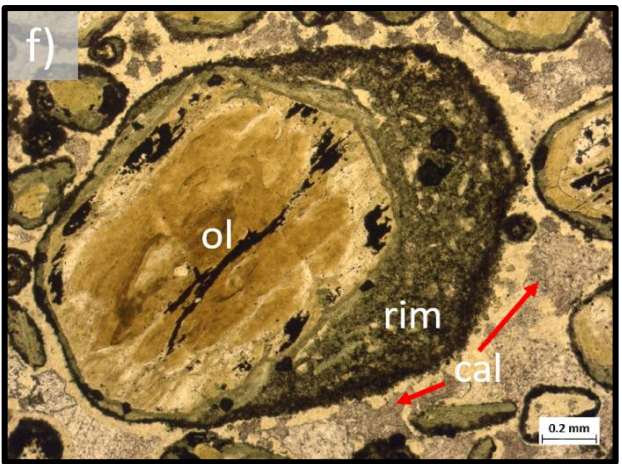
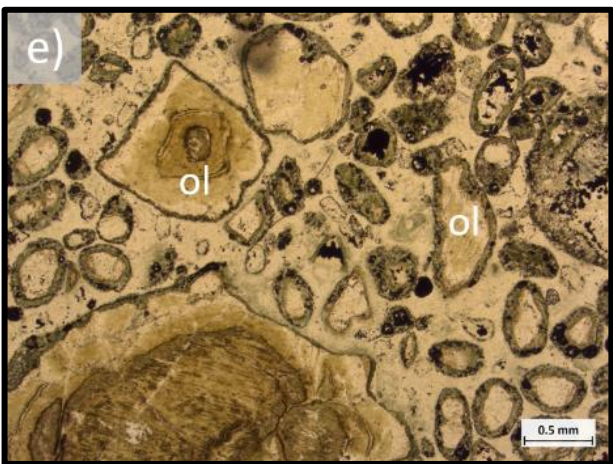
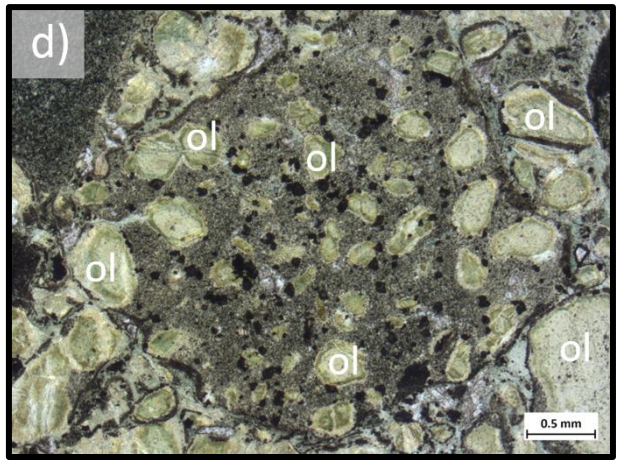
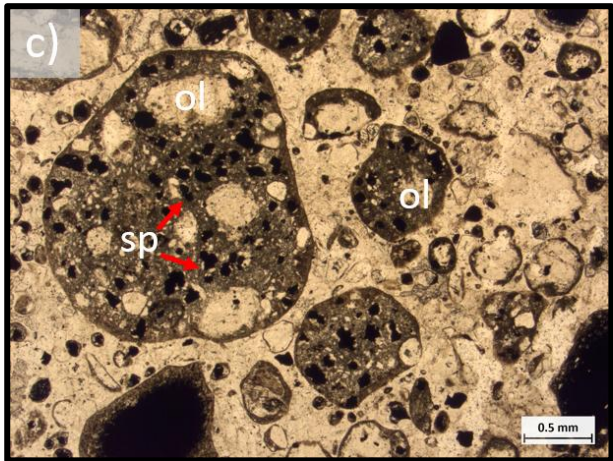
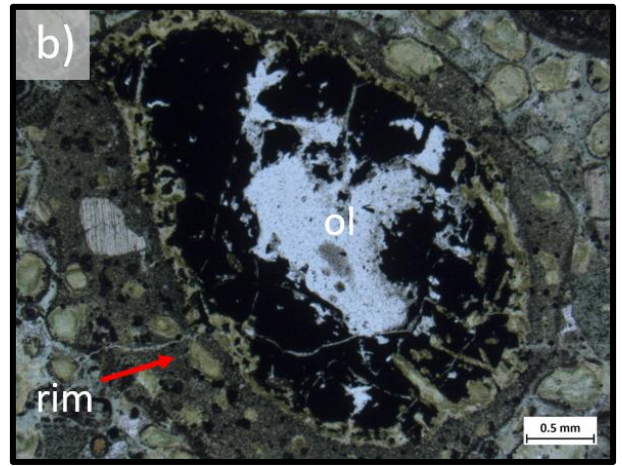
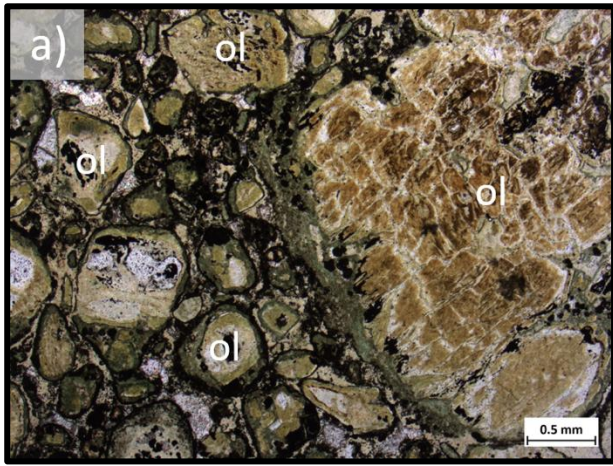
Magmaclast sizes vary widely, ranging from ultrafine to very coarse (0.125-15.0 mm), and can be categorized into cored (containing olivine or xenoliths) and uncored types. Cored and uncored magmaclasts are present in all samples in variable proportions. Cored magmaclasts are most prevalent in pipes L054, L030, and L048. Uncored

magmaclasts are more abundant in pipes L008, L219, L221, and L060. While pipe L032 contains equal amounts of cored and uncored varieties.

Olivine-cored magmaclasts show a wide range in grain size across the samples analysed with ultrafine to very coarse (0.125-15.0 mm), with pipe L048 showing a high abundance of ultrafine grains. In pipes L030, L221, L219, and L032, the clasts are predominantly very fine to fine-grained. Medium to coarse-grained olivine-cored varieties, reaching up to ~8.00 mm, are more common in pipes L054, L008, and L060 (Figures 10a and 10b). Xenolith-cored magmaclasts, primarily found in pipe L008 (Figure 10g), and less commonly L054 (Figures 10h) and L030 range from very fine to very coarse (0.50-15.0 mm). Rare phlogopite cored magmaclasts ~2.50 mm in size are seen exclusively in pipe L060 (Figures 10i). Uncored magmaclasts exhibit a broad size range (0.50-10.0 mm). Only very fine grains (0.50-1.00 mm) are found in pipes L048, while pipe L054 contains only a few uncored magmaclasts ~1.00 mm. Very fine to medium grains are observed in pipes L221 and L008 (Figure 10c) with coarser grains seen in pipes L219, L030, L032 and L060 (Figures 10d) with very coarse grains also present in pipe L008.

Cored magmaclasts occur in two main forms, with the most predominant type having a single kimberlitic rim that surrounds the central kernel (this can be described as the core of the magmaclast) on all sides (complete rims) displaying a symmetrical shape. This variety is frequently observed in pipes L008, L054, and L030 (Figure 10b and 10e) and is also seen in pipes L219, L221, L032, and L048, though less commonly due to the lower abundance of cored magmaclasts. The second form has a single kimberlitic rim that does not surround the central kernel on all sides (incomplete rims), in which certain sides of the central kernel have no surrounding kimberlitic rim and displays an asymmetrical shape. These are commonly found in pipes L008 and L054 (Figures 10f, 10g, and 10h) and appear less frequently in pipe L060 (Figure 10i).

These central kernels are surrounded by kimberlitic rims, these are generally ~0.10 mm in size and can be described as ultra-thin in pipes L054 and L030 with very thin rims seen in pipes L008 and L060.



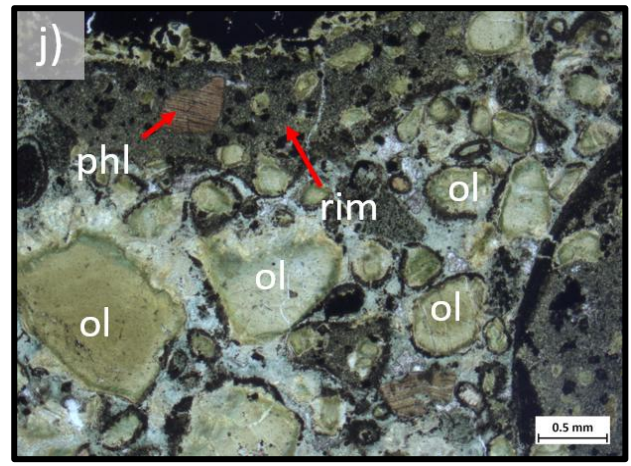
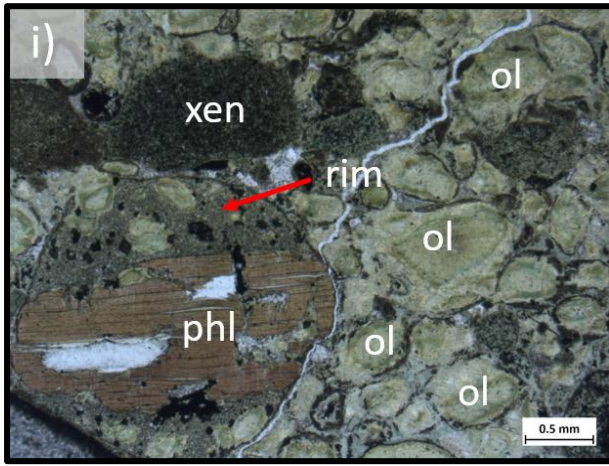
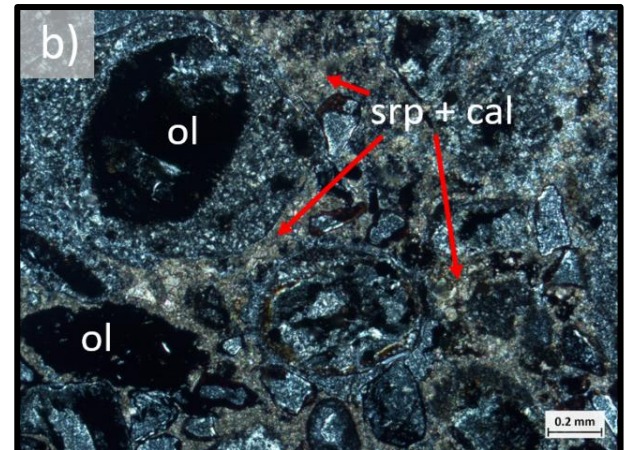


Figure 10: Photomicrographs in PPL of magmaclasts, primarily featuring olivine (ol) with less common occurrences of xenoliths (xen) and phlogopite (phl), with varying rim structures. All samples display cored or uncored varieties, very fine grain sizes to coarse and rims that range from incomplete to complete, symmetrical to asymmetrical. Distinct characteristics include: (a) HJ-054-01-96P, olivine (ol)-cored magmaclasts with medium to coarser varieties; (b) HJ-060-01-69P, olivine (ol)-cored magmaclasts with medium to coarser varieties; (c) RS-008-02-65P, very fine to medium grains of uncored magmaclasts; (d) HJ-060-01-69P, coarse uncored magmaclast; (e) HJ-030-01-76P, olivine (ol)-cored magmaclast with a single, complete, symmetrical rim and broken grains; (f) HJ-054-01-96P, olivine (ol)-cored magmaclast exhibiting euhedral morphology with an incomplete, asymmetrical rim surrounded by calcite-rich intermagmaclastic material; (g) RS-008-02-16P, olivine (ol) and xenolith (xen)-cored magmaclasts with single, incomplete, asymmetrical rims; (h) HJ-054-01-96P, xenolith (xen)-cored magmaclast with a symmetrical rim containing microcrystic olivine and spinel (i) HJ-060-01-69P, phlogopite (phl)-cored magmaclast with a single, incomplete, symmetrical rim; (j) HJ-060-01-69P, olivine (ol)-cored magmaclast with perovskite (prv), olivine (ol), and spinels (sp) in the kimberlitic rim.

The inter-magmaclast matrix is made up of ultra-fine-grained crystalline cement of serpentine and calcite in variable proportions in all samples. A serpentine dominated matrix with minor calcite is seen in pipes L008, L030, L060 and L032 (Figure 11a) and calcite dominated with minor serpentine in pipes L054, L219 and L221 (Figure 11b and 11c) with pipe L054 showing notable coarse crystalline calcite (Figure 11d).



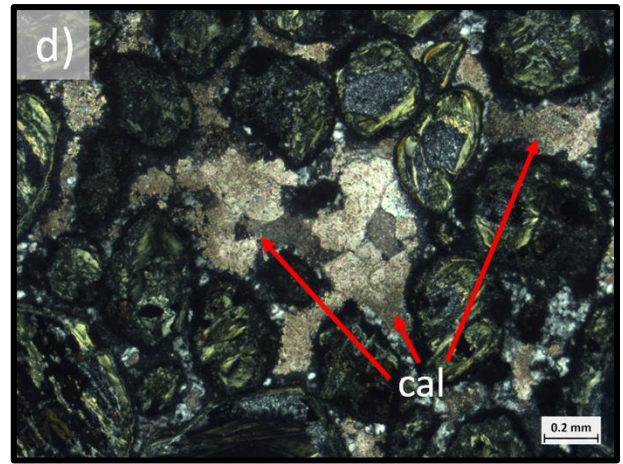
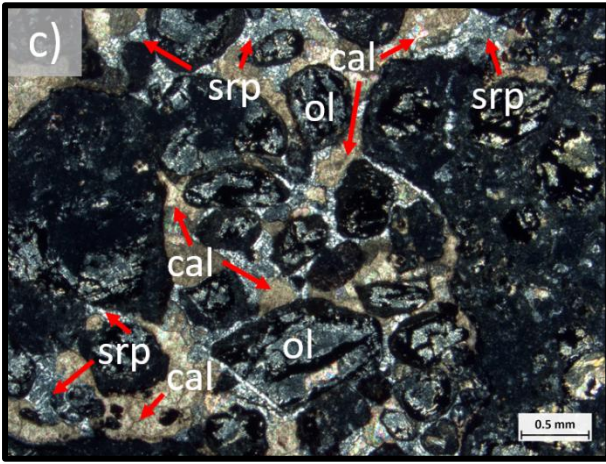
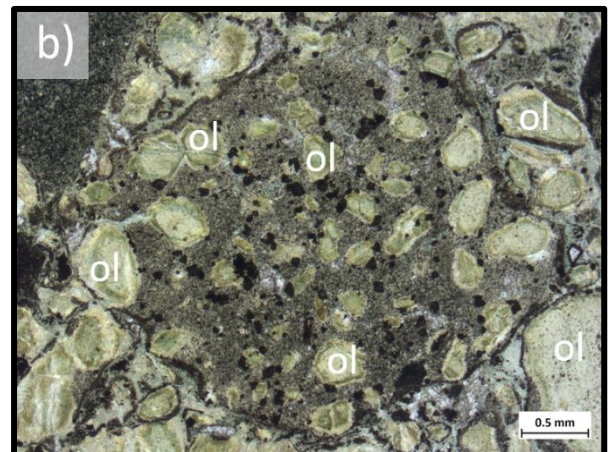
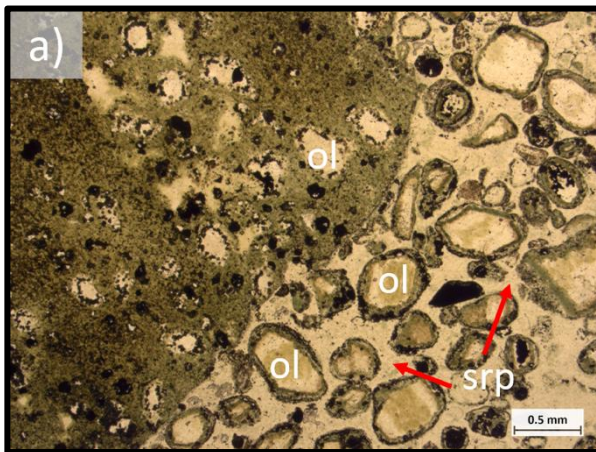


Figure 11: Photomicrographs in PPL of: (a) HJ-030-01-76P showing an ultra-fine grained crystalline cement of serpentine (minor calcite) dominated intermagmaclastic matrix. Photomicrographs in XPL of: (b) HJ-219-02-35P showing an ultra-fine grained crystalline cement of serpentine and calcite dominated intermagmaclastic matrix (c) RS-221-01-56P showing a crystalline cement of serpentine and calcite dominant intermagmaclast matrix (d) HJ-054-01-96P showing a predominantly crystalline cement of calcite-rich inter-magmaclast matrix

Olivine grains within the magmaclasts are generally finer than those in the surrounding matrix, as observed in pipe L030 (Figure 12a). However, some samples, such as those from pipes L060, L221, L219, L048, and L054 (Figure 12b), show olivine grains of equivalent size to the surrounding matrix. In contrast, coarser olivine grains within the magmaclasts are commonly observed in pipes L008 (Figure 12c) and L032 (Figure 12d).



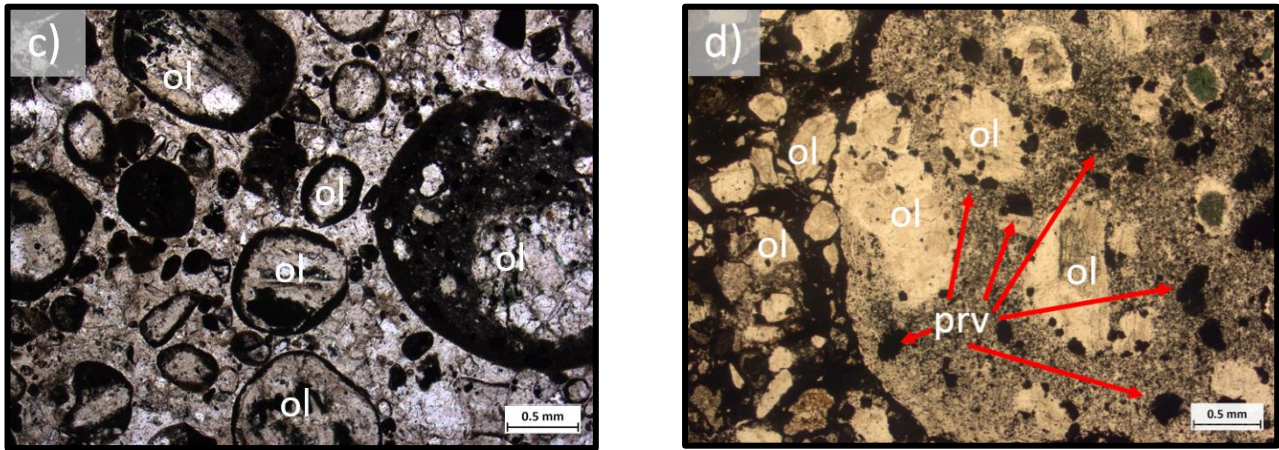


Figure 12: Photomicrographs in PPL of magmaclasts, featuring both cored and uncored varieties with varying olivine (ol) sizes and morphologies, highlighting the relative olivine size differences. All samples exhibit olivine (ol) grains within these magmaclast varieties with an intermagmaclastic matrix of calcite and serpentine. Distinct characteristics include: (a) HJ-030-01-76P, uncured and cored magmaclasts with the olivine (ol) size predominantly finer than the surrounding olivine (ol) grains; (b) HJ-032-01-86P, uncured magmaclast with the olivine (ol) size equivalent to the surrounding olivine (ol); (c) RS-008-02-16P, cored magmaclast showing coarser olivine (ol) relative to the surrounding olivine (ol); (d) HJ-032-01-86P, uncured magmaclast with coarser olivine (ol) relative to the surrounding olivine (ol).

The groundmass crystallinity of magmaclasts is poorly crystalline and consists of ultra-fine-grained (<0.125 mm) poorly crystalline groundmass consisting of serpentine and calcite. Kimberlitic groundmass as rims on magmaclasts commonly include microcrysts of olivine very very fine to fine olivine (Figure 13a-13h), spinels (Figure 13a, 13b and 13c) euhedral super fine to very very fine-grained perovskite (Figure 13d, 13e and 13f), and altered apatite laths (Figure 13g and 13h). Olivine microcrysts are present in all samples, with microcrystic spinel being most abundant in magmaclasts of pipes L008, L030, L219, L048 (Figures 13a, 13b and 13c). Perovskite is most seen in pipes L060, L054, and L032 (Figures 13d, 13e and 13f), while apatite laths are exclusively observed in pipe L221 (Figure 13g and 13h). One occurrence of phlogopite within a kimberlitic rim in L060 is to be noted (Figure 10j).

Spinel appears as super fine-grained (~0.10-0.20 mm), euhedral, opaque phases with 3 - 9% vol%. Perovskite occurs as super fine-grained (0.125-0.25 mm), high-relief, dark brown, semi-opaque phases making up 1 - 6 vol%.

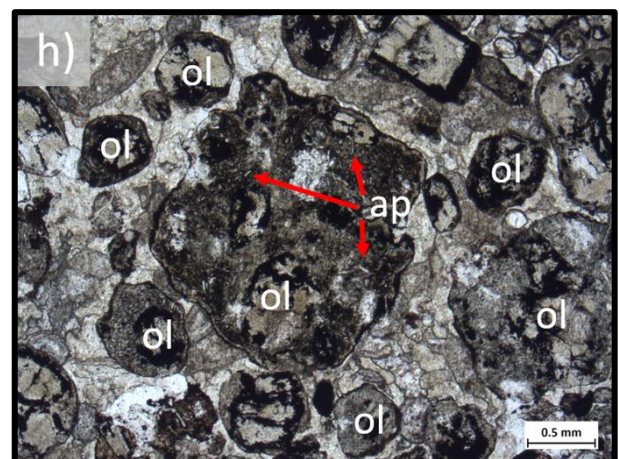
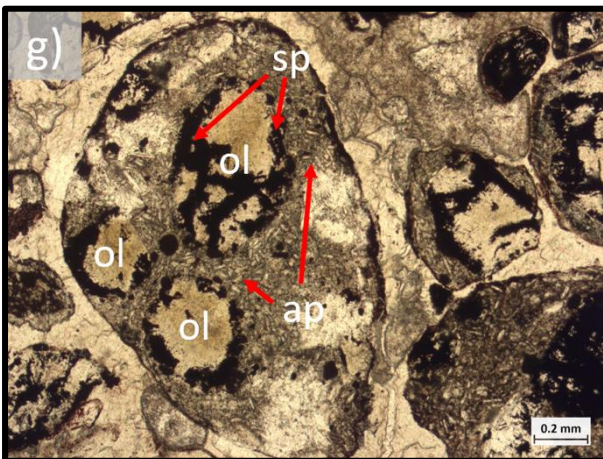
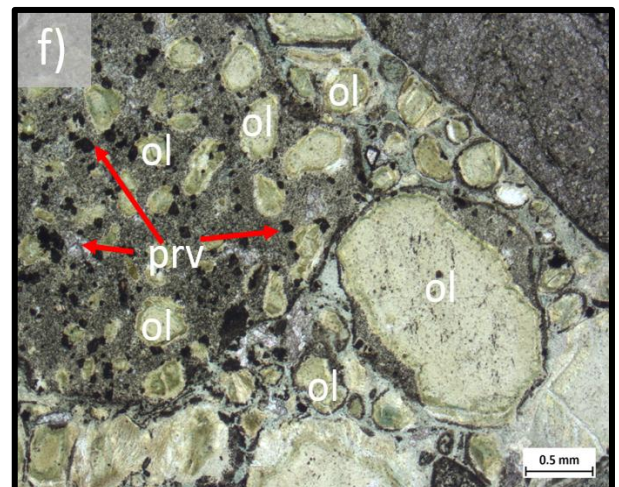
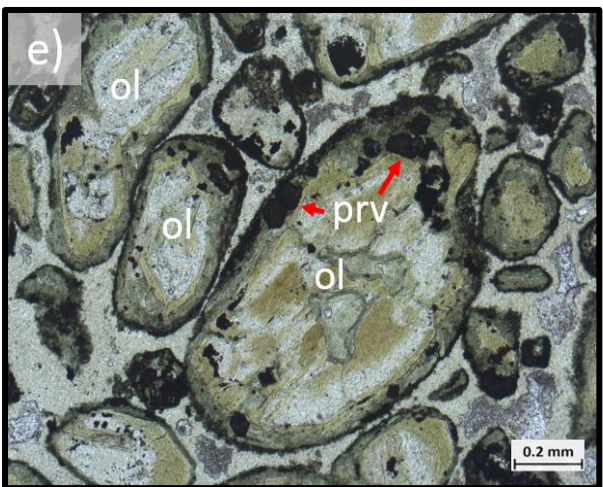
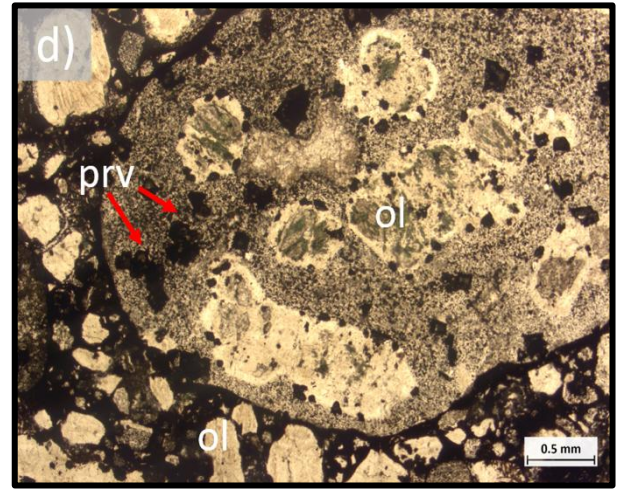
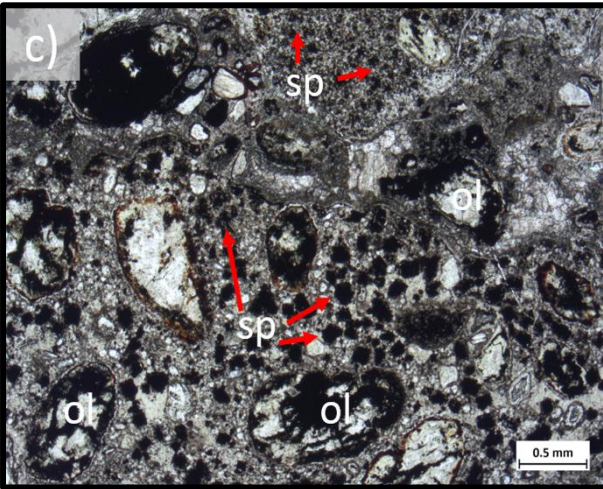
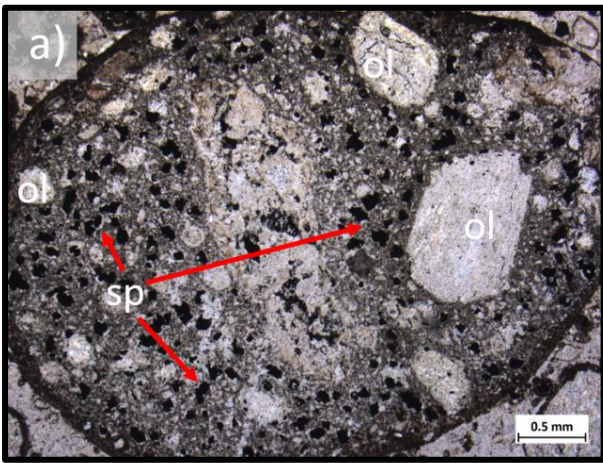


Figure 13: Photomicrographs in PPL of uncored and cored magmaclast varieties, all exhibiting regular/rounded to irregular/partially rounded or curvilinear/curved-edged morphologies with varying mineral compositions in the magmaclastic groundmass. Distinct characteristics include: (a) RS-008-02-16P, uncored magmaclast containing microcrystic olivine (ol) and spinel (sp); (b) and (c) HJ-219-02-35P, uncored magmaclast containing macrocrystic olivine (ol) and abundant spinel (sp); (d) HJ-032-01-86P, uncored magmaclast containing macrocrystic olivine (ol) and perovskite (prv); (e) HJ-054-01-96P, olivine (ol)-cored magmaclast containing macrocrystic olivine (ol) and abundant perovskite (prv); (f) HJ-060-01-69P, cored magmaclast with incomplete symmetrical rims and an uncored variety containing perovskite (prv) and microcrystic olivine (ol); (g) and (h) RS-221-01-56P, uncored magmaclast containing macrocrystic olivine (ol) and altered apatite (ap)

Olivine pyrocrysts

Olivine pyrocrysts are not commonly seen within samples but are observed in pipes L219 and L032. These olivine pyrocrysts range in size from super fine to very very fine and are subhedral in shape with most showing broken, angular edges (Figure 14a and 14b).

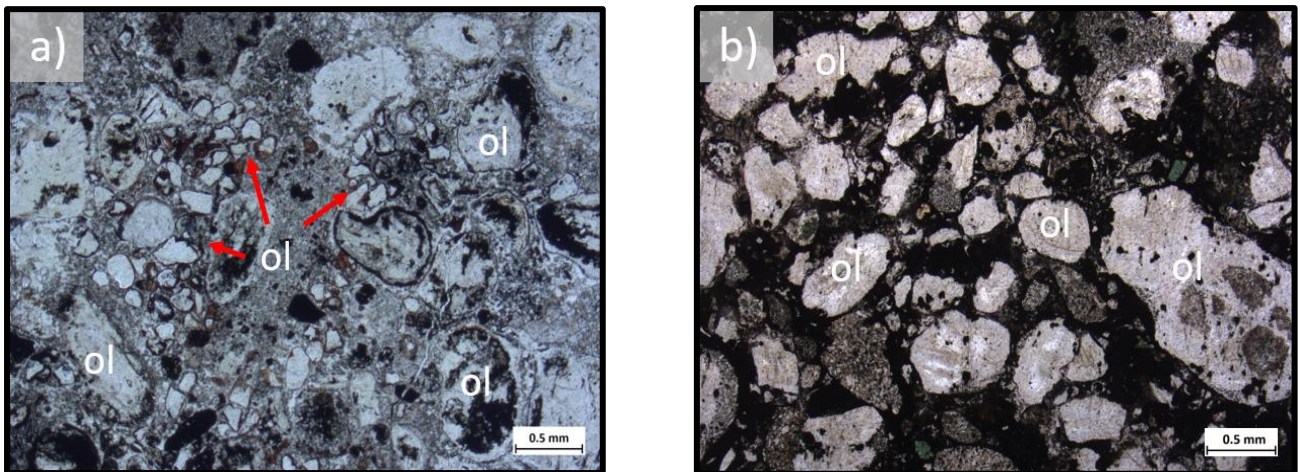


Figure 14: Photomicrographs in PPL showing subhedral microcrystic olivine (ol) pyrocrysts with broken edges in (a) HJ-219-02-35P and (b) HJ-032-01-86P.

Xenoliths

Crustal xenoliths (clastic sediments, likely Karoo origin) are present in varying abundances, from 1 to 13 vol%. Pipe L008 has the highest abundance, with 13 vol% mainly within magmaclasts (Figure 15a), followed by pipe L060, which contains 8 vol%. Pipes L054 and L030 have the lowest xenolith content, each at 1 vol%. Xenolith sizes range from 0.50 to 15.0 mm, with very fine grains (0.50-1.00 mm) occurring in L219, medium to coarse grains in all other pipes (Figure 15a-15h), and very coarse grains (up to ~15.0 mm) specifically in pipe L008.

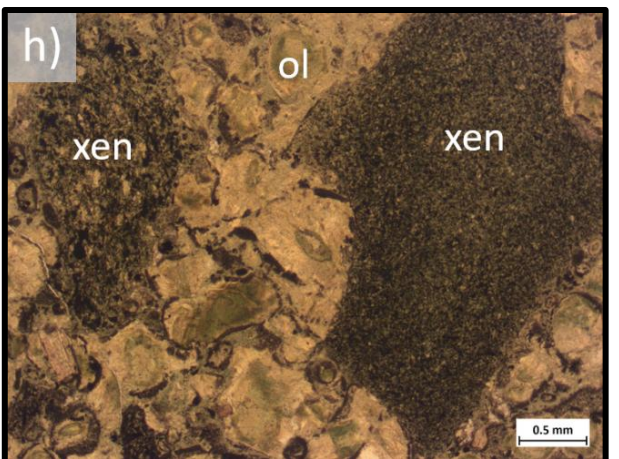
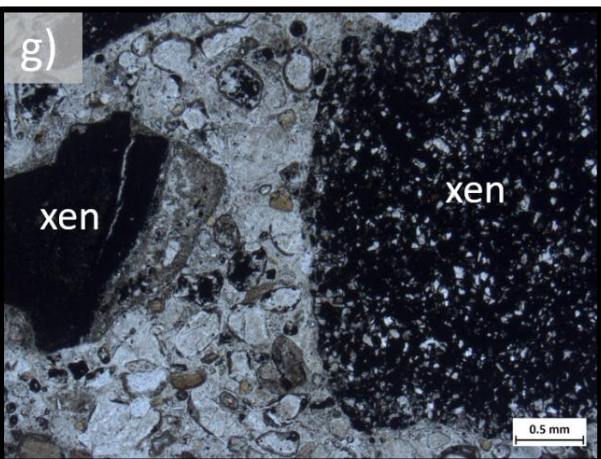
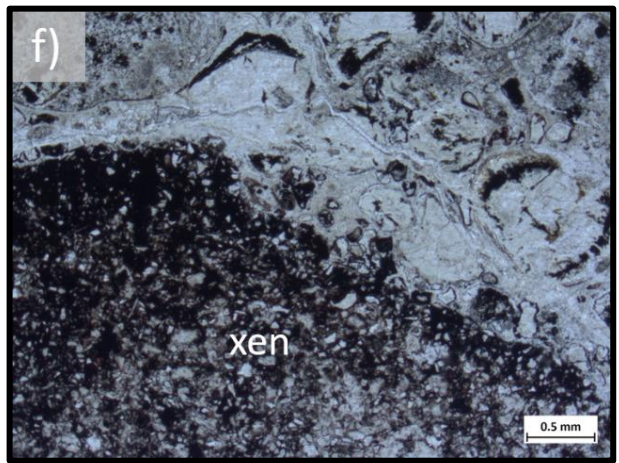
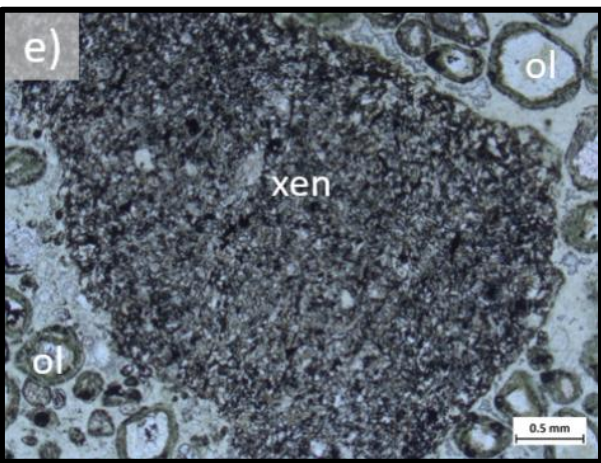
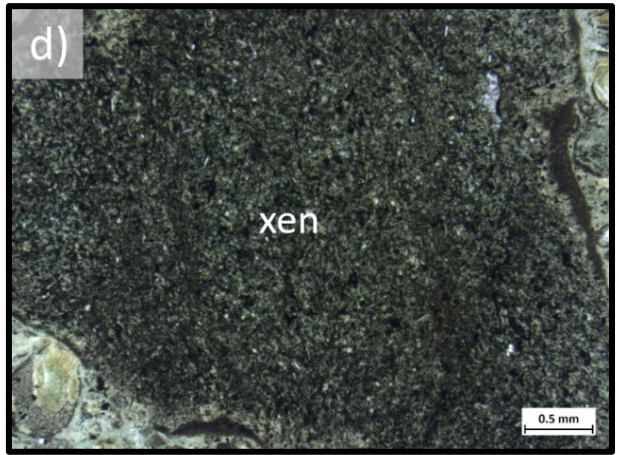
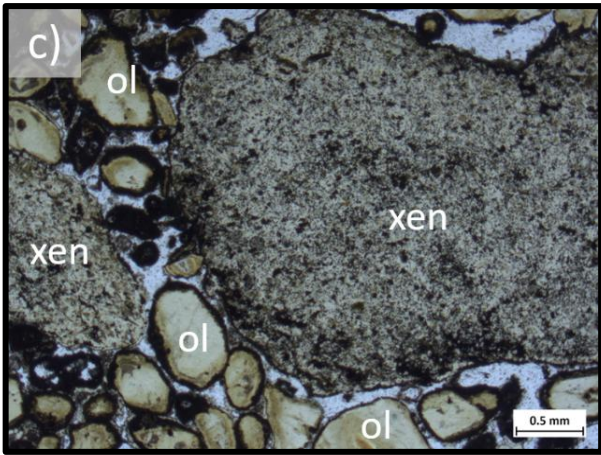
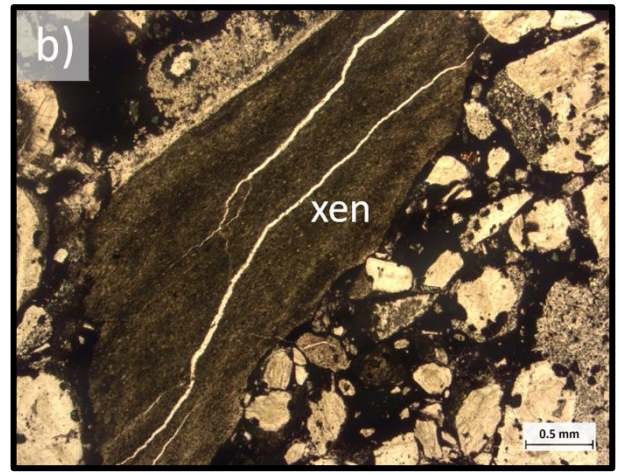
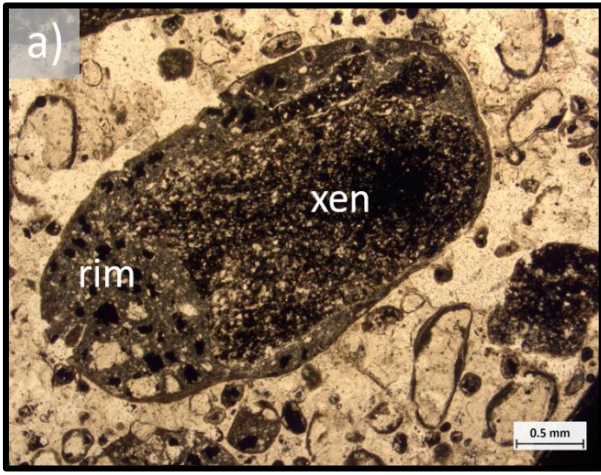


Figure 15: Photomicrographs of PPL of xenoliths in (a) RS-008-02-65P (b) HJ-032-01-86P (c) HJ-054-01-46P (d) HJ-054-01-96P (e) HJ-030-01-76P (f) RS-221-01-56P (g) HJ-048-02-180P (h) HJ-060-01-69P

Phlogopite

Phlogopite is also present as very very fine- to fine-grained sub-euhedral grains, though it is relatively rare, occurring at only 1-2 vol% (Figures 16a and 16b) within the inter-magmaclast matrix. It is exclusively observed in pipes L060 and L048. Phlogopite is present within magmaclast cores and rims in pipe L060 (Figure 10j).

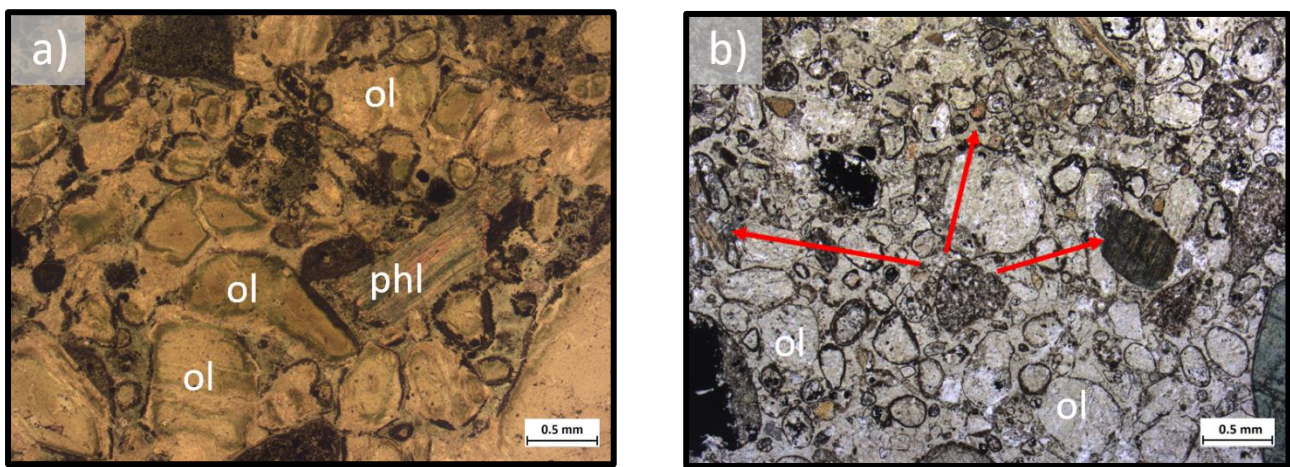


Figure 16: Photomicrographs in PPL of (a) HJ-060-01-69P showing a very-fine grain of phlogopite (b) HJ-048-02-43P showing a very very-fine grains of phlogopite

Stage 2 - Petrogenetic classification

The analysed samples are classified as kimberlites based on the mineralogical characteristics observed within the magmaclast rims. The high abundance of olivine micro and macrocrysts is ubiquitous across all samples, in addition to the groundmass of these rims being poorly crystalline and consisting of ultra-fine-grained serpentine and calcite, indicative of a carbonate-rich kimberlitic composition.

In addition to serpentine and calcite, the rims contain microcrysts of olivine (very very fine- to fine-grained), which is seen across all samples. Within these rims, spinel microcrysts are most abundant in pipes L008, L030, L219, and L048, while euhedral perovskite is particularly prominent in pipes L060, L054, and L032. Altered apatite laths are unique to pipe L221, and a single occurrence of phlogopite within a kimberlitic rim

in pipe L060 is also noted. All samples are classified as carbonate kimberlites in addition to the consideration of their relative abundance of other microcrysts.

Stage 3a and 3b - Textural-genetic classification

The fragmental textures observed in the samples are characteristic of volcanoclastic kimberlites, highlighted by the presence of magmaclasts, a variety of clasts, and olivine pyrocrysts, with some pipes showing evident sorting. Component sizes range from ultra-fine to very coarse (0.10-15.0 mm), and magmaclasts display diverse morphologies, including regular/rounded and curvilinear shapes. The samples also exhibit a clast-supported texture. The kimberlitic groundmass is predominantly cryptocrystalline, composed mainly of serpentine and carbonate, with occasional phlogopite, perovskite, spinel, and apatite inclusions. Most notably, the presence of abundant carbonate in the interclast material stands out as a defining feature seen in FPK's globally. In addition, large amoeboidal magmaclasts, occasional xenoliths, and fragmented olivine are observed, further supporting an eruptive emplacement. Given these features - specifically the sorting, clast-supported nature, and carbonate-rich groundmass - these samples are classified as Fort à la Corne (FPK) pyroclastic kimberlites, rather than Kimberley-type pyroclastic rocks (KPKs).

Stage 4 - Volcanic spatial context

All samples are classified as intra-crater FPK deposits, as they are exclusively derived from drill cores within kimberlite pipes. No extra-crater deposits have been identified.

4.2.2 Classification of representative samples

Based on the above descriptions, each representative sample can be classified, following the scheme of Scott Smith et al. (2018), outlined in Table 1, presented in Table 4.

Table 4: Summary table showing the classification of representative FPK samples

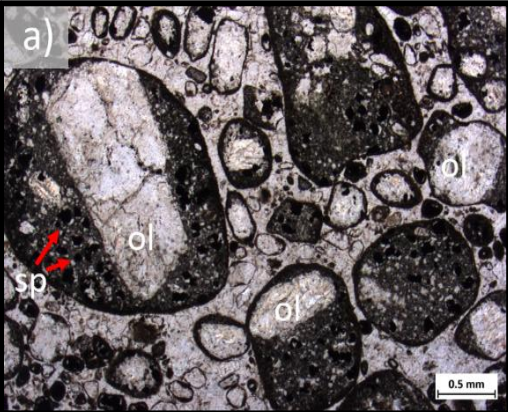
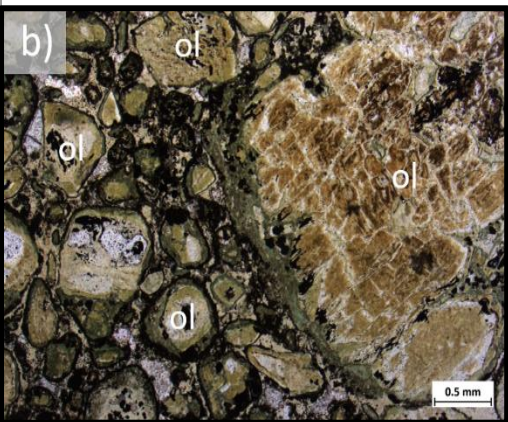
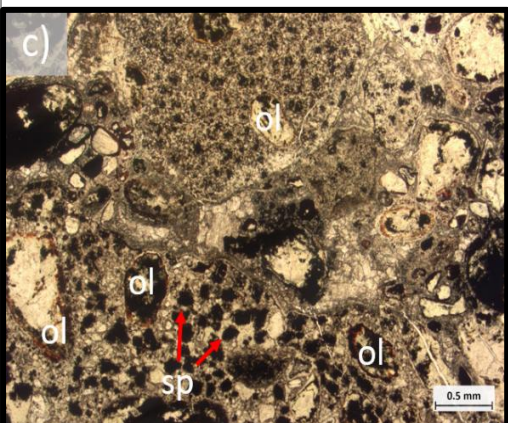
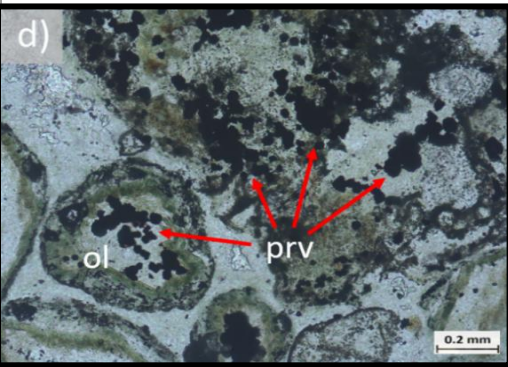
<i>Sample name</i>	<i>Classification</i>
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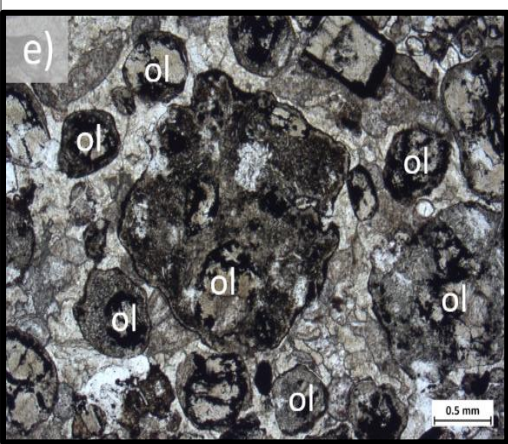
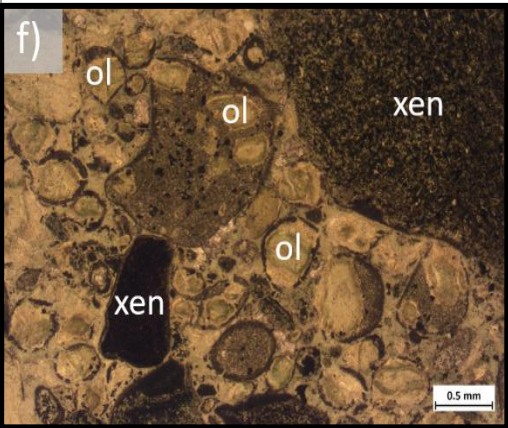
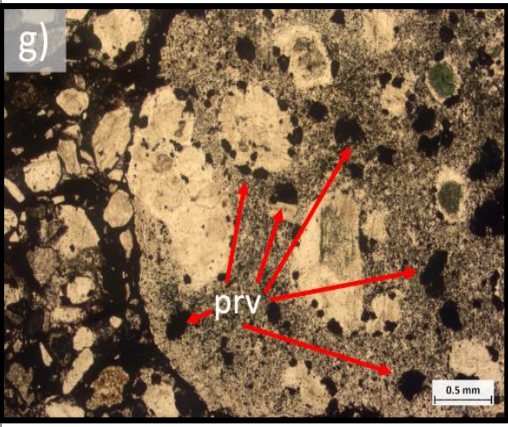
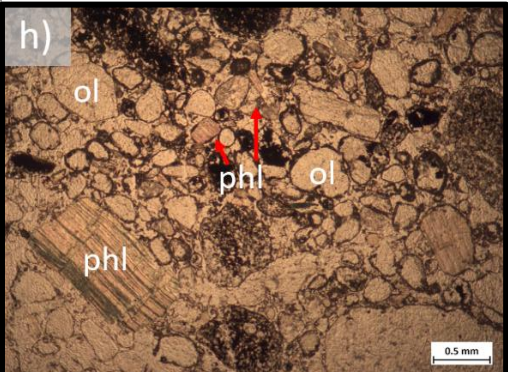
HJ-054-01-46P	Very xenolith-poor, very fine to coarse grained, very olivine macrocryst-rich, Fort à la Corne type pyroclastic kimberlite
RS-008-02-65P	Xenolith-poor, very fine to very coarse grained, olivine macrocryst-rich Fort à la Corne type pyroclastic kimberlite
RS-008-02-16P	Xenolith-poor, very fine to very coarse grained, olivine macrocryst-rich, Fort à la Corne type pyroclastic kimberlite
HJ-030-01-76P	Very xenolith-poor, very very fine to coarse grained, olivine microcrystic-rich, Fort à la Corne type pyroclastic kimberlite
RS-221-01-56P	Very xenolith-poor, super fine to coarse grained, olivine macrocrystic-rich, Fort à la Corne type pyroclastic kimberlite
HJ-219-02-35P	Very xenolith-poor, super fine to coarse grained, olivine microcryst-rich, Fort à la Corne type pyroclastic kimberlite
HJ-032-01-86P	Very xenolith-poor, very very fine to coarse grained, very olivine microcryst-rich, Fort à la Corne type pyroclastic kimberlite
HJ-060-01-69P	Xenolith-poor, very very fine to coarse grained, very olivine macrocryst-rich, Fort à la Corne type pyroclastic kimberlite
HJ-048-02-180P	Xenolith-poor, ultra fine to fine grained, olivine microcrystic-rich, Fort à la Corne type pyroclastic kimberlite

4.2.3 Summary of FPK's within the Lulo field

Of the 52 kimberlite pipes in the Lulo Field, 22 are identified as containing FPK. Similarities between these kimberlites can be seen in terms of: (1) Texture - all samples show a fragmental, volcanoclastic textures, whereby all thin sections have retained their primary volcanoclastic textures; (2) Magmaclast margins - magmaclasts all have sharp margins; (3) Magmaclast type - presence of both cored and uncored magmaclast varieties; (4) crustal xenoliths are present in all samples in low abundances (<15 vol.%); (5) Inter-magmaclastic matrix - contains both serpentine and calcite. Differences lie in a few factors; including; (1) Nature of support (clast vs matrix) - although most samples show a clast-supported structure, other samples are matrix supported in nature; (2) Magmaclast size and morphology - with samples showing varying sizes/abundances/morphology of cored and uncored magmaclasts; (3) Sorting - with samples ranging from poorly to well-sorted; (4) Magmaclast rim mineralogy shows variation with the presence of altered apatite laths, spinel and perovskite; (5) Xenolith abundance - with some samples showing higher xenolith abundance; (6) Olivine pyroclasts - only present in a few samples.

Table 5: Table showing the distribution of FPKs in pipes, with a focus on magmaclastic characteristic

<i>Sample</i>	<i>Pipe number</i>	<i>Key features/variations</i>
	L008	- Matrix supported - Strong alteration texture - Regular/rounded morphology of magmaclasts - Equal abundances of cored and uncored magmaclasts - Uncored: 0.50-10.0 mm - Cored: 0.25-15.0 mm - Xenolith poor - Kimberlitic rim predominantly consisting of ultra fine-grained serpentine with abundant spinel and microcrystic quartz - Intermagmaclastic matrix abundant in serpentine, minor calcite present
	L054	- Clast supported - Moderate to well sorted - Regular/rounded morphology of magmaclasts - Predominantly cored magmaclasts - Uncored: ~1.00 mm - Cored: 0.25-6.00 mm - Very xenolith poor - Broken clasts - Coarse xenoliths up to 8.00 mm - Kimberlitic rim predominantly consisting of green ultra fine-grained serpentine - Intermagmaclastic matrix abundant in crystalline calcite.
	L219	- Clast supported - Curvilinear/curved edged morphology of magmaclasts - Predominantly uncored magmaclasts - Uncored: 0.50-8.00 mm - Cored: 0.125-0.50 mm - Very xenolith poor - Broken clasts - Presence of olivine pyroclasts - Kimberlitic rim predominantly consisting of ultra fine-grained serpentine with abundant spinel and microcrystic quartz - Intermagmaclastic matrix abundant in crystalline calcite
	L030	- Matrix supported - Moderately sorted - Regular/rounded morphology of magmaclasts - Predominantly cored magmaclasts - Uncored: 0.50-8.00 mm - Cored: 0.50-1.00 mm - Very xenolith poor - Abundant broken clasts - Kimberlitic rim predominantly consisting of green ultra fine-grained serpentine - Serpentine dominated intermagmaclastic matrix, minor calcite present

	L221	• Matrix supported • Strong alteration texture • Curvilinear/curved edged morphology of magmaclasts • Predominantly uncored magmaclasts Uncored: 0.50-4.00 mm Cored: 0.25-0.50 mm • Very xenolith poor • Broken clasts • Kimberlitic rim predominantly consisting of ultra fine-grained serpentine with notable altered apatite laths in kimberlitic rim. • Intermagmaclastic matrix abundant in crystalline calcite
	L060	• Clast supported • Curvilinear/curved edged morphology of magmaclasts • Predominantly uncored magmaclasts Uncored: 0.50-6.00 mm Cored: 0.25-6.00 mm • Xenolith poor • Phlogopite present • Kimberlitic rim predominantly consisting of ultra fine-grained serpentine with abundant spinel, microcrystic quartz and less commonly phlogopite • Serpentine dominated intermagmaclastic matrix, minor calcite present
	L032	• Clast-matrix supported • Moderately sorted • Regular/rounded morphology of magmaclasts • Equal abundances of cored and uncored magmaclasts Uncored: 5.00-8.00 mm Cored: 0.50-1.00 mm • Very xenolith poor • Broken clasts • Presence of olivine pyroclasts • Serpentine-calcite dominated kimberlitic rims with abundant perovskite • Serpentine dominated intermagmaclastic matrix, minor calcite present
	L048	• Clast supported • Strong alteration texture • Poorly sorted • Curvilinear/curved edged morphology of magmaclasts • Equal abundances of cored and uncored magmaclasts Uncored: 0.125-1.00 mm Cored: 0.125-1.00 mm • Xenolith poor • Fine grained uncored olivine magmaclasts • Phlogopite present

		• Kimberlitic rim predominantly consisting of ultra fine-grained serpentine with abundant spinel and microcrystic quartz • Serpentine-calcite dominated intermagmaclastic matrix
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4.3 Resedimented volcanoclastic kimberlites (RVK)

4.3.1 Staged progressive interpretation scheme

Stage 1 - Rock description

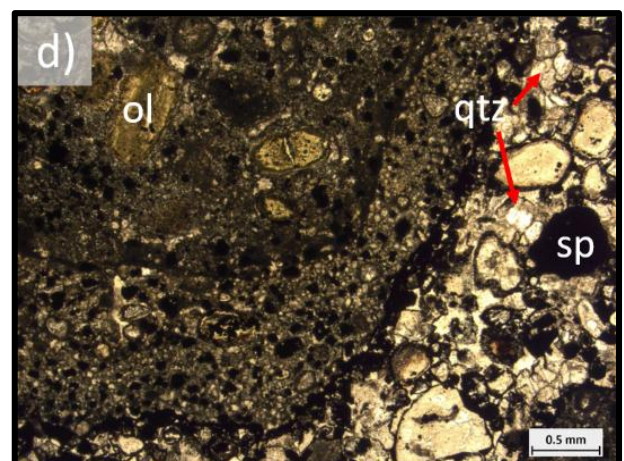
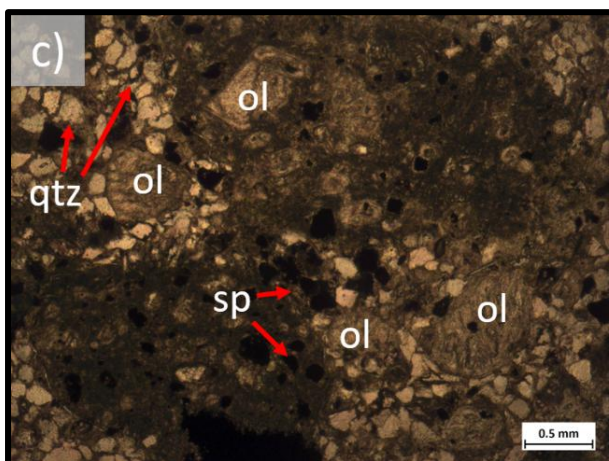
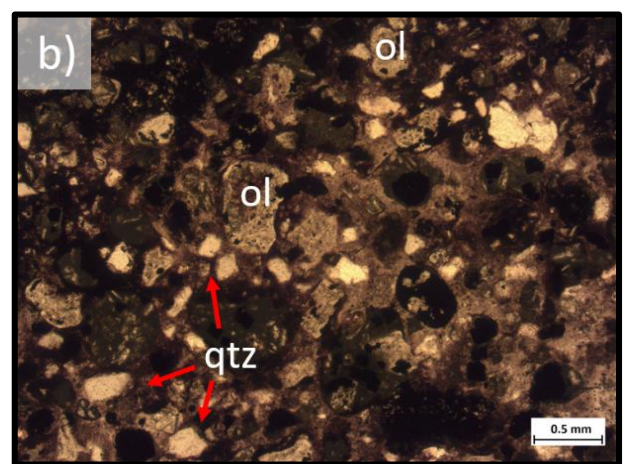
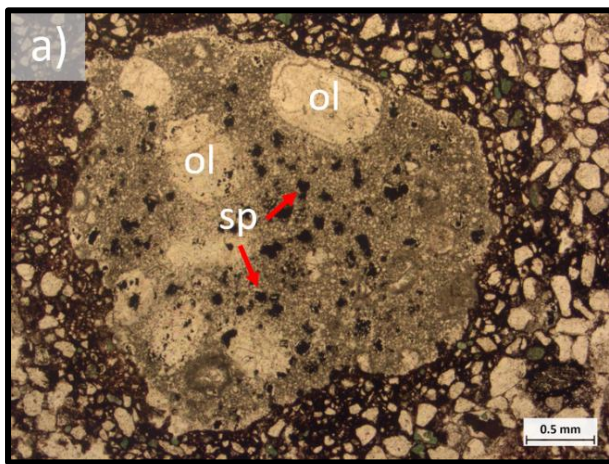
Alteration

The RVKs within pipes of the Lulo Field display a fragmental, clastic texture whereby the primary clastic textures have been preserved, however, olivine grains are completely serpentinized in all cases. Samples selected for representative descriptions below display minimal alteration and were selected to ensure the preservation of primary features, consistent with the selection for those observed in the FPK samples. Late-stage post-emplacement alteration has also led to significant serpentine development within the interclast material, a feature notably prominent in certain pipes such as L167, L033 and L011 (Figure 18d), with pipe L009 showing less serpentinization by comparison (Figure 17a). In addition, apatite is altered in all cases, as seen exclusively in pipes L167 and L011, with altered apatite laths consisting of calcite within the kimberlitic groundmass of magmaclasts. Phlogophite is relatively fresh as seen exclusively in pipe L033, with relatively little serpentinization.

Structure and texture

The overall structure visible in thin sections is massive and homogeneous in nature, however, core logs describe larger scale (i.e., metre scale) bedding in several pipes, including L009 and L167 from the representative samples and pipes L014, L020, L022, L048, L233 and L255 across the Lulo Field.

These volcanoclastic kimberlites exhibit a clast-supported texture (Figure 17a), with clasts embedded in an ultra-fine-grained crystalline cement predominantly composed of serpentine and calcite. Clast sizes range from ultra-fine to very coarse (~0.10-13.0 mm). Super fine to medium-grained examples, such as those from pipe L167 (Figure 17b), feature clasts between 0.125-4.00 mm in varying proportions. Pipe L033 (Figure 17c) contains a high abundance of very fine grains but also includes a comparable proportion of coarser grains up to 5.00 mm. In pipes L009 and L011, very fine-grained clasts (~0.50 mm) are abundant; however, both pipes also contain coarser magmaclasts. L009 is characterized by a high proportion of coarser magmaclasts, reaching up to 10.0 mm (Figure 17d), while L011 features an equal distribution of very fine and very coarse grains, with clasts as large as 13.0 mm (Figure 17e and 17f).



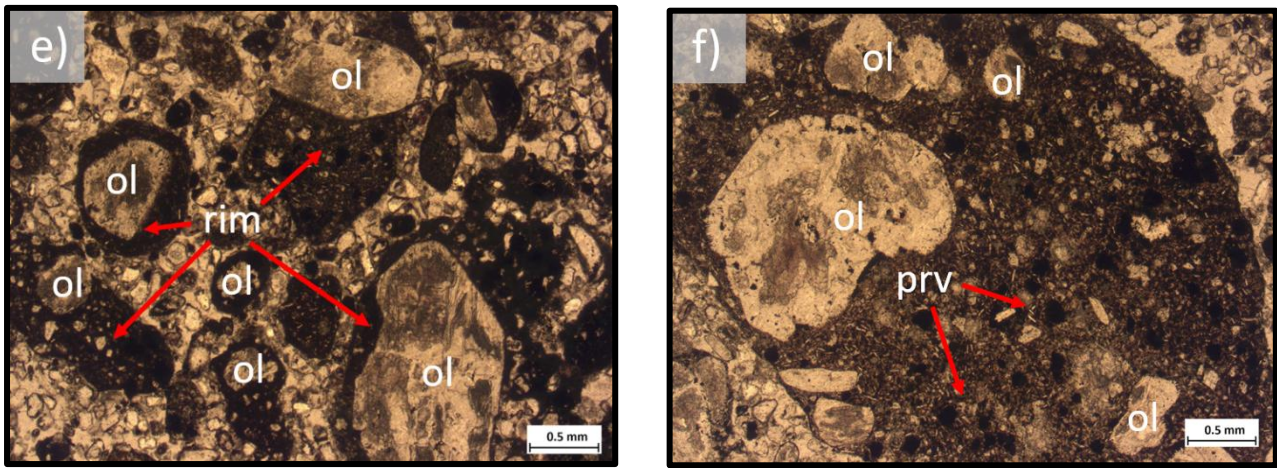


Figure 17: Photomicrographs in PPL of uncored and cored magmaclasts, all exhibiting varying clast sizes and morphologies. Distinct characteristics include: (a) HJ-009-01-23P, uncored magmaclast with regular/rounded to irregular/partially rounded morphology, containing macrocrystic olivine (ol) and spinels (sp) in a clast-supported nature; (b) RS-167-01-57P, showing super fine to medium-grained clasts; (c) HJ-033-01-78P, showing very fine to coarse-grained clasts; (d) HJ-009-01-96P-B, uncored magmaclast up to 13.0 mm; (e) HJ-011-01-91P, cored magmaclasts up to 3.00 mm; (f) HJ-011-01-91P, uncored magmaclast up to 10.0 mm.

Sorting is not clearly seen within pipes on a microscopic level, but core logs indicate sorting is relatively common on larger scales (i.e., metre scale) across the pipes of the Lulo field with moderate to well sorted beds observed in several pipes, e.g., L009 and L011.

Components

Magmaclasts

Magmaclast morphologies vary from regular/rounded in pipe L033 (Figure 18a) to amoeboidal in pipes L009, L011 and L167 (Figure 18b, 18c and 18d). Additionally, broken olivine clasts are common in pipes L009 and L167 (Figures 18e and 18f). All magmaclasts show sharp, defined margins and are non-vesicular in nature.

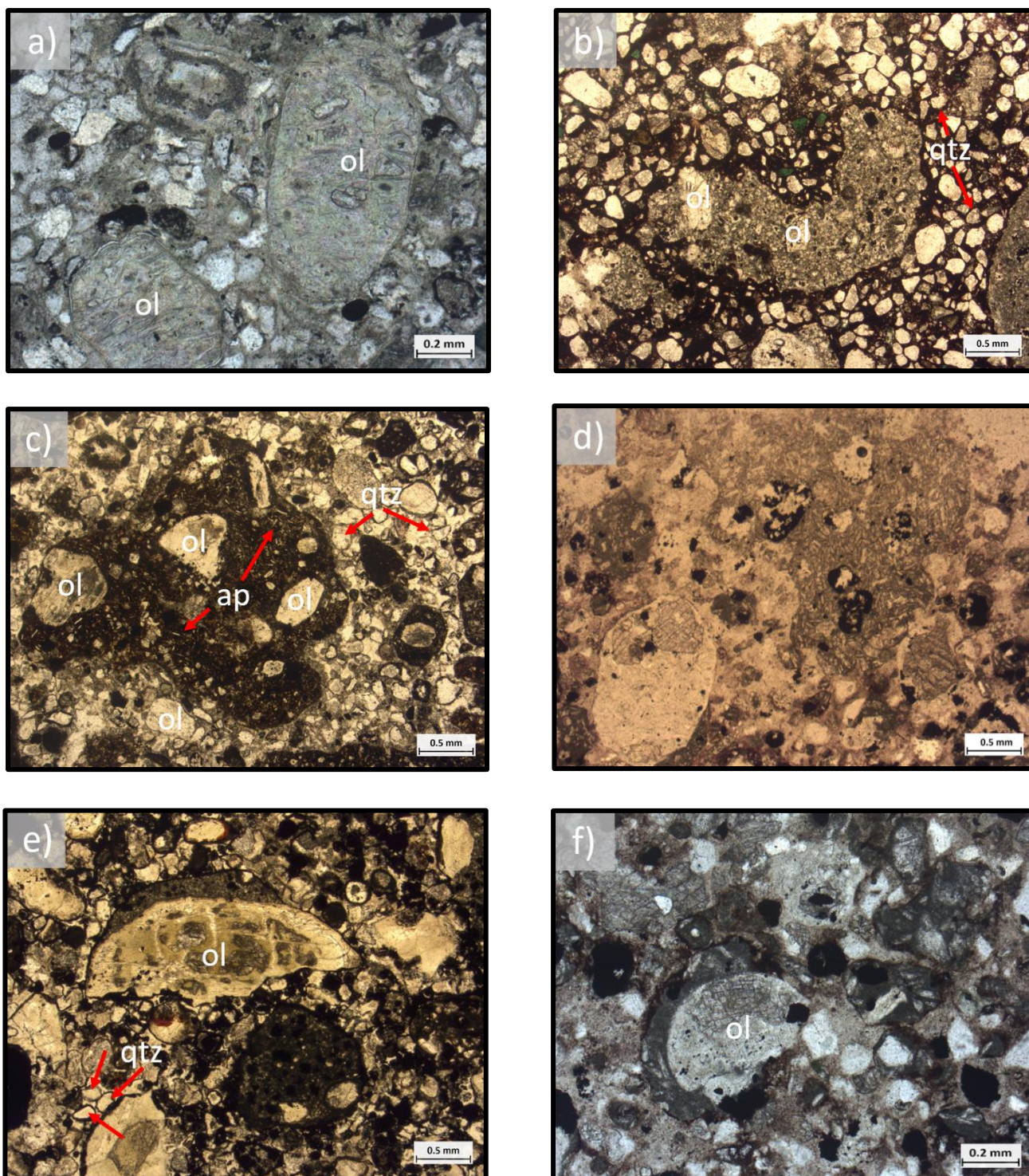


Figure 18: Photomicrographs in PPL of magmaclasts, showing a variety of morphologies. Distinct characteristics include: (a) HJ-033-01-78P, olivine (ol)-cored magmaclasts with regular/rounded morphology; (b) HJ-009-01-23P, uncored magmaclast with amoeboidal morphology; (c) HJ-011-01-91P, uncored magmaclast with amoeboidal morphology; (d) RS-167-01-57P, uncored magmaclast with high serpentinization and amoeboidal morphology; (e) HJ-009-01-96P-B, broken cored olivine (ol) magmaclast; (f) RS-167-01-57P, broken cored olivine (ol) magmaclast.

Magmaclast sizes exhibit a broad range, from super fine to very coarse (0.125-13.0 mm), and can be classified into cored and uncored varieties. Pipes L033 and L011 show equal proportions of cored and uncored (Figure 19f) with pipes L009 and L167 showing a higher abundance of uncored magmaclasts.

Olivine-cored magmaclasts, characterized by central kernels predominantly composed of pseudomorphed olivine, range in size from very fine to medium-grained (~0.50-3.00 mm). Very fine cored magmaclasts (~0.50 mm) are observed in pipes L009, L011, and L167, with larger grains reaching up to 3.00 mm in L009 and up to 5.00 mm in L011 (Figures 19a and 19b). In pipe L033, cored magmaclasts are exceptionally fine-grained (~0.20 mm) but can reach sizes of up to 1.00 mm. Xenolith-cored magmaclasts, primarily identified in pipe L167, are approximately 4.00 mm in size (Figure 22c).

Uncored magmaclasts exhibit a broader size range compared to cored varieties, spanning from 0.125-13.0 mm. Pipes L167 and L033 display narrower size distributions, with L167 containing magmaclasts ranging from super fine to medium (0.125-4.00 mm) (Figure 19c) and L033 containing very fine to coarse magmaclasts (0.50-5.00 mm) (Figure 19d). In contrast, pipes L009 and L011 include very coarse magmaclasts, with sizes reaching up to 13.0 mm in L009 (Figure 19e) and 10.0 mm in L011. While pipe L011 also contains very fine magmaclasts, pipe L009 predominantly features fine to very coarse magmaclasts.

Cored magmaclasts occur in two main forms, with both types showing equal proportions in the representative samples. The first form has a single kimberlitic rim that surrounds the central kernel on all sides (complete rims) and have symmetrical shape (Figure 19a). The second form is characterised by incomplete rims that do not surround the central kernel on all sides and have an asymmetrical shape (Figure 19b).

The central kernels are enclosed by kimberlitic rims that vary in thickness. In pipe L033, the rims are ultra-thin (~0.10 mm), while super-thin rims (~0.25 mm) are observed in pipe L011. Very thin rims (~0.50 mm) are present in both pipes L167 and L009, with

pipe L009 being particularly notable for the presence of multiple rims surrounding the kernels.

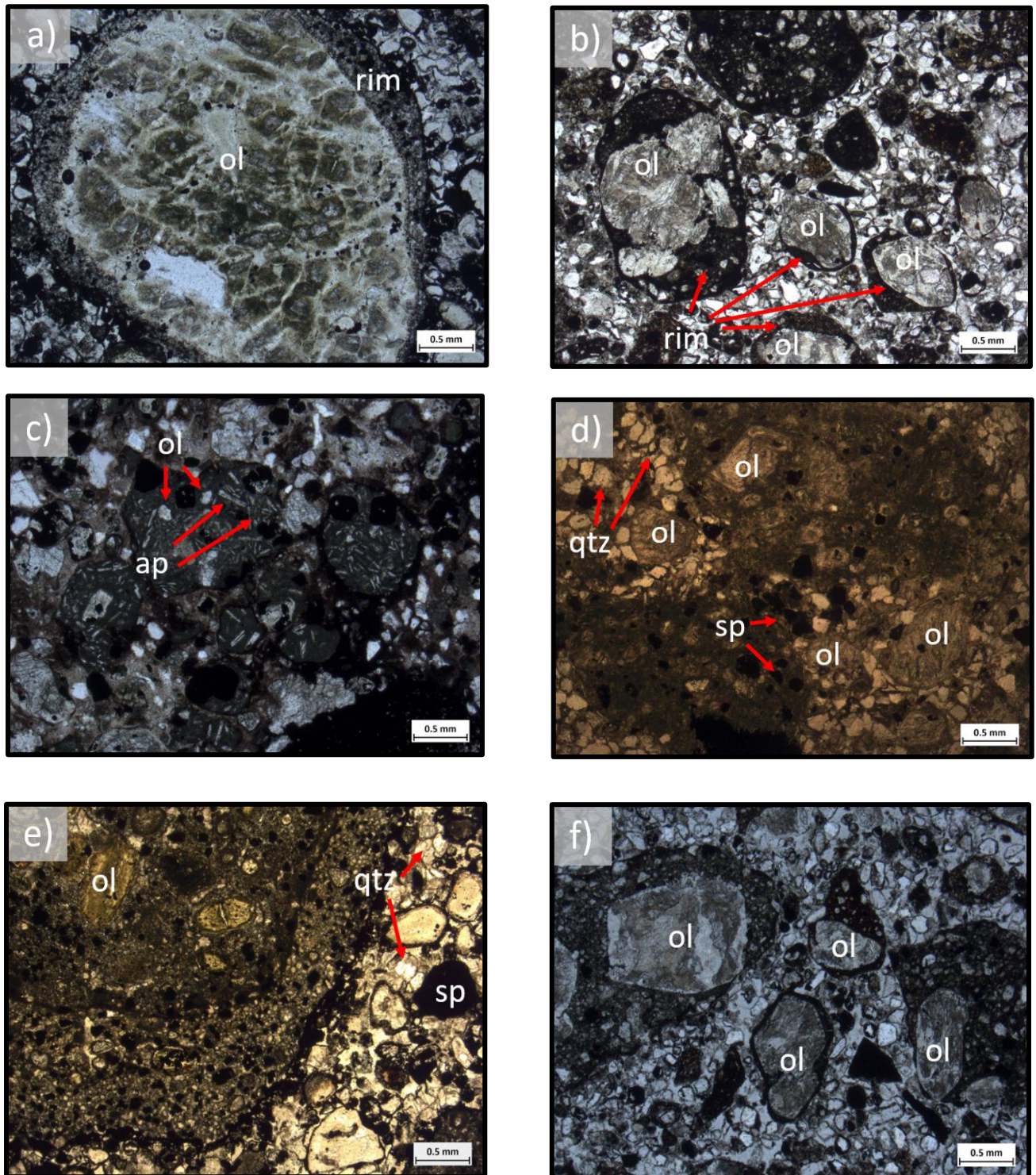
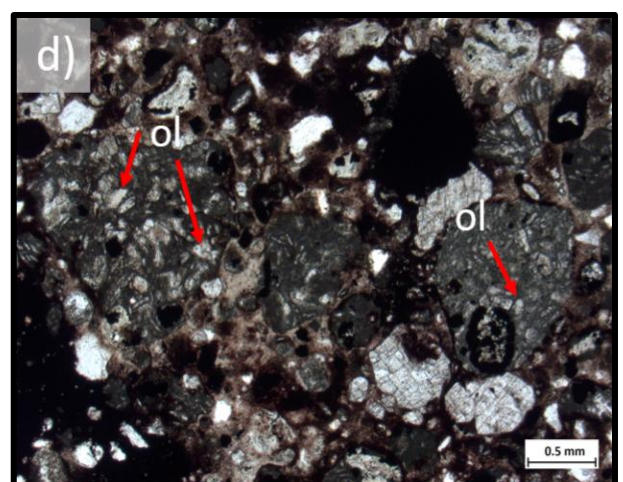
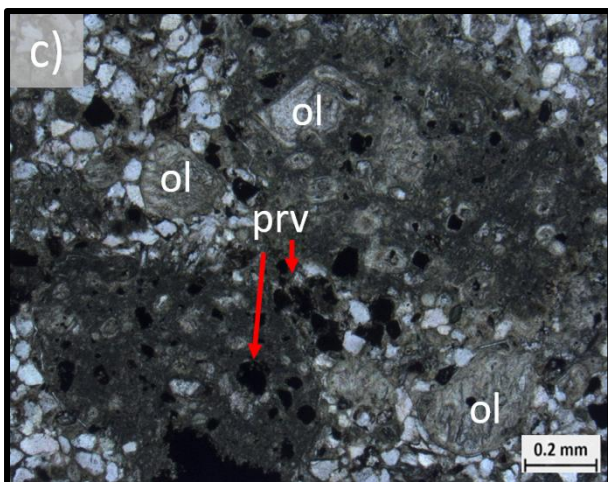
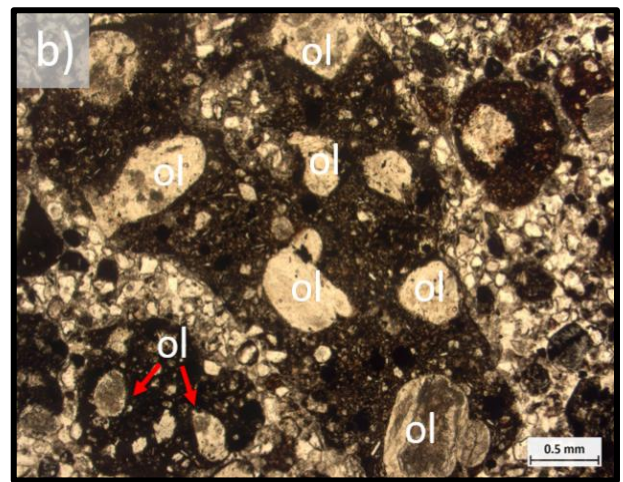
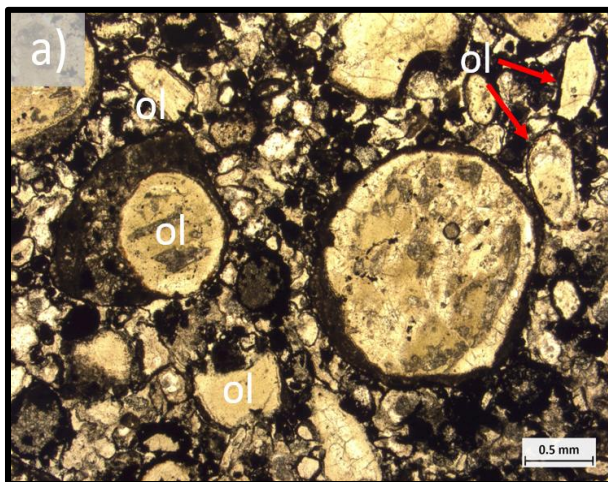


Figure 19: Photomicrographs in PPL of cored and uncored magmaclasts, with various rim structures and mineral compositions. Distinct characteristics include: (a) HJ-009-01-96P-B, olivine-cored magmaclast with a rim that has a single kimberlitic rim that surrounds the central kernel on all sides (complete rims) and have symmetrical shape; (b) HJ-011-01-91P, cored magmaclasts with rims that

does not surround the central kernel on all sides (incomplete rims), in which certain sides of the central kernel have no surrounding kimberlitic rim and displays an asymmetrical shape; (c) RS-167-01-52P, uncored magmaclasts containing altered apatite (ap) laths; (d) HJ-033-01-78P, uncored magmaclasts containing spinel (sp); (e) HJ-009-01-96P-B, uncored magmaclast with multiple rims; (f) HJ-011-01-91P, showing both cored and uncored magmaclasts.

The intermagmaclastic matrix is made up of ultra-fine-grained crystalline cement of serpentine and calcite with quartz highly abundant within the interclast matrix (Figure 20e & 20f).

Olivine grains within the magmaclasts primarily range from coarser to equivalent sizes to that of the surrounding olivine in the samples (~0.50 mm). In pipe L009, both coarser (Figure 20a) and equivalent-sized grains are observed, a trend similar to that in pipe L011 (Figure 20b). Pipe L033 primarily exhibits olivine grains of equivalent size (Figure 20c), whereas pipe L167 is characterized by finer olivine grains compared to the surrounding olivine (Figure 20d).



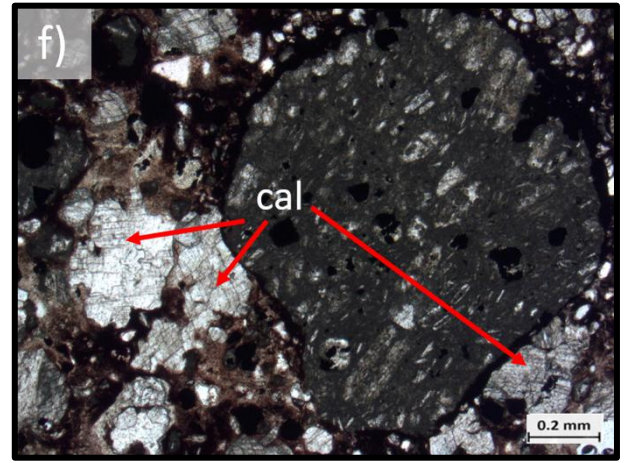
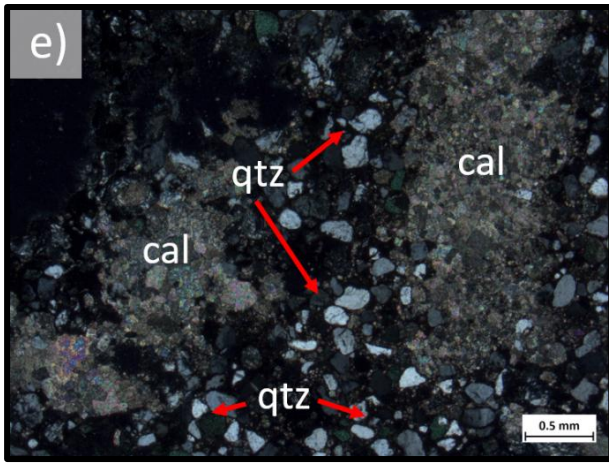


Figure 20: Photomicrographs in PPL of magmaclasts showing the comparative olivine (ol) grain sizes between olivine (ol) within magmaclasts and within the intermagmaclastic matrix. Distinct characteristics include: (a) HJ-009-01-96P-B, olivine (ol) grains within the magmaclasts coarser than the surrounding olivine (ol); (b) HJ-011-01-91P, olivine (ol) grains within the magmaclasts coarser and equivalent to the surrounding olivine (ol); (c) HJ-033-01-78P, olivine (ol) grains within the magmaclasts equivalent to the surrounding olivine (ol); (d) RS-167-01-52P, olivine (ol) grains within the magmaclasts finer than the surrounding olivine (ol); (e) HJ-009-01-23P and (f) RS-167-01-52P, showing crystalline calcite in the intermagmaclastic matrix.

The groundmass of the magmaclasts is poorly crystalline, consisting of an ultra-fine-grained matrix (~ 0.125 mm) predominantly composed of serpentine and calcite (Figure 21a). Kimberlitic rims frequently contain micro to macrocrysts of olivine, ranging from super fine to fine-grained (Figures 21a - 21f), as well as super fine-grained perovskite (Figures 21c - 21f), super fine-grained euhedral spinels (Figures 21a and 21b), and altered apatite laths (Figures 21d and 21e). Quartz is also notably observed within the magmaclasts (Figure 21a and 21b). Olivine and perovskite are present in all samples (Figures 21a - 21g), except in pipe L009. In contrast, apatite laths are restricted to pipes L167 and L176 (Figures 21g and 21e). Quartz and spinels are observed in magmaclasts exclusively in pipe L009 (Figure 21b). This highlights the variety of differing kimberlitic groundmass compositions.

Within the magmaclasts, perovskite occurs as super fine-grained (0.125-0.25 mm), high-relief, dark brown, semi-opaque phases with 3 - 10 vol%. Spinel appears as super fine-grained (~ 0.10 -0.20 mm), euhedral, opaque phases with $\sim 6\%$ vol% only in pipe L009.

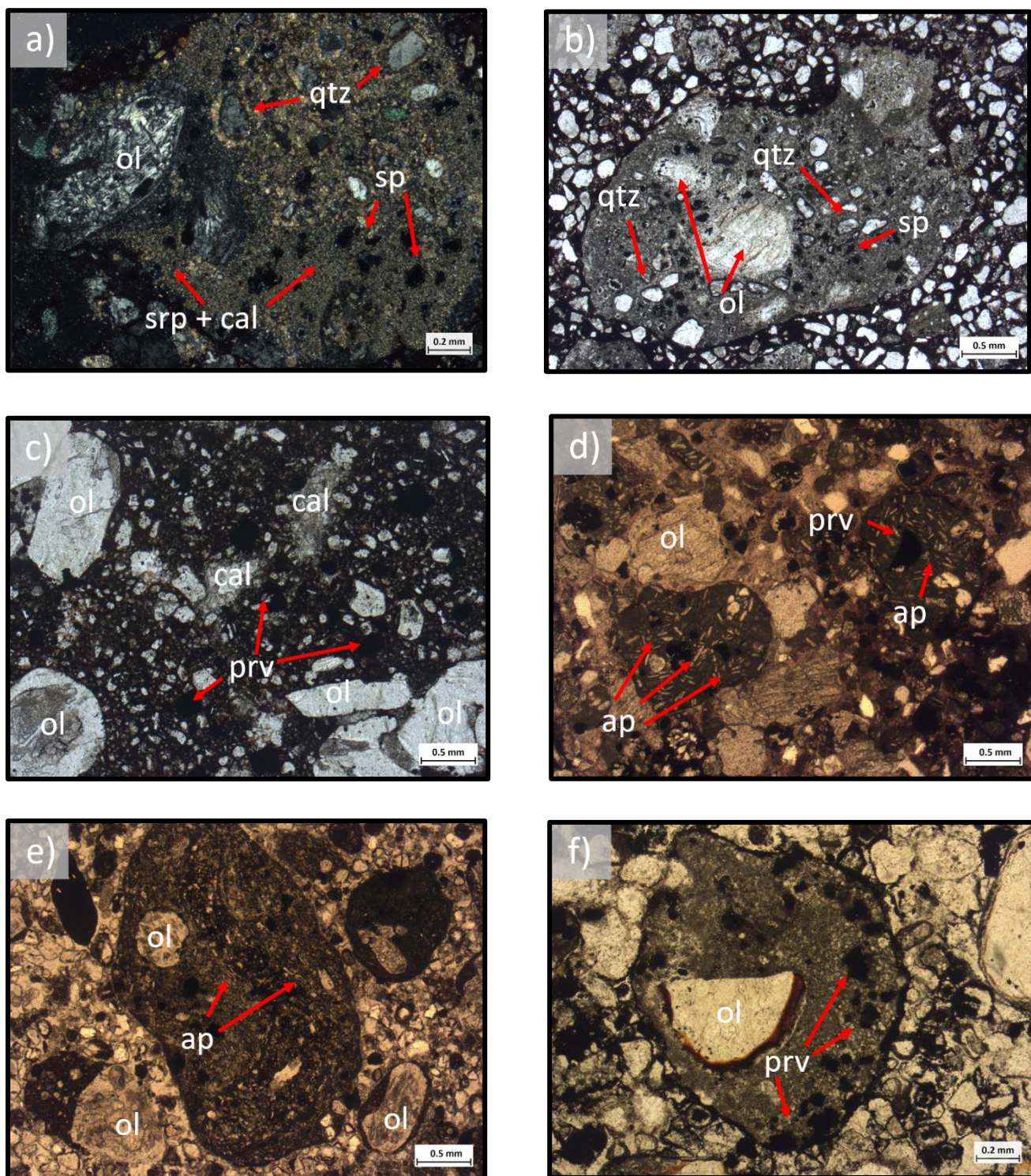


Figure 21: Photomicrographs in PPL of magmaclastic groundmasses with various mineral compositions. All samples feature a groundmass of serpentine and calcite consisting of different microcrysts including olivine (ol), perovskite (prv), spinels (sp) and less commonly quartz (qtz). Distinct characteristics include: (a) HJ-009-01-23P, containing microcrystic spinel (sp) and olivine (ol); (b) HJ-009-01-23P, containing microcrystic olivine (ol), quartz (qtz), and spinels (sp); (c) HJ-011-01-91P, containing microcrystic olivine (ol) and perovskite (prv); (d) RS-167-01-57P, containing

microcrystic altered apatite (ap); (e) HJ-011-01-91P, containing microcrystic altered apatite (ap); (f) HJ-009-01-96P-B, containing microcrystic olivine (ol) and perovskite (prv).

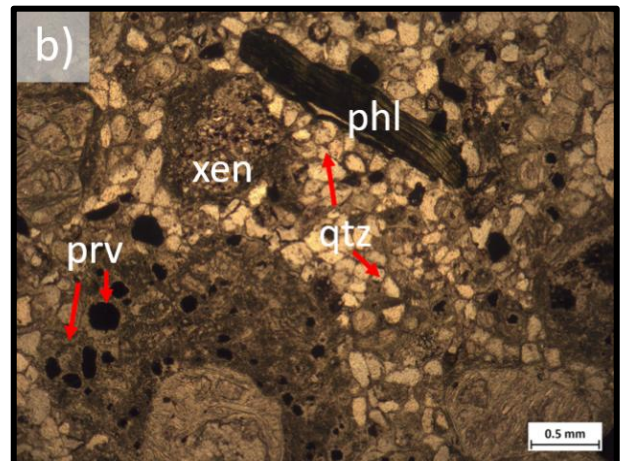
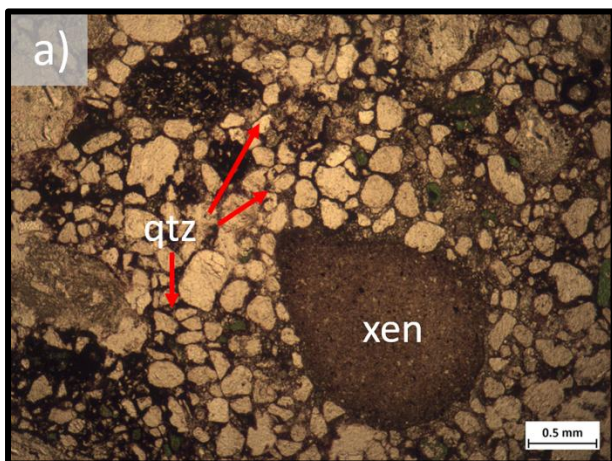
Xenoliths

Crustal xenoliths, like those observed in the FPKs, are present in varying proportions ranging from 0 to 10 vol%. Pipe L011 is xenolith-free (0 vol%), while pipe L009 contains very few xenoliths, classified as very xenolith-poor (~2 vol%) (Figure 22a). In contrast, pipes L033 (Figure 22b) and L167 exhibit higher xenolith content, reaching up to ~10 vol%, classifying them as xenolith-poor (Figure 22c).

Xenocrysts

Quartz is a highly abundant component of the inter-magmaclastic matrix in all samples, with concentrations ranging from 24 to 42 vol% (Figures 22a, 22b and 22d).

Phlogopite is observed as rare, fine-grained euhedral grains within the inter-magmaclast matrix, comprising approximately ~1 vol% (Figure 22b). Its occurrence is exclusive to pipe L033.



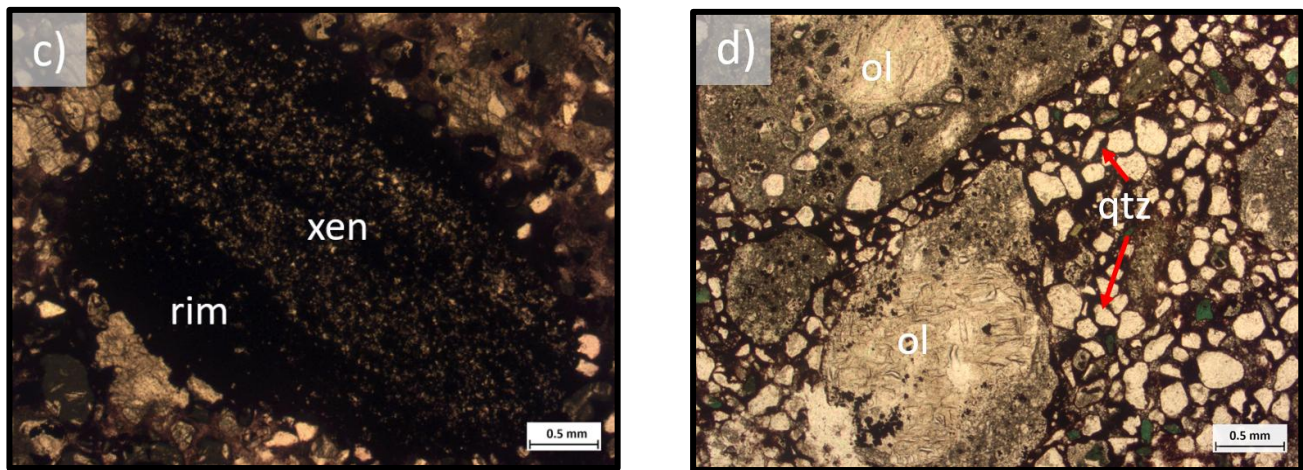


Figure 22: Photomicrographs in PPL of xenoliths within an intermagmatic matrix of predominantly quartz (qtz) in (a) HJ-009-01-23P; (b) HJ-033-01-78P, containing phlogopite within the intermagmatic matrix; (c) HJ-011-01-91P, xenolith (xen) cored magmaclast; (d) HJ-009-01-23P, showing abundant quartz within the inter-magmatic matrix.

Stage 2 - Petrogenetic classification

The classification of the analysed samples as kimberlites is supported by their mineralogical features, especially those observed in the magmaclast rims. These rims are characterized by a ubiquitous presence of olivine as both macrocrysts and microcrysts, similar to what is seen in FPK-type kimberlite. Furthermore, the matrices of the magmaclast rims are predominantly composed of extremely fine-grained serpentine and calcite, reflecting their carbonate-rich kimberlitic nature.

The magmatic matrices, in addition to serpentine and calcite, contains very fine- to fine-grained olivine microcrysts, a feature consistent across all samples. Perovskite microcrysts are notably abundant in pipes L033, L011, and L167, while euhedral spinels are particularly prominent in pipe L009. Altered apatite laths are distinctive to pipes L011 and L167, and quartz is observed within the magmatic groundmass of pipe L009. Based on these characteristics, along with the relative abundance of other microcrysts, all samples are classified as carbonate kimberlites.

Stage 3a and 3b - Textural-genetic classification

The clastic textures observed in the samples are typical of volcanoclastic rocks, characterized by the presence of quartz, magmaclasts, and a variety of other clasts. Component sizes range from super-fine to coarse (0.125-13.0 mm), with magmaclasts

displaying a range of morphologies, including regular/rounded and amoeboidal shapes, along with frequent occurrences of broken pyroclasts. The samples exhibit a clast-supported texture, and the kimberlitic rims are predominantly cryptocrystalline, consisting mainly of serpentine and carbonate, alongside perovskite, spinel, and altered apatite laths. A defining feature is the high abundance of quartz within the interclast matrix, indicative of a significant component of extrinsic material in RVKs. Notably, differences in the kimberlitic groundmass of magmaclasts, along with multiple rims on magmaclasts within a single pipe, suggest contributions from distinct magma batches. These characteristics - particularly the high quartz content, broken pyroclasts, clast-supported texture, and mixed magmaclast populations strongly support classification as Resedimented Volcaniclastic Kimberlites (RVKs).

Stage 4 - Volcanic spatial context

All samples are classified as intra-crater RVK deposits, as they are exclusively derived from drill cores within kimberlite pipes. No extra-crater deposits have been identified.

4.3.2 Classification of representative samples

Based on the results, each representative sample can be classified, following the scheme of Scott Smith et al. (2018) outlined in Table 1, as seen in Table 6:

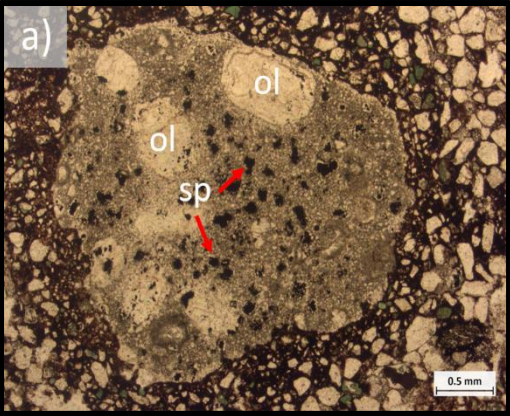
Table 6: Summary table showing the classification of representative RVK samples

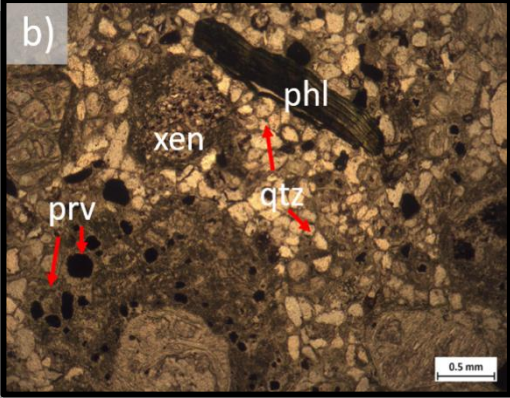
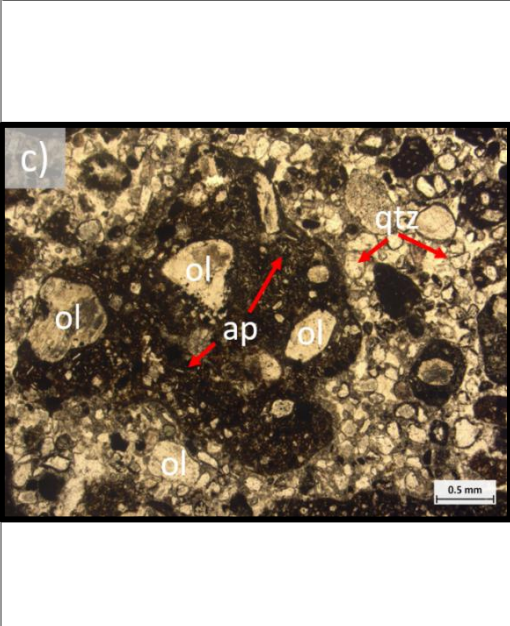
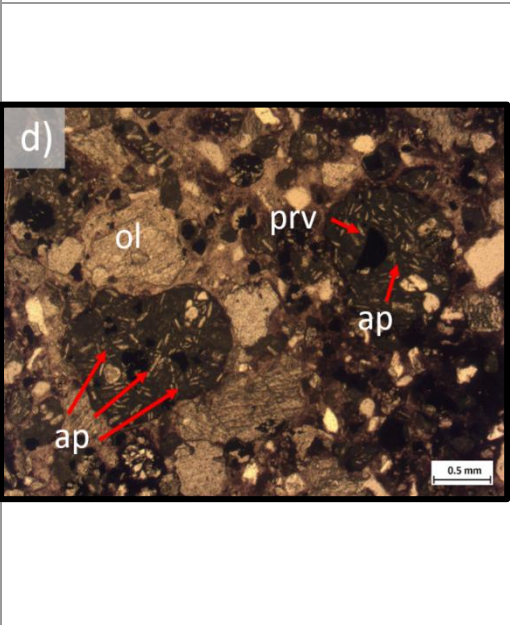
<i>Sample name</i>	<i>Classification</i>
HJ-009-01-23P	Very xenolith-poor, very fine to very coarse grained, olivine macrocryst-rich, Resedimented volcaniclastic kimberlite
HJ-009-01-96P-B	Very xenolith-poor, very fine to very coarse grained, olivine macrocryst-rich, Resedimented volcaniclastic kimberlite
HJ-033-01-78P	Xenolith-poor, very very fine to coarse grained, olivine macrocryst-rich, Resedimented volcaniclastic kimberlite
HJ-011-01-91P	Xenolith-free, very fine to very coarse grained, olivine macrocryst-rich, Resedimented volcaniclastic kimberlite
RS-167-01-52P	Xenolith-poor, super fine to medium grained, olivine macrocryst-rich, Resedimented volcaniclastic kimberlite

4.3.3 Summary of RVK's in the Lulo Field

Of the 52 kimberlite pipes in the Lulo Field, 13 are identified as containing RVK. Similarities in these kimberlites can be seen in; (1) Texture - All samples exhibit a fragmental, clastic texture, with primary volcanoclastic characteristics preserved across all thin sections; (2) Nature of support - A clast-supported texture is consistent across all samples; (3) Magmaclast margins - magmaclasts have sharp margins; (4) Magmaclast type - presence of both cored and uncored magmaclast varieties; (5) Inter-magmaclastic matrix - contains both serpentine and calcite; (6) Quartz abundant in all samples; (7) Notable broken pyroclasts; (8) Sorting - commonly moderate to well sorted samples. Differences lie in a few factors, including (1) Structure - with some pipes showing a bedded structure and others more massive; (2) Magmaclast size and morphology - with samples showing varying sizes/abundances/morphology of cored and uncored magmaclasts; (3) Kimberlitic rim/groundmass mineralogy - shows variations with the presence of altered apatite laths, spinel and perovskite; (4) Xenolith abundance - with some samples showing higher xenolith abundance.

Table 7: Table showing the distribution of RVKs in pipes, with a focus on magmaclastic characteristic

Sample	Pipe number	Key features/variations
	L009	• Clast supported • Moderately to well sorted • Bedded structure • Regular/rounded to amoeboidal morphology of magmaclasts • Predominantly uncored magmaclasts • Uncored: 1.00-13.0 mm • Cored: 0.50-5.00 mm • Very xenolith-poor • Notable broken clasts • Kimberlitic rim/groundmass predominantly consisting of ultra fine-grained serpentine and calcite with abundant spinel and microcrystic quartz • Intermagmaclastic matrix abundant in serpentine and calcite
		• Clast supported • Strong alteration texture • Massive structure • Regular/rounded morphology of magmaclasts • Equal abundances of cored and uncored magmaclasts • Uncored: 0.50-5.00 mm • Cored: 0.20-1.00 mm

b) 	L033	• Xenolith poor • Notable broken clasts • Occurrences of phlogopite • Coarse xenoliths up to 8.00mm • Kimberlitic rim/groundmass predominantly consisting of ultra fine-grained serpentine with abundant perovskite • Intermagmaclastic matrix abundant in serpentine with minor calcite
c) 	L011	• Clast supported • Strong alteration texture • Massive structure • Moderately to well sorted • Regular/rounded to amoeboidal morphology of magmaclasts • Equal abundances of cored and uncored magmaclasts Uncored: 0.50-3.00 mm Cored: 0.50-10.0 mm • Xenolith-free • Kimberlitic rim/groundmass predominantly consisting of ultra fine-grained serpentine and calcite with abundant perovskite and altered apatite laths • Intermagmaclastic matrix abundant in serpentine and calcite
d) 	L167	• Clast supported • Strong alteration texture • Massive structure • Regular/rounded to amoeboidal morphology of magmaclasts • Predominantly uncored magmaclasts Uncored: 0.125-4.00 mm Cored: 0~0.50 mm • Xenolith poor • Notable broken clasts • Kimberlitic rim predominantly consisting of ultra fine-grained serpentine with abundant perovskite and altered apatite laths • Intermagmaclastic matrix abundant in serpentine with minor calcite

4.4 Coherent kimberlites

4.4.1 Staged progressive interpretation scheme

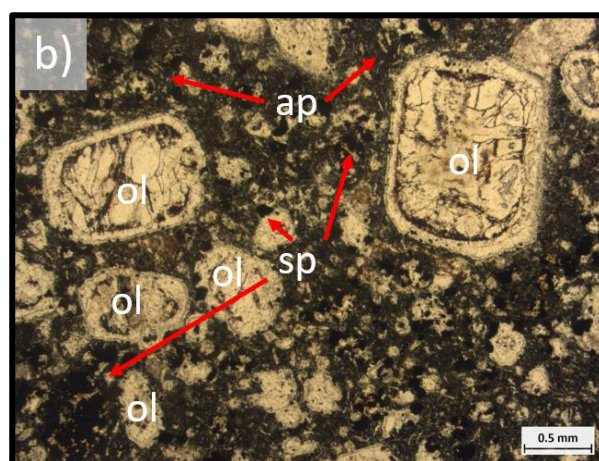
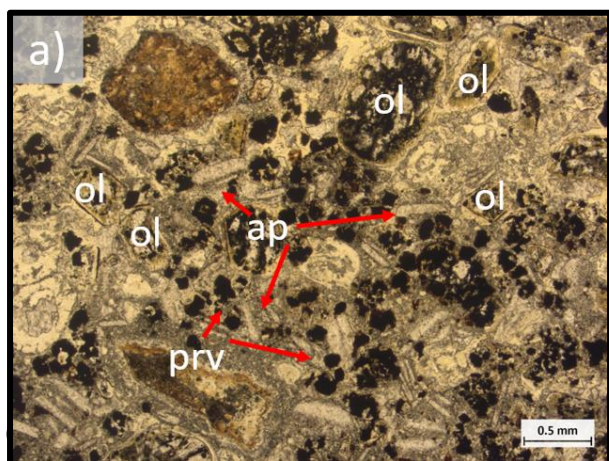
Stage 1 - Rock description

Alteration

Samples of coherent kimberlites from the Lulo Field exhibit well-preserved primary coherent textures. Samples with minimal alteration were specifically chosen for detailed petrographic descriptions to ensure the clear identification of primary features. In all cases, olivine grains are entirely serpentinized, with only rare occurrences of fresh olivine. Notably, late-stage alteration has extensively produced serpentine in the interclast material, particularly in pipes L050, L125, and L254, which display higher serpentine abundance and greater olivine alteration. In contrast, Pipe L026 exhibits comparatively less serpentinization, with a few occurrences of fresh olivine still present. In addition, apatite is altered in all cases, as seen exclusively in pipes L125, with altered apatite laths consisting of calcite within the interclast matrix.

Texture

The overall texture is porphyritic with no evidence for fragmentation, i.e., volcanoclastic processes. The rock is characterised by the presence of macrocrysts (>0.50 mm) and microcrysts (0.10 - 0.50 mm) in a finer grained kimberlitic groundmass. These components are set within an ultra-fine-grained crystalline groundmass predominantly composed of serpentine and calcite (Figure 23f, 23g and 23h). Grain sizes vary from super fine to coarse (0.10 - 8.00 mm). Pipe L125 is characterized by a very fine-grained texture, with olivine ranging from 0.10 - 1.00 mm (Figure 23a). In comparison, Pipes L050, L254, and L026 contain abundant very fine grains (~ 0.50 mm) alongside fewer macrocrysts reaching sizes of up to 2.00 mm (Figure 23g), 4.00 mm (Figure 23d), and 8.00 mm, respectively (Figure 23e).



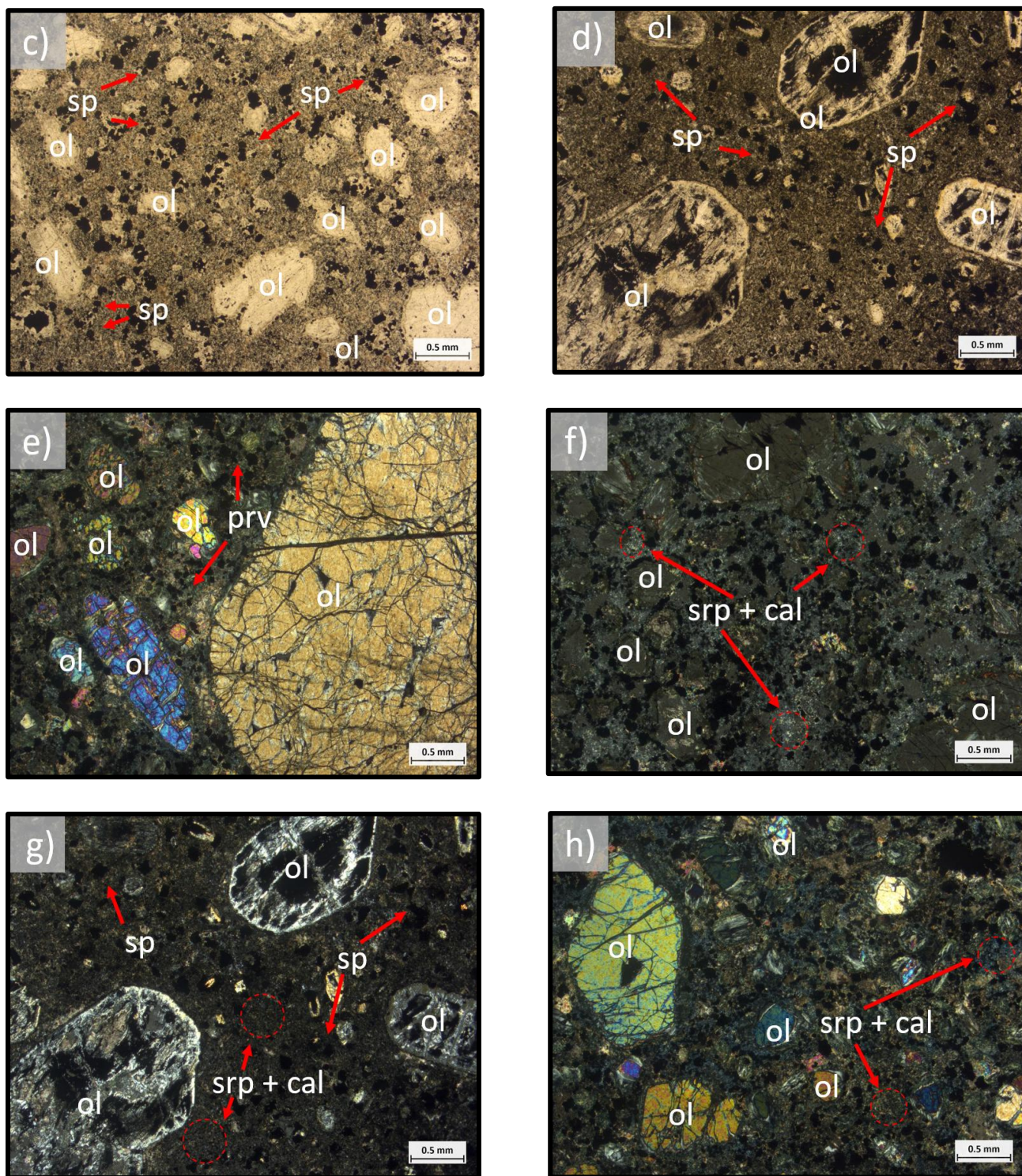


Figure 23: Photomicrographs in PPL and XPL of samples with varying grain sizes and mineral compositions. All samples show olivine clasts in a fine-grained or crystalline matrix, with serpentine and calcite in the intermagmatic matrix. Distinct characteristics include in PPL: (a) RS-125-01-63P, very fine-grained texture with olivine clasts ranging from 0.50 to 1.00 mm; (b) HJ-050-01-45P and (c) RS-050-03-32P olivine grains that are euhedral to subhedral in shape; (d) RS-254-01-53P, abundant very fine grains (~0.50 mm) alongside fewer clasts reaching up to 4.00 mm;

Photomicrographs XPL: (e) HJ-026-02-102P, fresh olivine micro and macrocrysts up to 8.00 mm containing perovskite (prv) present as very fine grains (~0.50 mm); (f) HJ-026-02-55P, (g) RS-254-01-53P and (h) HJ-026-02-102P, intermagmatic matrix of ultra-fine-grained serpentine and calcite.

Components

Olivine macrocrysts

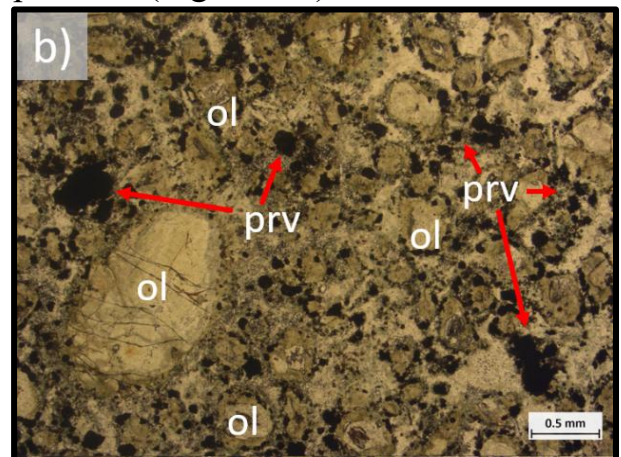
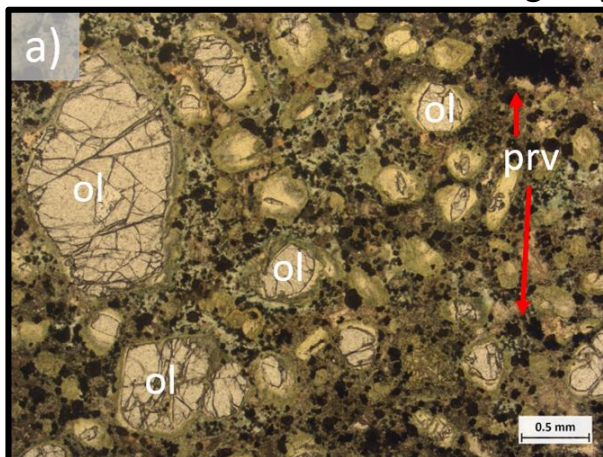
Olivine is the most abundant mineral, primarily present as macrocrysts with sizes ranging from 0.50 to 8.00 mm, though smaller grains down to approximately 0.10 mm are also observed. Both macrocrystic and microcrystic varieties collectively constitute 53-54 vol%. These olivine grains are euhedral to subhedral in shape (Figure 23b). Fresh olivine is observed exclusively in pipe L026, as shown in Figure 23e. Pipe L026 is present as a sill.

Groundmass mineralogy

Perovskite occurs as super fine-grained (0.125-0.25 mm), high-relief, dark brown, semi-opaque phases, comprising 13-16 vol% (Figures 24a, 24b, and 24e). Spinels are present as super fine-grained (~0.10-0.20 mm), euhedral, opaque phases, constituting 1-2 vol%, primarily observed as microcrysts within the interclast groundmass (Figures 24d and 24e). Altered apatite laths, ranging in size from 0.10-0.70 mm, are exclusively identified in samples from pipes L050 and L125 (Figures 24d and 24e).

Xenoliths

Crustal xenoliths are rare, occurring only in pipe L125 (Figure 24f).



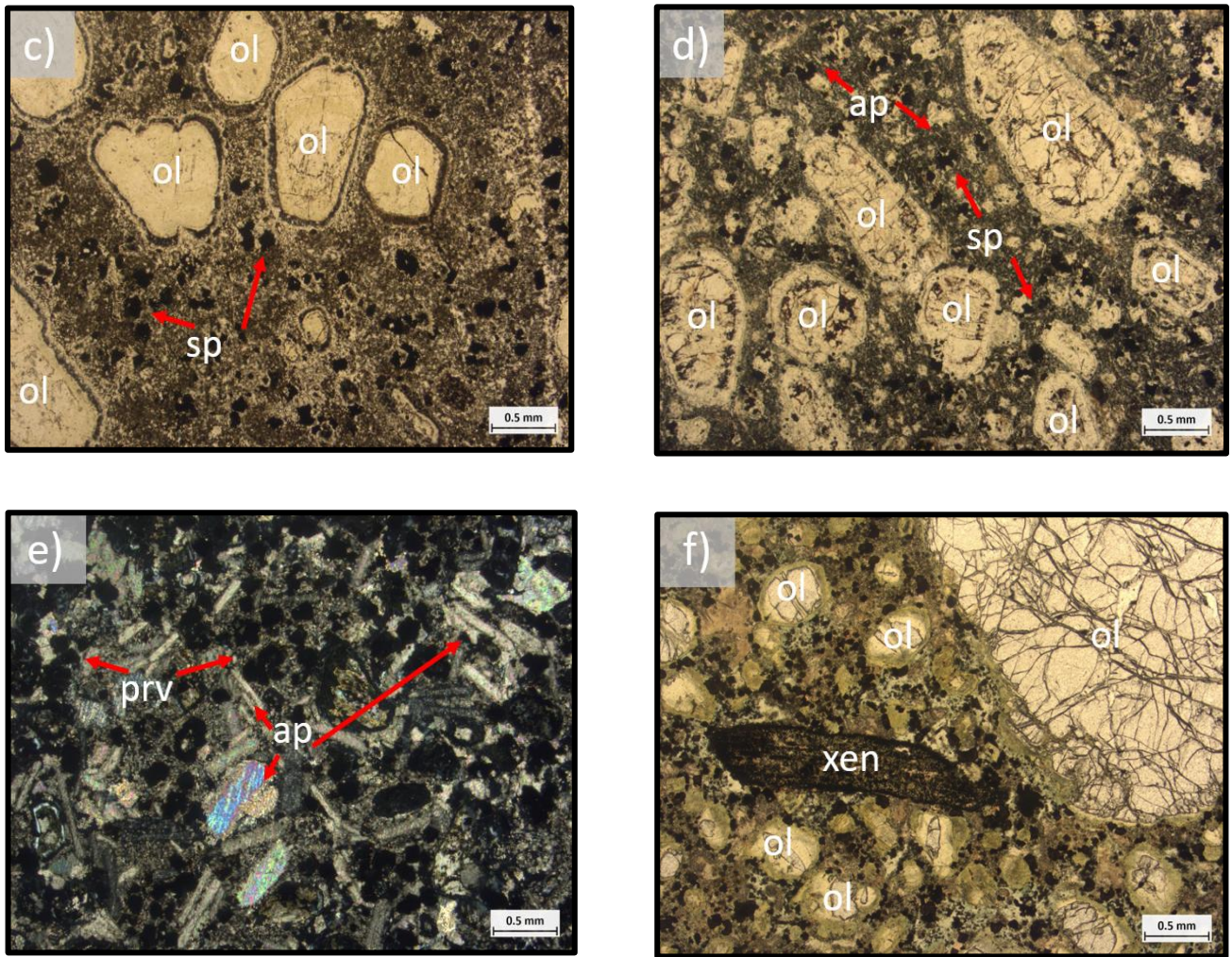


Figure 24: Photomicrographs in PPL and XPL of samples with olivine (ol) micro and macrocrysts in addition to perovskite (prv), spinels (sp), apatite (ap) and xenoliths (xen) within the interclast matrix. Distinct characteristics include: (a) HJ-026-02-102P and (b) HJ-026-02-55P, with perovskite in the interclast matrix; (c) RS-254-01-19P and (d) HJ-050-01-45P, with spinel in the interclast matrix; (e) RS-125-01-63P, with altered microcrysts of apatite laths and perovskite (prv) within the interclast matrix; (f) HJ-026-02-102P, showing a crustal xenolith within the interclast matrix.

Stage 2 - Petrogenetic classification

The analysed samples are classified as kimberlites based on the high abundance of olivine macrocrysts and microcrysts, combined with the poorly crystalline interclast groundmass composed of ultra-fine-grained serpentine and calcite, indicative of a carbonate-rich kimberlitic composition.

In addition to serpentine and calcite, the samples contain euhedral perovskite, which is particularly prominent in pipes L026 and L125. Spinel microcrysts are most abundant in pipes L050 and L254, while altered apatite laths are exclusively observed in pipes L050 and L125. Considering the composition of the interclast groundmass and the relative abundance of associated microcrysts, all samples are classified as carbonate kimberlites.

Stage 3a and 3b - Textural-genetic classification

The textures observed in the samples are characteristic of coherent kimberlites, defined by a high abundance of olivine macrocrysts and microcrysts. Olivine grains range in size from very fine to coarse (0.50-8.00 mm) and are predominantly euhedral. The samples have a groundmass comprising perovskite, spinels, apatite laths, and, less commonly, xenoliths. Notably, the abundant carbonate within the interclast matrix is a distinctive feature. Based on these characteristics - specifically the prevalence of olivine, the matrix-supported, coherent texture, and the carbonate-rich groundmass - the samples are classified as intrusive coherent kimberlites (ICK).

Pipe L018 is classified as a dyke based on core logs, while L050 is identified as a sill. The remaining samples are contained within pipes, characterized by the presence of upper and lower volcanoclastic units observed within the core logs.

Stage 4 - Volcanic spatial context

All samples are classified as intra-crater ICK deposits, as they are exclusively derived from drill cores within kimberlite pipes.

4.4.2 Classification of representative samples

Based on the results, each representative sample can be classified, following the scheme of Scott Smith et al. (2018) outlined in Table 1, as seen in Table 8:

Table 8: Summary table showing the classification of representative coherent kimberlite samples

<i>Sample name</i>	<i>Classification</i>
HJ-026-02-102P	Very xenolith-poor, very fine to coarse grained, very olivine macrocryst-rich, Coherent kimberlite sill
HJ-026-02-55P	Very xenolith-poor, very fine to coarse grained, very olivine microcryst-rich, Coherent kimberlite sill
RS-050-03-32P	Xenolith-free, very fine to fine grained, very olivine microcryst-rich, Coherent kimberlite sill
HJ-050-01-45P	Xenolith-free, very fine to fine grained, very olivine macrocryst-rich, Coherent kimberlite sill
RS-254-01-19P	Xenolith-free, very fine to medium grained, olivine macrocryst-rich, Coherent kimberlite sill
RS-254-01-53P	Xenolith-free, very fine to medium grained, olivine macrocryst-rich, Coherent kimberlite sill
RS-125-01-63P	Xenolith-free, very fine grained, olivine microcryst-rich, Coherent kimberlite sill

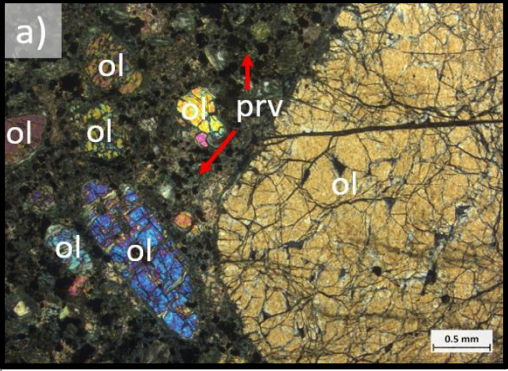
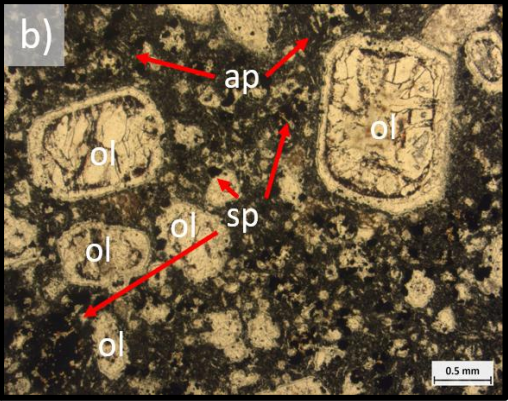
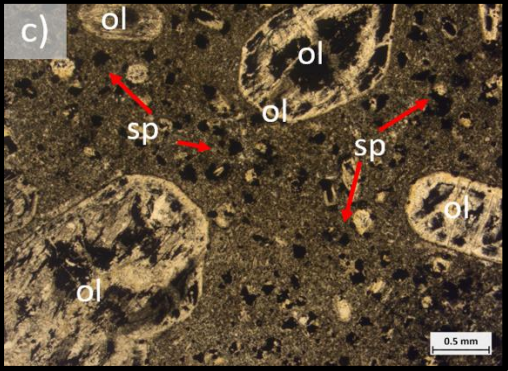
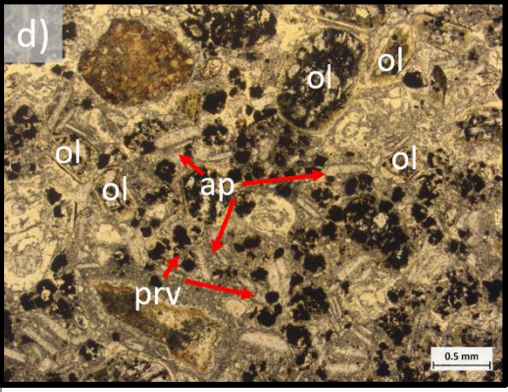
4.4.3 Summary of CK's in the Lulo Field

Of the 52 kimberlite pipes in the Lulo Field, 7 are identified as containing CK.

The kimberlites exhibit several similarities, including (1) Texture - All samples display a coherent texture, with coherent characteristics preserved across all thin sections; (2) Nature of support - A matrix-supported texture is consistently observed in all samples; (3) Olivine - Microcrysts and macrocrysts of olivine are abundant in all samples; (4) Inter-magmaclastic matrix - The matrix consistently contains both serpentine and calcite. Key differences are observed in the following aspects (1) Olivine alteration - One pipe contains fresh olivine, while in others all olivine is replaced by secondary minerals; (2) Interclast groundmass mineralogy - Variations occur in the relative abundances of altered apatite laths, spinel, and perovskite, with some samples containing only one or two of these minerals; (3) Xenolith abundance - Some samples contain xenoliths, while others do not.

Table 9: Table showing the distribution of CKs in pipes

<i>Sample</i>	<i>Pipe number</i>	<i>Key features/variatio</i>
		- Matrix supported - Contains fresh olivine - Euhedral olivine

	L026	• Very fine to coarse grained olivine (0.50 – 8.00 mm) • Very xenolith-poor • Intermagmaclastic groundmass predominantly consisting of ultra fine-grained serpentine and crystalline calcite with abundant perovskite microcrysts
	L050	• Matrix supported • Strong alteration texture • Euhedral olivine • Very fine to fine grained olivine (0.50 – 2.00 mm) • Xenolith-free • Intermagmaclastic groundmass predominantly consisting of ultra fine-grained serpentine and calcite with abundant spinel microcrysts and minor altered apatite laths
	L254	• Matrix supported • Strong alteration texture • Euhedral olivine • Very fine to medium grained olivine (0.50 – 4.00 mm) • Xenolith-free • Intermagmaclastic groundmass predominantly consisting of ultra fine-grained serpentine and calcite with abundant spinel microcrysts
	L125	• Matrix supported • Strong alteration texture • Euhedral olivine • Very fine-grained olivine (0.50 – 1.00 mm) • Xenolith-free • Intermagmaclastic groundmass predominantly consisting of ultra fine-grained serpentine and calcite with abundant perovskite microcrysts and abundant altered apatite laths

4.5 Simplified geology of pipes in the Lulo Field

The following table (Table 10) is intended to highlight the variability of kimberlite units across different pipes. Specifically, it focuses on pipes characterised by more than two samples described in this study, specifically focusing on those displaying differing kimberlite units, as these offer a broader representation of the geological variation within each pipe.

Table 10: Simplified overview of the Lulo Field kimberlite pipes, highlighting the variation in lithological classifications at different depths and across multiple pipes

<i>Pipe</i>	<i>Classification</i>	<i>Depth (m)</i>
L242	MVK	19
	MVK	19
	FPK	21
	FPK	25
	RVK	36
	RVK	43
	RVK	47
L015	RVK	30
	RVK	32
	RVK	38
	RVK	50
	RVK	77
	RVK	87
L048	MVK	16
	MVK	43
	FPK	59
	FPK	106
	FPK	127
L275	FPK	29
	FPK	64
	FPK	95
L009	RVK	109
	RVK	23
	Sandstone	33
	RVK	45

L026	FPK	96
	RVK	96
	Coherent	55
	Coherent	102
L050-01	Coherent	45
L050-03	Coherent	32
L050-08	FPK	32
	FPK	45
	FPK	52
	FPK	68
	FPK	84
L254-01	Coherent	53
	Coherent	55
	Coherent	19
L254-02	Sandstone	45
	MVK	63
	MVK	98
	Coherent	53

Table 10 highlights the variability in the lithologies with depths across pipes in the Lulo Field. Pipe L242 exhibits a predominance of RVK at deeper levels (36.0-47.0 m) with MVK and FPK at shallower levels 19.0-25.0 m. In contrast, pipe L015 shows RVK from surface and extending to significant depths of up to 87.0 m. Pipe L048 contains FPK reaching depths of 127m, with MVK overlying it between 16.0-43.0 m. Similarly, the upper sections of pipe L275 are dominated by FPK, contrasting with deeper RVK at 109m. L009 contains a notable FPK unit at 96 m underlying RVK and sandstone at depths between 23.0-43.0 m. Pipe L026 contain only coherent kimberlites, with pipe L050 showing only coherent kimberlites in L050-01 and L050-03, in contrast to L050-08 that only contains FPK. A similar pattern is observed in pipe L254, where L254-01 contains only coherent kimberlite, while L254-02 features coherent kimberlite at 53.0 m overlain by sandstone and MVK from 45.0-98.0 m.

4.6 Geochemistry

Major and trace element compositions for selected bulk-rock, coherent kimberlite samples are given in Appendix C (Table 15) and illustrated in the figures below.

Table 11: Summary table of samples used for the bulk-rock analysis showing pipe number, depth within pipe and kimberlite type

Sample name	Pipe number	Depth (m)	Type
RS-050-03-32P	L050	32.00	Coherent
RS-254-01-19P	L254	19.00	Coherent
RS-254-01-53P	L254	53.00	Coherent
RS-125-01-63P	L125	63.07	Coherent
HJ-050-01-45P	L050	45.00	Coherent
HJ-026-02-55P	L026	55.48	Coherent
HJ-026-02-102P	L026	102.36	Coherent

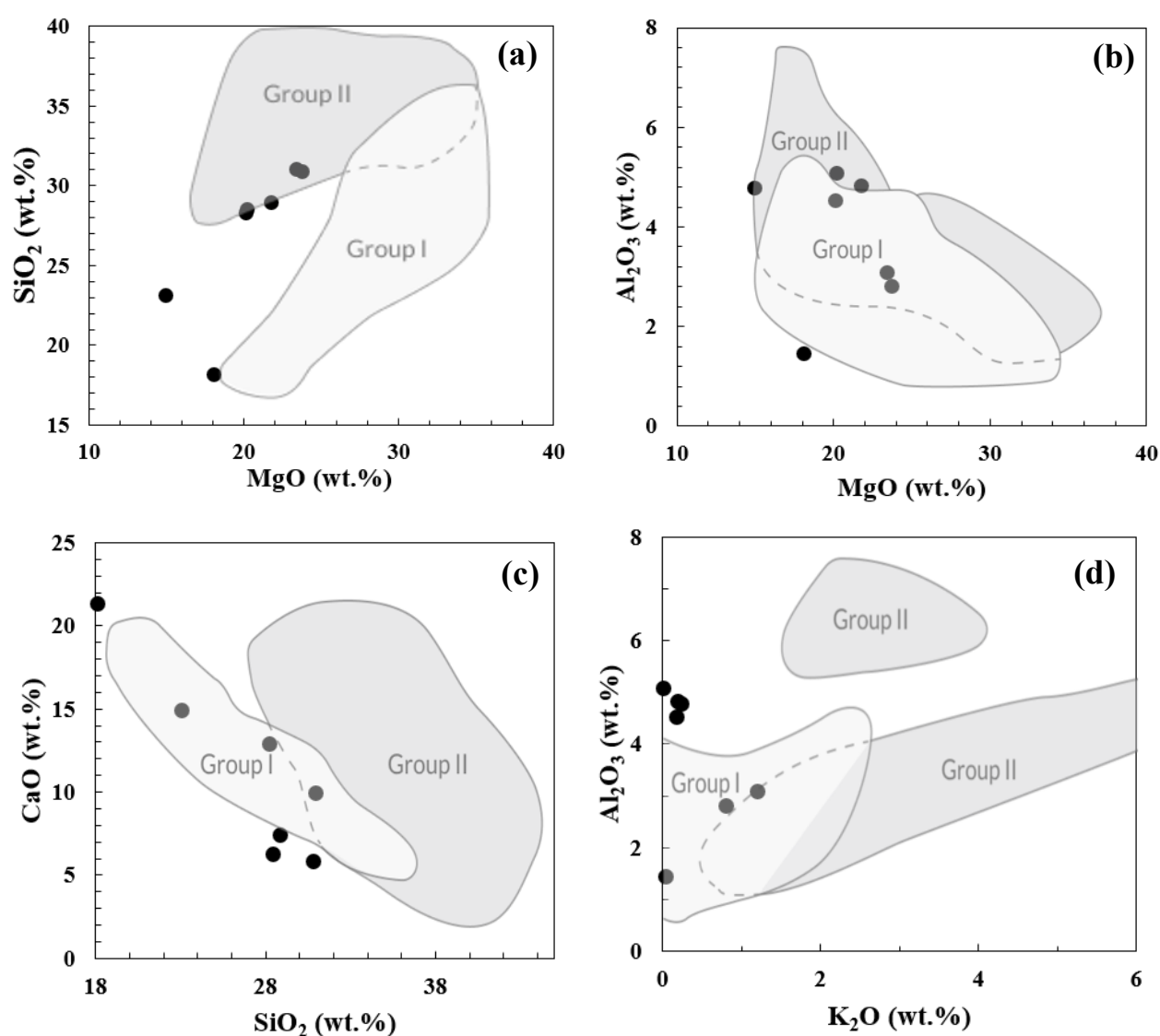
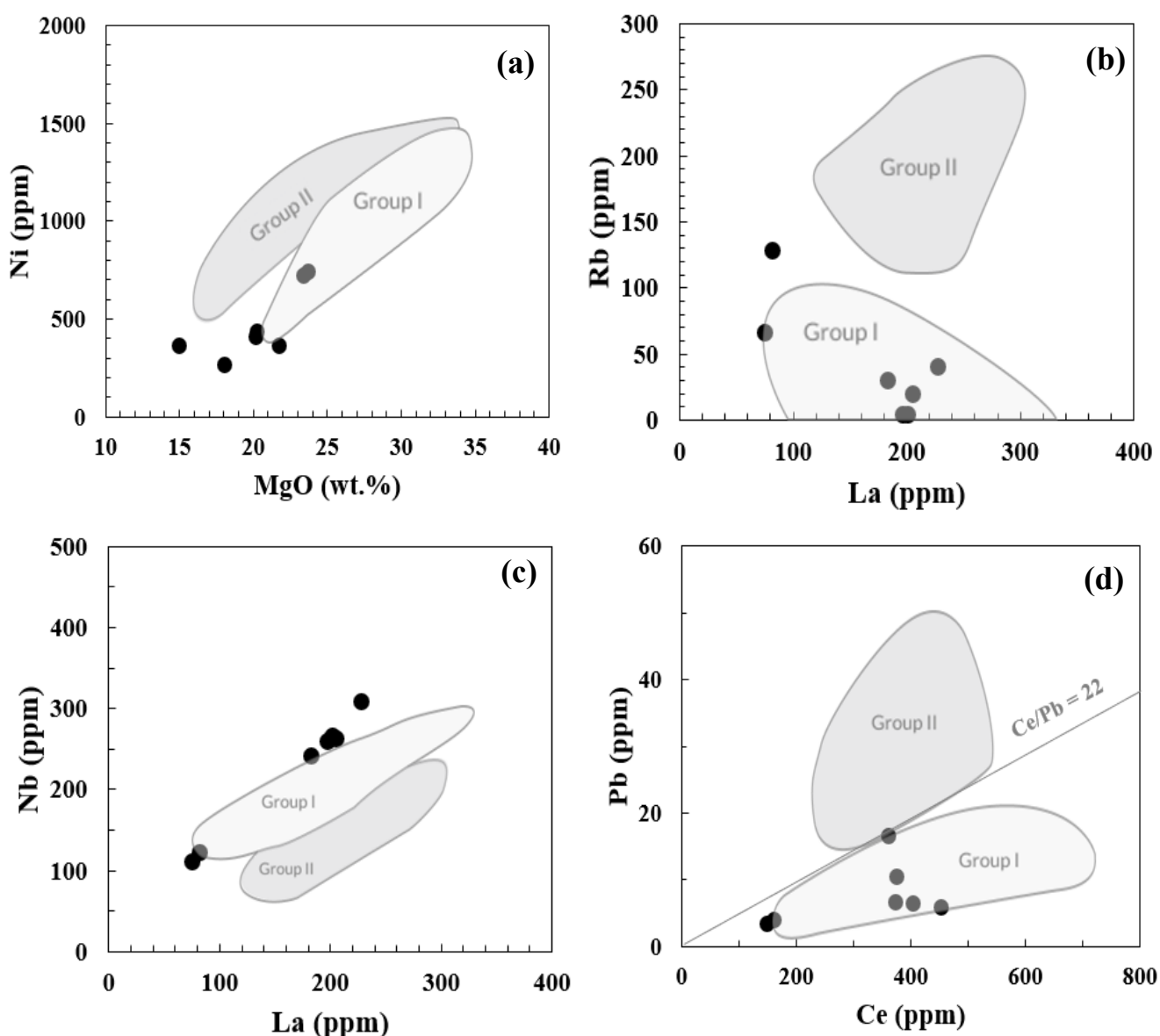


Figure 25: Graphs displaying selected major element variations showing (a) SiO₂ vs MgO (b) Al₂O₃ vs MgO (c) CaO vs SiO₂ (d) Al₂O₃ vs K₂O. The fields for Group I and Group II kimberlites are sourced from le Roex et al., (2003) and Becker & le Roex, (2006), respectively.

In the selected major element variation plots, SiO₂ values range from 18.1 to 30.9 wt.% while MgO values range from 15.0 to 23.7 wt.% (Figure 25a). A positive correlation is observed, with higher MgO values generally corresponding to higher SiO₂ values. Al₂O₃ values range from 1.44 to 5.06 wt.%, but no clear correlation with MgO is evident (Figure 25b). CaO values range from 5.76 to 21.2 wt.%, and a weak negative correlation ($r = -0.90$) is observed, with higher SiO₂ values typically corresponding to lower CaO values (Figure 25c). K₂O values range from 0.02 to 1.21 wt.%, and no significant correlation with Al₂O₃ observed (Figure 25d).



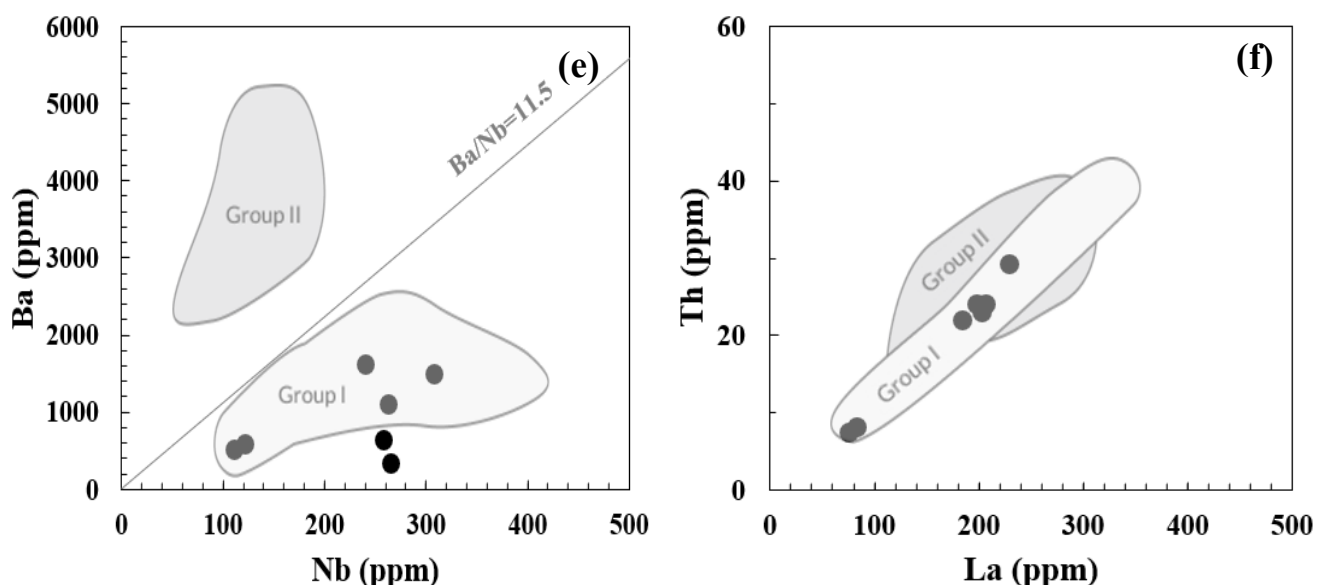


Figure 26: Graphs displaying selected incompatible trace element variations showing (a) Ni vs MgO (b) Rb vs La (c) Nb vs La (d) Pb vs Ce (e) Ba vs Nb (f) Th vs La. The fields for Group I and Group II kimberlites are sourced from le Roex et al., (2003) and Becker & le Roex, (2006), respectively.

Ni concentrations range from 262 to 735 ppm. There is a positive correlation between Ni and MgO (Figure 26a). Rb concentrations range from 3.90 to 127 ppm, and La from 75.6 to 228 ppm. A negative correlation is observed, where higher La values correspond to lower Rb concentrations, particularly notable in higher Rb for certain samples (Figure 26b). Nb concentrations range from 111 to 308 ppm, while La ranges from 75.6 to 227 ppm. The data shows a strong positive correlation ($r=0.99$), with higher La values associated with higher Nb concentrations across samples (Figure 26c). Pb concentrations vary between 3.40 and 16.5 ppm, while Ce ranges from 150 to 454 ppm. A generally positive relationship exists, with higher Ce associated with increased Pb, although the trend is less pronounced (Figure 26d). Ba concentrations range from 343 to 1626 ppm, while Nb varies between 111 to 308 ppm. A moderate correlation is observed ($r=0.48$), with Ba concentrations increasing alongside Nb (Figure 26e). Th concentrations range from 7.48 to 29.4 ppm, while La ranges from 75.6 to 229 ppm. There is a strong positive correlation ($r=0.99$), as higher La values correspond to elevated Th concentrations (Figure 26f). This correlation is consistent across the dataset.

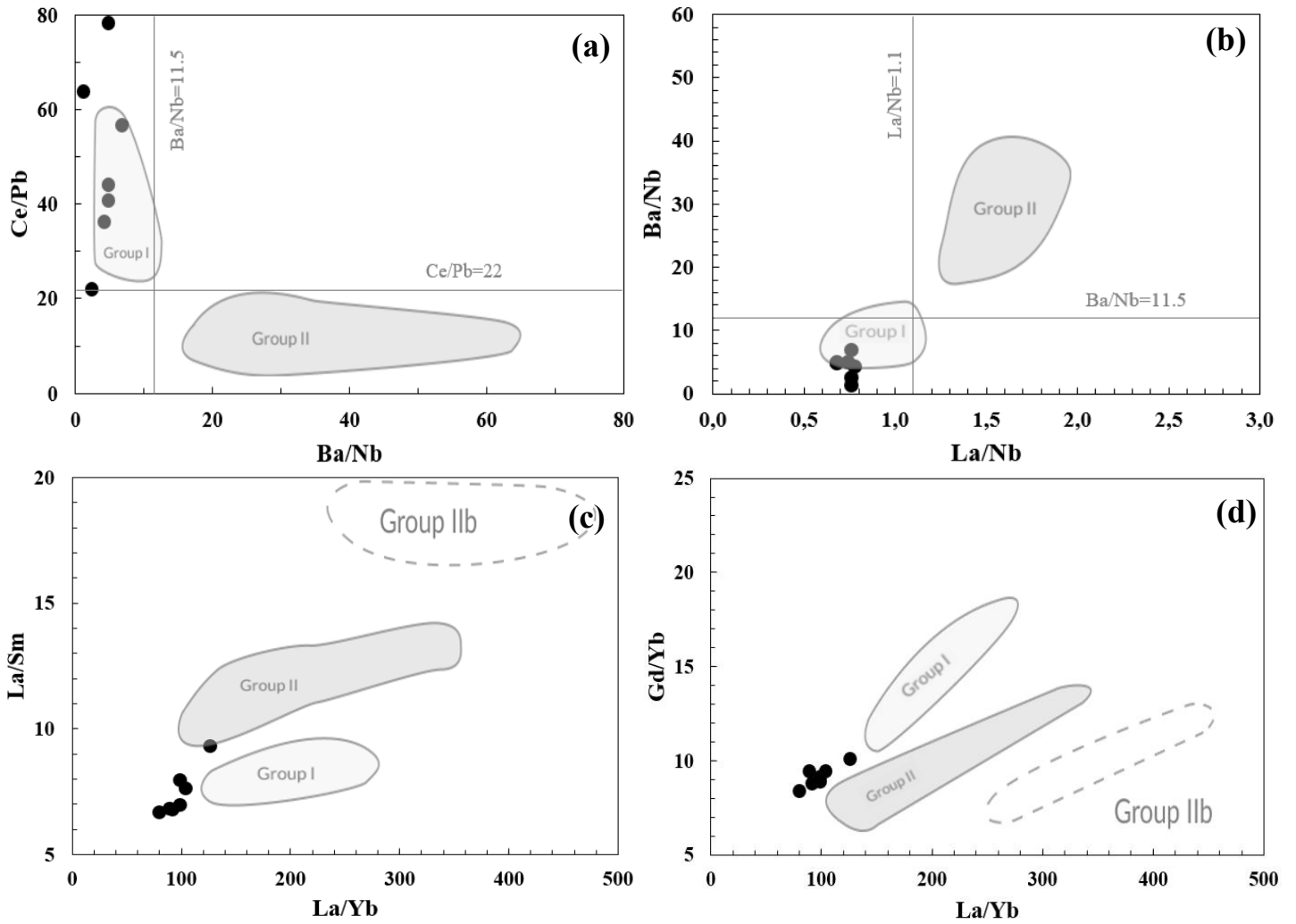


Figure 27: Graph displaying selected incompatible trace element ratios showing (a) Ce/Pb vs Ba/Nb (b) Ba/Nb vs La/Nb (c) La/Sm vs La/Yb (d) Gd/Yb vs La/Yb. The fields for Group I and Group II kimberlites are sourced from le Roex et al., (2003) and Becker & le Roex, (2006), respectively.

Ce/Pb ratios range from 21.9 to 78.1, while Ba/Nb ratios vary from 1.29 to 6.77. There is no evident correlation in the data with Ba/Nb showing no significant changes with increasing Ce/Pb (Figure 27a). Ba/Nb ratios range from 1.29 to 6.77, while La/Nb ratios vary between 0.68 and 0.78. No correlation is evident (Figure 27b). La/Sm ratios range from 6.80 to 9.35, La/Yb ratios vary from 79.7 to 125.6, and Gd/Yb ratios range from 8.43 to 10.1. A positive correlation is observed between La/Yb and both La/Sm and Gd/Yb ratios (Figure 27c and 27d respectively), indicating that higher La/Yb values are associated with higher La/Sm and Gd/Yb ratios.

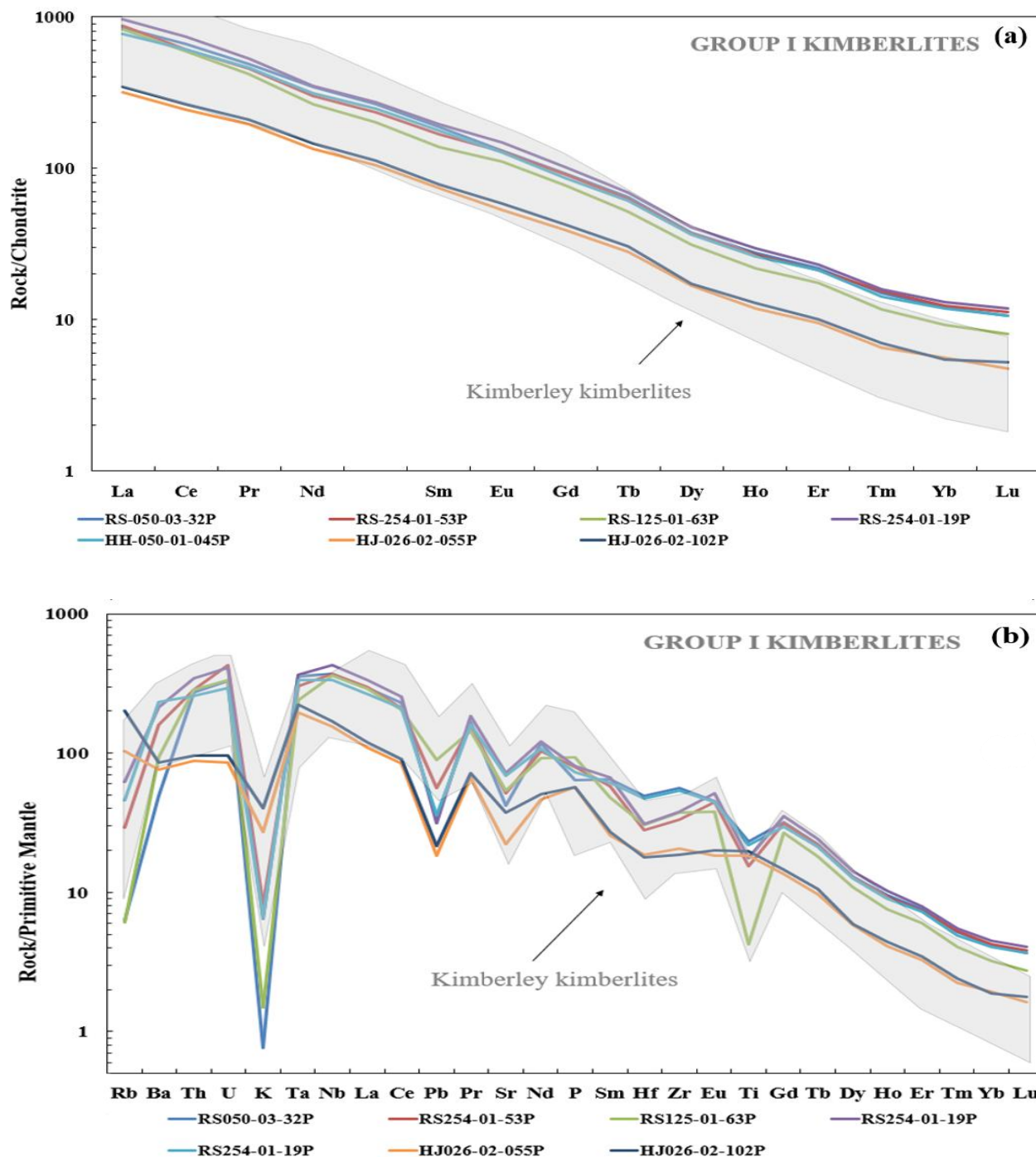


Figure 28: Graphs displaying (a) Chondrite-normalized REE diagrams for samples showing on-craton Group I kimberlites (b) Primitive mantle-normalized incompatible element patterns for samples compared with on-craton Group I kimberlites from South Africa.

In the chondrite-normalized REE diagrams (Figure 28a), there is a general decrease in concentrations from LREEs (light rare earth elements) to HREEs (heavy rare earth elements). The plots show strong enrichment in LREEs (La, Ce, Pr, Nd), with values typically higher than 100 times chondrite in addition to depletion in HREEs (Dy, Ho,

Er, Tm, Yb, Lu), with values closer to 30 times chondrite or slightly lower. HJ-026-02-055P and RS-050-03-32P plot the lowest rock/chondrite values, depicting less enrichment of both LREE and HREE's. While RS-254-01-19P and RS-254-01-53P plot the highest rock/chondrite values.

In the primitive mantle-normalized trace element patterns (Figure 28b), there is significant variability in trace element concentrations. There is a prominent enrichment in LILEs (large-ion lithophile elements) such as Rb, Ba, Th and U apart from samples HJ-026-02-055P and RS-050-03-32P in there is an enrichment in Rb and relatively lower enrichment in Ba, Th and U. There is also a notable enrichment in HFSEs (high-field-strength elements) like Nb and Ta with notable exceptions by HJ-026-02-055P and RS-050-03-32P. Pb, Sr and Ti are highly depleted in addition to consistent HREE depletion (from Gd to Lu)

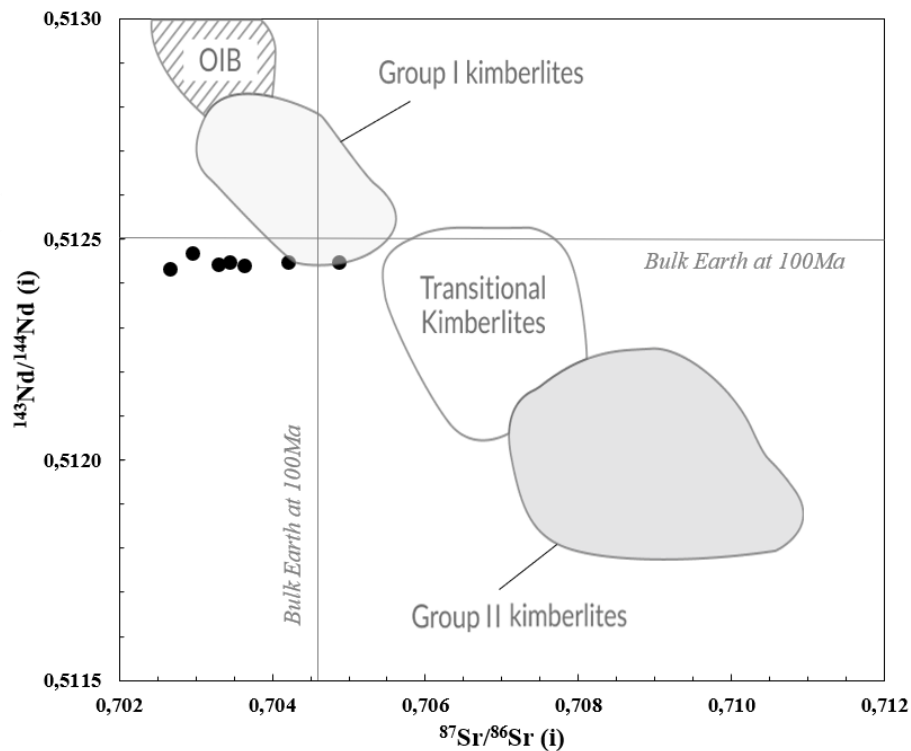


Figure 29: Graph displaying initial $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$. The fields for Group I and Group II kimberlites are sourced from le Roex et al., (2003) and Becker & le Roex, (2006), respectively.

The following measured ratios were age corrected to initial values using an age of $t = 1.35 \times 10^8$ years. This is due to isotopic compositions evolving over time due to the radioactive decay of parent isotopes; thus, the calculated initial ratios are more representative of the sample at the time it formed.

$^{87}\text{Sr}/^{86}\text{Sr}$ ratios vary between 0.70266 and 0.70487 with $^{143}\text{Nd}/^{144}\text{Nd}$ ratios ranging from 0.51243 to 0.51247, with epsilon Nd (t) values ranging from 3.40 – 4.24 (Figure 29). Samples show a limited variation in both strontium and neodymium isotopic ratios. The $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios exhibit a wide range, in contrast to the Nd isotopic compositions, which show a much narrower range.

Chapter 5: Discussion

5.1 Pipe classification and implications for eruption style

The pyroclastic kimberlites from the Lulo field are classified as Fort à la Corne-type pyroclastic kimberlites (FPKs) based on several key features that distinguish them from Kimberley-type pyroclastic kimberlites (KPKs), as highlighted in section 3.1 in this paper. They exhibit sorting and a clast-supported texture, which are characteristic of FPKs, in contrast to the unsorted, matrix-supported texture typically seen in KPKs (Scott Smith et al., 2018). The magmaclasts within the Lulo field kimberlites show a wide range of sizes, from ultra-fine to coarse (~0.10-15.0 mm), and a variety of morphologies, ranging from regular to curvilinear. This contrasts with KPKs, where clast sizes tend to be more uniform and magmaclasts typically have subspherical-to-ovoid shapes (Scott Smith et al., 2018). A feature of the Lulo field FPKs is the presence of central kernels of olivine and/or xenoliths, which can range up to 15.0 mm in size, which is in the characteristic 10.0-20.0 mm range for FPKs in general. Additionally, these FPKs display a thin kimberlitic rim around the melt-bearing pyroclasts, which contains significant amounts of carbonate - a defining feature of FPKs (Scott Smith et al., 2018). Although KPKs also show melt-bearing pyroclasts with distinctive kimberlitic rims, they are notably absent of calcite, further distinguishing the Lulo field kimberlites as FPKs. The groundmass of the melt-bearing pyroclasts in the Lulo field kimberlites is characterized by a cryptocrystalline matrix composed primarily of serpentine and carbonate, with microcrystic perovskite, spinel, phlogopite, and apatite. This composition contrasts with that of KPKs, which generally feature a groundmass dominated by olivine crystals, along with perovskite, spinel, phlogopite, and serpentine, but without carbonate (Scott Smith et al., 2018). Another notable difference is the presence of broken olivine grains in the Lulo field FPKs, a feature rarely observed in KPKs, where broken olivine is generally absent (Scott Smith et al., 2018). Furthermore, the xenolith content in the Lulo field FPKs is relatively low (1-13 vol%), whereas KPKs typically contain a much higher abundance of xenoliths (15-90 vol%) (Scott Smith et al., 2018). Finally, the interclast matrix of the Lulo field FPKs is predominantly composed of serpentine and carbonate, in contrast to the interclast matrix of KPKs, which contains serpentine and microlitic diopside in varying amounts. The absence of microlitic diopside in the Lulo field kimberlites is another distinctive feature that supports their classification as FPKs rather than KPKs (Scott Smith et al., 2018).

The internal geology of the Lulo Field pipes offers valuable insights into their classification and eruptive behaviour, identifying them predominantly as Class 3 kimberlites, like those at Lac de Gras. Class 3 kimberlites are characterized by eruptions that effectively cleared vents (Scott Smith, 2008a). This classification is supported by the internal distributions of volcanoclastic kimberlite (VK) facies - massive (MVK), resedimented (RVK), and primary pyroclastic (PK) - as well as coherent kimberlite (CK) and intervals of sandstone. For example, the deepest RVK facies across the Lulo Field are seen in pipe L010, extending to depths of 102 m, whereas the deepest MVK facies in L025 are observed at 108 m, suggesting eruptions resulted in pipe clearing up to significant depths. FPK at shallow depths in contrast to deeper RVK units, such as pipe L242 and L275 suggests resedimentation followed by pyroclastic deposition in the upper sections. In addition, pipe L242 shows MVK overlaying the FPK, which then suggests, another resedimentation process post pyroclastic emplacement in which this is commonly seen in pipe L048. Other pipes, such as L015, containing only RVK throughout, extending to significant depths of up to 87 m, highlight only pipe clearing and resedimentation processes. In contrast, pipes like L026 consists entirely of coherent kimberlite, representing emplacement under magmatic rather than explosive conditions. With pipes L050 and L254 showing coherent kimberlites with MVK and FPK, suggesting coherent sills. These distributions provide insights into the variations in vent-clearing behaviours, eruptive styles, and depositional environments across the Lulo Field, highlighting the complexity of processes that governed their formation.

The eruption style of the Lulo Field kimberlites is inferred from the fragmental, volcanoclastic nature of the samples. The preservation of primary volcanoclastic textures and the absence of vesicles in the magmaclasts suggest a relatively explosive, yet shallow subsurface eruption. The variety in melt-bearing pyroclast morphologies - ranging from regular/rounded to amoeboidal - suggests the presence of multiple fragmentation mechanisms and rapid cooling of magma during the eruption (Webb & Hetman, 2021). The dominance of cored magmaclasts, with central kernels of olivine and xenoliths, with sharp margins and ultra-fine-grained rims surrounding these cores suggest rapid cooling and quenching, indicative of a pyroclastic fragmentation and emplacement process (Webb & Hetman, 2021). The presence of incomplete rims around some cored magmaclasts may reflect differential cooling rates or post-emplacement alteration, pointing to variations in the eruption dynamics. The presence of xenolith-poor varieties with 1-13 vol% xenoliths further support the notion of an explosive eruption where the country rock was not significantly incorporated into the eruptive products (Scott Smith, 2006). Instead, the eruption may have been driven by magmatic volatiles, resulting in the fragmentation of the kimberlite magma into magmaclasts with

varying morphologies and sizes. Furthermore, the low xenolith content and high abundance of RVKs (subsequent extrusive infill) suggests that the pipes were an open system.

5.2 Comparison with worldwide occurrences

Kimberlite pipes are distributed globally across several key regions, with distinct classes prevalent in specific locations. Class 1 kimberlite pipes are concentrated in southern Africa, with notable occurrences in Canada such as Gahcho Kue (Skinner & Marsh, 2004). Class 2 pipes are primarily found in the Canadian Prairies, northeast Angola, and Siberia, aligning closely with areas of shallow crater zones (Skinner & Marsh, 2004). Class 3 pipes have the broadest distribution, spanning Canada, Africa, and Siberia. Prominent examples include the Ekati cluster in Canada, the Jwaneng pipe in Botswana, and various pipes in northeastern Angola and Siberia, such as Sytikanskaya and Aichal (Skinner & Marsh, 2004). Some regions exhibit multiple kimberlite classes within the same geological setting - Ekati hosts both Class 1 and Class 3 pipes, while northeastern Angola and Siberia are known to contain all three classes (Skinner & Marsh, 2004). This overlapping distribution underscores the widespread nature of kimberlite emplacement and the geological diversity across different regions (Skinner & Marsh, 2004).

Voorspoed mine, located north of Kroonstad in the Free State Province of South Africa, is, among southern African kimberlites, perhaps the most comparable to Lulo Field kimberlites. Voorspoed is part of a cluster of eleven kimberlites, with Voorspoed and Lace being the only economically significant bodies in this cluster (Field et al., 2008). The mine is characterized by the presence of antecedent and consequent dykes related to the pipe, comparable to those found in the Lulo field, as well as a large Stormberg basalt floating reef (Wagner, 1914). Voorspoed is classified as a Group-2 kimberlite (Phillips et al., 1998;1999) and has been dated at 131.3 ± 0.6 Ma, similar in age to the 114-140ma dated Lulo Field kimberlites. It has been noted by J. Stiefenhofer (unpublished communication) that the presence of graded bedding and pyroclastic textures indicates that Voorspoed should be considered a volcanoclastic kimberlite - indicative of Class 3 kimberlite pipes and thus share in the internal distribution of pipes being variable, like the Lulo Field. Voorspoed is an example of a case whereby country-rock dilution has adversely affected the viability of a mine (Field et al., 2008), a consideration that becomes relevant as there are 1-13 vol% of crustal xenoliths seen in the Lulo field kimberlites.

Most comparable to kimberlites found in the Lulo field, are those found in Canada, namely the La de Gras kimberlite field. These kimberlites, dated to the Paleogene period, were emplaced between 75 and 45 Ma (Sarkar et al., 2015). This includes economically significant kimberlites such as those from the Diavik and Ekati mines. Within this field, the local geology consists of basement overlain by predominantly Cretaceous sediments that are poorly consolidated (Scott Smith, 2008a) and is depicted in Figure 3b and Figure 30. The classification and depths of the different infill types across five studied kimberlite pipes of the Lulo field (L242, L015, L048, L275, and L009) are summarized in Table 10. The pipes exhibit varying sequences of Massive Volcaniclastic Kimberlite (MVK), Resedimented Volcaniclastic Kimberlite (RVK), and Primary Kimberlite (PK) infills, with occasional occurrences of sandstone - this pipe style is comparable to that of the pipe structure observed at La de gras as seen in Figure 30 with the interbedding of VK and PK units varying over depth.

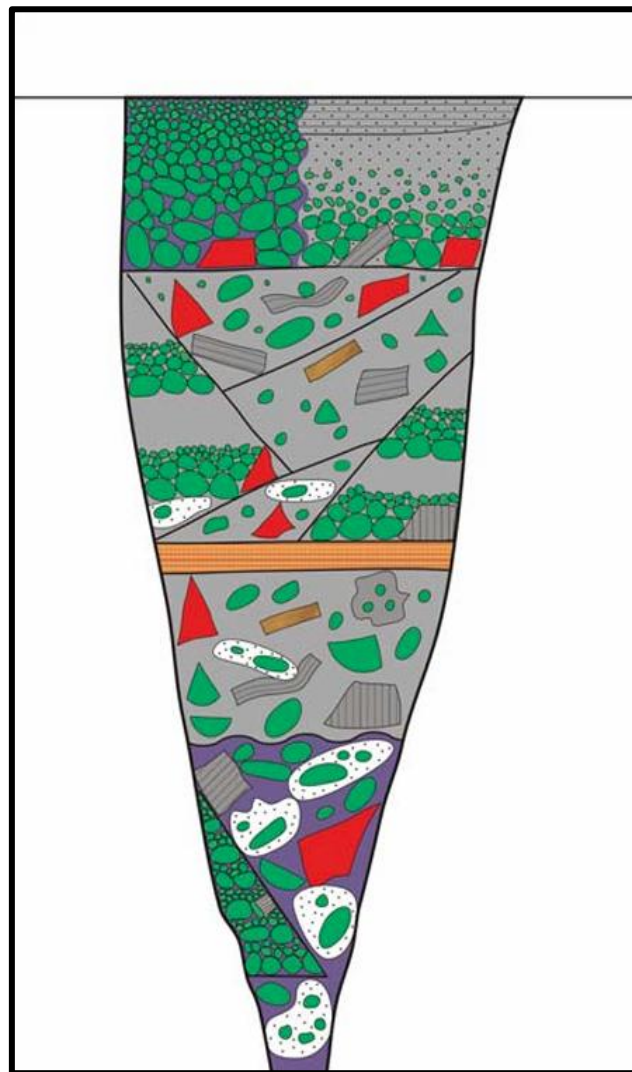


Figure 30: Adapted from (Scott Smith, 2006). Image showing the dominant pipe infill composition of the Lac Le Gras kimberlite beneath the erosion surface. The pipe infill predominantly consists of RVK, a mix of fresh, angular olivine grains (green), shale xenoliths (dark grey with lines), granitoids

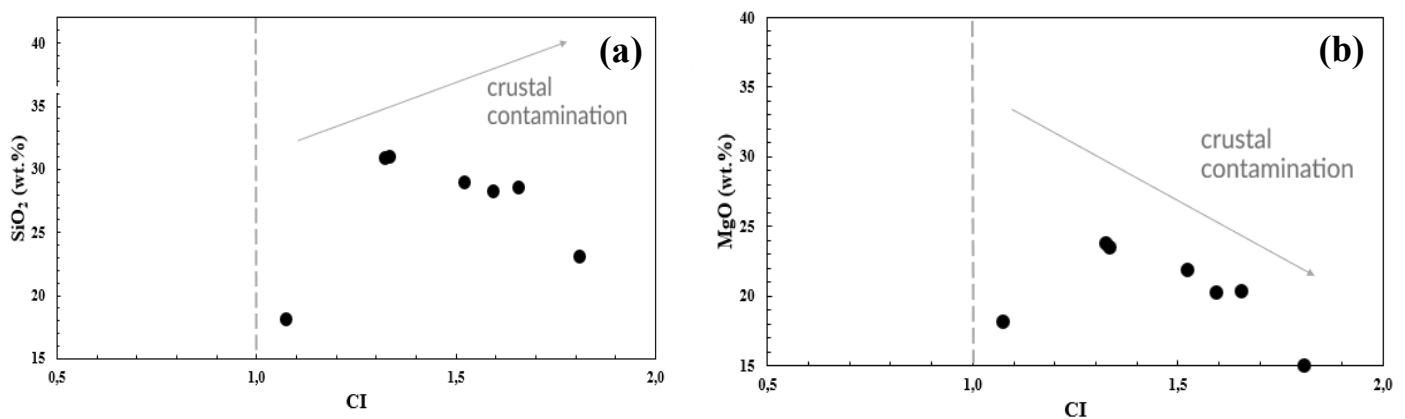
(red), juvenile lapilli (white), autoliths (dark grey with olivines), and wood fragments (brown), all set in a pale grey disaggregated shale matrix. The RVK features matrix-supported textures with well-sorted layers and displays variations in xenolith type and size, olivine abundance, and wood content. Additionally, minor kimberlite-poor sediments include siltstone (orange) and mudstone (upper grey). Rare PK appears with a serpentine matrix and more juvenile material, featuring occasional mega-graded beds rich in olivine

5.3 Geochemical classification and petrogenesis of coherent textured kimberlites and comparison with global kimberlites

5.3.1 Contamination index

Due to the explosive nature of kimberlites, there can be high levels of contamination of crustal xenoliths near the surface (Clement, 1982; Skinner, 2008; Sparks et al., 2006; Ramokgaba et al., 2021). Thus, a contamination index ($CI = \text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Na}_2\text{O} / (\text{MgO} + 2\text{K}_2\text{O})$) was proposed by Clement 1982. This is assessed by considering that a kimberlite with $CI > 1.0$ is contaminated by the incorporation of crustal xenoliths during sample preparation whereas $CI < 1.0$ is contamination-free.

Figure 31: Plot of selected major elements versus Contamination Index (C.I.) for samples showing (a) SiO_2 vs CI (b) MgO vs CI (c) Al_2O_3 vs CI (d) $\text{Sr}^{87}/\text{Sr}^{86}$ vs CI (e) $\text{Nd}^{143}/\text{Nd}^{144}$ vs CI (f) La/Yb vs CI (g) La/Sm vs CI (h) La/Nb vs CI (i) Ba/Nb vs CI (j) Gd/Yb vs CI



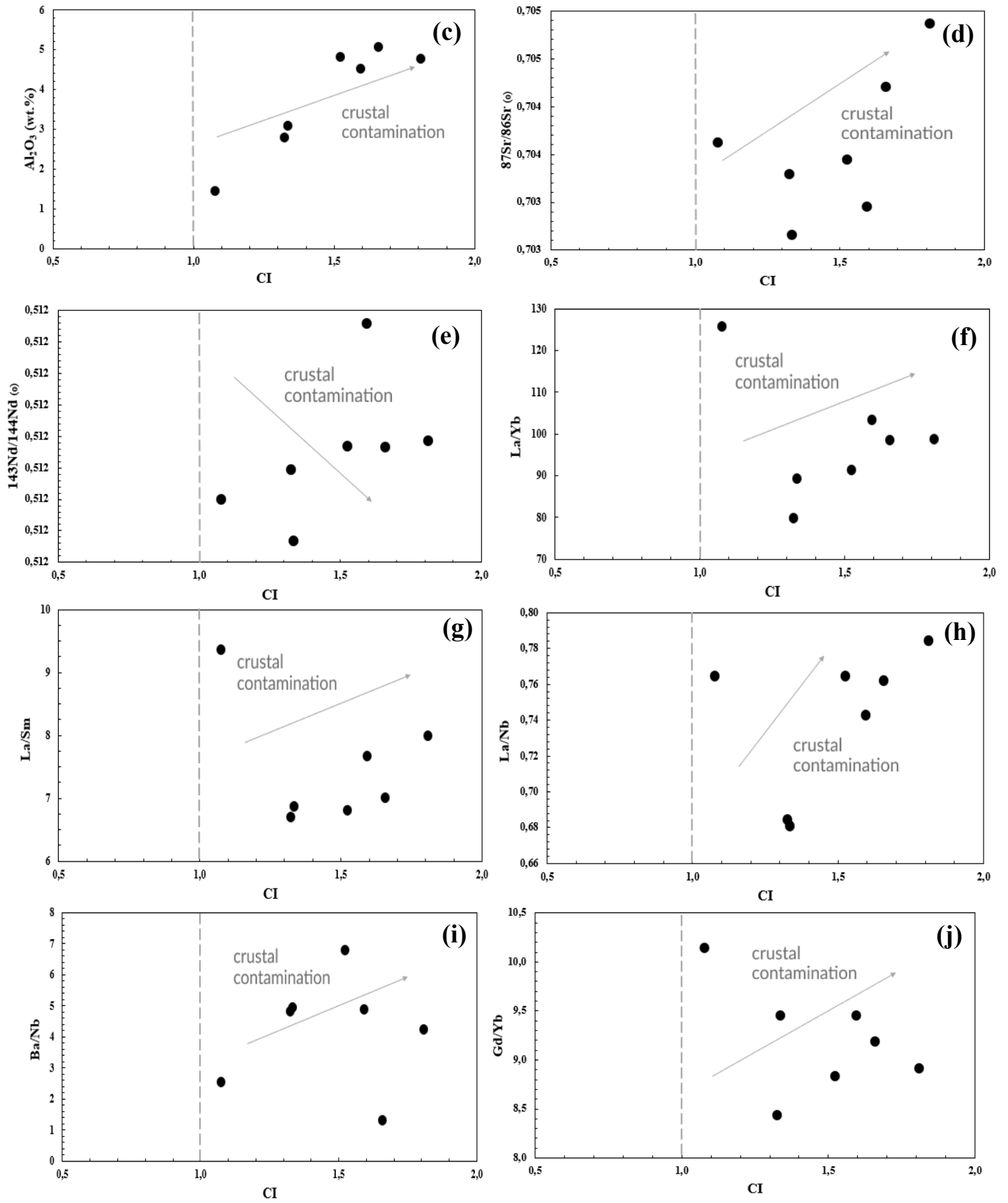


Table 12: Correlation coefficient for each plot in addition to the expected trend to show crustal contamination

Plot (vs CI)	Correlation coefficient	Expected trend	Affected by contamination
SiO ₂	0.2	Strong positive	No
MgO	-0.4	Strong negative	Yes
Al ₂ O ₃	0.9	Strong positive	Yes
⁸⁷ Sr/ ⁸⁶ Sr	0.6	Strong positive	Yes
¹⁴³ Nd/ ¹⁴⁴ Nd	0.5	Strong negative	No
La/Yb	-0.3	Strong positive	No
La/Sm	-0.3	Strong positive	No
La/Nb	0.4	Strong positive	Potential
Ba/Nb	0.06	Strong positive	No
Gd/Yb	-0.5	Strong positive	No

The contamination indexes for all samples are > 1.0 and thus can be considered contaminated (Figure 31a – 31j). In addition, plots showing strong positive/negative correlations can provide further evidence for contamination by specific elements, as summarized in Table 12. For the major elements, SiO₂ shows no significant effects by contamination (Figure 31a) whereas MgO and Al₂O₃ show a strong negative and positive correlation respectively (Figure 31b and 31c), thus have been affected. This is reflected in the high concentrations of Al₂O₃ and low concentrations of MgO which caused plots outside of the expected Group I field for the major element plots in Figure 25a and 25d. Crustal contamination affecting MgO is further seen in the incompatible trace element for Ni vs MgO (Figure 26a) in which plots outside of the Group I field can be attributed to low MgO concentrations. None of the incompatible trace element ratios show a correlation with the contamination index (Figure 31f – 31j) thus, high Nb concentrations and low La/Yb and Gd/Yb cannot be attributed to crustal contamination. This is also true for low ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd (Figure 31d and 31e), as only ⁸⁷Sr/⁸⁶Sr is affected by crustal contamination, and would be expected to be relatively higher not lower as a result.

5.3.2 Geochemical classification and petrogenesis of coherent kimberlite representative bulk samples

Geochemical classification was presented in Figures 25-29 with the aim of the classification of Lulo field kimberlites as Group I or Group II.

Major element graphs (Figure 25) plot predominantly within the Group I field apart from SiO₂, in which we see elevated concentrations and thus plotting within the Group II field. The Al₂O₃ concentrations are also seen to be plotting outside of the Group I

field, as they are relatively higher. Plots within the Group I field is further highlighted with the incompatible trace element graphs (Figure 26) whereby plots fall mainly within Group I, apart from Ni vs MgO in which lower a MgO wt.% for multiple samples result in plots outside the Group I field, in addition to a relatively higher Nb ppm for samples depicted in Figure 26c. The incompatible trace element ratios in Figure 27 further highlights plots in the Group I field, but relatively lower La/Sm, La/Yb and Gd/Yb results in plots outside of Group I within Figures 27c and 27d. The Chondrite-normalized REE diagrams and primitive mantle-normalized trace element patterns both fall within the Group I kimberlite field with minor exceptions. In the chondrite-normalized REE diagram (Figure 28a), these samples display slightly higher or lower concentrations of REEs, though the overall trend remains consistent. Notably, the samples that deviate from the shaded region exhibit slightly higher HREE values, indicating a slightly stronger enrichment of these elements compared to the Kimberley kimberlites. In the primitive mantle-normalized trace element diagram (Figure 28b) the samples follow the general trace element trends of Group I Kimberley kimberlites. Except for some samples outside the shaded area, in which they display more variability in the enrichment of LILEs (Rb, Ba, Th, U) and the depletion of HFSEs (Nb, Ta) with notable depletion in K and Pb and enrichment of Ti.

5.3.3 Geochemical comparison with South African kimberlites

The geochemical characteristics of the Lulo field kimberlites show a strong resemblance to South African Group I kimberlites, particularly in their major element compositions and trace element patterns. In both the chondrite-normalized REE and primitive mantle-normalized trace element diagrams (Figure 28a and 28b), the Lulo kimberlites show strong similarities to South African Group I kimberlites. However, some deviations are noted, such as extending to elevated concentrations of SiO₂ and Al₂O₃, lower MgO content, and higher Nb concentrations, which cause a few samples to plot outside the Group I field. Additionally, the Lulo kimberlites display a slightly stronger enrichment in heavy REEs (HREEs) compared to the Kimberley kimberlites. Greater variability is also observed in large-ion lithophile elements (Rb, Ba, Th, U), along with more pronounced depletion of high-field-strength elements (Nb, Ta) and elements like K and Pb. These differences can be partially explained by crustal contamination, as indicated by the elevated Al₂O₃ and depleted MgO levels (Figure 31c and 31b, respectively). Despite these minor variations, the overall geochemical signature of the Lulo kimberlites remains broadly consistent with Group I Kimberlites from South Africa, suggesting they share a common mantle source with the addition of some geochemical modifications.

5.4 Implications for diamond grade evaluation of kimberlite pipes of the Lulo field

The Lulo field is known for containing alluvial deposits of large, high-value, Type IIa diamonds, which are believed to originate from primary kimberlite deposits within the area. This underscores the significance of ongoing exploration efforts, including drilling and bulk sampling, to estimate diamond grade and locate potential primary diamond sources.

Active exploration is underway to understand the relationship between these alluvial deposits and the spatially associated kimberlite pipes. The internal geology of the Lulo pipes is complex, with pipes classified as Class 3, indicating multiple volcanoclastic units of both FPK and RVK within individual pipes. These pipes consist of multiple units with distinct geological characteristics, leading to significant variation in diamond grade over short intervals. Units within the same pipe can exhibit vastly different diamond contents (Scott Smith, 2017), underscoring the need for detailed stratigraphic analysis to accurately assess diamond distribution. This complexity has important implications for bulk sampling, as surface sampling may not represent the diamond content at depth. Accurate diamond grade estimation requires a thorough understanding of the internal geology, ensuring that variations across units are accounted for during exploration and evaluation.

Olivine macrocrysts, a significant component of kimberlites, provide insights into the diamond-carrying potential of magmas. In coherent kimberlites of the Lulo field, olivine content ranges between 53-54 vol.%, indicating a high proportion of mantle-derived material. Similarly, in the FPK kimberlites of the Lulo field, olivine content varies between 25-53 vol.%, reflecting the maximum mantle cargo directly correlated with the magma's ability to transport diamonds. However, this assessment remains speculative as olivine grading across the full length of boreholes has not yet been investigated in this study. Higher olivine content is generally associated with greater potential for diamond preservation and higher diamond grades (Scott Smith, 2017).

Furthermore, higher xenolith abundance in RVKs contributes to dilution, potentially lowering diamond grades compared to FPKs, which generally exhibit lower xenolith abundance. Consequently, diamond grades are often better in FPKs due to their higher concentration of olivine and lower dilution by external material. If RVK dominates the surface material, bulk sampling strategies that focus solely on surface sampling may fail

to accurately reflect the deeper diamond grades, in potentially more diamond-rich FPK layers. This again highlights the importance of considering internal geological variability due to complexities in diamond grade distribution.

The degree of sorting of olivine macrocrysts plays a critical role in determining diamond grade. Poorly sorted kimberlites display a wide range of olivine sizes and abundances, affecting diamond distribution within the pipe. Better sorting results in more consistent olivine abundances and predictable diamond grades. However, uneven sorting can lead to fluctuating diamond grades between different sections of the pipe. Borehole logs provided by Lucapa Diamond Company highlight sorting variations, ranging from poorly to well-sorted, reflecting the variable nature of with the Lulo field kimberlites. Understanding these variations offers valuable insight into diamond distribution, although, as with the olivine macrocrysts, this assessment remains speculative as sorting across the full length of boreholes has not yet been investigated in this study.

Diamond grade in kimberlite pipes is a function of olivine abundance, sorting, xenolith abundance and the intricate internal geology of the pipe. The highest diamond grades are likely to be associated with units where olivine macrocrysts are abundant and well-sorted, and where the internal complexity of the pipe is well-understood. Within the context of the Lulo Field, this can be accomplished through a comprehensive understanding of the vertical and lateral distribution of RVK and FPK within individual pipes.

Consideration for the aforementioned factors will ensure more accurate evaluations of diamond potential and provide beneficial insights for future exploration efforts.

Chapter 6: Conclusion

This study of the Lulo Kimberlite Field in Angola provides valuable insights into the geology, classification, geochemistry, and eruptive processes of the field's variety of kimberlites. The research also highlights the critical implications for diamond grade, which is of significant economic importance considering the growing global demand for diamonds, projected to expand with a compound annual growth rate of 3.0% over the next decade. The identification of over 560 geophysical anomalies and the discovery of large, high-value alluvial diamonds along the Caculo River underscore the potential for primary economic diamond deposits within this region, making a detailed understanding of kimberlite characteristics essential for effective exploration.

The Lulo field kimberlites, classified in this study as predominantly Fort à la Corne-type pyroclastic kimberlites, are marked by their clast-supported nature, evident sorting, variable abundance of olivine macrocrysts including high abundance of olivine-dominated pyrocrysts, regular to curvilinear magmaclast shapes, low xenolith content, and lastly, serpentine and, most notably, calcite-rich kimberlite groundmass and interclast matrix - all of which are key indicators of their explosive volcanic origins. The presence of magmaclasts with sharp margins, cored with olivine or xenoliths, suggests a dynamic fragmentation process during eruption, further supported by variable sorting. These units are interbedded with Resedimented Volcaniclastic kimberlites, characterized by their clast-supported nature, variable melt-bearing pyroclasts from different magma batches and intermagmaclastic matrix of predominantly extrinsic material (most commonly quartz) with serpentine and calcite-rich kimberlite groundmass and interclast matrix.

The Lulo Field kimberlites are classified as Class 3, distinguished by the interbedded nature of FPK and RVK units. This complex internal geology plays a crucial role in shaping the distribution and grade variability of diamonds. Such complexity emphasizes the need for comprehensive stratigraphic analysis to accurately assess diamond potential, as surface sampling alone may not provide a true representation of deeper diamond content.

The eruption style of the Lulo Field kimberlites is inferred to be explosive and shallow, typical of Class 3 kimberlite pipes. The preservation of primary volcanoclastic textures and the absence of vesicles in magmaclasts suggest rapid, shallow subsurface eruptions. The variety in pyroclast morphologies points to multiple fragmentation mechanisms and quick cooling. Cored magmaclasts with olivine and xenoliths, along with sharp margins and fine-grained rims, indicate rapid cooling and pyroclastic fragmentation. Incomplete rims suggest variations in cooling rates or post-emplacement alteration. Low xenolith content and high RVK abundance further support an explosive eruption driven by magmatic volatiles, with minimal incorporation of country rock. This points to an open-system pipe formation.

The Lulo Field kimberlites are comparable with Voorspoed and Lac de gras kimberlites, Voorspoed shares volcanic textures and complex internal geology with Lulo, and both fields have comparable ages (Lulo 114-140 Ma, Voorspoed 131.3 Ma). Like Lulo, Voorspoed exhibits variable diamond distribution due to its complex stratigraphy and the has shown impacts of country-rock dilution. Similarly, the Lac de Gras kimberlites also feature varying infill types, such as Massive and Resedimented Volcanoclastic Kimberlite, which is comparable to the Lulo pipe structure. These similarities emphasize the shared geological characteristics influencing diamond grade variability and exploration strategies across these regions.

Additionally, the geochemical analysis of Lulo field kimberlites reveals a strong resemblance to South African Group I Kimberlites, known for their diamondiferous nature. While notable deviations, such as depleted MgO and enriched Al_2O_3 and Nb concentrations, along with other minor deviations, suggest some degree of crustal contamination, the overall geochemical trends remain consistent with other economically significant diamond-hosting kimberlites worldwide. This alignment with well-established diamond-rich kimberlite fields, like those in South Africa, further enhances the economic potential of the Lulo field.

In conclusion, the Lulo Kimberlite Field presents a complex but potentially highly prospective target for diamond exploration. This can be attributed to a combination of its favourable geological setting, the presence of diamond-bearing alluvial deposits, and the geochemical and geological resemblance to diamond-rich worldwide kimberlites occurrences. This study emphasizes the importance of integrating detailed petrographic,

geochemical, and subsequently geological analyses to fully understand the factors that control diamond grade, which is critical for the successful development and exploitation of Angola's primary diamond resources.

References

- Al-Hajri, Y., White, N., & Fishwick, S. (2009). Scales of transient convective support beneath Africa. *Geology*, 37(10), 883–886.
- Allsopp, H. L., & Hargraves, R. B. (1985). Rb-Sr ages and palaeomagnetic data for some Angolan alkaline intrusives. *Transactions of the Geological Society of South Africa*, 88(2), 295–299.
- Bain & Company. (2014). *Strong origins: current perspectives on the diamond industry*.
- Bain & Company. (2021). *The Global Diamond Industry 2021–22*.
- Clement, C. R. (1982). *A comparative geological study of some major kimberlite pipes in the Northern Cape and Orange Free State*. University of Cape Town.
- De Araujo, A. G., & Perevalov, O. V. (1998). Carta de recursos minerais – Mineral Resources Map. *Ministério Geol. e Minas. Inst. Geol. Angola, Luanda*.
- De Araujo, A. G., Perevalov, O. V., & Jukov R.A. (1988). Carta geológica de Angola – Geological Map of Angola. Scale 1 : 1 000 000. *Ministério Da Indústria. Inst. Nac. Geol., Luanda*.
- De Carvalho, H., Tassinari, C., & Alves, P. H. (2000). Geochronological review of the Precambrian in western Angola: links with Brazil. *J. Afr. Earth Sci.*, 31((2)), 383–402.
- De Carvalho, H., Tassinari, C., Alves, P. M., Guimarães, F., & Simões, M. C. (2000). Geochronological review of the Precambrian in western Angola: links with Brazil. *Journal of African Earth Sciences*, 31(2), 383–402.
[https://doi.org/10.1016/S0899-5362\(00\)00095-6](https://doi.org/10.1016/S0899-5362(00)00095-6)
- Egorov, K. N., Roman'ko, E. F., Podvysotsky, V. T., Sablukov, S. M., Garanin, V. K., & D'yakonov, D. B. (2007). New data on kimberlite magmatism in southwestern Angola. *Russian Geology and Geophysics*, 48(4), 323–336.
- Elvira, S., & Cruz, R. (2012). Kimberlites associated with the Lucapa structure, Angola. www.tdx.cat
- Fedortchouk, Y. (2019). A new approach to understanding diamond surface features based on a review of experimental and natural diamond studies. In *Earth-Science Reviews* (Vol. 193, pp. 45–65). Elsevier B.V.
<https://doi.org/10.1016/j.earscirev.2019.02.013>

- Field, M., Stiefenhofer, J., Robey, J., & Kurszlauskis, S. (2008). Kimberlite-hosted diamond deposits of southern Africa: A review. *Ore Geology Reviews*, 34(1–2), 33–75. <https://doi.org/10.1016/j.oregeorev.2007.11.002>
- Giuliani, A., Campeny, M., Kamenetsky, V. S., Afonso, J. C., Maas, R., Melgarejo, J. C., Kohn, B. P., Matchan, E. L., Mangas, J., Gonçalves, A. O., & Manuel, J. (2017). Southwestern Africa on the burner: Pleistocene carbonatite volcanism linked to deep mantle upwelling in Angola. *Geology*, 45(11), 971–974. <https://doi.org/10.1130/G39344.1>
- Globig, J., Fernández, M., Torne, M., Vergés, J., Robert, A., & Faccenna, C. (2016). New insights into the crust and lithospheric mantle structure of Africa from elevation, geoid, and thermal analysis. *Journal of Geophysical Research: Solid Earth*, 121(7), 5389–5424. <https://doi.org/10.1002/2016JB012972>
- Goodman, S., Bratt, M., & Brantberg, L. (2014). *Basic Materials Perspectives on the diamond industry*. mckinsey.com
- Google. (2025). *Lulo Mine, Angola*.
- Grunsky, E. C., & Kjarsgaard, B. A. (2008). Classification of distinct eruptive phases of the diamondiferous Star kimberlite, Saskatchewan, Canada based on statistical treatment of whole rock geochemical analyses. *Applied Geochemistry*, 23(12), 3321–3336. <https://doi.org/10.1016/j.apgeochem.2008.04.027>
- Guiraud, R., Bosworth, W., Thierry, J., & Delplanque, A. (2005). Phanerozoic geological evolution of Northern and Central Africa: An overview. *Journal of African Earth Sciences*, 43(1–3), 83–143. <https://doi.org/10.1016/j.jafrearsci.2005.07.017>
- Janse, B. A., & Sheahan, P. A. (1995). Catalogue of world wide diamond and kimberlite occurrences: a selective and annotative approach. In *Journal of Geochemical Exploration* (Vol. 53).
- Jelsma, H., Barnett, W., Richards, S., & Lister, G. (2009). Tectonic setting of kimberlites. *Lithos*, 112, 155–165. <https://doi.org/10.1016/j.lithos.2009.06.030>
- Jelsma, H., Krishnan, U., Perritt, S., Preston, R., Winter, F., Lemotlo, L., van der Linde, G., Armstrong, R., Phillips, D., Joy, S., Costa, J., Facatino, M., Posser, A., Kumar, M., Wallace, C., Chinn, I., & Henning, A. (2013). Kimberlites from Central Angola: A Case Study of Exploration Findings. In *Proceedings of 10th International Kimberlite Conference* (pp. 173–190). Springer India. https://doi.org/10.1007/978-81-322-1173-0_12

- Kjarsgaard, B. (2007). Kimberlite Pipe Models: Significance for Exploration. *Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration*. <https://www.researchgate.net/publication/264872972>
- Kjarsgaard, B. A. (2007). Kimberlite Diamond Deposits. *Goodfellow, W.D., Ed., Mineral Deposits of Canada: A Synthesis of Major Deposit Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: Geological Association of Canada, Mineral Deposits Division, Special Publication, 5*, 245–272.
- Le Roex, A. P., Bell, D. R., & Davis, P. (2003). Petrogenesis of group I Kimberlites from Kimberley, South Africa: Evidence from bulk-rock geochemistry. *Journal of Petrology*, 44(12), 2261–2286. <https://doi.org/10.1093/petrology/egg077>
- Lucapa Diamond Company. (2024). *Lulo Kimberlite Exploration*. <https://www.lucapa.com.au/projects/lulo/>
- Mitchell, R. H., Giuliani, A., & O'Brien, H. (2019). What is a kimberlite? Petrology and mineralogy of hypabyssal kimberlites. *Elements*, 15(6), 381–386. <https://doi.org/10.2138/GSELEMENTS.15.6.381>
- Pearson, D. G., Woodhead, J., & Janney, P. E. (2019). Kimberlites as geochemical probes of Earth's mantle. *Elements: An International Magazine of Mineralogy, Geochemistry, and Petrology*, 15(6), 387–392.
- Pereira, B., Teah, K., Sung, B., & Teah, M. (2019). Building blocks of the luxury jewellery industry: conversations with a CEO. *Asia Pacific Journal of Marketing and Logistics*, 31(4), 817–829. <https://doi.org/10.1108/APJML-10-2018-0415>
- Pereira, E., Rodrigues, J., & Reis, B. (2003). Synopsis of Lunda geology, NE Angola: Implications for diamond exploration. In *Comun.Inst. Geol. e Mineiro* (Vol. 1).
- Phillips, D., Kiviets, G. B., Barton, E. S., Smith, C. B., Viljoen, K. S., & Fourie, L. F. (1999). $^{40}\text{Ar}/^{39}\text{Ar}$ dating of kimberlites and related rocks: problems and solutions. In J. J. Gurney, J. L. Gurney, M. D. Pascoe, & S. H. Richardson (Eds.), *The Nixon Volume: Proceedings of the VIIth International Kimberlite Conference* (pp. 677–688).
- Phillips, D., Machin, K., Kiviets, G. B., Fourie, L. F., Roberts, M. A., & Skinner, E. M. W. (1998). A petrographic and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological study of the Voorspoed kimberlite, South Africa; implications for the origin of Group II kimberlite magmatism. *South African Journal of Geology*, 101, 299–306.

- Pin, C., Gannoun, A., & Dupont, A. (2014). Rapid, simultaneous separation of Sr, Pb, and Nd by extraction chromatography prior to isotope ratios determination by TIMS and MC-ICP-MS. *J. Anal. At. Spectrom.*, 29, 1858–1870.
- Ramokgaba, L., le Roex, A., & Robey, J. (2021). Phlogopite-rich and phlogopite-poor kimberlite intrusions within the Du Toitspan kimberlite pipe, South Africa: Petrogenetic relationships and localised source heterogeneity. *Lithos*, 390–391. <https://doi.org/10.1016/j.lithos.2021.106125>
- Richardson, S. H. (1986). Latter-day origin of diamonds of eclogitic paragenesis. *Nature* 322.6080, 623–626.
- Robles-Cruz, S. E., Melgarejo, J. C., Galí, S., & Escayola, M. (2012). Major- and trace-element compositions of indicator minerals that occur as macro- and megacrysts, and of xenoliths, from kimberlites in Northeastern Angola. *Minerals*, 2(4), 318–337. <https://doi.org/10.3390/min2040318>
- Rousseau, R. M., Willis, J. P., & Duncan, A. R. (1996). Practical XRF Calibration Procedures for Major and Trace Elements. *X-Ray Spectrometry*, 25(4), 179–189. [https://doi.org/10.1002/\(SICI\)1097-4539\(199607\)25:4<179::AID-XRS162>3.0.CO;2-Y](https://doi.org/10.1002/(SICI)1097-4539(199607)25:4<179::AID-XRS162>3.0.CO;2-Y)
- Sarkar, C., Heaman, L. M., & Pearson, D. G. (2015). Duration and periodicity of kimberlite volcanic activity in the Lac de Gras kimberlite field, Canada and some recommendations for kimberlite geochronology. *Lithos*, 218–219, 155–166. <https://doi.org/10.1016/j.lithos.2015.01.017>
- Scott Smith, B. H. (2006). Canadian kimberlites: geological characteristics relevant to emplacement. *2006 Kimberlite Emplacement Workshop, Saskatoon, Canada*. www.8ikc.ca.
- Scott Smith, B. H. (2008a). Canadian kimberlites: Geological characteristics relevant to emplacement. *Journal of Volcanology and Geothermal Research*, 174(1–3), 9–19. <https://doi.org/10.1016/j.jvolgeores.2007.12.023>
- Scott Smith, B. H. (2008b). The Fort à la Corne Kimberlites, Saskatchewan, Canada: Geology, Emplacement and Economics. In *JOURNAL GEOLOGICAL SOCIETY OF INDIA* (Vol. 71).
- Scott Smith, B. H. (2017). Kimberlites – from Mantle to Mine. *11th International Kimberlite Conference Extended Abstract No. 11IKC-4914*.
- Scott Smith, B. H., & Field, M. (1999). Contrasting geology and near-surface emplacement of kimberlite pipes in southern Africa and Canada. In J. J. Gurney

(Ed.), *Proceedings of the 7th International Kimberlite Conference* (Vol. 1, pp. 214–237). Red Roof Design.

Scott Smith, B. H., Russell, J. K., & Webb, K. J. (2018). *A Glossary of Kimberlite and Related Terms*. www.scottsmithpetrology.com

Skinner, E. M. W. (2008). The emplacement of class 1 kimberlites. *Journal of Volcanology and Geothermal Research*, 174(1–3), 40–48.
<https://doi.org/10.1016/j.jvolgeores.2007.12.022>

Skinner, E. M. W., & Marsh, J. S. (2004). Distinct kimberlite pipe classes with contrasting eruption processes. *Lithos*, 76(1–4 SPEC. ISS.), 183–200.
<https://doi.org/10.1016/j.lithos.2004.03.044>

Smith, C. B. (1983). Pb, Sr and Nd isotopic evidence for sources of southern African Cretaceous kimberlites. *Nature*, 304, 51–54.

Sparks, R. S. J., Baker, L., Brown, R. J., Field, M., Schumacher, J., Stripp, G., & Walters, A. (2006). Dynamical constraints on kimberlite volcanism. *Journal of Volcanology and Geothermal Research*, 155(1–2), 18–48.
<https://doi.org/10.1016/j.jvolgeores.2006.02.010>

Stachel, T., & Luth, R. W. (2015). Diamond formation - Where, when and how? In *Lithos* (Vols. 220–223, pp. 200–220). Elsevier.
<https://doi.org/10.1016/j.lithos.2015.01.028>

Sun, Y., Jiang, S., & Wang, S. (2024). The environmental impacts and sustainable pathways of the global diamond industry. *Humanities and Social Sciences Communications*, 11(1). <https://doi.org/10.1057/s41599-024-03195-y>

Tanaka, T., Togashi, S., Kamioka, H., Amakawa, H., Kagami, H., Hamamoto, T., Yuhara, M., Orihashi, Y., Yoneda, S., Shimizu, H., Kunimaru, T., Takahashi, K., Yanagi, T., Nakano, T., Fujimaki, H., Shinjo, R., Asahara, Y., Tanimizu, M., & Dragusanu, C. (2000). JNdi-1: a neodymium isotopic reference in consistency with LaJolla neodymium. In *Chemical Geology* (Vol. 168). www.elsevier.com/locate/chemgeo

Wagner, P. A. (1914). The Diamond Fields of South Africa. *Transvaal Leader*, 347.

Waight, T., Baker, J., & Peate, D. (2002). Sr isotope ratio measurements by double-focusing MC-ICPMS: techniques, observations and pitfalls. *Int. J. Mass Spectrom*, 221, 229–244.

Walker, R. T., Telfer, M., Kahle, R. L., Dee, M. W., Kahle, B., Schwenninger, J. L., Sloan, R. A., & Watts, A. B. (2016). Rapid mantle-driven uplift along the

Angolan margin in the late Quaternary. *Nature Geoscience*, 9(12), 909–914.
<https://doi.org/10.1038/ngeo2835>

Webb, K., & Hetman, C. (2021). Magmaclasts in kimberlite. *Lithos*, 396–397.
<https://doi.org/10.1016/j.lithos.2021.106197>

Appendix A

Table 13: List of pipes, depths and number of thin sections

Pipe	Depth from (m)	Depth to (m)	Number of thin sections
L008	16.02	65.73	3
L009	23.73	96.74	5
L010	51.74	102.19	4
L011	38.40	91.47	2
L013	19.00	63.00	9
L014	13.00	73.00	8
L015	21.00	87.00	9
L018	12.00	40.00	7
L020	70.62	70.75	1
L021	89,79	89,91	1
L022	51.19	84.84	2
L025	64,96	108,41	2
L026	55,48	102,45	2
L027	48,19	48,3	1
L028	85.00	86,9	2
L029	88,65	88,78	1
L030	76,38	76,5	1
L031	37,08	37,16	1
L032	34,5	86,84	2
L033	78,55	78,74	1
L034	75,08	75,21	1
L047	35,74	36,04	1
L048	16.33	202.03	7
L050	32.00	84.07	7
L052	62,24	62,5	1
L054	46.6	96.97	2

L060	69,58	69,74	1
L071	45,03	45,12	1
L072	37,82	37,95	1
L090	55,27	91,94	2
L104	45,79	175,98	2
L116	65,4	65,52	1
L124	97,78	97,88	1
L125	63,07	63,17	1
L167	52,13	52,25	1
L171	5,00	23,00	4
L177	52,69	52,82	1
L204	89,43	89,73	1
L218	29,00	60,3	2
L219	35,67	35,79	1
L221	56,36	56,66	1
L232	51,87	52,12	1
L233	102,27	102,47	1
L241	78,57	78,69	1
L242	14,00	47,00	10
L248	45	90,15	2
L252	34,00	57,00	4
L254	53,00	98,15	6
L255	37	95,15	2
L256	54,78	54,95	1
L275	29,00	95,15	4
E217	20,00	71,00	5

Appendix B

Table 14: List of 83 thin sections obtained from the Lulo kimberlite field

Sample Name	Pipe no.	Depth from (m)	Depth to (m)	Classification	Description
HJ/009/01/23P	L009	23,73	23,86	RVK	A clastic textured section that is quartz-rich and consists of a variety of amoeboidal fine - coarse magmaclasts.
HJ/009/01/33P	L009	33,74	33,86	Sandstone	A clastic textured section that is predominantly quartz - kimberlite absent.
HJ/009/01/45P	L009	45,82	45,93	RVK	A clastic textured section that is quartz-rich and consists of a variety of irregular to curvilinear fine - medium magmaclasts.
HJ/009/01/96P-A	L009	96,6	96,74	PK	A predominantly altered, volcanoclastic textured section with altered olivine and a serpentine and calcite-rich matrix.
HJ/009/01/96P-B	L009	96,6	96,74	RVK	A clastic textured section containing minor quartz with predominantly macrocrystic olivine set in a serpentine matrix. Fine - coarse magmaclasts are present with few layered magmaclasts within the coarse varieties.
HJ/010/01/51P	L010	51,74	51,89	RVK	A clastic textured section that is quartz-rich and consists of a variety of irregular to curvilinear fine - medium magmaclasts.
HJ/010/01/90P	L010	90,58	90,7	Sandstone	A clastic textured section that is predominantly quartz - kimberlite absent.
HJ/010/01/95P	L010	95,05	95,18	Sandstone	A clastic textured section that is predominantly quartz - kimberlite absent.
HJ/010/01/102P	L010	102,09	102,19	RVK	A clastic textured section that is quartz-rich and consists of a variety of irregular to curvilinear fine - medium magmaclasts.
HJ/011/01/38P	L011	38,4	38,51	RVK	A clastic textured section that is quartz-rich with a chlorite and serpentine dominated alteration texture.
HJ/011/01/91P	L011	91,36	91,47	RVK	A clastic textured section that is rich in quartz with a variety of magmaclasts within a serpentine dominated matrix.

HJ/026/02/55P	L026	55,48	55,59	Coherent	A coherent textured section that is rich in altered olivine with equally distributed opaque and perovskite.
HJ/026/02/102P	L026	102,36	102,45	Coherent	A coherent textured section that is rich in fresh olivine with equally distributed opaque and perovskite.
HJ/241/01/78P	L241	78,57	78,69	RVK	A clastic textured section that is quartz and magmaclast-rich within a serpentine matrix.
HJ/275/01/29P	L275	29	29,15	PK	A volcanoclastic textured section, containing altered subhedral olivine rimmed with fine-grained kimberlitic material - in addition to subhedral opaque oxides set in a serpentine-calcite matrix
HJ/275/01/64P	L275	64	64,15	PK	A volcanoclastic textured section, mostly serpentinized, making it hard to characterize with certainty.
HJ/275/01/95P	L275	95	95,15	PK	A volcanoclastic textured section, mostly serpentinized, making it hard to characterize with certainty.
HJ/275/01/109P	L275	9	9,15	RVK	A clastic textured section, containing abundant subhedral quartz grains and altered olivine, set in a calcite matrix and largely serpentinized.
HJ/050/01/45P	L050	45	45,15	Coherent	A coherent textured section, containing equally distributed subhedral opaque oxides and almost fully serpentinized olivine phenocrysts, set in a serpentine matrix.
RS/050/03/32P	L050	32	32,15	Coherent	A coherent textured section, containing equally distributed subhedral opaque oxides and almost fully serpentinized olivine phenocrysts, set in a serpentine matrix.
HJ/255/02/95P	L255	95	95,15	MVK	A massive volcanoclastic textured section, containing large magmaclasts, crustal xenoliths, and partially serpentinized olivine phenocrysts set in a serpentine matrix.
HJ/255/02/37P	L255	37	37,15	PK	A volcanoclastic textured section, containing olivine grains with phlogopite alteration and serpentine alteration.
HJ/248/08/90P	L248	90	90,15	RVK	A clastic textured section, mostly serpentinized, making it hard to characterize with certainty.
HJ/248/08/45P	L248	45	45,15	RVK	A clastic textured section, mostly serpentinized, making it hard to characterize with certainty.

RS/254/01/53P	L254	53	53,15	Coherent	A coherent textured section, containing equally distributed subhedral opaque oxides with almost fully-serpentinized olivine phenocrysts, set in a fine-grained serpentine-chlorite matrix.
RS/254/01/55P	L254	55	55,15	Coherent	A coherent textured section, containing equally distributed subhedral opaque oxides with serpentinized olivine, with prominent chlorite alteration and xenocrysts.
RS/254/01/19P	L254	19	19,15	Coherent	A coherent textured section, containing equally distributed subhedral opaque oxides with serpentinized olivine and fresh olivine grains, set in a brown serpentine-chlorite matrix.
RS/254/02/45P	L254	45	45,15	Sandstone	A clastic textured section that is predominantly quartz - kimberlite absent.
RS/254/02/63P	L254	63	63,15	MVK	A massive volcanoclastic textured section, mostly serpentinized, making it hard to characterize with certainty.
RS/254/02/98P	L254	98	98,15	MVK	A massive volcanoclastic textured section, containing large, subhedral green phlogopite, and partially serpentinized olivine phenocrysts, set in a serpentine matrix.
HJ/027/01/48P	L027	48,19	48,3	PK	A volcanoclastic textured section, containing altered subhedral olivine rimmed with fine-grained kimberlitic material, and subhedral opaque oxides set in a serpentine-calcite matrix.
RS/124/02/97P	L124	97,78	97,88	MVK	A massive volcanoclastic textured section, containing subhedral, partially serpentinized olivine phenocrysts set in a serpentine matrix, along with crustal xenoliths.
HJ/090/02/55P	L090	55,27	55,44	Coherent	A coherent textured section, containing equally distributed subhedral opaque oxides, euhedral perovskite, and almost fully-serpentinized olivine phenocrysts set in a brown serpentine-chlorite matrix.
HJ/090/02/91P	L090	91,76	91,94	Coherent	A coherent textured section, containing equally distributed subhedral opaque oxides, euhedral perovskite, and almost fully-serpentinized olivine phenocrysts set in a brown serpentine-chlorite matrix.
HJ/233/01/102P	L233	102,27	102,47	PK	A volcanoclastic textured section, containing coarse-grained subhedral olivine rimmed with fine-grained kimberlitic material, and subhedral opaque oxides. Xenocrysts are abundant.
HJ/116/01/65P	L116	65,4	65,52	PK	A volcanoclastic textured section, highly altered, containing serpentinized olivine and large xenocrysts. Perovskite is abundant.

RS/125/01/63P	L125	63,07	63,17	Coherent	A coherent textured section, containing equally distributed subhedral opaque oxides and almost fully-serpentinized olivine phenocrysts, set in a brown serpentine-chlorite matrix.
HJ/218/01/29P	L218	29	29,9	PK	A volcanoclastic textured section, containing coarse-grained subhedral olivine rimmed with fine-grained kimberlitic material, subhedral opaque oxides, and phlogopite alteration.
HJ/218/01/60P	L218	60,19	60,3	PK	A volcanoclastic textured section, where glue is present, making it hard to characterize with certainty.
HJ/050/08/32P	L050	32	32,2	PK	A volcanoclastic textured section, containing magmaclasts and altered quartz, with high degrees of alteration.
HJ/050/08/45P	L050	45,39	45,69	PK	A volcanoclastic textured section, containing large amoeboidal magmaclasts and altered quartz, with high degrees of alteration.
HJ/050/08/52P	L050	52	52,24	PK	A volcanoclastic textured section, where glue is present, making it hard to characterize with certainty.
HJ/050/08/67P	L050	67,5	67,77	PK	A volcanoclastic textured section, where glue is present, making it hard to characterize with certainty.
HJ/050/08/83P	L050	83,77	84,07	PK	A volcanoclastic textured section, where glue is present, making it hard to characterize with certainty.
RS/008/02/16P	L008	16,02	16,22	PK	A volcanoclastic textured section, containing altered subhedral olivine rimmed with fine-grained kimberlitic material, and subhedral opaque oxides set in a serpentine-calcite matrix.
RS/008/02/34P	L008	34,31	34,53	PK	A volcanoclastic textured section, containing altered subhedral olivine rimmed with fine-grained kimberlitic material, and subhedral opaque oxides set in a serpentine-calcite matrix.
RS/008/02/65P	L008	65,47	65,73	PK	A volcanoclastic textured section, containing altered subhedral olivine rimmed with fine-grained kimberlitic material, and subhedral opaque oxides set in a serpentine-calcite matrix.
HJ/048/02/16P	L048	16,33	16,54	MVK	A massive volcanoclastic textured section, badly preserved, making it hard to characterize with certainty.
HJ/048/02/43P	L048	43,71	43,96	MVK	A massive volcanoclastic textured section, where glue is present, making it hard to characterize with certainty.
HJ/048/02/59P	L048	59,34	59,47	PK	A volcanoclastic textured section, containing serpentinized olivine and a large mantle xenocryst set in a serpentine-calcite matrix.

HJ/048/02/106P	L048	106,63	106,85	PK	A volcanoclastic textured section, containing a high abundance of phlogopite, subhedral olivine grains with kimberlitic rim, and a large mantle xenocryst.
HJ/048/02/127P	L048	127,72	127,95	PK	A volcanoclastic textured section, containing a high abundance of phlogopite, subhedral olivine grains with kimberlitic rim, and a large mantle xenocryst.
HJ/048/02/180P	L048	180,02	180,23	PK	A volcanoclastic textured section, highly altered to carbonate and serpentine, containing a high abundance of phlogopite and subhedral olivine grains with kimberlitic rims.
RS/204/03/89P	L204	89,43	89,73	PK	A volcanoclastic textured section, with broken olivine grains and amoeboidal magmaclasts.
SLT208514-061	-	-	-	Coherent	A coherent textured section, containing equally distributed subhedral opaque oxides and subhedral macro- and microcrysts of olivine, set in a serpentine-calcite matrix.
HJ/054/01/46P	L054	46,6	46,88	PK	A volcanoclastic textured section, containing altered macro- and microcrystic subhedral olivine, rimmed with fine-grained kimberlitic material, and subhedral opaque oxides set in a serpentine matrix.
HJ/054/01/96P	L054	96,74	96,97	PK	A volcanoclastic textured section, containing altered macro- and microcrystic subhedral olivine, rimmed with fine-grained kimberlitic material, and magmaclasts containing serpentized olivine, perovskite, and spinel.
RS/221/01/56P	L221	56,36	56,66	PK	A volcanoclastic textured section, xenolith-poor, with very fine to coarse olivine-rich matrix. Opaque minerals are associated with olivine and magmaclasts.
HJ/104/02/175P	L104	175,77	175,98	PK	A volcanoclastic textured section, containing a high abundance of phlogopite and subhedral olivine grains with kimberlitic rims.
HJ/052/02/62P	L052	62,24	62,5	MVK	A massive volcanoclastic textured section, containing subhedral, partially serpentized olivine phenocrysts set in a serpentine matrix, with abundant opaques and crustal xenoliths.
HJ/232/02/51P	L232	51,87	52,12	PK	A volcanoclastic textured section, highly altered, containing predominantly microcrystic quartz.

RS/256/01/54P	L256	54,78	54,95	MVK	A massive volcanoclastic textured section, containing subhedral olivine phenocrysts set in a serpentine matrix, and rich in opaque minerals.
HJ/047/04/35P	L047	35,74	36,04	RVK	A clastic textured section, very quartz-rich with an interstitial matrix of serpentinized olivine.
RS/167/01/52P	L167	52,13	52,25	RVK	A clastic textured section, containing abundant subhedral quartz grains with subhedral, altered olivine set in a calcite matrix. Abundant opaques and magmaclasts containing laths of calcite.
RS/031/01/37P	L031	37,08	37,16	RVK	A clastic textured section with abundant quartz and altered olivine. The section is very altered with brown material present throughout.
RS/177/01/52P	L177	52,69	52,82	PK	A volcanoclastic textured section, containing altered subhedral olivine rimmed with fine-grained kimberlitic material, along with subhedral opaque oxides set in a serpentine matrix.
RS/071/01/45P	L071	45,03	45,12	RVK	A clastic textured section, containing abundant subhedral quartz grains with subhedral, altered olivine set in a calcite matrix. Abundant xenocrysts.
RS/072/01/37P	L072	37,82	37,95	MVK	A massive volcanoclastic textured section, containing sub-euhedral, partially serpentinized olivine phenocrysts set in a serpentine matrix. Includes a variety of crustal xenoliths.
HJ/022/02/84P	L022	84,73	84,84	RVK	A clastic textured section with abundant opaques, quartz, and altered olivine. Large xenocrysts present alongside coarse-grained phlogopite.
HJ/022/02/51P	L022	51,19	51,32	RVK	A clastic textured section with abundant opaques, quartz, and altered olivine. Large xenocrysts present alongside coarse-grained phlogopite.
HJ/219/02/35P	L219	35,67	35,79	PK	A volcanoclastic textured section, containing broken olivine grains largely associated with opaques, all set in a calcite matrix.
HJ/025/01/108P	L025	108,34	108,41	MVK	A massive volcanoclastic textured section, containing sub-euhedral, fully altered olivine phenocrysts set in a serpentine matrix. Glue present, making it hard to describe with certainty.
HJ/021/01/89P	L021	89,79	89,91	PK	A volcanoclastic textured section, containing sub-euhedral olivine grains set in a serpentine matrix.
HJ/025/01/64P	L025	64,96	65,08	MVK	A massive volcanoclastic textured section, containing sub-euhedral, fully altered olivine phenocrysts set in a serpentine matrix. Very altered.

HJ/020/01/70P	L020	70,62	70,75	RVK	A clastic textured section with abundant opaques, fine-grained quartz, and altered olivine. Highly serpentinized.
HJ/034/01/75P	L034	75,08	75,21	PK	A volcanoclastic textured section, containing almost completely serpentinized macro- and microcrystic subhedral olivine rimmed with fine-grained kimberlitic material, alongside abundant xenocrysts set in a calcite matrix.
HJ/033/01/78P	L033	78,55	78,74	RVK	A clastic textured section with abundant opaques, quartz, and altered olivine. Large magmaclasts present.
HJ/032/01/34P	L032	34,5	34,59	PK	A volcanoclastic textured section, containing altered macro- and microcrystic subhedral olivine, rimmed with fine-grained kimberlitic material, and magmaclasts containing serpentinized olivine, abundant perovskite, and spinel.
HJ/032/01/86P	L032	86,73	86,84	PK	A volcanoclastic textured section, containing altered macro- and microcrystic subhedral olivine, rimmed with fine-grained kimberlitic material, and magmaclasts containing serpentinized olivine, abundant perovskite, and spinel.
HJ/030/01/76P	L030	76,38	76,5	PK	A volcanoclastic textured section, containing almost completely serpentinized macro- and microcrystic subhedral broken olivine grains rimmed with fine-grained kimberlitic material, alongside abundant magmaclasts containing microcrysts of olivine all set in serpentine.
RS/028/01/86P	L028	86,81	86,9	MVK	A massive volcanoclastic textured section, containing highly altered olivine and abundant xenocrysts. Minor quartz and phlogopite.
RS/028/01/85P	L028	-	-	MVK	A massive volcanoclastic textured section, containing highly altered olivine and abundant xenocrysts. Minor quartz and phlogopite.
HJ/060/01/69P	L060	69,58	69,74	PK	A volcanoclastic textured section with sub-euhedral olivine and coarse magmaclasts.

Appendix C

Table 15: Table showing the measured major element composition (wt.%)

Major element	Unit	RS050-03-32P	RS254-01-53P	RS125-01-63P	RS254-01-19P	HH050-01-045P	HJ026-02-055P	HJ026-02-102P
SiO ₂	wt.%	28,48	23,10	18,13	28,26	28,90	30,83	30,98
TiO ₂	wt.%	4,99	3,35	0,92	3,83	4,73	3,97	4,25
Al ₂ O ₃	wt.%	5,06	4,76	1,44	4,51	4,81	2,79	3,07
Fe ₂ O ₃	wt.%	17,18	13,87	14,49	15,98	16,13	15,72	14,93
MnO	wt.%	0,23	0,16	0,26	0,30	0,25	0,20	0,20
MgO	wt.%	20,27	15,00	18,12	20,18	21,79	23,77	23,45
CaO	wt.%	6,18	14,83	21,27	12,88	7,39	5,76	9,91
Na ₂ O	wt.%	0,14	0,18	0,05	0,02	0,08	0,02	0,50
K ₂ O	wt.%	0,02	0,25	0,04	0,19	0,20	0,81	1,21
P ₂ O ₅	wt.%	1,39	1,73	2,02	1,74	1,58	1,25	1,24
SO ₃	wt.%	0,02	0,02	0,01	0,14	0,05	0,00	0,05
Cr ₂ O ₃	wt.%	0,11	0,11	0,01	0,12	0,11	0,10	0,10
NiO	wt.%	0,05	0,05	0,04	0,06	0,05	0,09	0,09
H ₂ O	wt.%	6,88	6,56	1,60	1,72	4,21	4,43	1,46
LOI	wt.%	8,22	14,81	20,61	8,95	8,59	9,41	7,65
Sum	wt.%	99,24	98,78	99,00	98,87	98,88	99,15	99,10

Table 16: Table showing the measured XRF trace elements (ppm)

XRF trace elements	Unit	RS050-03-32P	RS254-01-53P	RS125-01-63P	RS254-01-19P	HH050-01-045P	HJ026-02-055P	HJ026-02-102P
Zn	ppm	94,3	93,5	87,5	108,5	94,3	86,7	81,6

Cu	ppm	84,9	90,7	26,6	69,8	115,8	136,6	134,7
Ni	ppm	436,9	346,8	226,3	419,0	404,6	800,4	710,0
Mo	ppm	<5	<5	<5	<5	<5	<5	<5
Nb	ppm	248,8	247,4	246,0	297,4	248,2	97,6	111,4
Zr	ppm	514,1	284,8	292,1	311,5	526,3	201,3	174,4
Y	ppm	34,6	29,2	23,9	29,4	20,4	<5	<5
Sr	ppm	793,0	939,1	1054,5	1365,3	1256,5	424,8	692,4
Rb	ppm	11,5	23,1	11,8	41,1	34,0	70,6	126,5
U	ppm	<5	6,5	6,0	13,1	8,4	<5	9,3
Th	ppm	25,3	23,2	29,1	23,4	20,6	13,3	11,7
Pb	ppm	31,2	34,1	38,7	29,4	30,0	31,7	31,6
Co	ppm	124,7	105,6	87,9	110,3	121,3	144,0	139,2
Mn	ppm	2164,0	1676,3	2506,1	2804,9	2464,1	1846,8	1833,4
Cr	ppm	736,2	636,6	66,4	692,4	754,2	675,2	736,6
V	ppm	140,5	285,0	142,0	226,8	277,1	161,4	252,2
F	ppm	1186,4	1979,5	1910,1	1397,8	1463,7	1435,1	1730,9
S	ppm	127,3	148,0	101,1	609,2	281,2	86,2	302,5
Cl	ppm	26,0	12,9	64,6	159,7	35,9	59,0	51,7
Sc	ppm	23,8	27,5	23,8	24,7	22,7	14,5	15,5
Ba	ppm	567,9	1104,7	494,3	1394,9	1652,4	689,2	721,9

Table 17: Table showing the measured LA-ICP-MS trace elements (ppm)

LA-ICP-MS trace elements	Unit	RS050-03-32P	RS254-01-53P	RS125-01-63P	RS254-01-19P	HH050-01-045P	HJ026-02-055P	HJ026-02-102P
Li	ppm	122,8	223,9	29,4	60,7	194,1	9,4	5,6
Sc	ppm	29,3	29,4	23,6	33,3	28,0	15,2	15,7
V	ppm	96,2	258,8	168,3	201,0	243,0	146,7	230,5

Cr	ppm	772,7	755,4	74,5	765,1	732,4	657,1	674,4
Co	ppm	82,5	67,3	65,1	76,1	77,6	89,9	92,4
Ni	ppm	432,3	360,8	262,9	408,9	363,2	735,1	718,1
Cu	ppm	88,2	104,9	26,6	69,4	137,7	140,2	162,1
Zn	ppm	144,0	124,1	116,8	142,2	136,6	108,5	107,3
Rb	ppm	3,9	18,6	3,9	39,3	29,0	65,4	127,7
Sr	ppm	889,1	1087,3	1134,4	1504,3	1443,7	465,5	793,5
Y	ppm	36,3	39,2	30,9	40,9	33,4	16,3	17,4
Zr	ppm	624,3	372,9	421,5	423,1	603,1	230,8	209,0
Nb	ppm	265,2	262,7	258,3	307,7	240,1	110,5	120,7
Ba	ppm	343,3	1110,4	648,5	1494,8	1626,2	530,4	593,2
La	ppm	202,0	206,0	197,4	228,6	183,5	75,6	82,1
Ce	ppm	405,6	375,5	361,5	453,7	375,0	149,6	161,5
Pr	ppm	46,3	43,4	39,6	50,6	44,0	18,5	19,8
Nd	ppm	160,0	139,8	124,4	163,6	147,1	62,7	68,5
Sm	ppm	28,8	25,8	21,1	29,8	27,0	11,3	12,0
Eu	ppm	7,6	7,4	6,4	8,6	7,4	3,1	3,4
Tb	ppm	2,4	2,3	1,9	2,6	2,3	1,1	1,1
Gd	ppm	18,9	18,6	15,9	20,9	17,8	8,0	8,7
Dy	ppm	9,5	9,4	8,0	10,4	9,3	4,3	4,4
Ho	ppm	1,6	1,5	1,2	1,7	1,5	0,7	0,7
Er	ppm	3,6	3,5	2,9	3,8	3,5	1,6	1,7
Tm	ppm	0,4	0,4	0,3	0,4	0,4	0,2	0,2
Yb	ppm	2,1	2,1	1,6	2,2	2,0	0,9	0,9
Lu	ppm	0,3	0,3	0,2	0,3	0,3	0,1	0,1
Hf	ppm	15,2	8,7	9,5	9,5	14,6	5,7	5,5
Ta	ppm	14,5	12,5	9,8	15,0	13,7	8,1	9,1
Pb	ppm	6,4	10,4	16,5	5,8	6,6	3,4	4,0
Th	ppm	23,1	24,1	24,1	29,3	22,0	7,5	8,2

U	ppm	6,9	9,0	7,0	8,6	6,2	1,8	2,0
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Table 18: (a) Table showing the measured $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios with the epsilon Nd (t) value (b) Table showing the natural occurrences (%) of isotopes: ^{86}Sr , ^{87}Rb , ^{147}Sm , and ^{144}Nd (c) Table showing the calculated ppm of ^{86}Sr , ^{87}Rb , ^{147}Sm , and ^{144}Nd based on Sr, Rb, Sm and Nd values in Table 17 and natural occurrences in Table 18b (d) Table showing the initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios calculated using: $^{87}\text{Sr}/^{86}\text{Sr}$ measured = $^{87}\text{Sr}/^{86}\text{Sr}$ initial + $(^{87}\text{Rb}/^{86}\text{Sr})(e^{\gamma t} - 1)$, and $^{143}\text{Nd}/^{144}\text{Nd}$ measured = $^{143}\text{Nd}/^{144}\text{Nd}$ initial + $(^{147}\text{Sm}/^{144}\text{Nd})(e^{\gamma t} - 1)$, respectively with $\gamma = 1,42\text{E-}11$ and $t = 135\,000\,000$.

(a) Isotope ratio (measured) and epsilon Nd	Unit	RS050-03-32P	RS254-01-53P	RS125-01-63P	RS254-01-19P	HH050-01-045P	HJ026-02-055P	HJ026-02-102P
$^{87}\text{Sr}/^{86}\text{Sr}$ measured	ppm	0,70423	0,70497	0,70365	0,70309	0,70355	0,70405	0,70353
$^{143}\text{Nd}/^{144}\text{Nd}$ measured	ppm	0,51267	0,51267	0,51264	0,51269	0,51267	0,51266	0,51264
Epsilon Nd	t	3,81	3,93	3,40	4,24	3,89	3,74	3,40

(b) Naturally occurring isotope	Unit	
^{86}Sr	%	9,86
^{87}Rb	%	27,80
^{147}Sm	%	15,00
^{144}Nd	%	23,80

(c) Isotope (ppm)	RS050-03-32P	RS254-01-53P	RS125-01-63P	RS254-01-19P	HH050-01-045P	HJ026-02-055P	HJ026-02-102P
^{86}Sr	87,66	107,20	111,85	148,33	142,34	45,90	78,24
^{87}Rb	1,10	5,18	1,07	10,93	8,06	18,19	35,50
^{147}Sm	4,33	3,87	3,17	4,47	4,05	1,69	1,80
^{144}Nd	38,09	33,28	29,60	38,93	35,00	14,93	16,29

(d) Isotope ratio (initial)	RS050-03-32P	RS254-01-53P	RS125-01-63P	RS254-01-19P	HH050-01-045P	HJ026-02-055P	HJ026-02-102P
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$^{87}\text{Sr}/^{86}\text{Sr}_0$	0,70421	0,70487	0,70363	0,70295	0,70344	0,70329	0,70266
$^{143}\text{Nd}/^{144}\text{Nd}_0$	0,51245	0,51245	0,51244	0,51247	0,51245	0,51244	0,51243