

**MARGINAL FACIES AND COMPOSITIONAL EQUIVALENTS OF BUSHVELD
PARENTAL SILLS FROM THE MOLOPO FARMS COMPLEX LAYERED INTRUSION,
BOTSWANA: PETROGENETIC AND MINERALIZATION IMPLICATIONS**

by

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**A Thesis Submitted to the College of Sciences in Partial Fulfilment of the Requirements for the
Award of the Degree of Master of Science in Geology of BIUST**

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November, 2017

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CERTIFICATION

The undersigned certifies that he has read and hereby recommends for acceptance by the College of Sciences a dissertation/thesis titled: Marginal facies and compositional equivalents of Bushveld parental sills from the Molopo Farms Complex layered intrusion, Botswana: Petrogenetic and mineralization implications, in fulfilment of the requirements for the degree of Master of Science in Geology of the BIUST.



.....
Prof. Rajesh Hariharan

Date: ...14/11/2017.....

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Abstract

Parental magma composition to layered ultramafic to mafic intrusions are commonly studied using rocks occurring along their contact with the surrounding country rock. These include sills, dykes and/or rare chill margins. In comparison to the well-studied ~2.05 Ga Bushveld Complex layered intrusion, no study is available on the parental magma composition of the Molopo Farms Complex layered intrusion in southern Botswana. With a size, approximately $1/3^{\text{rd}}$ of the Bushveld Complex, mafic to ultramafic rocks of the Molopo Farms Complex are suggested to have formed from the same magma that formed the Bushveld rocks. Of the different drill cores available, the base of MF38 intersects the country rock. Two other drill cores, MF9 and MF11, were also logged for comparison. MF38 preserves remobilized country rock at the base, followed up by mafic (norite) to ultramafic (peridotite-pyroxenite) rocks. The norite is quench textured with elongate, skeletal, compositionally zoned orthopyroxene crystals, and contain phlogopite. Significantly, the orthopyroxene mineral chemical composition is similar to that reported for chill margins from the Bushveld Complex. Together with the remobilized country rock beneath, norite at the base of MF38 is interpreted to represent a marginal facies unit. Close similarity with whole-rock geochemical characteristics of chill margin and B1 compositions from the Bushveld Complex argues for the marginal facies norite to represent the earliest known parental magma composition to the Molopo Farms Complex. In contrast to the typical cumulate textured ultramafic rocks, a medium-grained phlogopite-bearing pyroxenite occurs higher up the stratigraphy in MF38, and is considered compositional equivalent to B1UM from the Bushveld Complex.

Geochemical exercise also indicates that the gabbro-norites from MF9 preserve compositions equivalent to B3, considered parental to differentiated end members of the Bushveld Complex. No compositional equivalent to B2 from the Bushveld Complex was observed in the Molopo Farms Complex rocks. Considering the fact that the Molopo Farms Complex is less thick than the Bushveld Complex, and it preserves mafic and ultramafic rocks showing similarity to the earliest magma (B1, B1UM and chill margins) as well as the most differentiated of the Bushveld magma (B3), it is argued that the Molopo Farms Complex evolved faster and likely did not form rocks of the Bushveld Complex, which hosts the chromite-bearing layers (known for PGE mineralization). Instead, it is argued that the Molopo Farms Complex is a better target for Cu-Ni sulphide mineralization. The studied samples, including the marginal facies unit, hosts a sulphide assemblage of pyrrhotite, pentlandite and chalcopyrite with traces of pyrite and sphalerite, the association similar to that typically found in layered mafic to ultramafic rocks.

Chapter 1

Introduction, geologic setting and objectives

1.1 Introduction – Inferring parental magma composition of layered intrusions

Parental magma composition of layered ultramafic to mafic intrusions are often inferred from fine-grained rocks occurring in the marginal portion, which separates the overlying layered intrusion from adjacent country rocks. These include chill margins/sequences, which are considered to have formed when the primary magma is rapidly emplaced into the relatively cold country rock (Wager and Brown, 1968; Huppert and Sparks, 1989; Hoover, 1989; Wilson, 2012), and sills/dykes that penetrate into the country rock (Brooks and Nielsen, 1978; Cawthorn et al., 1981; Sharpe, 1981; Barnes et al., 2010) (Fig. 1.1).

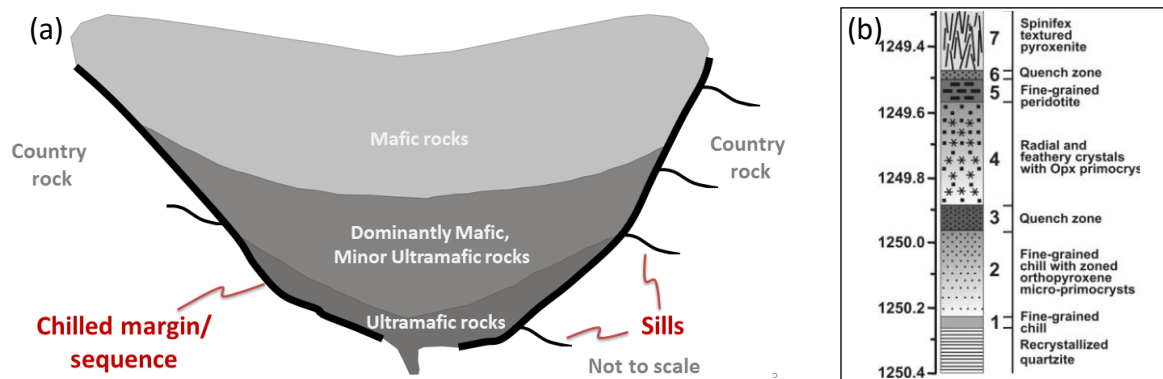


Figure 1.1. (a) Schematic diagram illustrating the importance of marginal rocks (chilled margin/sequence, sills, dykes) in inferring the parental magma composition to layered intrusion. (b) Typical rock types in a well preserved chill sequence from Bushveld Complex [from Wilson (2012)].

However, various factors often complicate the marginal rocks from representing preserved primary, unmodified composition of the parental magma during emplacement. For example, they could be contaminated by interaction of the magmas with the country rocks during emplacement and subsequent rapid cooling (e.g., Francis, 1994; Mackie et al.,

2009; Maier et al., 2016). In spite of the caveats involved in using marginal rocks (e.g., Wager and Brown, 1968; Cox et al., 1979; Hoover, 1989; Latypov et al., 2007), their identification and characterization represent an important step forward in understanding the parental composition of a layered intrusion; after all information on parental magma composition is also of paramount importance in prospecting and exploration strategies for various ore deposits [Ni-Cu sulphides, platinum group elements (PGEs)] associated with layered intrusions (e.g., Naldrett, 2004).

Southern Africa hosts two of the largest and richest (in terms of hosting mineral deposits) Proterozoic layered intrusions in the world. These are the ~2.58 Ga (Oberthür et al., 2002) Great Dyke layered intrusion (Wilson and Prendergast, 1989) within the Zimbabwe Craton and the ~2.05 Ga (Scoates and Friedman, 2008) Bushveld Complex layered intrusion (Eales and Cawthorn, 1996) within the Kaapvaal Craton (Fig. 1.2). The rocks occurring at the margins of these layered intrusions have been fairly well studied in terms of understanding the respective parental magma compositions. In spite of the limitations of obtaining access to samples from the lower portions, as the layers abut against the surrounding country rock at high angles, a fine-grained series of rocks (referred to as the Border Group) occurring towards the margin of the doubly-plunging synclinal (boat-like) structure of the Great Dyke layered intrusion has been instrumental in providing information on its parental magma composition (Fig. 1.3; Wilson and Prendergast, 1989; Wilson, 1996). Although the transverse geometry is comparable, the marginal rocks from the Bushveld Complex are better studied, with a number of studies inferring parental magma composition using marginal sills and chilled margins (Davies et al., 1980; Cawthorn et al., 1981; Sharpe, 1981; Davies and

Tredoux, 1985; Harmer and Sharpe, 1985; Sharpe and Hulbert, 1985; Barnes et al., 2010; Wilson, 2012, 2015; Maier et al., 2016).

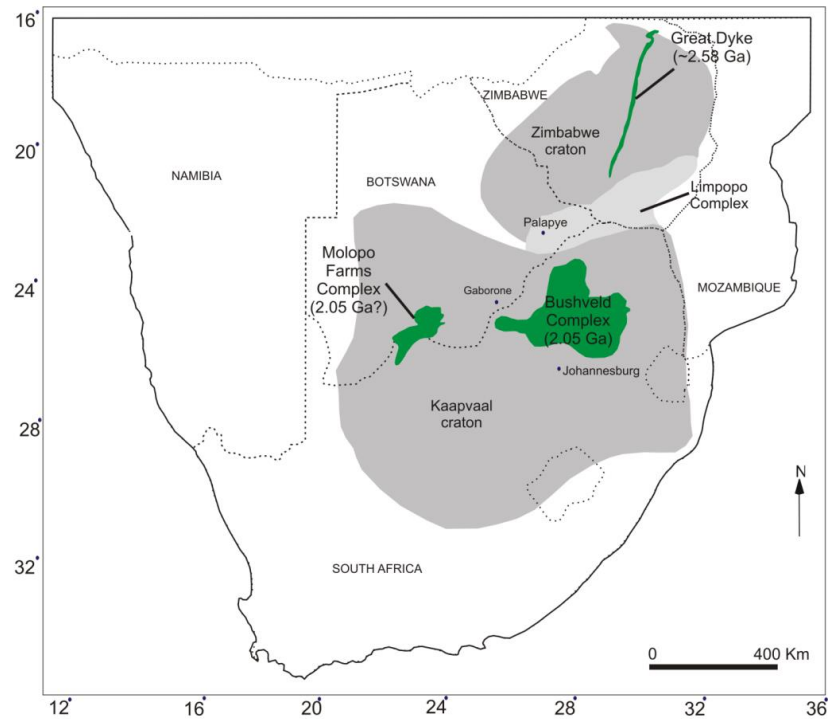


Figure 1.2. General outline of southern Africa showing the approximate location and extent of the ~2.58 Ga Great Dyke layered intrusion within the Zimbabwe Craton, and the ~2.05 Ga Bushveld Complex and Molopo Farms Complex layered intrusions within the Kaapvaal Craton [modified from Hoal et al. (1995)].

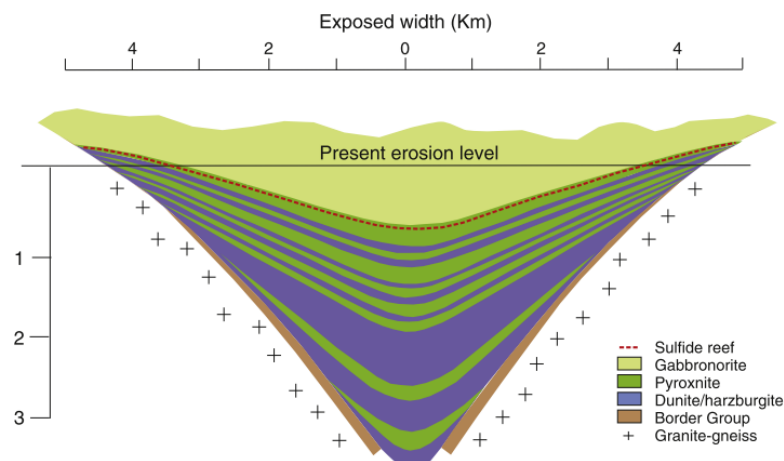


Figure 1.3. Transverse section of the Darwendale Subchamber, in the northern part of the Great Dyke layered intrusion, showing the marginal series of rocks (Border Group). Note that the dip of the layers decreases, and the layers get gradually thinner towards the margins [from Wilson and Prendergast (1989) and Maier et al. (2015)].

As shown in Figure 1.2, a third Proterozoic layered ultramafic to mafic intrusion – the Molopo Farms Complex – occurs in southern Africa. Although its size is approximately 1/3rd of the Bushveld Complex, the Molopo Farms Complex is poorly studied. Virtually no detailed petrographic and geochemical study is available in peer reviewed literature on any rock, including marginal rocks, from this layered intrusion. One of the main contributing factors to this scenario is the lack of exposures; the Molopo Farms Complex is almost entirely concealed beneath later cover, and conventional geological mapping and surface sampling are impractical (Prendergast, 2012). The present study is an initiative aimed at providing preliminary petrogenetic constraints on the Molopo Farms Complex using drill core samples.

1.2. Parental magma composition to the Bushveld Complex

Available studies, mostly carried out as part of exploration programs, have all pointed out the co-genetic relation of the Molopo Farms Complex and Bushveld Complex layered intrusions, as indicated by their geographic proximity, similar age, lithological units and country rocks, and intra-cratonic nature (Gould et al., 1987; Von Gruenewaldt et al., 1989; Reichhardt, 1994; Walker et al., 2010; Prendergast, 2012). Although less precise, the available ages, close to ~2.05 Ga (Gould et al., 1987; Kruger, 1989) from the Molopo Farms Complex supports this. Considering that the mafic to ultramafic rocks of the Molopo Farms Complex are suggested to have formed from the same magma that formed the Bushveld rocks, it is important to first summarize the pertinent geologic information on rocks, especially the marginal rocks, from the Bushveld Complex.

Covering an area of $\sim 65,000 \text{ km}^2$, the $\sim 2.054 \text{ Ga}$ (Scoates and Friedman, 2008) Bushveld Complex consists mainly of a 350 km-wide, 7- to 9-km-thick, shallowly dipping, interconnected sheet of layered ultramafic to mafic rocks (Rustenburg layered suite) (Von Gruenewaldt and Walraven, 1980; Eales and Cawthorn, 1996), marginal ultramafic to mafic sills and intrusions associated with the layered suite (Sharpe, 1981; Barnes et al., 2010), and a 2.5-km thick sequence of granitoids (Rashoop granophyre suite and Lebowa granite suite; Kleemann and Twist, 1989) which occur in the roof (Fig. 1.4). The Rustenburg layered suite intruded at a paleo-unconformity between the 2.06 Ga Rooiberg Group volcanic suite, a 6-km thick sequence of mafic and silicic volcanic rocks interbedded with laterally extensive sedimentary strata (Walraven, 1997; Schweitzer et al., 1995; Buchanan et al., 2002), and the underlying Pretoria Group of the Neoarchean to Paleoproterozoic Transvaal Supergroup (Cheney and Twist, 1991).

The ultramafic to mafic rocks that makes up the layered sequence (Rustenburg layered suite) of the Bushveld Complex occurs mainly within four zones, from bottom to top – Lower, Critical, Main and Upper zones (Fig. 1.4), the subdivision based mainly on the appearance and disappearance of cumulus minerals (Hall, 1932; Maier et al., 2013). Fine-grained rocks that intrude into the country rock (Transvaal Supergroup) and occurring as chilled margins or as sills, at or near the margin of the main layered body form part of the Marginal zone (Sharpe, 1981; Harmer and Sharpe, 1985; Davies and Tredoux, 1985; Barnes et al., 2010). In addition, Wilson (2015) recently reported the existence of a basal ultramafic sequence, stratigraphically beneath the Marginal zone in the eastern Bushveld Complex. This sequence is yet to be identified in other parts of the Bushveld Complex.

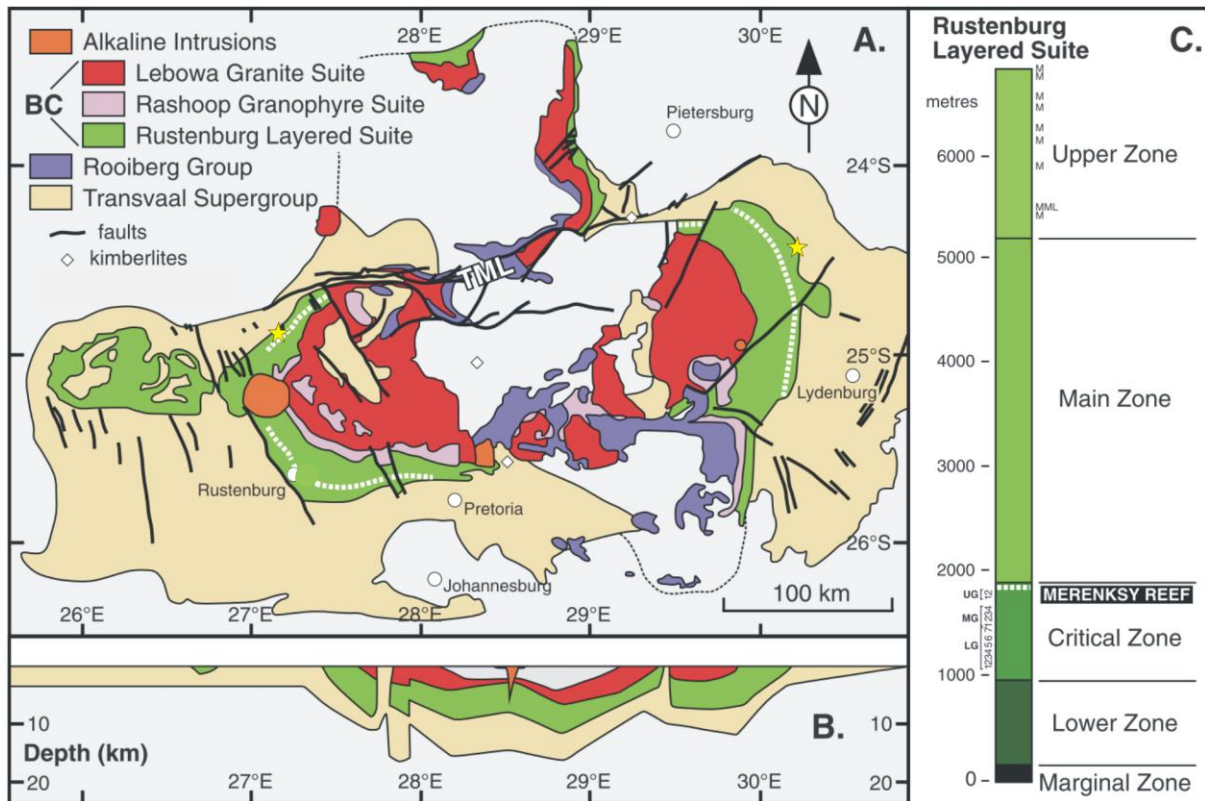


Figure 1.4. (a) Generalized geologic map of the Bushveld Complex (BC). **(b)** Cross section of the Bushveld Complex based on gravity modeling. **(c)** Simplified stratigraphic section showing the major subdivisions of the layered mafic-ultramafic rocks of the Rustenburg Layered Suite, and the approximate position of major chromitite (LG = Lower Group, MG = Middle Group, UG = Upper Group) and magnetite (MML = main magnetite layer, M = magnetite horizon) horizons [from Li et al. (2001), Webb et al. (2004), Scoates and Friedman (2008)]. The approximate locations of the chilled margins/sequences reported by Wilson (2012), (2015) and Maier et al. (2016) are shown by stars.

Based on their stratigraphic position and composition, Sharpe (1981), Harmer and Sharpe (1985) and Sharpe and Hulbert (1985) divided the marginal rocks into: (1) ultramafic rocks in the country rock to the Lower zone (B1 UM; B1 stands for Bushveld 1; UM stands for ultramafic), (2) mafic rocks in contact with the Lower zone and lower Critical zone (B1), (3) rocks in contact with the upper Critical zone (B2; Bushveld 2) and (4) rocks in contact with the Main zone (B3; Bushveld 3) (Fig. 1.5). While B1 are quench-textured (e.g., Fig. 1.6a) norites, compositionally and texturally, the B1 UM rocks are orthocumulates consisting of a mixture of B1 liquid and cumulate olivine and chromite (Davies and Tredoux, 1985; Sharpe

and Hulbert, 1985). B2 and B3 are fine-grained gabbronorites (Sharpe, 1981; Sharpe and Hulbert, 1985).

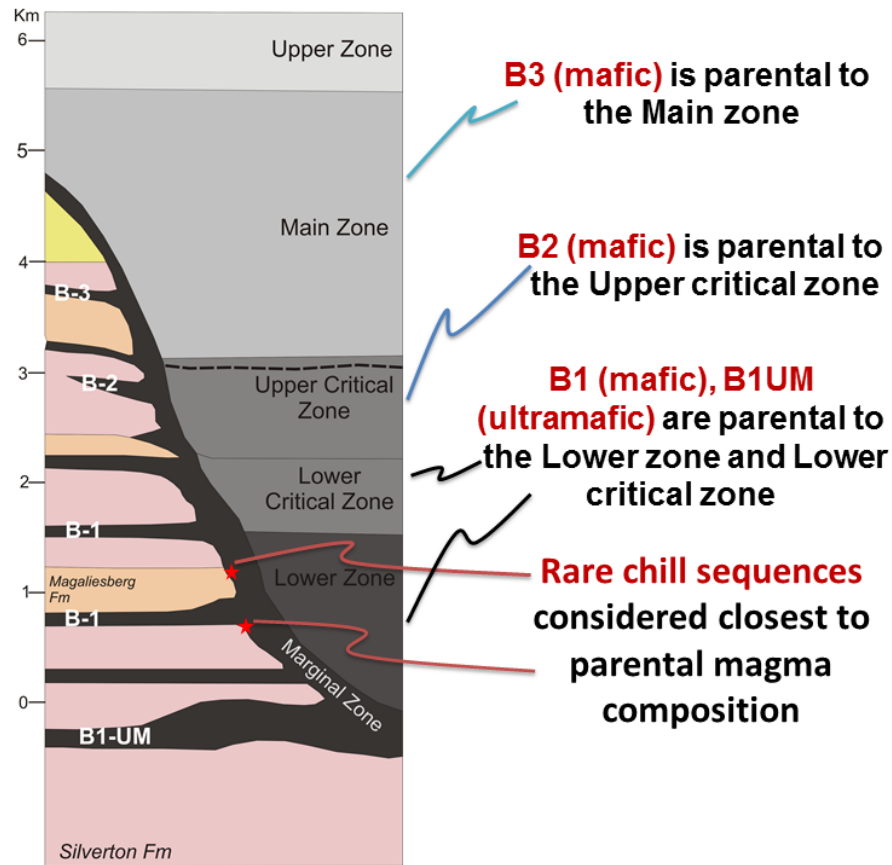


Figure 1.5. Simplified stratigraphy of the Rustenburg Layered Suite and associated marginal sills (B1UM, B1, B2, B3) that intrude the Transvaal Supergroup sediments [modified from Sharpe (1981) and Von Gruenewaldt et al. (1985)]. The approximate position of chilled margins reported by Wilson (2012), (2015) from the same drill core (star towards the top of the Lower zone), and by Maier et al. (2016) (star towards the bottom of the Lower zone) are also indicated.

Three recent studies reported rare chilled margins, as part of chill sequences, from the eastern and western Bushveld Complex (Figs. 1.4 and 1.5). Wilson (2012) identified a chill sequence with a basal chill against quartzite (e.g., Fig. 1.6b) followed by quench-textured (e.g., Fig. 1.6c) and spinifex-textured rocks as well as olivine and orthopyroxene cumulates from the eastern Bushveld Complex. Wilson (2015) further characterized this chill sequence from the same drill core (e.g., Fig. 1.6d).

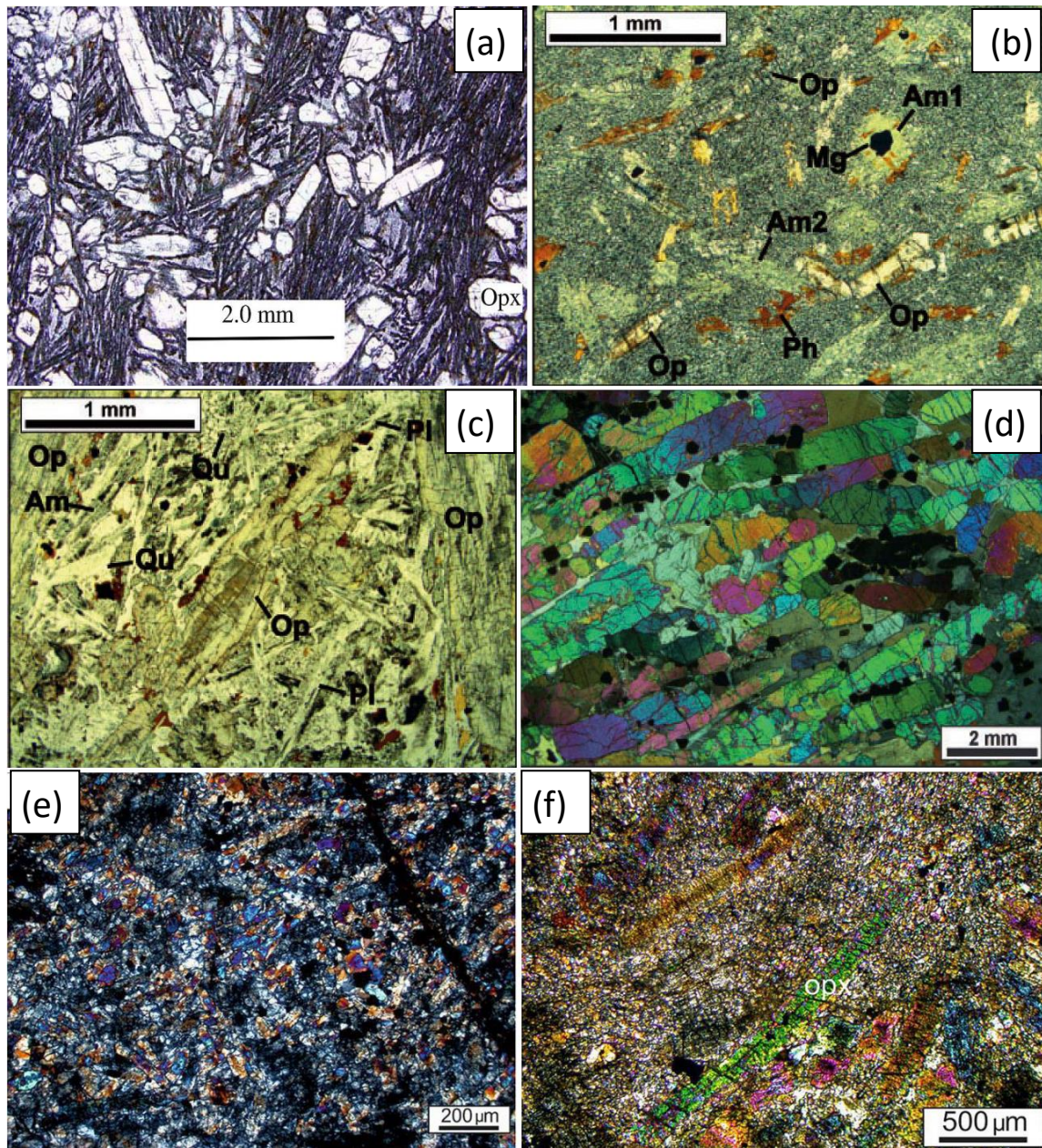


Figure 1.6. Representative photomicrographs illustrating quench-texture **(a)** in B1 sill [from Barnes et al. (2010)], basal chill **(b)** as well as elongate orthopyroxene crystal **(c)** in chill sequence [from Wilson (2012)], elongate olivine crystals in the chill sequence **(d)** associated with basal ultramafic sequence [from Wilson (2015)], fine-grained chilled margin **(e)** and elongated orthopyroxene **(f)** in komatiitic sample in the chill sequence from western Bushveld [from Maier et al. (2016)]. Opx/Op – orthopyroxene; Am – amphibole; Ph – phlogopite; Qu – quartz; Mg – magnetite; Pl – plagioclase

Maier et al. (2016) reported a relatively unevolved chilled sequence [a basal aphanitic chill (e.g., Fig. 1.6e), overlain by spinifex-textured (e.g., Fig. 16f) and coarse-grained rocks] at the base of the Lower zone overlying quartzite from the western Bushveld Complex. As

summarized in this section, the world's largest layered intrusion has been quite extensively studied in terms of the possible parental magma compositions. The different sill compositions – B1UM, B1, B2, B3 (Sharpe, 1981; Barnes et al., 2010) – and the rare chill sequences reported by Wilson (2012), (2015) and Maier et al. (2016) forms a framework for understanding/infering parental magma composition to the Molopo Farms Complex.

1.3. Geologic setting of the Molopo Farms Complex

The Molopo Farms Complex layered ultramafic-mafic intrusion underlies an area of about 13000 km² of southernmost Botswana and adjacent parts of South Africa across the Molopo River (Fig. 1.7a). Like the Bushveld Complex, the Molopo Farms Complex rocks are also emplaced into equivalents of the Pretoria Group sediments of the Transvaal Supergroup, although downward transgression of the Complex into lower stratigraphic units, e.g., dolomites and banded iron formation of the Transvaal sequence, and pre-Transvaal rocks is inferred from borehole data (Gould et al., 1987; Von Gruenewaldt et al., 1989). Parts of the intrusion and its roof-rocks were later eroded and unconformably overlain by rocks of the mid-Proterozoic Waterberg Group and Phanerozoic Karoo Supergroup, and finally by unconsolidated Kalahari sands; in consequence, the uppermost preserved parts of the complex now lie at depths of up to 200 m below ground surface (Gould et al., 1987; Reichhardt, 1994; Prendergast, 2012). As the complex is mostly under Kalahari sand cover, the currently known geology is a geological interpretation of the regional geophysical survey data combined with drill core samples (Figs. 1.7 to 1.9; Gould et al., 1987; Von Gruenewaldt et al., 1989; Reichhardt, 1994; Walker et al., 2010; Prendergast, 2012).

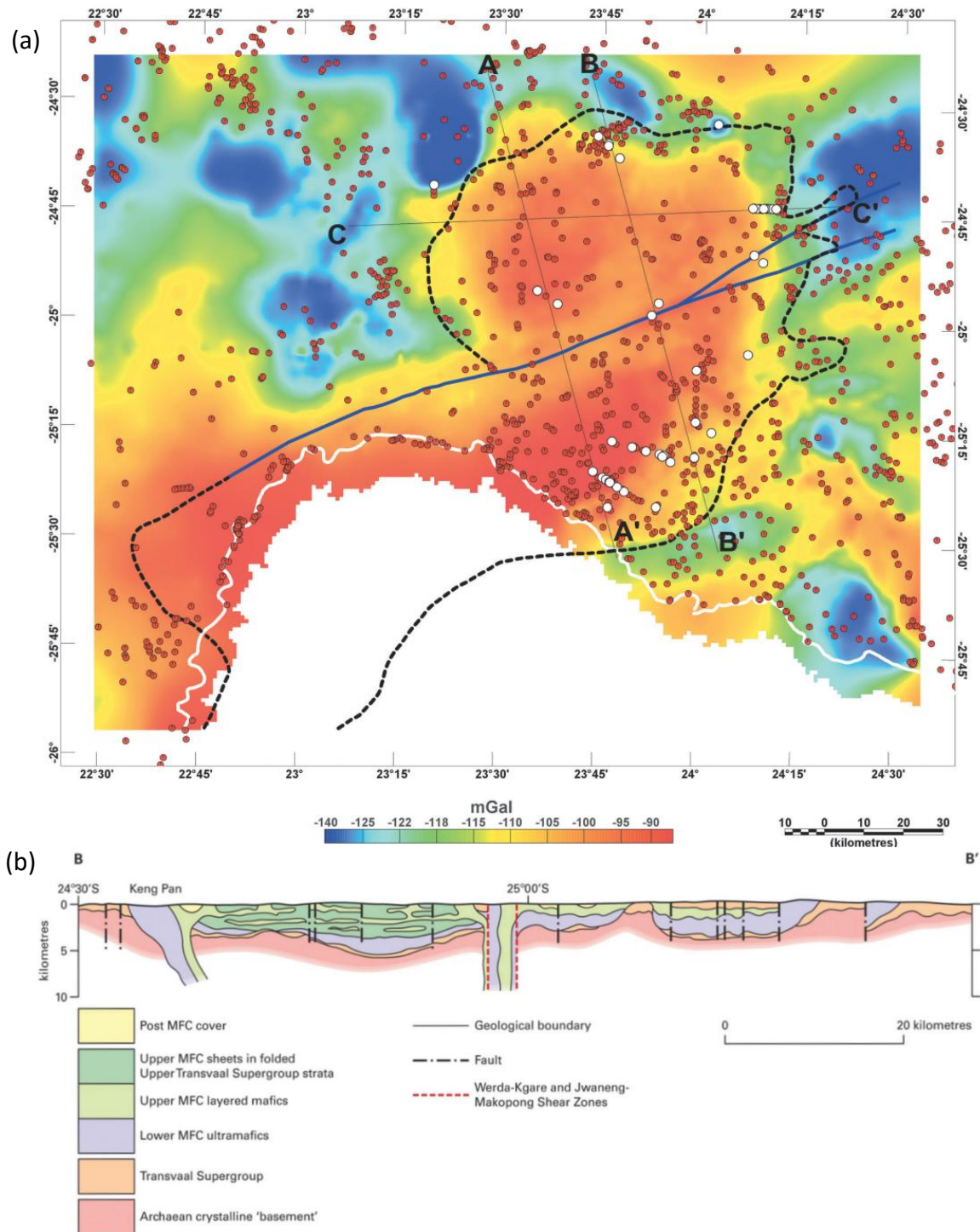


Figure 1.7. (a) Bouguer gravity anomaly map of the Molopo Farms Complex and surroundings. The subsurface extent of the Molopo Farms Complex (as inferred from available gravity and magnetic data) is marked as a dashed line. Principal linaments tracing the interpreted divide between the northern and southern lobes of the Molopo Farms Complex are marked as blue lines. Exploration drillcore holes (Gould et al., 1987) are indicated as filled white circles [from Walker et al. (2010)]. **(b)** Schematic north-south cross-section of the Molopo Farms Complex [along transect B-B' shown in (a)], based on borehole logs [from Walker et al. (2010)].

From the gravity data, which shows up the distribution of the Molopo Farms Complex perfectly (Fig. 1.7a), the Molopo Farms Complex is an elliptical, saucer shaped intrusion elongated in a NE-SW direction (Gould et al., 1987; Von Gruenewaldt et al., 1989; Walker et al., 2010). With a total thickness of about 3.2 km, the layered intrusion is divided into northern and southern lobes by the ENE-WSW trending Kgomodikae lineament (Fig. 1.7a; Gould et al., 1987; Walker et al., 2010). Lithologically, it consists of a lower ultramafic sequence of cyclic units of harzburgites and subordinate pyroxenites with minor dunite, overlain by a predominantly mafic sequence comprising norites, gabbro-norites, gabbros and subordinate feldspathic pyroxenites (Figs. 1.8 and 1.9), together with a group of gabbro-norite to gabbro sills lying within the uppermost layered mafic rocks and Transvaal roof-rocks (Gould et al., 1987; Reichhardt, 1994; Walker et al., 2010; Prendergast, 2012).

Estimated thickness of the lower ultramafic sequence exceeds 1300 m, up to 1850 m, while the mafic sequence is 1400 to 1500 m thick (Gould et al., 1987; Reichhardt, 1994; Walker et al., 2010). In general, each cyclic unit in the ultramafic sequence exhibits a gradual transition from an olivine-rich base to an orthopyroxene-rich top, and has a sharp contact with the overlying cyclic unit (Gould et al., 1987; Reichhardt, 1994). Serpentinization is widespread in the olivine-rich rocks and chromite is a prominent accessory phase within the ultramafic sequence (Gould et al., 1987; Von Gruenewaldt et al., 1989; Reichhardt, 1994). Although cumulate layering is well developed throughout the ultramafic sequence, finer-grained essentially non-cumulate textured noritic rocks can occur at the marginal portions (Gould et al., 1987). These marginal norites are only reported in drill cores from the northern lobe (Tubane area), and such rocks are of interest to the present study, aimed at

characterizing preserved parental magma composition to the Molopo Farms Complex (see next section).

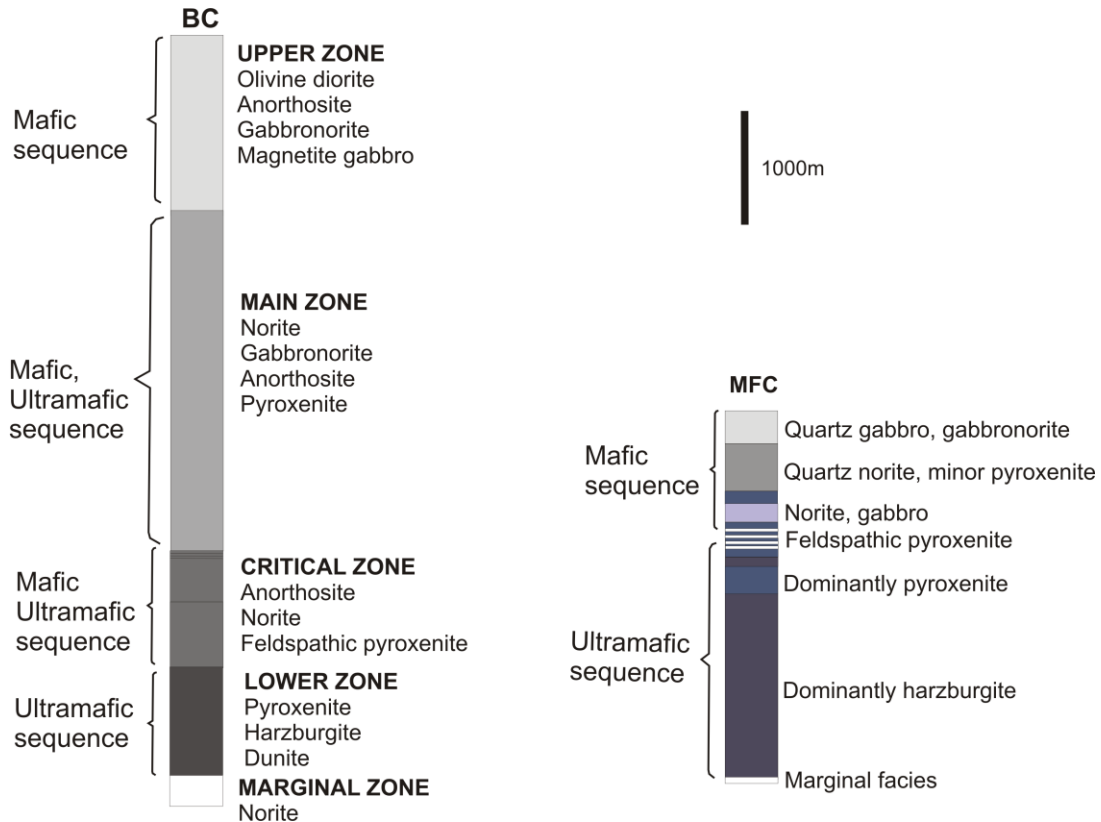


Figure 1.8. Simplified stratigraphic section comparing the size, zone/sequence and rock types of the Rustenburg Layered Suite of the Bushveld Complex (BC) with the Mafic and Ultramafic sequences of the Molopo Farms Complex (MFC) [modified from Eales and Cawthorn (1996), Reichhardt (1994) and Prendergast (2012)].

The mafic-ultramafic contact is essentially interlayered (e.g., pyroxenite occurring above a thick norite unit; Reichhardt, 1994; Prendergast, 2012). Two prominent feldspathic pyroxenite layers up to 100 m-thick with minor norite occur approximately 50 m and 350 m above the mafic-ultramafic contact (Reichhardt, 1994; Prendergast, 2012).

The mafic sequence exhibits an overall upward fractionation from norite and gabbronorite to quartz-norite and quartz-gabbronorite to quartz-hornblende gabbro (Reichhardt, 1994). Cumulate layering is better preserved in the lower part of the mafic

sequence, with the development of quartz-feldspar-rich contaminated gabbro-noritic rocks towards the upper part; the latter associated with widespread assimilation (inclusions of country rocks) (Gould et al., 1987). Unlike the pyroxenites in the ultramafic sequence, chromite is not a prominent accessory phase in the feldspathic pyroxenites from the mafic sequence (Reichhardt, 1994; Gould et al., 1987).

Comparison of the cumulate sequence of the Molopo Farms Complex with that of the Rustenburg layered suite of the Bushveld Complex shows that the total thickness of the former is considerably less than that of the latter (Fig. 1.8; Gould et al., 1987; Von Gruenewaldt et al., 1989; Reichhardt, 1994; Prendergast, 2012). Equivalents of most of the Critical zone and whole of the Upper zone of the Rustenburg layered suite have not been located in the Molopo Farms Complex. Although minor chromite-rich intervals occur in places, no prominent chromitite horizons, like in the Critical zone of the Bushveld Complex (see Fig. 1.4), are reported from the Molopo Farms Complex. Narrow horizons of sulphide mineralization in both the ultramafic and mafic sequences are the only type of mineralization reported from the Molopo Farms Complex (Gould et al., 1987; Reichhardt, 1994).

Barton (in Gould et al., 1987) presented whole-rock Rb-Sr and Pb errorchron plots covering samples from both ultramafic and mafic rocks, indicating that the age of the Molopo Farms Complex should be close to ~2050 Ma. Reichhardt (1994) also presented whole-rock Rb-Sr data on ultramafic and mafic rocks from the Complex. High initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (ultramafic sequence: 0.703-0.705; mafic sequence: 0.705-0.709) and variation across

the stratigraphy (e.g., sudden increase to 0.707, some 500 m below the base of the mafic sequence) (Gould et al., 1987; Reichhardt, 1994) is comparable to that obtained from the Bushveld Complex (Sharpe, 1985; Harmer and Sharpe, 1985; Kruger, 1993). Kruger (1989) presented a combined Rb-Sr mica and whole-rock age of 2044 ± 24 Ma from the harzburgite of the Molopo Farms Complex.

1.4. Objectives and approach

The prime objective of the study is to provide preliminary petrogenetic characteristics, including parental magma composition, on the layered ultramafic to mafic rocks of the Molopo Farms Complex. A petrographic, mineral chemical and whole-rock geochemical study of rock samples from selected drill core samples was conceived in late 2014. Evaluating the mineralization potential of the studied rocks was an obvious addendum.

Other than basic petrographic and exploration-oriented whole-rock geochemical studies (Gould et al., 1987; Von Gruenewaldt et al., 1989; Reichhardt, 1994; Prendergast, 2012), no detailed petrographic, mineral chemical and whole-rock geochemical study is available for the Molopo Farms Complex. Further, much of the results of works on the Molopo Farms Complex are located in unpublished reports from the Government and Exploration companies available at the Botswana Geoscience Institute (the former Department of Geological Surveys of Botswana). All boreholes (drilled from Tubane and Lobatse-Werda sections) from the complex is preserved in the Botswana Geoscience Institute core-yard at Kang. Because of prominent block-faulting in the northern and northeastern portions (see Fig. 1.9), depending on the relative vertical movement of individual blocks, various

stratigraphic levels of the Complex and country rocks are preserved in boreholes from the Tubane area in the northern lobe (Gould et al., 1987). In comparison, bore holes drilled in the Lobatse-Werda section of the Bray area (southern lobe) contained a relatively undisturbed and complete succession of ultramafic sequence overlain by the mafic sequence. After going through the available drill core logs and related cross-sections (summarized in Gould et al., 1989), three drill cores were selected for detailed study (see Fig. 1.9 for their approximate location).

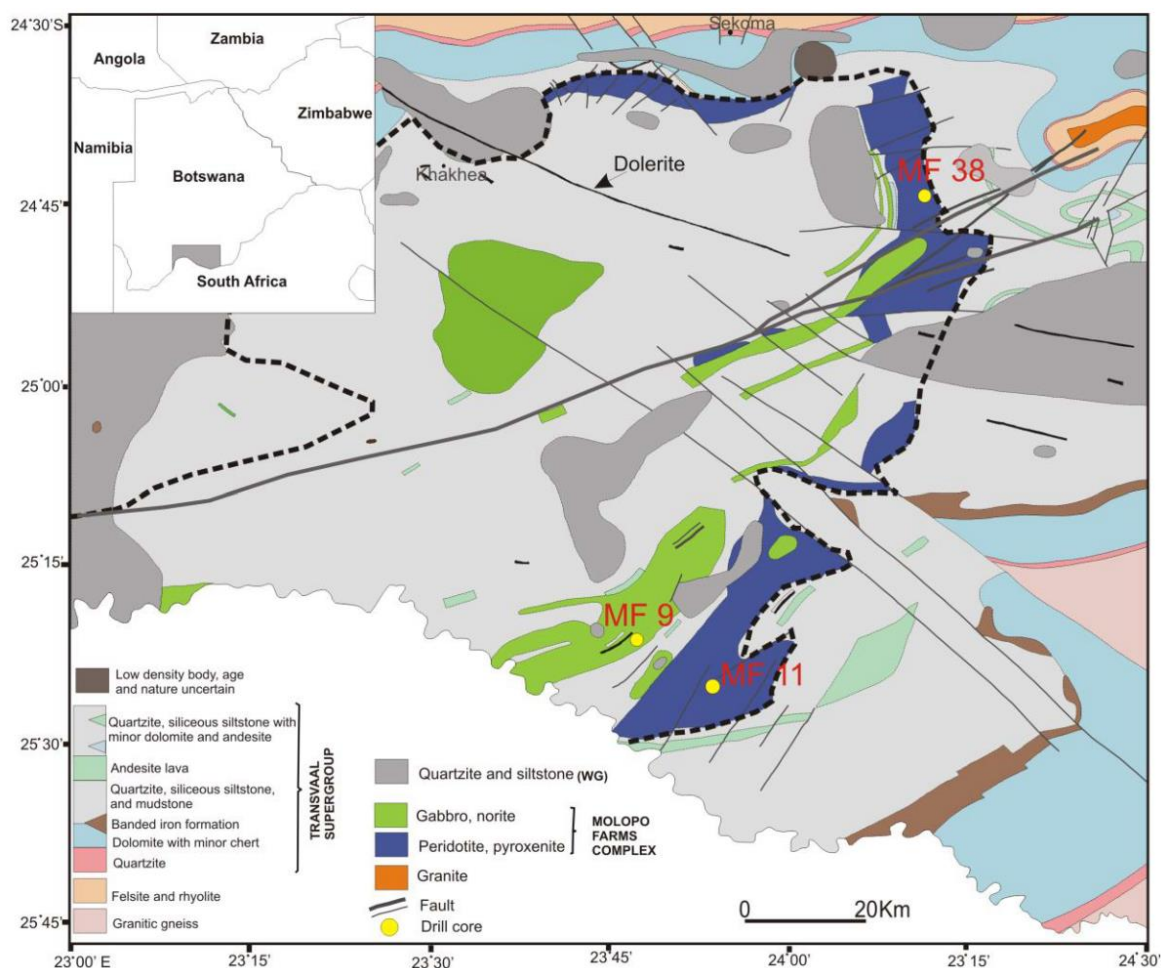


Figure 1.9. Geologic map of the Molopo Farms Complex (green and blue color) and surroundings, mostly inferred from aeromagnetic and drill core data, showing the location of the three drill cores studied here. Transvaal Supergroup sediments constitute the country rock to the Molopo Farms Complex. WG – Waterberg Group. [from Gould et al. (1987)].

Drill core MF38 is from the northern lobe (Tubane area), while drill cores MF9 and MF11 are from the southern lobe (Bray area). MF38, which represents a typical ultramafic sequence from the Molopo Farms Complex, was selected as it is one of the two drill cores which intersect the country rock, with the possibility of preserving a chilled margin. Further, up to 0.5 m thick bands of sulphide mineralization was recorded from this drill core (Gould et al., 1987). MF9 was selected based on the occurrence of all rocks, including minor feldspathic pyroxenite, representative of the mafic sequence, and associated minor sulphide-bearing horizons. Further, Gould et al. (1987) and Von Gruenewaldt et al. (1989) pointed out the occurrence of inverted pigeonite in rocks from this drill core, which could be used to estimate crystallization conditions. MF11 was selected based on the occurrence of intermittent noritic layers and minor feldspathic pyroxenite within a predominant ultramafic sequence, representing a typical ultramafic sequence of the layered intrusion. It also has associated sulphide-bearing horizons. It should be pointed out that the samples used for the Rb-Sr geochronologic study presented in Gould et al. (1987) include those from the drill cores MF11 and MF9.

Although marginal gabbroic sills have been intersected by some of the drill cores (e.g., MF25, MF27), they are not studied here due to their strongly fractionated nature, as reported in Gould et al. (1987), Von Gruenewaldt et al. (1989) and Reichhardt (1994). Further, there is no convincing evidence to relate them to the Molopo Farms Complex. For example, the interpretation of paleomagnetic data was inconclusive, with possibilities of an age only slightly different from that of the Molopo Farms Complex or may indicate a much later (Karoo) age (see Gould et al., 1987).

After going through available literature on the Molopo Farms Complex and the extensive literature on the Bushveld Complex, especially those focusing on the latter's parental magma composition, the following objectives and related approach were laid out.

- The re-core logging of the drill cores.
- Petrographic characterization of samples (using transmitted and reflected light microscopy, and backscatter imaging) of the different rock types in the drill cores to understand the minerals present, including sulphide mineralogy, and their mutual relation.
- Mineral chemical characterization of petrographically characterized samples to study the chemical composition of prominent minerals. Application of geothermobarometers to obtain pressure and temperature constraints.
- Whole-rock geochemical characterization of petrographically characterized samples, which can give a plethora of information including the likely origin of the rock, parental magma composition and its tectonic setting.

1.5. Sampling and analytical methods

Since starting the project in late 2014, three sessions of core logging was carried out at the Botswana Geoscience Institute core-yard at Kang. Representative cut samples of different rock types from the three drill cores (MF38, MF9, MF11) were collected and transported to the geologic lab at BIUST. Selected samples were cut and polished rock thin

sections were prepared at the University of Johannesburg (UJ), South Africa. These thin sections were subjected to detailed petrographic analysis using transmitted and reflected light microscopy at the geologic lab in BIUST.

After petrographic study, representative polished rock thin sections were subjected to back-scattered electron (BSE) imaging using a scanning electron microscope (SEM) to understand the textural relation between different rock-forming minerals. The BSE-SEM imaging was carried out at the central analytical facility of UJ. Electron microprobe analyses of minerals in thin sections were carried out using a CAMECA SX100, equipped with four WDS spectrometers which contain TAP, LIF, LLIF, PET, LPET, PC1, PC2 and PC3 crystals, housed at UJ. Analytical conditions were 15 kV accelerating voltage, 20 nA beam current, counting times of 10-20s for most elements, except 50s for F and 30s for Cl, and 1 to 5µm beam spot size were used. Corrections were made using the ZAF method.

Petrographically studied bulk samples were powdered at the rock crushing facility at UJ. Major and trace element contents of powdered rock samples were determined by X-ray fluorescence (XRF) spectrometry at ACME Labs, Canada, on glass beads prepared from powdered whole-rock samples with a sample-to-flux (lithium tetraborate) ratio of 1:10. Volatiles were determined by loss on ignition. Trace and rare earth elements (REE) were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) at ACME Labs. The sample powders were mixed in lithium metaborate flux fusion and the resulting molten bead was rapidly digested in a nitric acid solution. Precision based on replicate analysis of

international rock standards (SQ-18, OREAS76A, OREAS45CA, DS8, CSC) are 2-5% (1σ) for most elements and $\pm 10\%$ for U, Sr, Nd, and Ni.

1.6. Outline of the thesis

The different chapters of the thesis are structured so that it correlates with the core logging-petrography-mineral chemistry-whole-rock geochemistry approach mentioned above. A brief introduction to the geologic setting of the Molopo Farms Complex is given in chapter 1. The thesis commences with first addressing the results of core-logging, explaining the different rock types occurring within the three drill cores (chapter 2). Chapter 3 details the petrographic characteristics, including sulphide mineralogy, of the different rocks occurring in the three drill cores. Chapter 4 addresses mineral chemical characteristics of prominent minerals from selected units of relevance to addressing the parental magma composition of the Molopo Farms Complex. Whole-rock geochemical characteristics of these selected ultramafic- to- mafic rocks are presented in chapter 5. Finally, in chapter 6, the results from different studies are discussed in comparison to information on petrogenetic characteristics, including parental magma composition, of the Bushveld Complex from literature, and the resulting concluding remarks are given in chapter 7.

Chapter 2

Core logging

2.1 Introduction

This chapter presents the results of the core logging exercise, giving description of rock types that constitute the drill cores MF38, MF11 and MF9. While MF38 and MF11 are from the ultramafic sequence of the Molopo Farms Complex, MF9 is representative of the mafic sequence. Rock types occurring within a single drill core are described together under a single section, aided with the core log prepared as part of the study, as well as representative photographs of samples of the different rock types. For each drill core, the rock types are described from bottom (stratigraphically deepest) to the top.

2.2. MF38

MF38 is part of the boreholes drilled in the Tubane area in the northern lobe (Fig. 2.1a). The geology of the traverse section is shown in Fig. 2.1a. The core log is given in Fig. 2.1b. This drill core is approximately 613 metres in depth and intersects the country rock (pre-Transvaal basement). The base of the core comprises a thin ~10 m layer of remobilised country rock (granitoid), with (seemingly) melted country rock fragments. This is followed by a nearly 90 m thick noritic unit. The noritic unit consists of a sequence starting with medium-grained gabbro-norite (~32 m thick) (Fig. 2.2a), followed by a ~3 m thick intrusion of fine-grained dolerite with cross-cutting quartz filled veinlets (Fig. 2.2b), and two prominent

medium-grained quench-textured norite layers. The dolerite intrusion is late, probably of Karoo age. The norite layers include a ~20 m thick norite followed up by a ~54 m thick leuconorite (Figs. 2.2c, d). Based on the remobilised nature of the country rock and quench-textured medium-grained rocks above, the noritic unit is considered as a marginal facies.

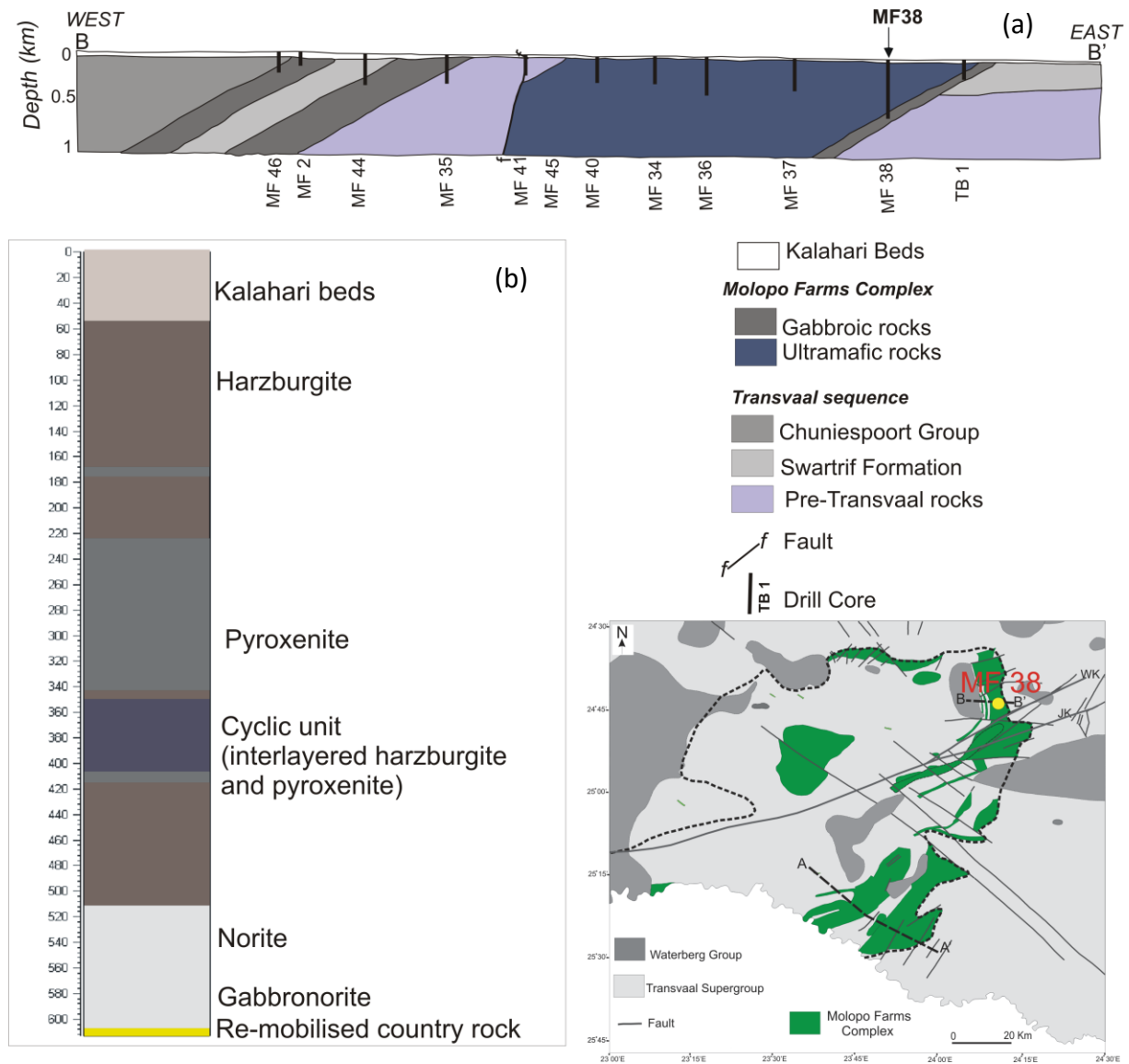


Figure 2.1. (a) Schematic section (B-B') through the Molopo Farms Complex in the Tubane area showing the location of drill core MF38, among others [modified from Gould and Rathbone (1985) and Von Gruenewaldt et al. (1989)]. The bottom inset shows the approximate location of the traverse B-B', in a simplified version of Fig. 1.9. **(b)** Result of re-core logging of bore hole MF38.

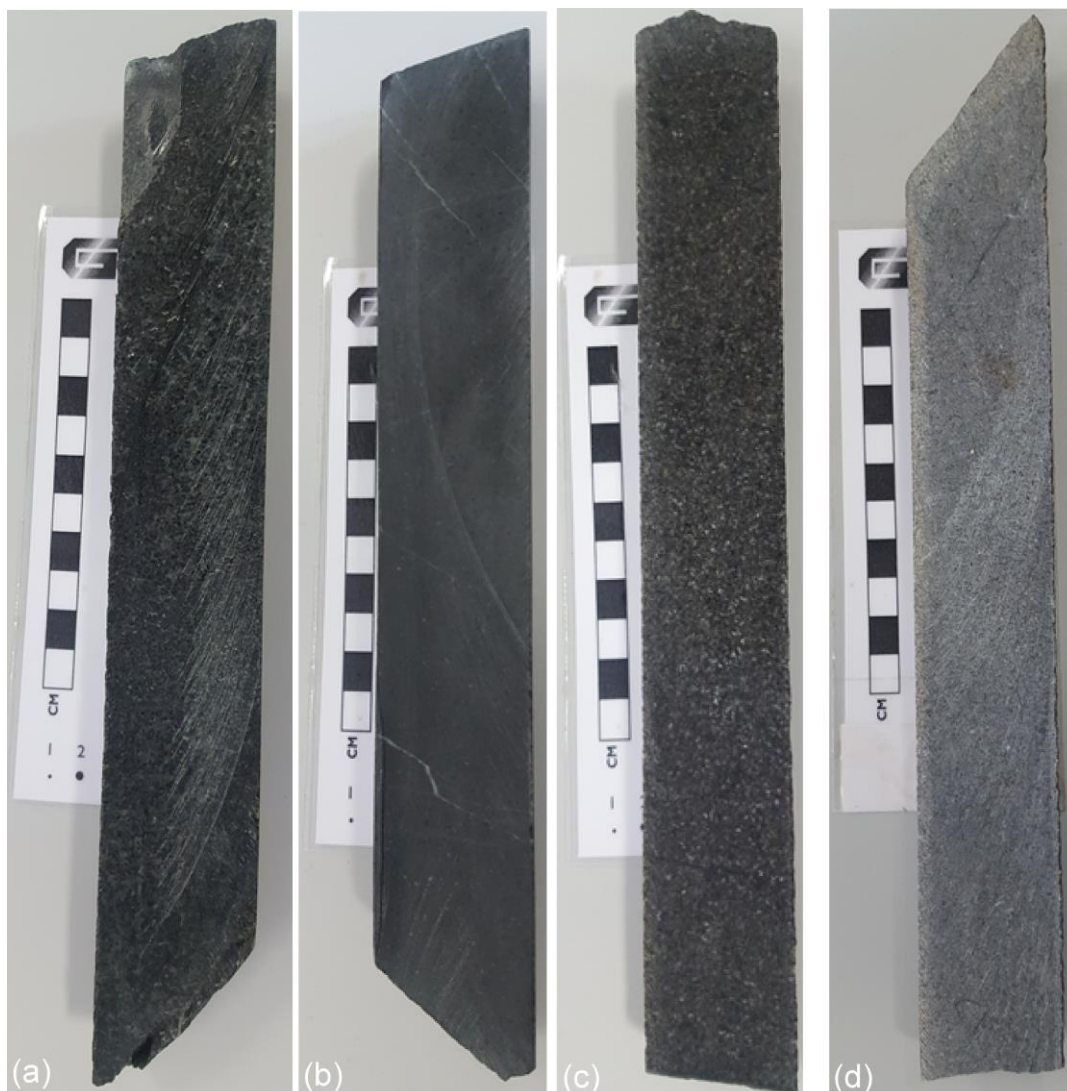


Figure 2.2. Photographs illustrating rock types from the marginal facies to the ultramafic sequence in MF38. **(a)** gabbro-norite, **(b)** fine-grained dolerite, **(c)** quench-textured medium-grained norite, **(d)** quench-textured medium-grained leuconorite.

Aside from the marginal noritic unit and the younger cover rock at the top, the rest of the drill core is ultramafic, made up mostly of olivine and orthopyroxene cumulates (Figs. 2.1b; 2.3 to 2.5). Mottled texture can be seen in both harzburgite and pyroxenite (e.g., Figs. 2.3a, c and Fig. 2.4a). Pyroxenite is essentially orthopyroxenite, with local occurrence of feldspathic pyroxenite. Serpentinization is more prominent in the olivine-rich portions than in the orthopyroxene-rich portions.

A thin (~7 m) feldspathic pyroxenite layer separates the ultramafic sequence from the marginal unit and the contact is gradational. The ultramafic sequence starts with a ~107 m thick harzburgite (dominant) unit with thin pyroxenite layers in between. The portion of harzburgite near the pyroxenite is serpentinized and highly fractured. Pyroxenite is also altered and invaded by a series of serpentine veins (Figs. 2.3a, b). This is succeeded by a cyclic unit of nearly 60 m thick with alternating harzburgite and pyroxenite layers (Figs. 2.1, 2.3c, d). Disseminated sulphide mineralization occurs in the cyclic unit.

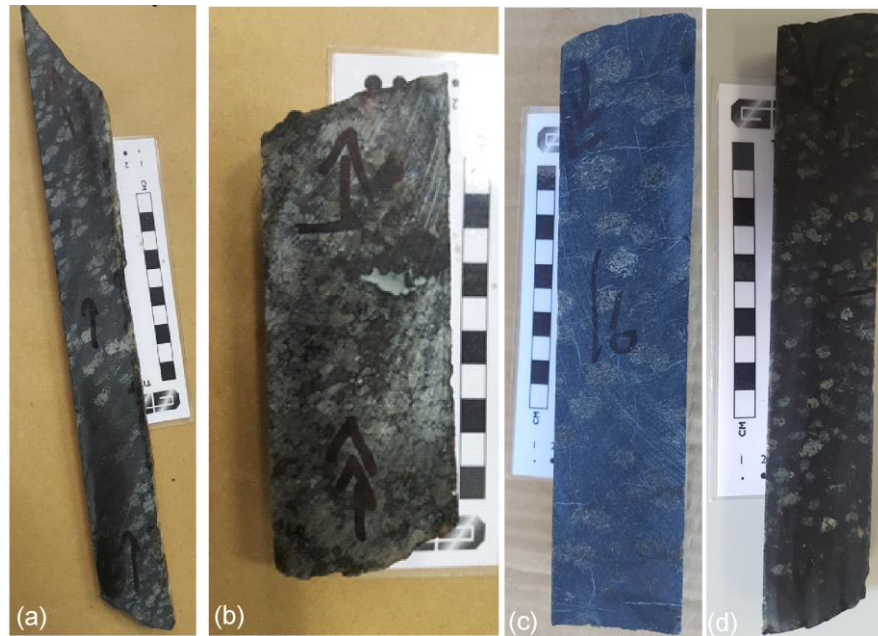


Figure 2.3. Photographs illustrating rock types from the dominant harzburgite **(a)** with minor pyroxenite **(b)** unit, and cyclic unit, with alternating harzburgite **(c)** and pyroxenite **(d)** layers, of the the ultramafic sequence in MF38. Serpentine veins can be seen in (c).

The cyclic unit is followed up by a ~55 m thick pyroxenite (dominant) unit with minor harzburgite and dunite (Figs. 2.1 and 2.4). In addition to the typical cumulate textured occurrence (Fig. 2.4a), a medium-grained variant of pyroxenite also occurs in this unit (Fig. 2.4b). Two such medium-grained pyroxenite layers were logged, and are of interest to the

main objective (characterizing primary compositions) of the study. The topmost unit of the ultramafic sequence in MF38 is a nearly 150 m thick massive harzburgite/dunite unit with minor pyroxenite and feldspathic pyroxenite layers in between (Figs. 2.1b and 2.5).



Figure 2.4. Photographs of rock types from the dominant pyroxenite (a, b) with minor harzburgite (c) and dunite (d) unit of the the cumulate textured ultramafic sequence in MF38. Unlike the typical cumulate textured occurrence (a), a medium-grained pyroxenite variant (b) occurs in this unit.



Figure 2.5. Photographs of rock types of the massive harzburgite (a) unit with minor pyroxenite (b) and feldspathic pyroxenite (c) to the ultramafic sequence in MF38. The sharp contact between harzburgite and feldspathic pyroxenite is shown in (c).

2.3. MF11

MF11 is part of the boreholes drilled along the Lobatse-Werda section in the Bray area in the southern lobe (Fig. 2.6a). The geology of the traverse section is shown in Fig. 2.6a. The core log is given in Fig. 2.6b. This drill core is approximately 597 metres in depth, and represents a typical ultramafic sequence with minor mafic rock (norite) layers. Like in the case of MF38, cumulate layering is prominent in the ultramafic rocks of MF11. Serpentinization is less prevalent than in MF38.

It starts with a ~73 m thick pyroxenite unit with minor norite (Fig. 2.6b). Two types of pyroxenite occur – feldspathic pyroxenite (Figs. 2.7a, b) and massive pyroxenite (Fig. 2.7d). A melanorite layer occurs in between (Fig. 2.7c). A ~51 m thick harzburgite unit separates the basal pyroxenite unit from the one above (Fig. 2.6b). The pyroxenite unit (~71 m thick) (Fig. 2.6b) above harzburgite is similar to the basal pyroxenite unit, and consists of feldspathic pyroxenite (Fig. 2.7e), massive pyroxenite and few thin (~5 cm) layers of norite. A thin norite layer separates the pyroxenite unit from the prominent (~215 m thick) cyclic unit above, with alternating pyroxenite and harzburgite/dunite layers (Fig. 2.6b). Both feldspathic and massive pyroxenites occur in the cyclic unit (Figs. 2.8a to c). Feldspathic pyroxenite is finer grained and exhibits a sharp contact with the massive pyroxenite (Fig. 2.8b). The alternating pyroxenite and harzburgite/dunite layers vary from thin (up to 10 cm) to thick (~10 to 20 m) layers. Serpentinization is prominent in the upper portions, especially in the olivine-rich portions, with magnesite veins invading feldspathic pyroxenite (Figs. 2.8d, e). The topmost

unit of the ultramafic sequence in MF11 is a thin (~14 m) heavily serpentinized harzburgite/dunite unit (Figs. 2.6b, 2.8f).

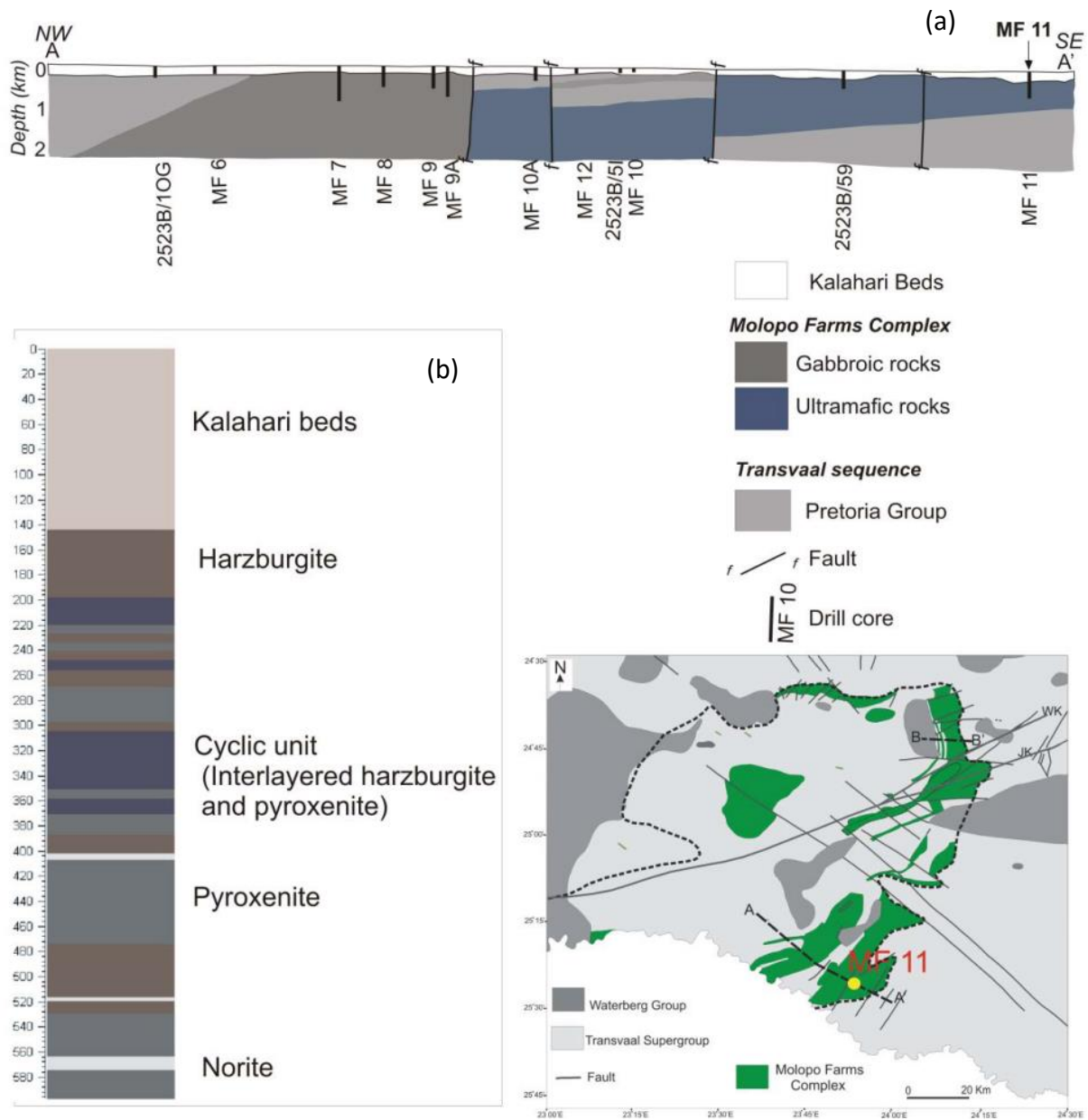


Figure 2.6. (a) Schematic section (A-A') through the Molopo Farms Complex along the Lobatse-Werda section in the Bray area showing the location of drill core MF11, among others [modified from Gould and Rathbone (1985) and Von Gruenewaldt et al. (1989)]. The bottom inset shows the approximate location of the traverse A-A', in a simplified version of Fig. 1.9. **(b)** Results of re-core logging of bore hole MF11.



Figure 2.7. Photographs illustrating rock types of the basal pyroxenite with minor norite unit to the ultramafic sequence in MF11. **(a), (b)** feldspathic pyroxenite; **(c)** melanorite; **(d)** massive pyroxenite. Feldspathic pyroxenite from a similar pyroxenite unit above in the stratigraphy is shown in **(e)**.

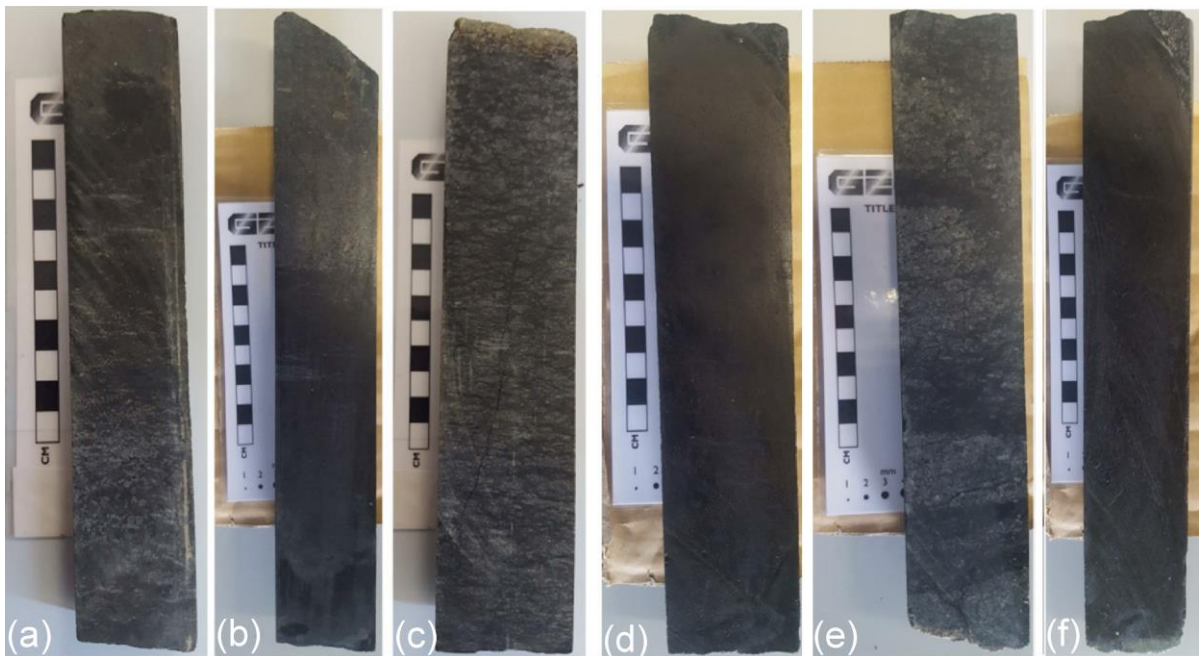


Figure 2.8. Photographs illustrating rock types of the cyclic unit with alternating pyroxenite-harzburgite/dunite layers to the ultramafic sequence in MF11. **(a)** finer-grained feldspathic pyroxenite; **(b)** contact of finer-grained feldspathic pyroxenite and massive pyroxenite; **(c)** feldspathic pyroxenite invaded by black magnesite veins; **(d)** serpentinized dunite; **(e)** serpentinized pyroxenite. **(f)** The topmost serpentinized harzburgite unit of the ultramafic sequence in MF11.

With the exception of the marginal fine-grained norite unit in MF38 and the prominence of feldspathic pyroxenite in MF11, the general lithology of ultramafic sequence in MF38 and MF11 is similar.

2.4. MF9

MF9 is part of the boreholes drilled along the Lobatse-Werda section in the Bray area in the southern lobe (Fig. 2.9a). The geology of the traverse section is shown in Fig. 2.9a. The core log is given in Fig. 2.9b. This drill core is approximately 382 metres in depth, and represents a typical mafic sequence of the Molopo Farms Complex. It dominantly consists of gabbronorite and norite, with minor feldspathic pyroxenite (Fig. 2.9b). The contact between the different units is generally gradational and defined by changes in grain size. Disseminated sulphide mineralization occurs at various levels in MF9.

Both gabbronorite and norite occurs as melanocratic and leucocratic variants (Fig. 2.10). While cumulate texture is prevalent, norite also occurs as a finer-grained variant. A ~38 m thick feldspathic pyroxenite (Fig. 2.10d) unit occurs between two gabbronorite units (the basal ~40 m thick unit and a ~96 m thick unit with minor norite) (Fig. 2.9b). The gabbronorite unit above the feldspathic pyroxenite is traversed by quartz veins and shearing-related fractures filled with epidote (Figs. 2.11a, b). The gabbronorite in this unit is dominantly leucocratic with minor melanocratic variant (Figs. 2.11). The topmost unit of the mafic sequence in MF9 is a ~47 m thick norite unit (Fig. 2.9b). It is a fine-grained leucocratic rock, heavily altered and traversed by a network of calcite veins (Fig. 2.11e).

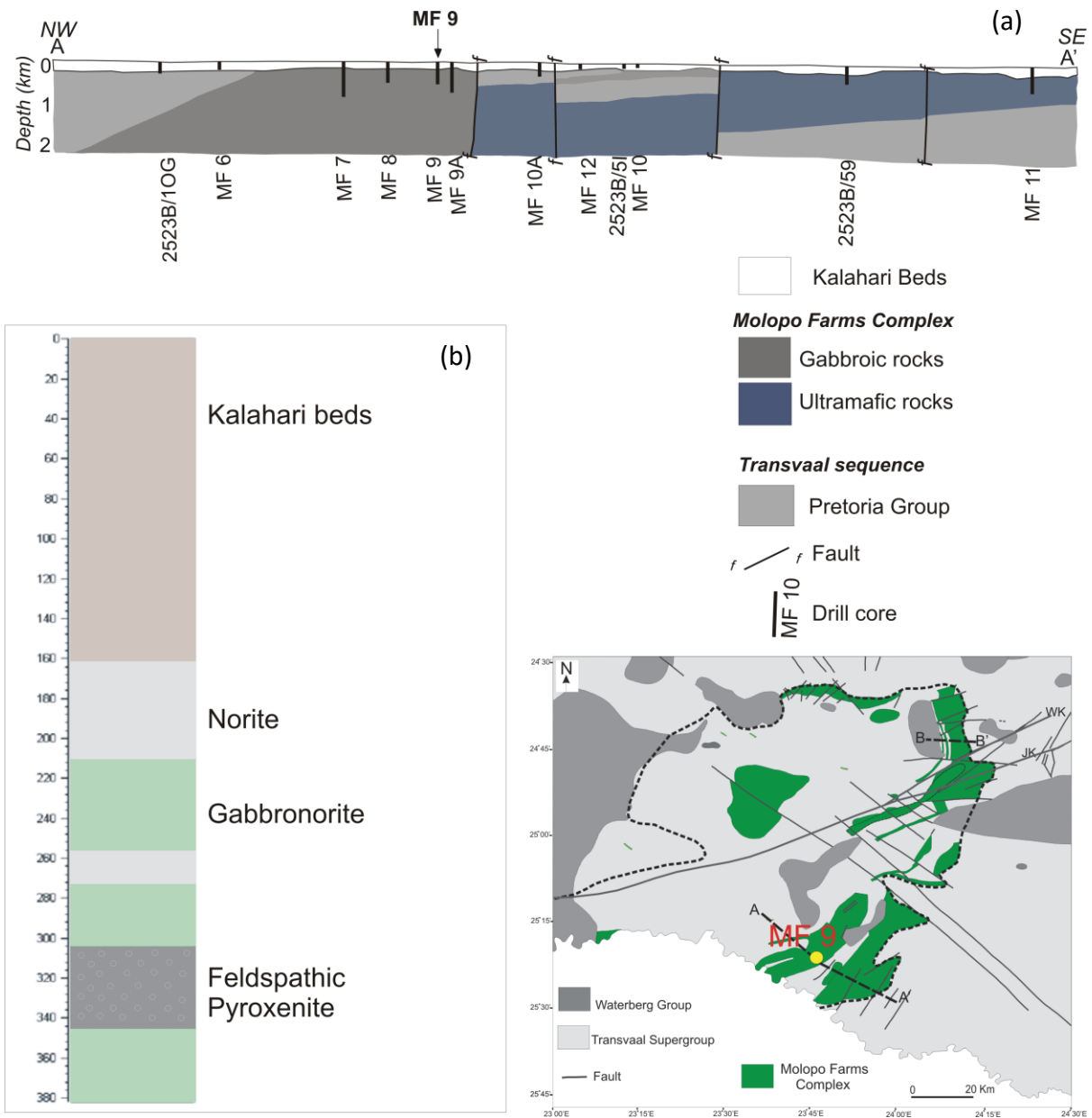


Figure 2.9. (a) Schematic section (A-A') through the Molopo Farms Complex along the Lobatse-Werda section in the Bray area showing the location of drill core MF9, among others [modified from Gould and Rathbone (1985) and Von Gruenewaldt et al. (1989)]. The bottom inset shows the approximate location of the traverse A-A', in a simplified version of Fig. 1.9. **(b)** Results of re-core logging of bore hole MF9.



Figure 2.10. Photographs illustrating rock types of the basal gabbronorite unit with feldspathic pyroxenite from the mafic sequence in MF9. **(a), (b), (e), (f)** melanocratic gabbronorite; **(c)** leucocratic gabbronorite; **(d)** feldspathic pyroxenite.

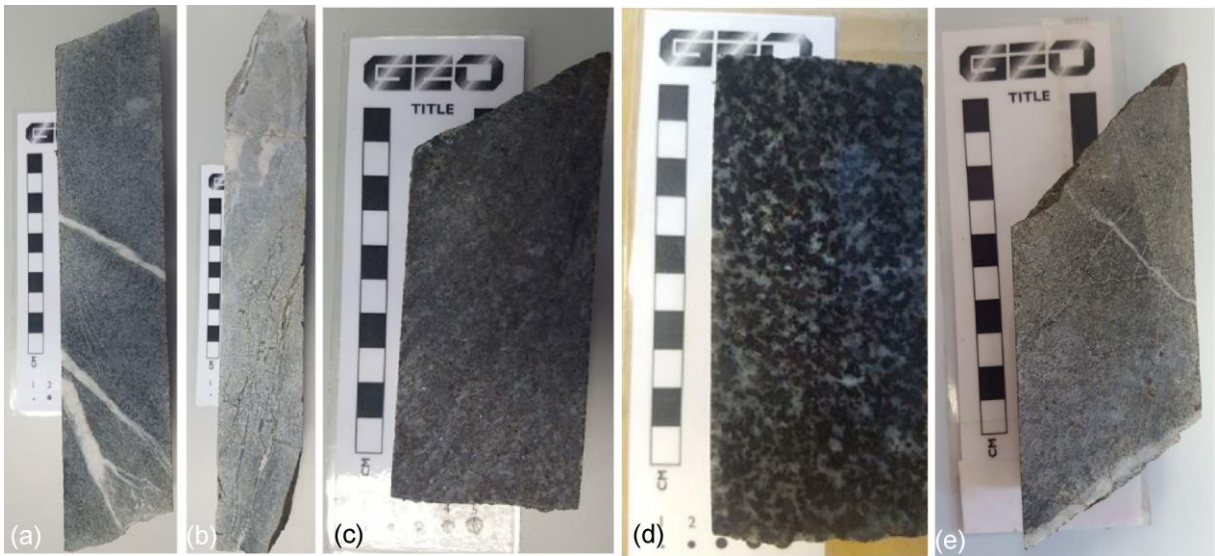


Figure 2.11. Photographs illustrating rock types of the gabbronorite unit above feldspathic pyroxenite from the mafic sequence in MF9. **(a)** leucocratic gabbronorite traversed by quartz veins; **(b)** leucocratic gabbronorite with fractures filled with epidote; **(c), (d)** melanocratic gabbronorite; **(e)** fine-grained leucocratic norite traversed by a network of calcite veins, forming the topmost unit of the mafic sequence in MF9.

Chapter 3

Petrographic characteristics

3.1. Introduction

The chapter presents petrographic characteristics of rock types occurring within the drill cores MF38, MF11 and MF9. The main focus is on petrographically characterizing units suitable for characterizing the parental magma composition. In the process, description of common cumulate rock units of the layered intrusion is combined together. Transmitted light photomicrographs form the primary method of characterization and are used to illustrate the textures and mineral assemblages observed in the different rocks. Sulphide minerals associated with each rock unit are presented together with the aid of reflected light photomicrographs. BSE-SEM images compliment the process.

3.2. MF38

The marginal norite unit comprises of gabbronorite and quench-textured norite/leuconorite, intruded in between by late dolerite. The medium- to coarse-grained gabbronorite adjacent to the remobilised country rock is heavily altered (Figs. 3.1a, b). Plagioclase is saussuritised. Locally, veins filled with fibrous minerals cut across (Fig. 3.1c). Sulphides are rare (<1 modal%), but conspicuous among the altered silicates in gabbronorite (Fig. 3.2a), and consists of pyrrhotite, pentlandite, chalcopyrite and traces of sphalerite (Figs. 3.2b to f). They occur as composite grains (Figs. 3.2b, c) and disseminations (Fig. 3.2d)

associated with altered silicates. While pyrrhotite often occurs intergrown with pentlandite (Figs. 3.2e, f), chalcopyrite occurs along the margin of pyrrhotite. The late fine-grained dolerite intrusion has a typical ophitic texture with clinopyroxene phenocrysts and matrix grains almost completely replaced by chlorite (Fig. 3.1e).

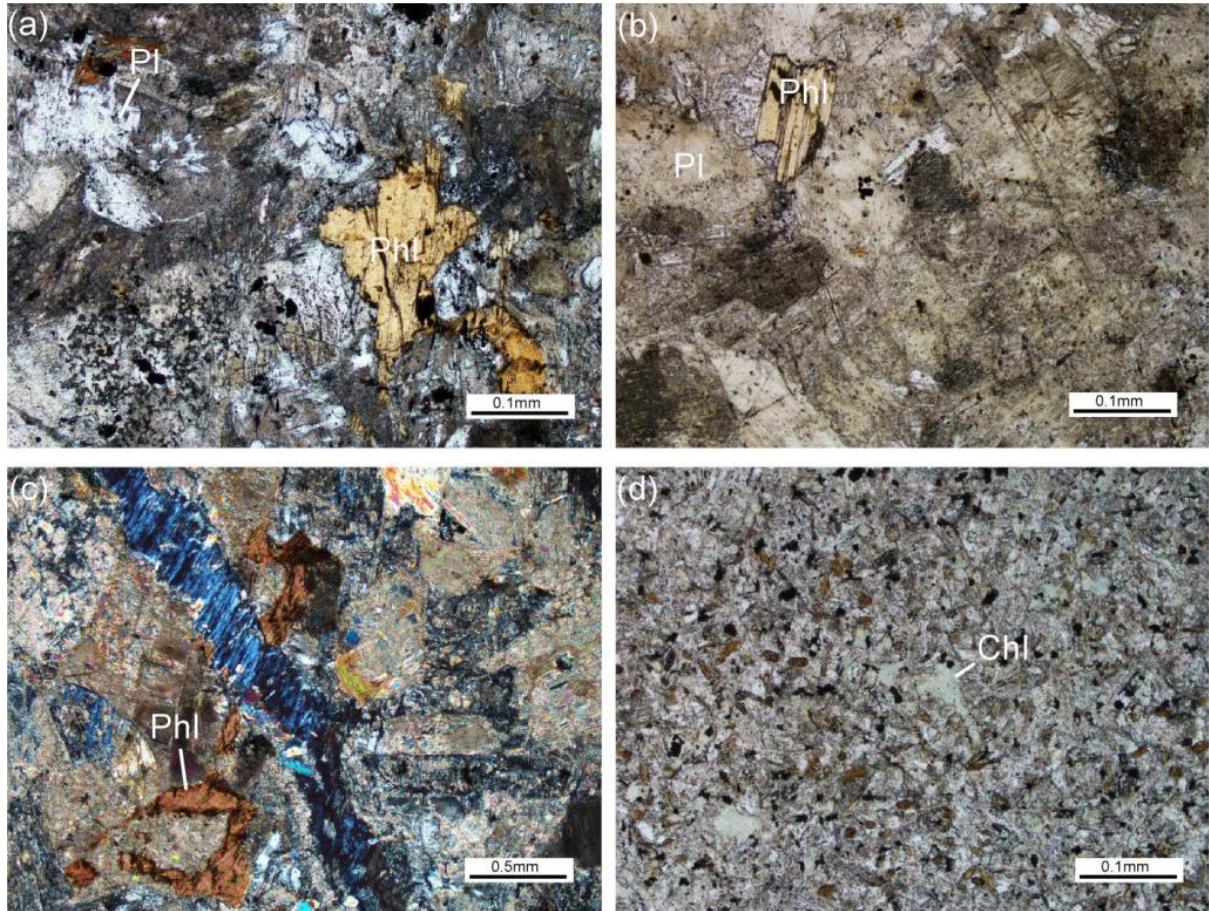


Figure 3.1. Representative photomicrographs illustrating the petrographic characteristics of gabbro-norite and late dolerite intrusion from MF38. **(a), (b), (c)** – highly altered gabbro-norite; **(d)** fine-grained ophitic texture in late dolerite intrusion; Pl – plagioclase; Phl – phlogopite; Chl – chlorite; (a), (b), (d) – PPL; (c) – XPL.

The medium-grained norite and leuconorite are characterised by a distinctive quench texture, and are dominantly made up of elongate (up to 0.8 mm), skeletal (width up to 0.05 mm) orthopyroxene (up to 60 modal%) and plagioclase (25 %), with minor clinopyroxene (~5

%), phlogopite (~3 %) and quartz (~7 %) (Figs. 3.3 and 3.4). Plagioclase and quartz content decreases from leuconorite to norite. Orthopyroxene also occurs as subhedral to euhedral grains. Clinopyroxene rarely occurs as *elongated* grains bordering orthopyroxene (Fig. 3.4).

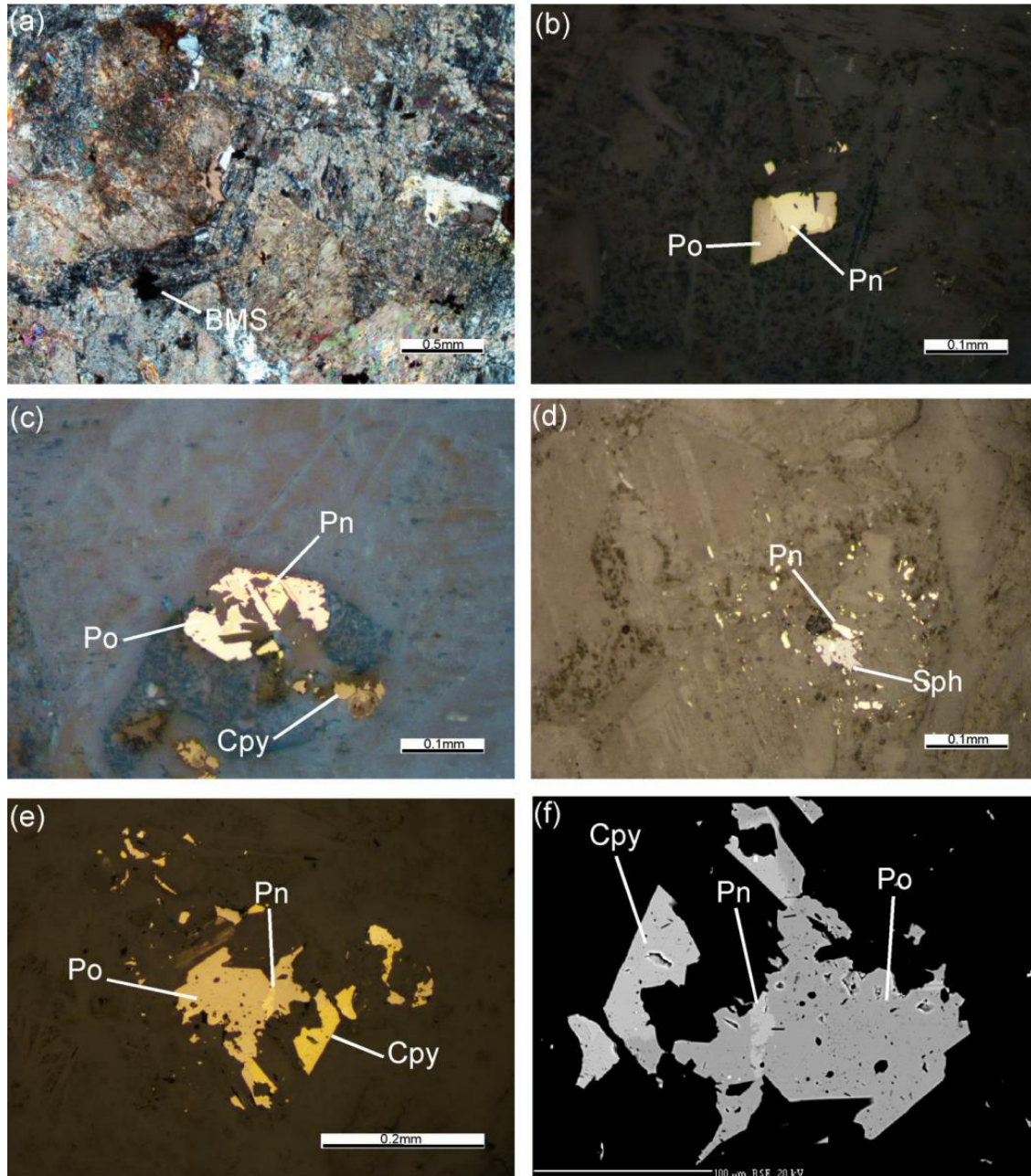


Figure 3.2. Representative photomicrographs illustrating the occurrence of sulphides among altered silicates from the gabbro-norite of MF38. BMS – base metal sulphide; Po – pyrrhotite; Pn – pentlandite; Cpy – chalcopyrite; Sph – sphalerite; (a) – XPL; (b) to (e) – reflected light; (f) – BSE image.

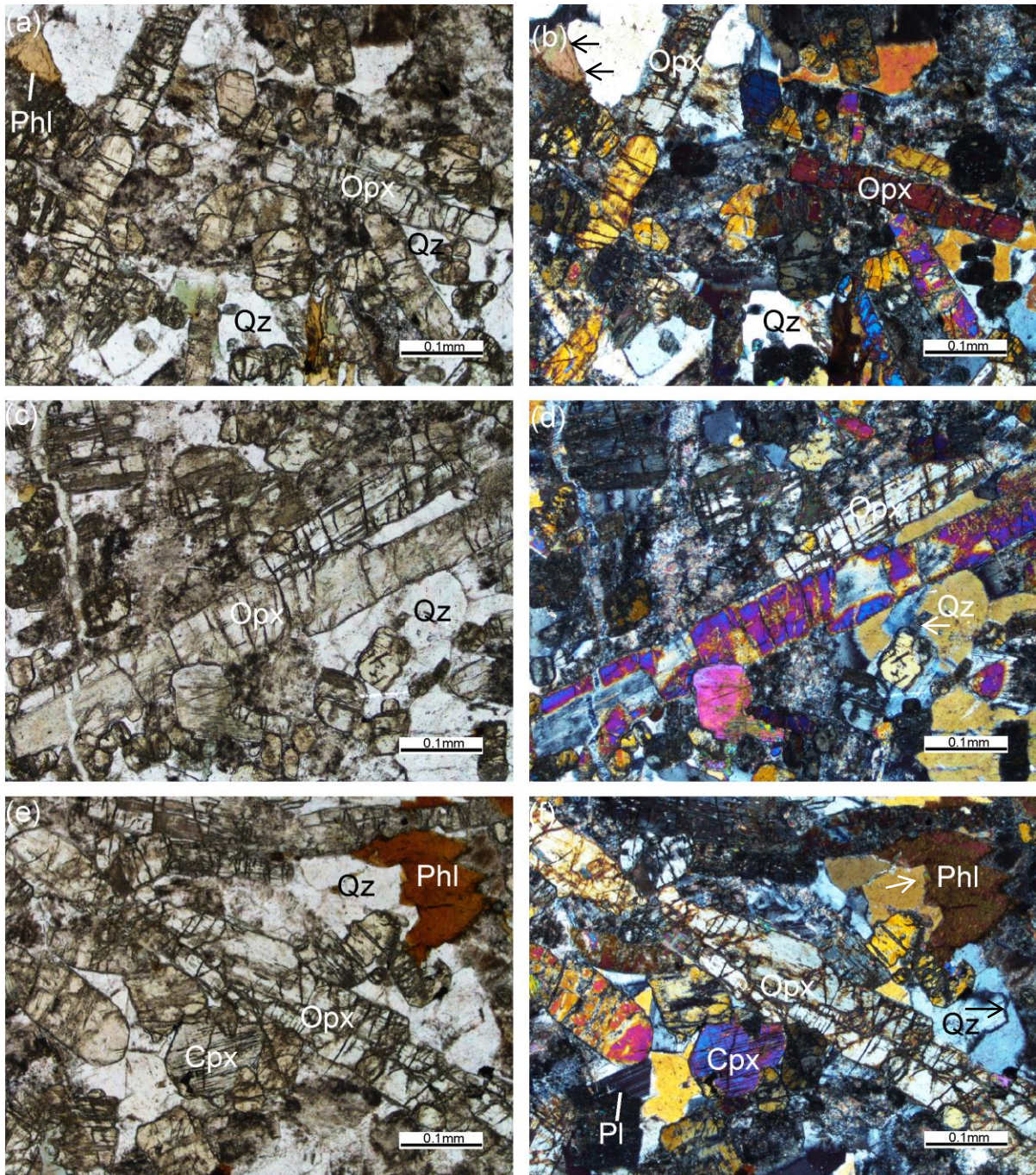


Figure 3.3. (a to f) Representative photomicrographs illustrating the distinctive quench texture observed in norite from the marginal facies of MF38. Opx – orthopyroxene; Cpx – clinopyroxene; Qz – quartz; (a), (c), (e) – PPL; (b),(d), (f) – XPL.

Another important feature of the quench-textured norite and leuconorite is the grain margin relation of quartz with the surrounding grains. Quartz in the quench-textured norites are

characterized by irregular curved protruding (melt-like) grain margins with plagioclase and clinopyroxene (arrowed grains in Figs. 3.3 and 3.4). Minor K-feldspar, biotite, ilmenite and amphibole occur.

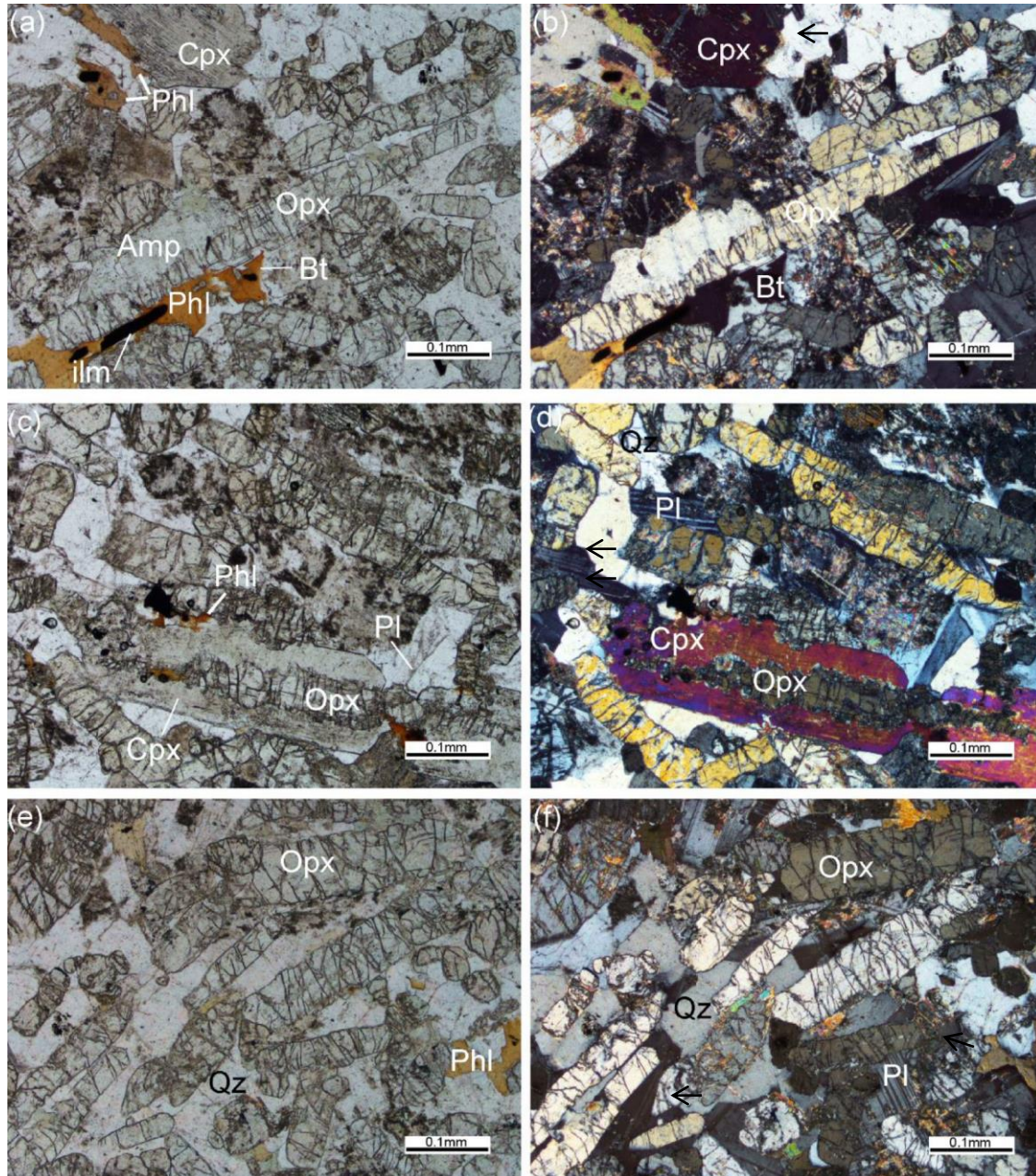


Figure 3.4. (a to f) Representative photomicrographs illustrating the distinctive quench texture observed in leuconorite from the marginal facies of MF38. Amp – amphibole; Bt – biotite; ilm – ilmenite; (a), (c), (e) – PPL; (b),(d), (f) – XPL.

Phlogopite associated with sulphide occur adjacent to/or along pyroxene grain margins (Figs. 3.3 and 3.4). Chlorite replaces pyroxene (Figs. 3.5a, b). Alteration in norite and leuconorite is less prominent than in the gabbro-norite, and involves saussuritisation of plagioclase and veins with fibrous minerals cutting across (Figs. 3.5c, d).

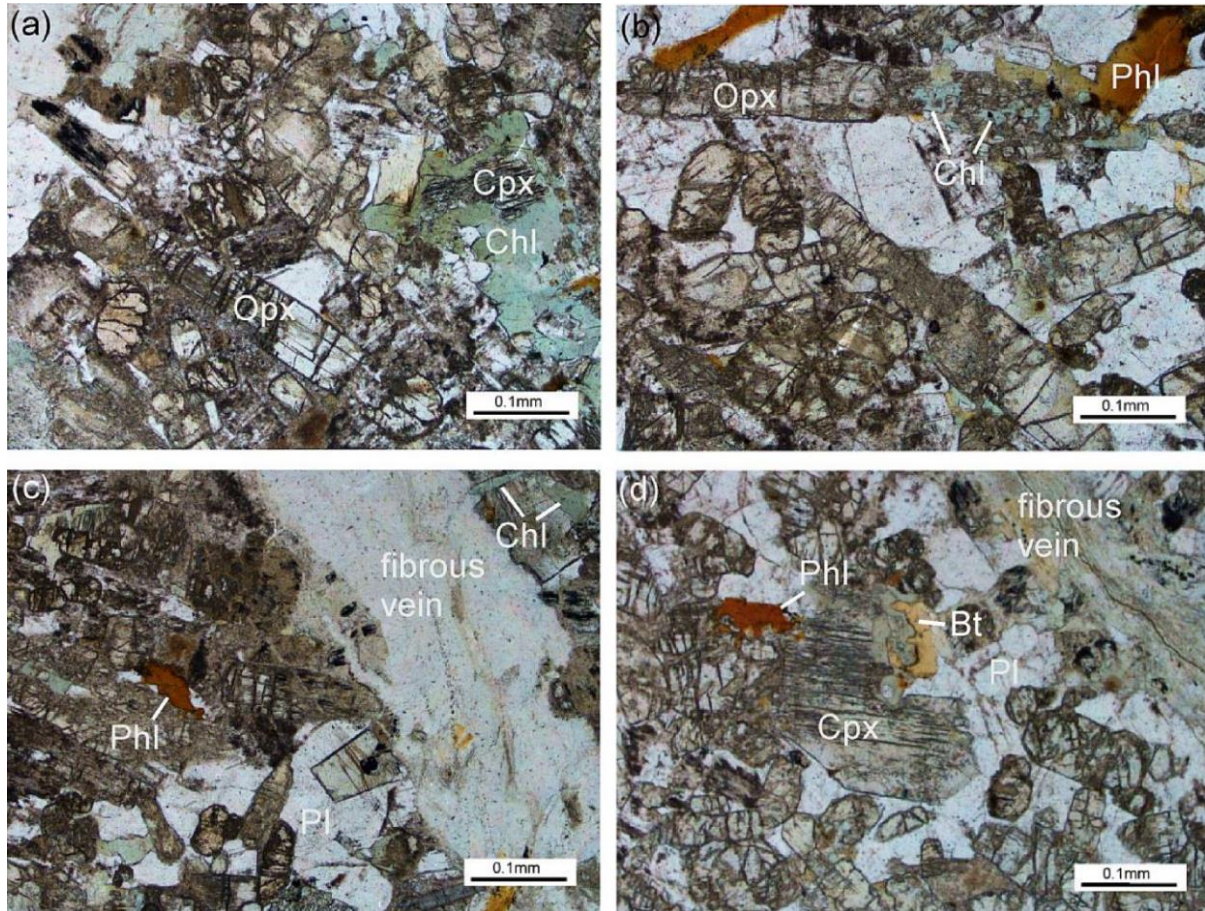


Figure 3.5. Representative photomicrographs illustrating the alteration/replacement features observed in norite **(a to c)** leuconorite **(d)** from the marginal facies of MF38. All images in PPL.

Sulphides typically constitute up to 1 modal% of the norite and leuconorite, and include pyrrhotite (60-70 %), pentlandite (20-40%), minor chalcopyrite (~5%) and trace pyrite (Fig. 3.6). They occur as composite grains interstitial to silicates and disseminations associated with alteration minerals/veins. Pyrrhotite dominantly occurs intergrown with pentlandite

and minor pyrite (Figs. 3.6a to h). Flame-type exsolution intergrowth between pyrrhotite and pentlandite (Fig. 3.6b), and the reverse scenario with pentlandite exsolution is observed (Figs. 3.6j, k).

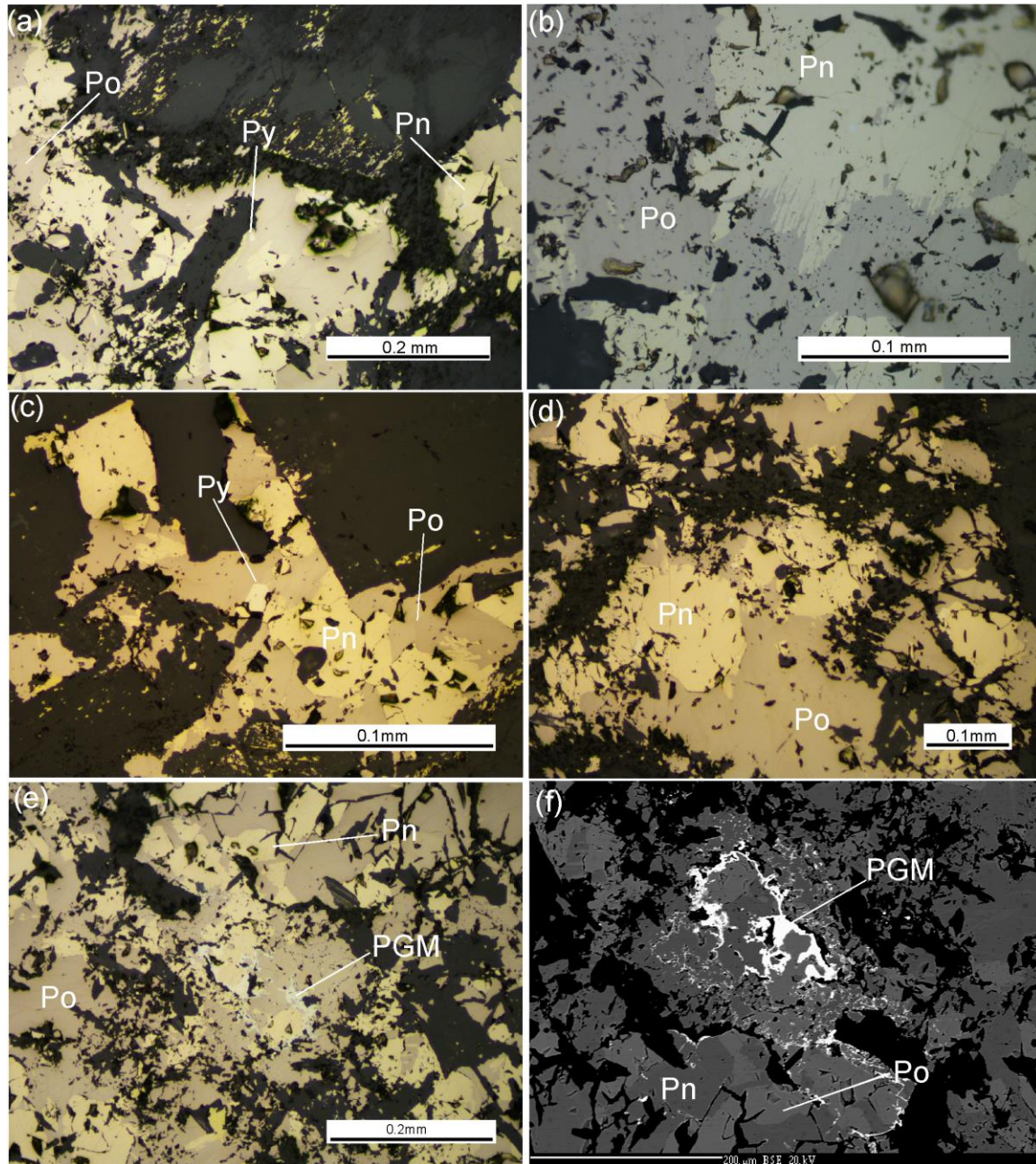


Figure 3.6. Representative reflected light photomicrographs (a to e) and BSE image (f) illustrating the occurrence of sulphides and platinum group minerals (PGMs) in norite/leuconorite from the marginal facies of MF38.

PGMs occur as traces on the margins of pentlandite and pyrrhotite (Figs. 3.6e, f, i).

Chalcopyrite occurs along the margin of pyrrhotite (Figs. 3.6j to l).

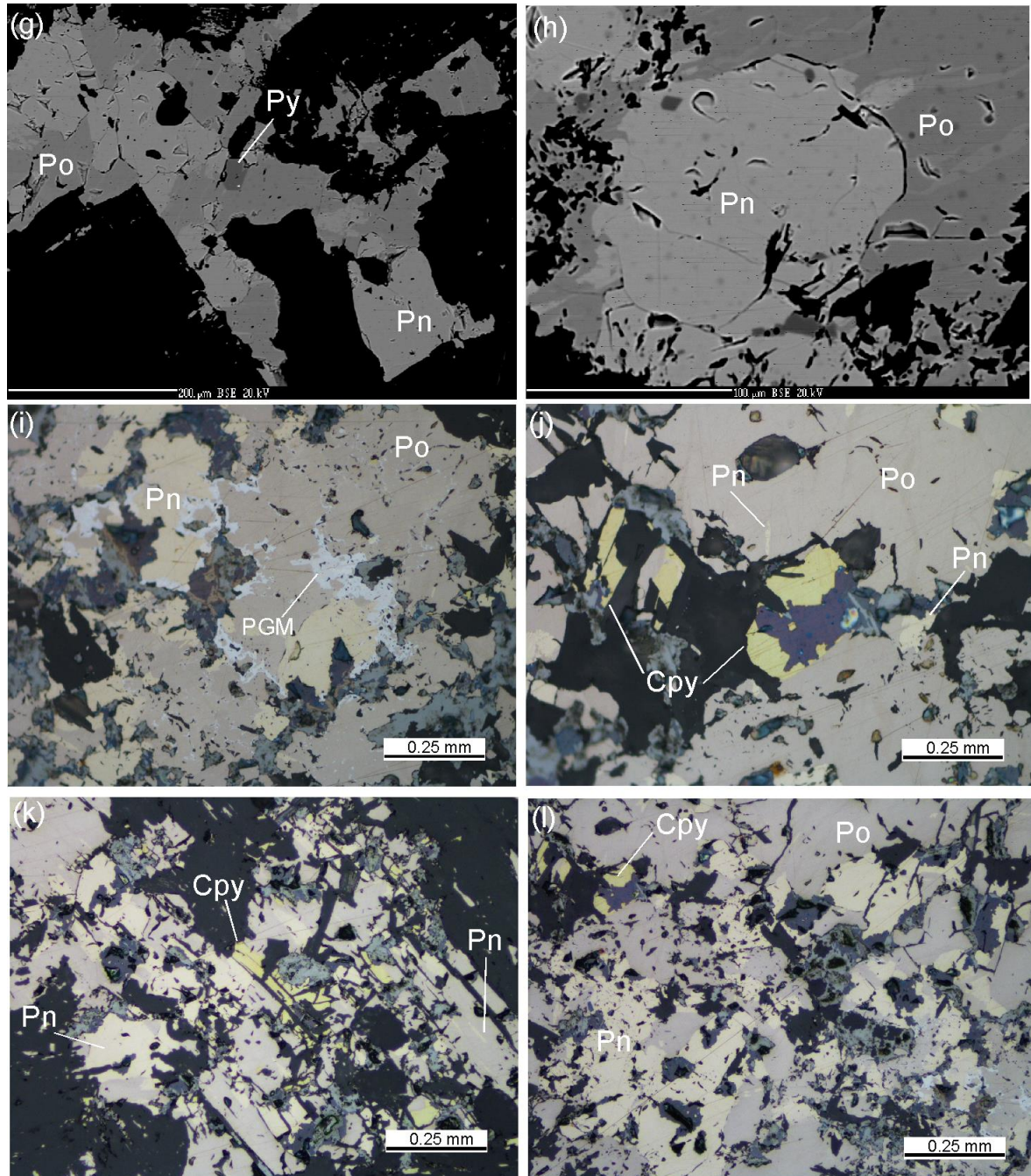


Figure 3.6. (continued) Representative BSE image (g, h) and reflected light photomicrographs (i to l) illustrating the occurrence of sulphides and platinum group minerals (PGMs) in norite/leuconorite from the marginal facies of MF38.

The contact between the marginal noritic unit and the dominant ultramafic sequence is gradational, with a thin feldspathic pyroxenite layer occurring at the base of the ultramafic sequence. Unlike the quench-textured norites, the ultramafic sequence is made up of olivine and orthopyroxene cumulates, and include dominant harzburgites, less dominant pyroxenite and least dominant dunite (Fig. 3.7). The ultramafic rocks are mostly adcumulates, with less intercumulus material. Serpentinization is widespread, with variable preservation of olivine and orthopyroxene (Fig. 3.7). Mesh, hourglass and bastitic textures characterize the serpentinization. Magnetite occurs as subhedral to anhedral grains, as well as thin elongate grains associated with serpentinization (Fig. 3.7). The cyclic unit consists of repetition of similar type of olivine and orthopyroxene cumulates, with variable degrees of serpentinization.

In contrast to the typical ultramafic rocks in the sequence, a medium-grained highly altered pyroxenite with more intercumulus material occur within the ultramafic sequence (Fig. 3.8). This orthocumulate unit is not serpentinized. Both the altered pyroxenes and intercumulus material (plagioclase+orthopyroxene+clinopyroxene?) has irregular rounded grain margins (Fig. 3.8). Like the marginal norite, minor phlogopite occurs associated with orthopyroxene in this pyroxenite unit. Sulphides are prominently associated with this pyroxenite, constituting up to 3 modal%, and include pyrrhotite (50-70%), chalcopyrite (30-40%), pentlandite (~20%) and traces of sphalerite (Fig. 3.9). The sulphides occur as composite grains, interstitial to silicates and often part of the intercumulus material, and as

disseminated small monomineralic grains within the altered grains (Fig. 3.9). Chalcopyrite with irregular grain margins occurs along the margin of pyrrhotite and pentlandite.

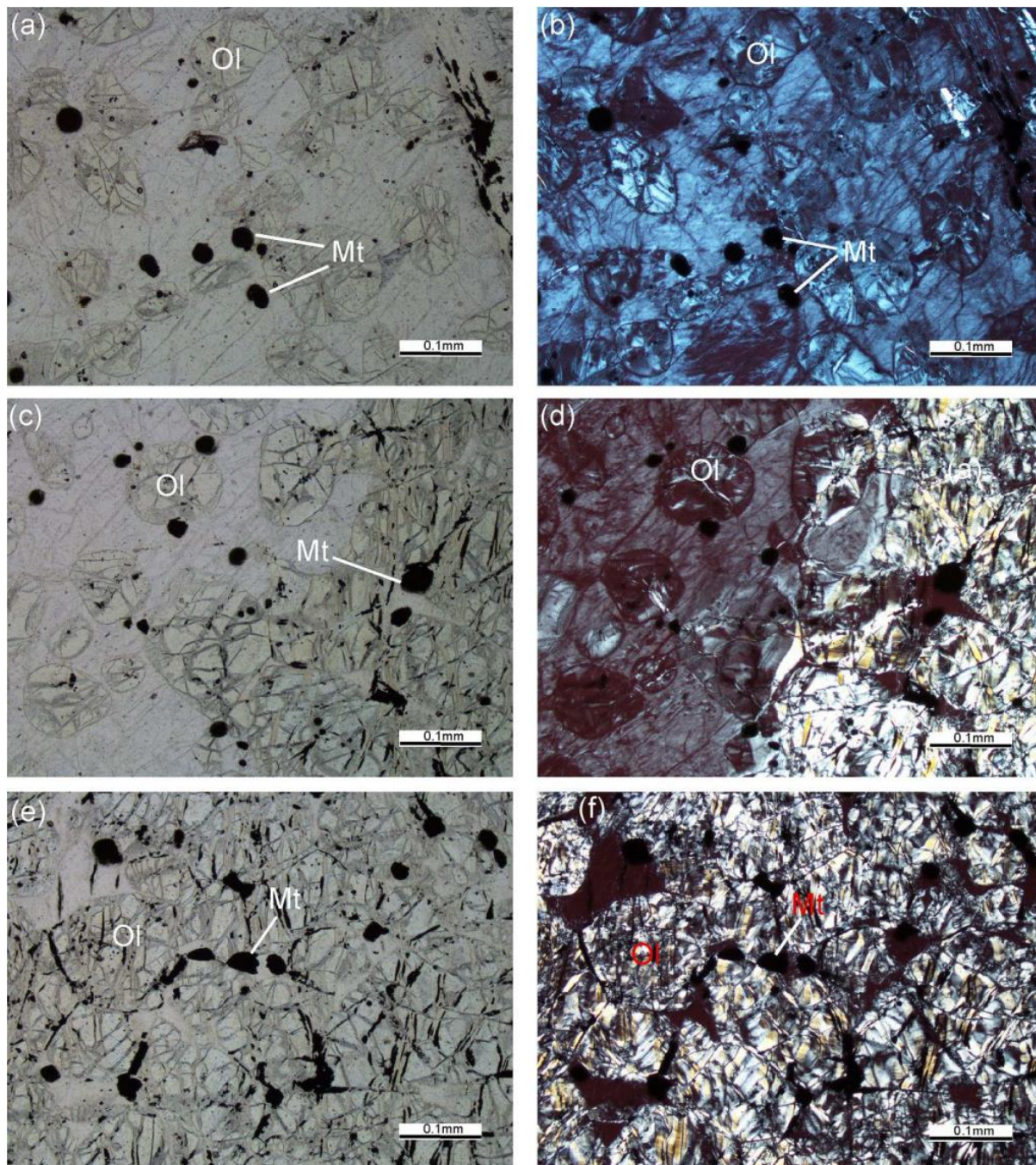


Figure 3.7. (a to f) Representative photomicrographs illustrating the typical occurrence of serpentinized olivine and orthopyroxene cumulate from the ultramafic sequence of MF38. Ol – olivine; Mt – magnetite (a), (c), (e) – PPL; (b),(d), (f) – XPL.

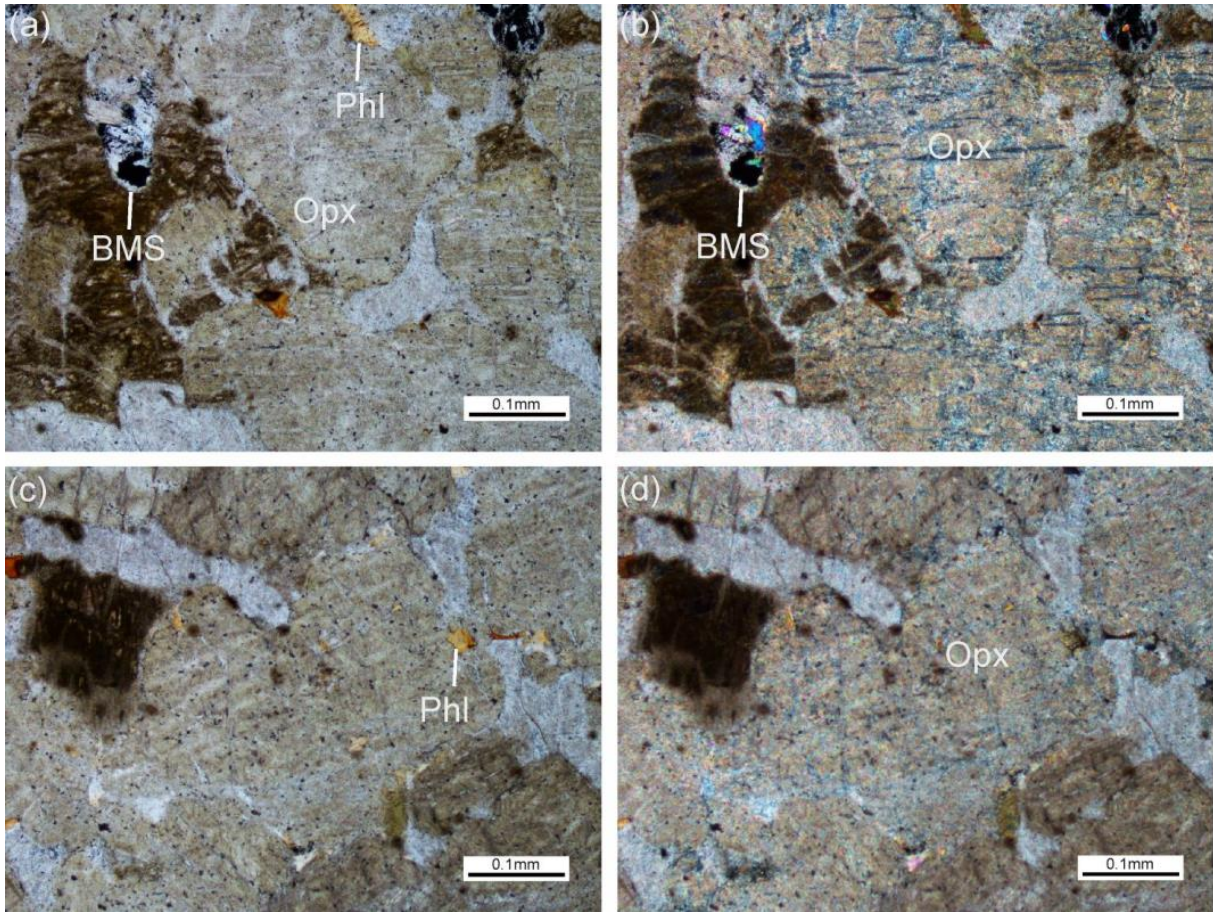


Figure 3.8. (a to d) Representative photomicrographs illustrating the occurrence of the altered pyroxenite unit with more intercumulus material from the ultramafic sequence of MF38. This orthocumulate unit is different from the rest of the ultramafic rocks, which are adcumulates, and was selected for detailed study together with the marginal norite unit. (a), (c) – PPL; (b),(d) – XPL.

3.3. MF11

In comparison to MF38, MF11 better preserves the typical ultramafic sequence of the Molopo Farms Complex. The different cumulate rocks include dominant harzburgite/dunite and less dominant pyroxenite. Thin norite layers occur associated with the pyroxenite, and are orthopyroxene and plagioclase cumulates, similar to those occurring in the mafic sequence in MF9 (see section 3.4). Pyroxenite is prominent in the lower portion of MF11 and occurs as both feldspathic and massive variants. In comparison to MF38, feldspathic

pyroxenite is better preserved in MF11. Cumulate layering is characteristic of most of the feldspathic pyroxenite units (Fig. 3.10).

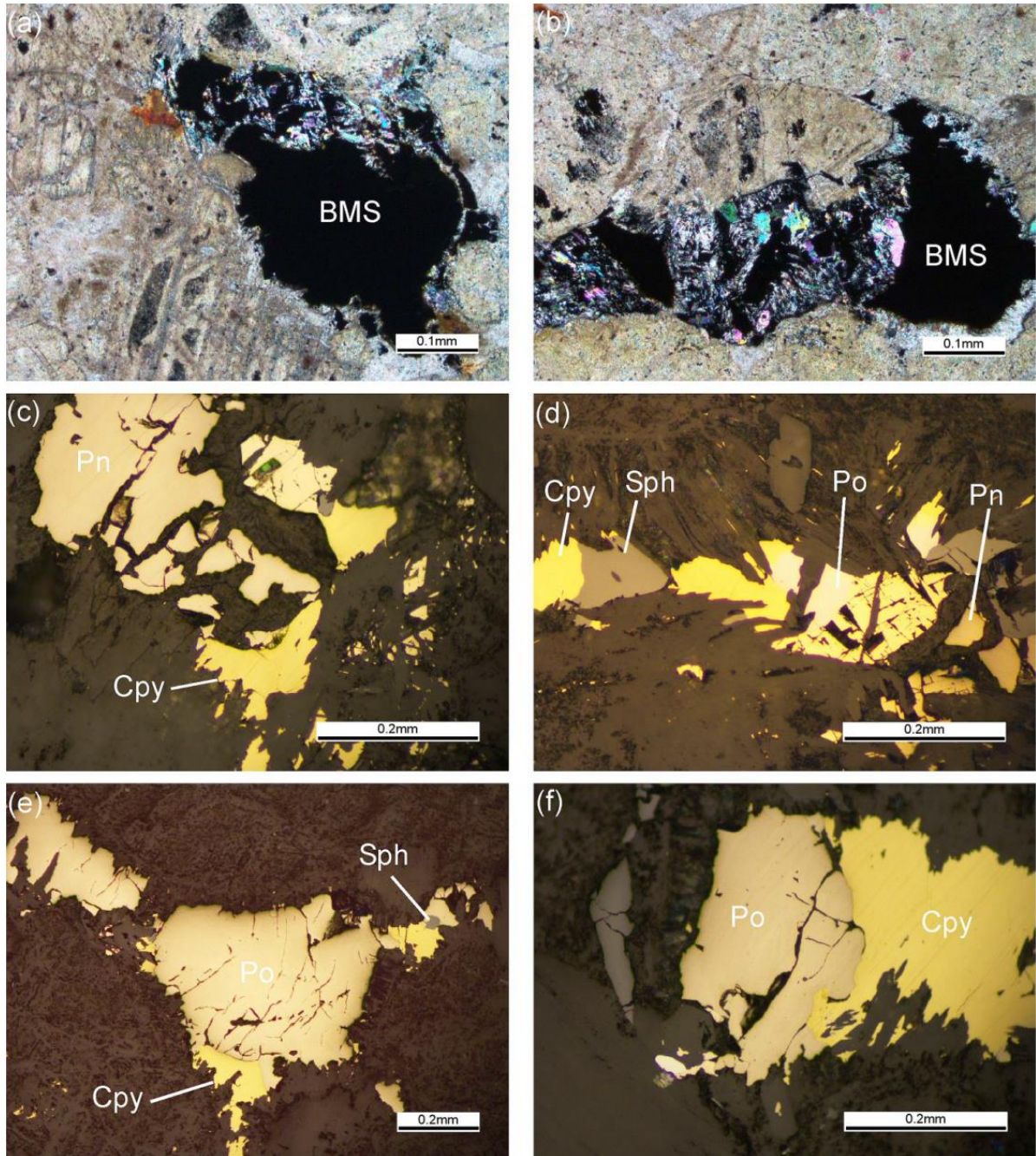


Figure 3.9. (a to f) Representative photomicrographs illustrating the occurrence of sulphides in the medium-grained altered pyroxenite unit with more intercumulus material from the ultramafic sequence of MF38. (a), (b) – XPL; (c) to (f) – reflected light.

Orthopyroxene occurs as both elongate (up to 0.4 mm) as well as subhedral grains together with minor interstitial plagioclase and clinopyroxene (Figs. 3.10a to d).

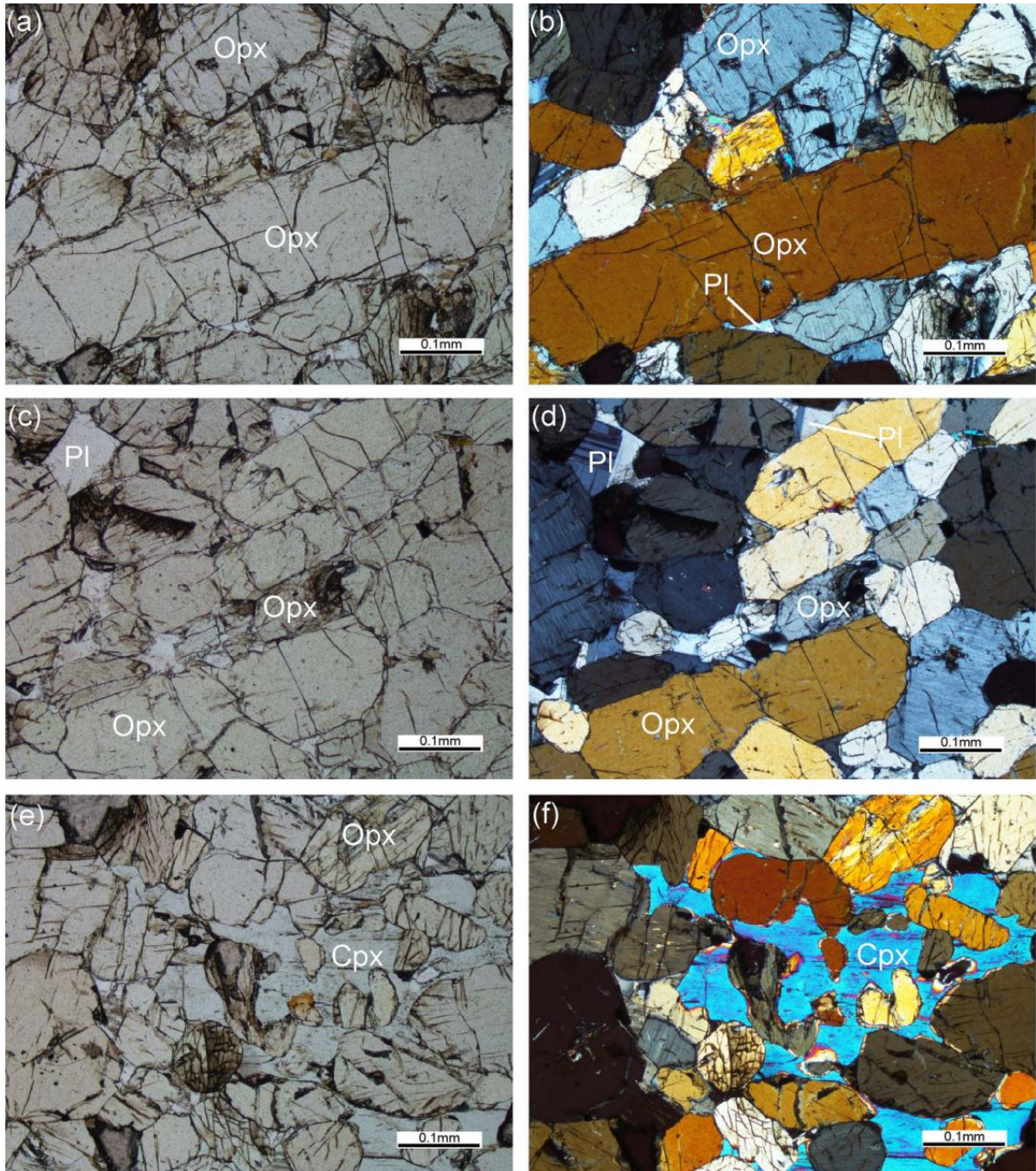


Figure 3.10. (a to f) Representative photomicrographs illustrating the occurrence of the feldspathic pyroxenite from MF11. (e) and (f), with more intercumulus plagioclase, are from a stratigraphically lower unit. (a), (c), (e) – PPL; (b), (d), (f) – XPL.

Where the cumulate layering is seen, a well-developed planar fabric is obvious. Where the igneous layering is absent, orthopyroxene does not form elongate grains. Intercumulus plagioclase becomes more prominent with depth (Figs. 3.10e, f). Minor phlogopite occurs. Alteration is minimal in feldspathic pyroxenite units from the lower portion of MF11.

The harzburgite unit adjacent to feldspathic pyroxenite has minor intercumulus plagioclase. Locally, it also preserves cumulate layering with adjacent pyroxene-rich and olivine-rich domains (Figs. 3.11a to c). Unlike the pyroxene-rich domains, the olivine-rich domains are variably serpentinized (Fig. 3.11). Veining related to serpentinization is locally seen (Fig. 3.11d). Magnetite occur as subhedral to anhedral grains associated with olivine and orthopyroxene. With the progress of serpentinization, the occurrence of magnetite varies from elongated adjoined grains to veins to layers (Figs. 3.11c to f). Layers become prominent with widening of the fluid pathways associated with serpentinization (Fig. 3.11f).

In comparison to the rocks occurring in the lower portion, those ultramafic cumulate rocks occurring towards the upper portion of MF11 are heavily serpentinized (Figs. 3.12 to 3.14). Veining related to serpentinization is conspicuous and becomes prominent towards the ultramafic rocks at the top of MF11 (Figs. 3.12 to 3.14). No fluid pathways, like in the harzburgite from the lower portion (e.g., Fig. 3.11f), are seen in serpentinized rocks from the upper portion of MF11 (Figs. 3.12 to 3.14). As a result (?), no magnetite layers (as seen in Fig. 3.11f) are observed. Olivine relics, with former grain outlines, are variably preserved (Figs. 3.12 to 3.14). Orthopyroxene shows bastitic texture. Serpentine variants include antigorite,

lizardite and chrysotile. Magnetite occurs as minor disseminated grains. In comparison to ultramafic rocks from MF38, no prominent sulphide occurs in similar rocks from MF11.

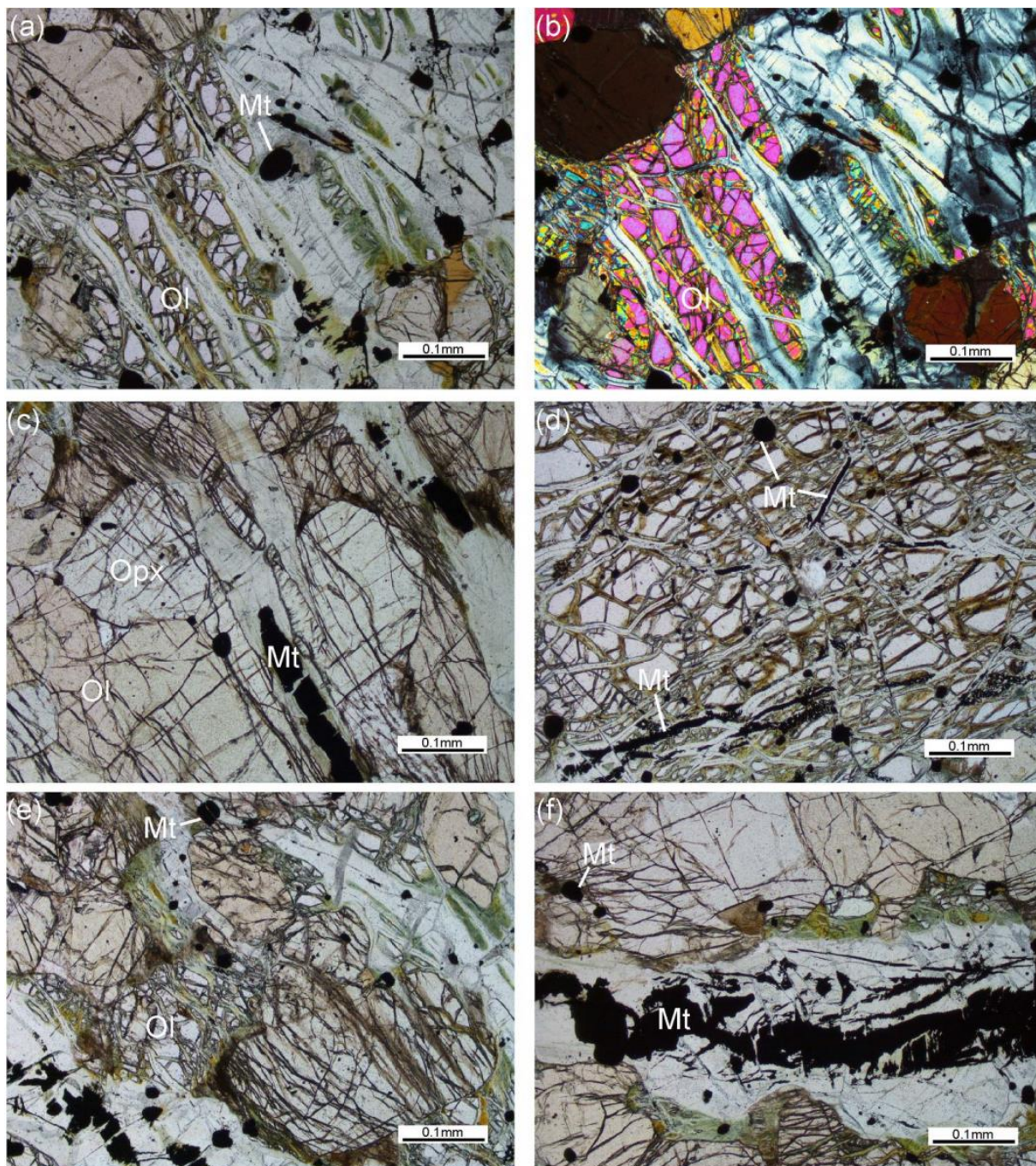


Figure 3.11. (a to f) Representative photomicrographs illustrating a harzburgite unit adjacent to feldspathic pyroxenite from the lower portion of MF11. All images except (b) in PPL. (b) – XPL.

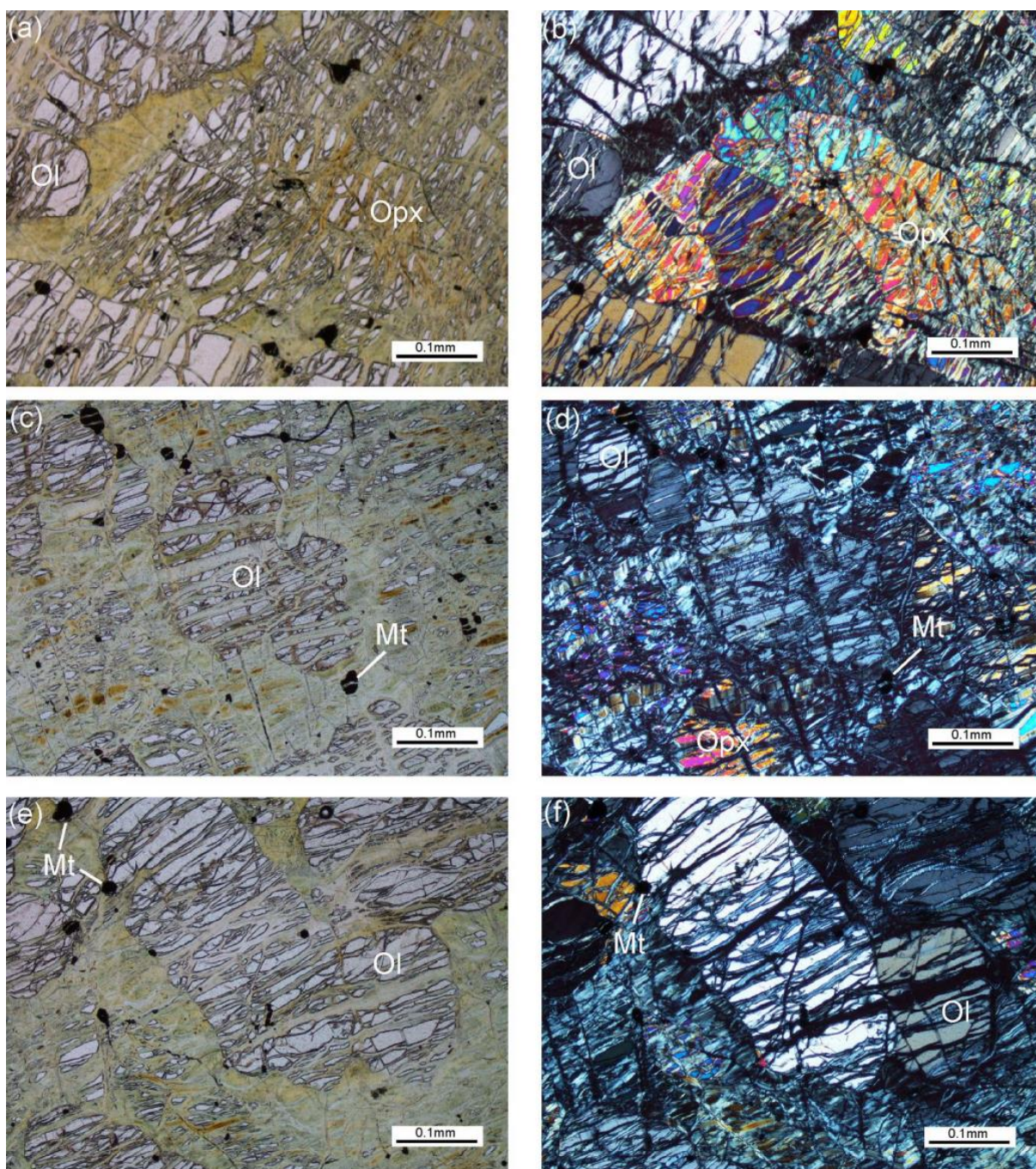


Figure 3.12. (a to f) Representative photomicrographs illustrating the heavily serpentinized harzburgite from the upper portion of MF11. Former olivine and orthopyroxene grain outline can be seen from relics. Notice the less concentration of magnetite associated with the serpentinization associated with harzburgite from the upper portion. In comparison, magnetite occur prominently as grains to elongated grains to veins to layers in serpentinized harzburgite adjacent to feldspathic pyroxenite from the lower portion of MF11 (see Fig. 3.11). (a), (c), (e) – PPL; (b), (d), (f) – XPL.

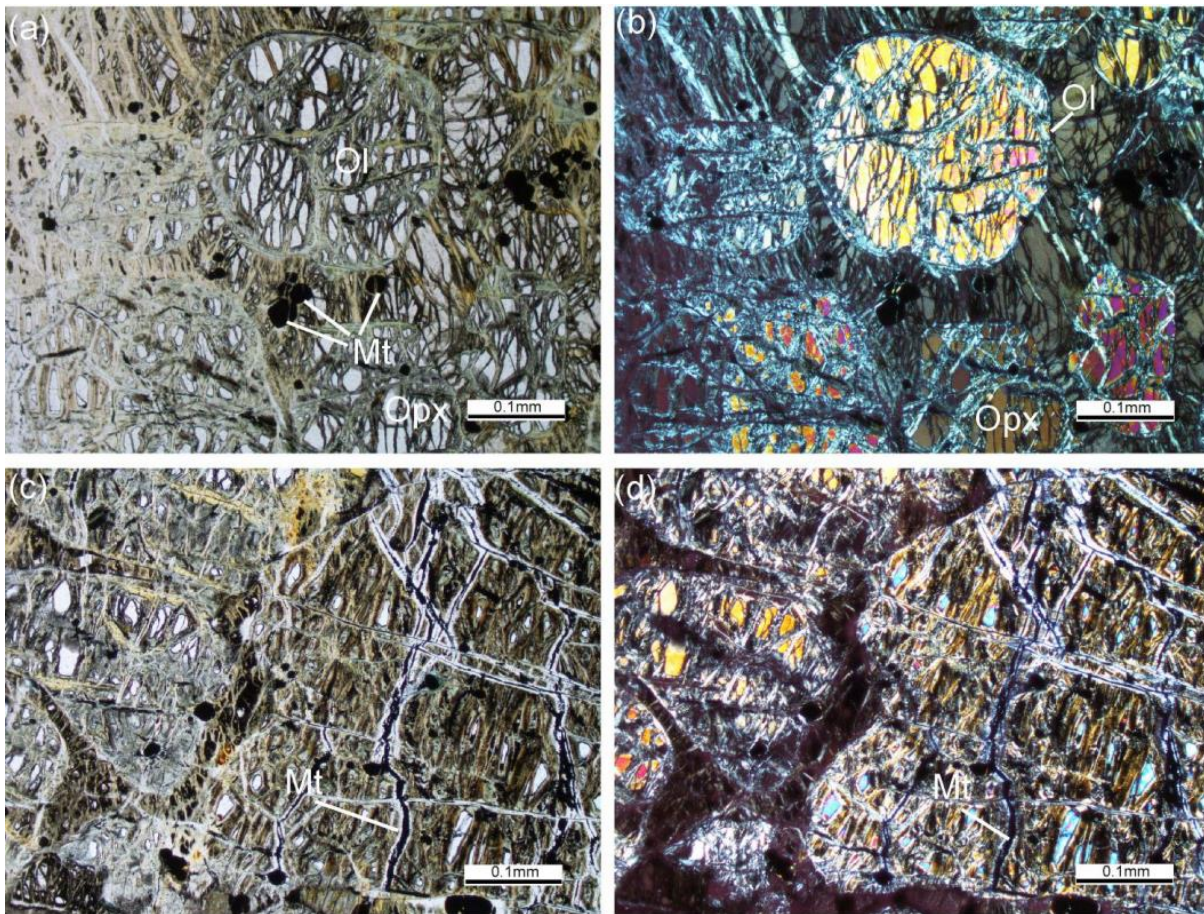


Figure 3.13. (a to d) Representative photomicrographs illustrating the heavily serpentinized harzburgite from the upper portion of MF11. This set of images is from a unit above those shown in Fig. 3.12. (a), (c) – PPL; (b), (d) – XPL.

3.4. MF9

MF9 represents a typical mafic sequence from the Molopo Farms Complex and consists of dominant gabbronorite, less dominant norite and minor feldspathic pyroxenite. Unlike the quench-textured noritic units from MF38, the mafic rocks in MF9 are cumulates, made up of orthopyroxene, plagioclase and clinopyroxene (Figs. 3.15, 3.16, 3.19 and 3.20). Poikilitic texture is conspicuous in gabbronorites, and typical occurrences include orthopyroxene and

plagioclase chadacrysts in clinopyroxene, clinopyroxene and plagioclase chadacrysts in orthopyroxene, and pyroxene chadacrysts in plagioclase (Figs. 3.15 and 3.16).

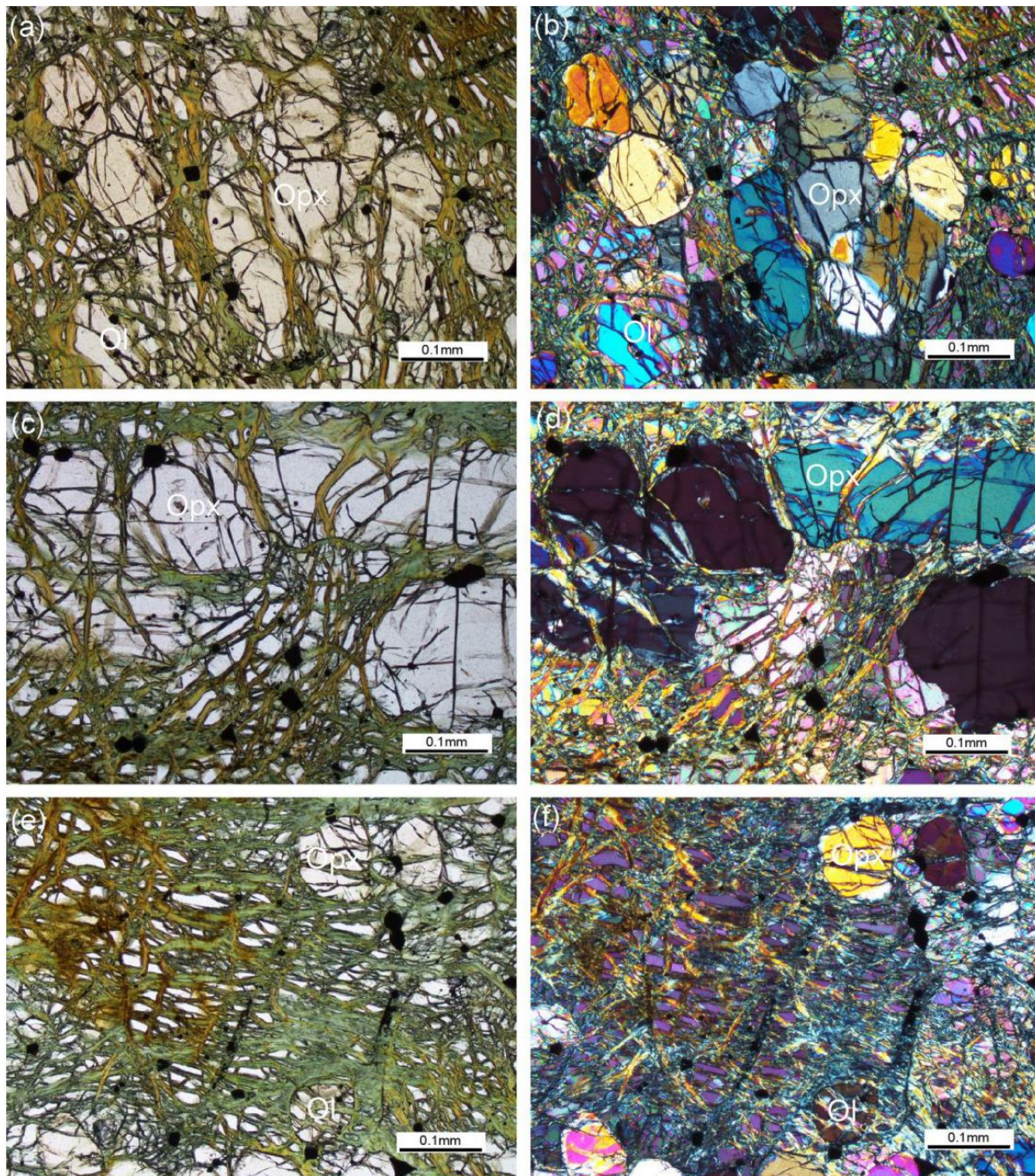


Figure 3.14. (a to f) Representative photomicrographs illustrating the heavily serpentinized harzburgite from the top portion of MF11. (a), (c), (e) – PPL; (b), (d), (f) – XPL.

Plagioclase is subhedral to euhedral. Inverted pigeonite is prominent in the gabbronorites (Fig. 3.16). Exsolution lamellae in pyroxene occurs as either closely spaced linear or widely spaced bleb-shaped ones.

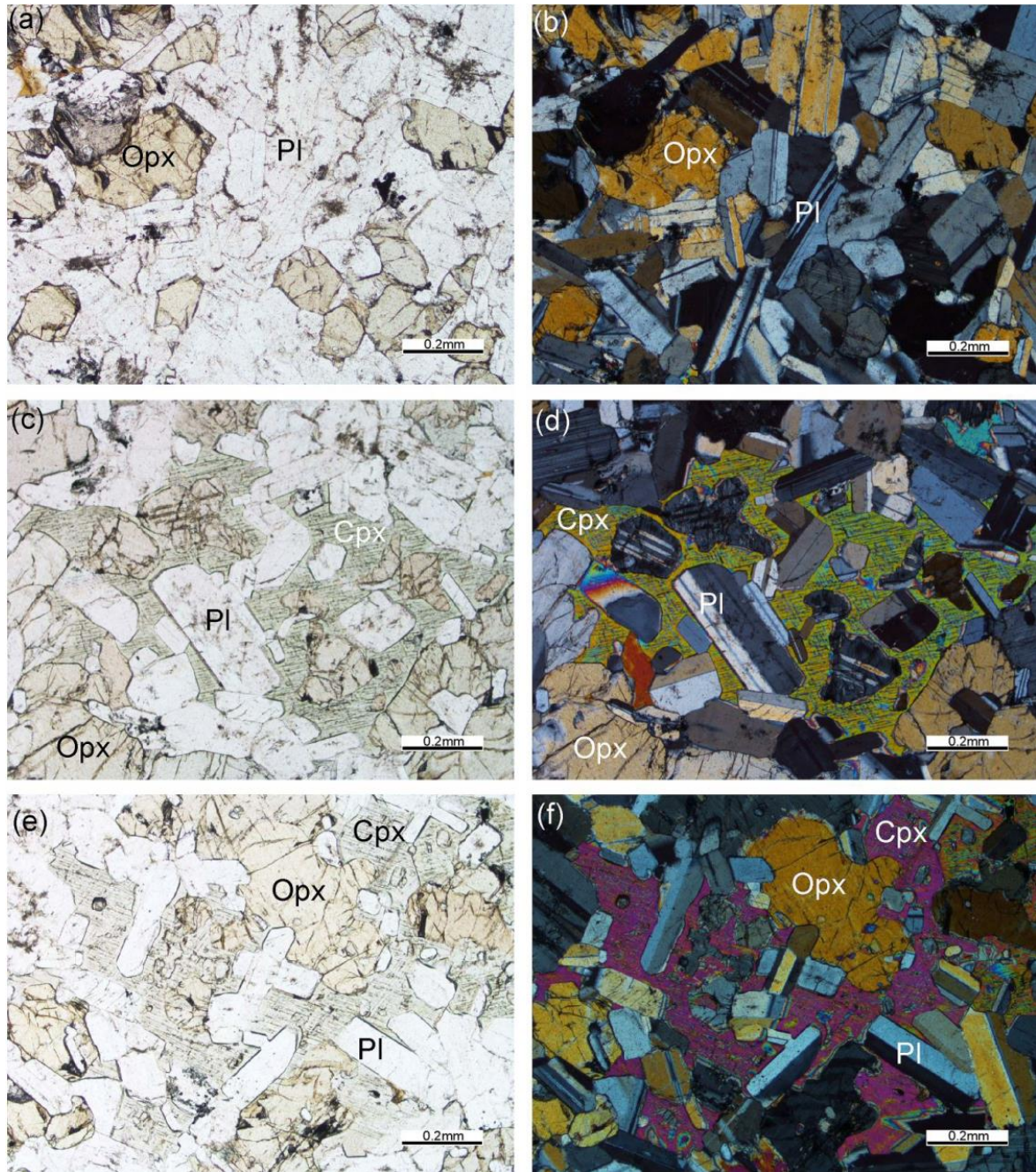


Figure 3.15. (a to f) Representative photomicrographs illustrating the gabbronorite from MF19. Poikilitic texture involving pyroxenes and plagioclase is shown. (a), (c), (e) – PPL; (b), (d), (f) – XPL.

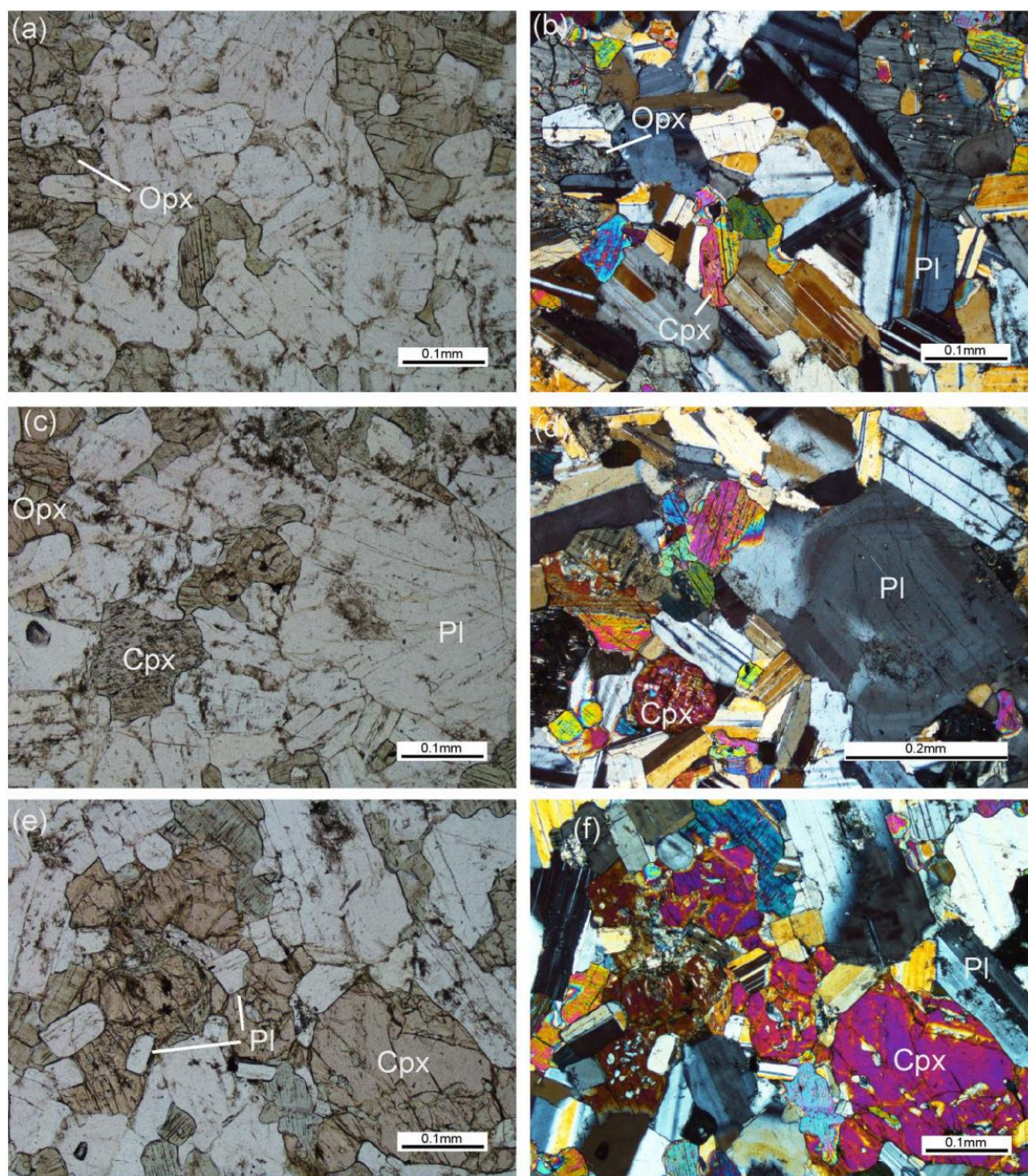


Figure 3.16. (a to f) Representative photomicrographs illustrating the gabbronorite from MF19. Poikilitic texture involving pyroxenes and plagioclase is shown. (a), (c), (e) – PPL; (b), (d), (f) – XPL.

Minor sulphide occurs as composite grains and disseminations associated with orthopyroxene and plagioclase in the gabbronorite (Figs. 3.17 and 3.18). Composite grains include pyrrhotite-pentlandite and pyrrhotite-chalcopyrite associations (Fig. 3.17). Locally,

pyrite occurs as large grains interstitial to the silicates (Fig. 3.18). Chalcopyrite occurs along the margin of these pyrites, and as disseminations in the adjacent silicates (Fig. 3.18).

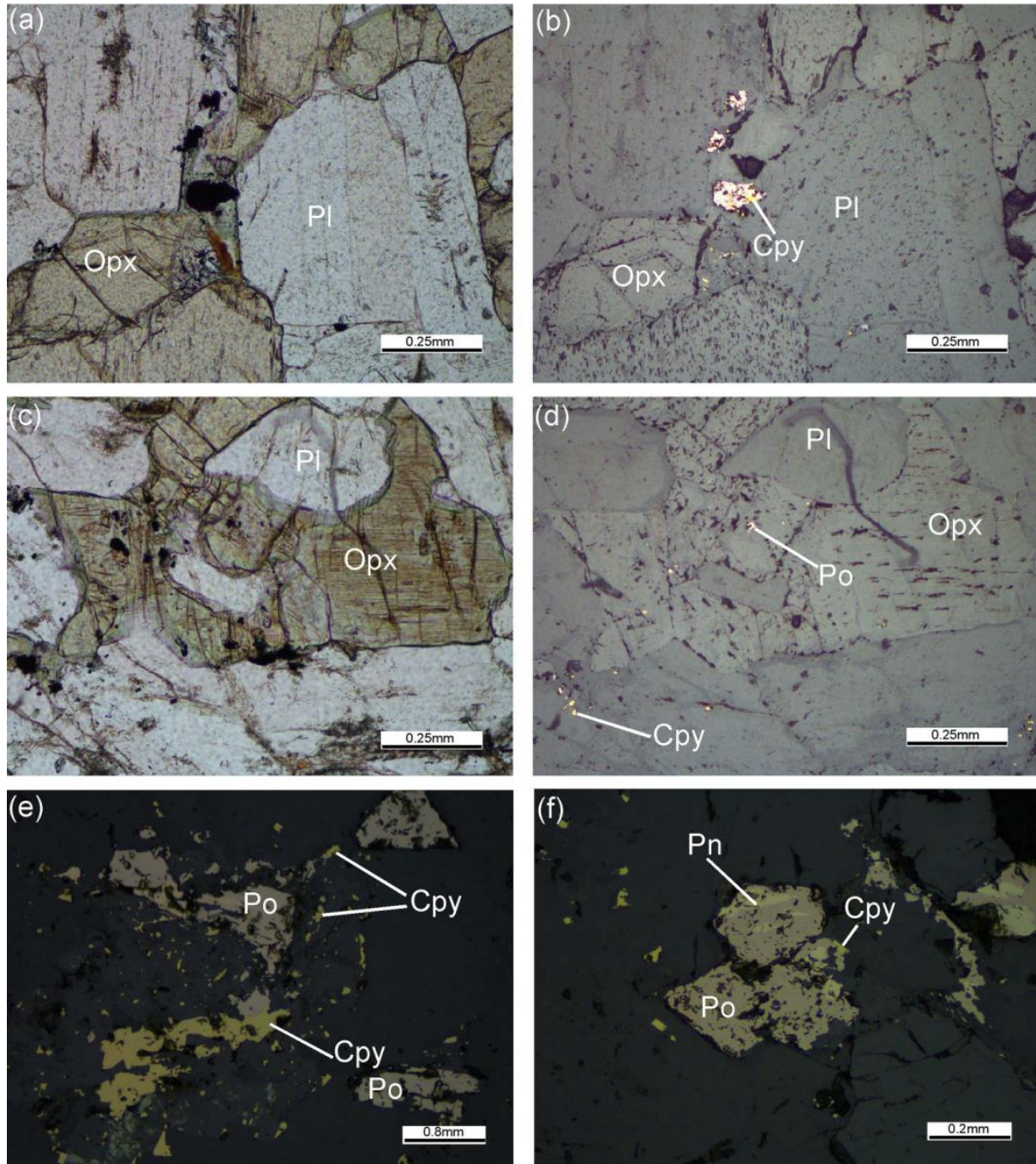


Figure 3.17. (a to f) Representative photomicrographs illustrating the minor sulphide occurrence in gabbro-norite from MF9. (a), (c) – PPL; (b), (d), (e), (f) – reflected light.

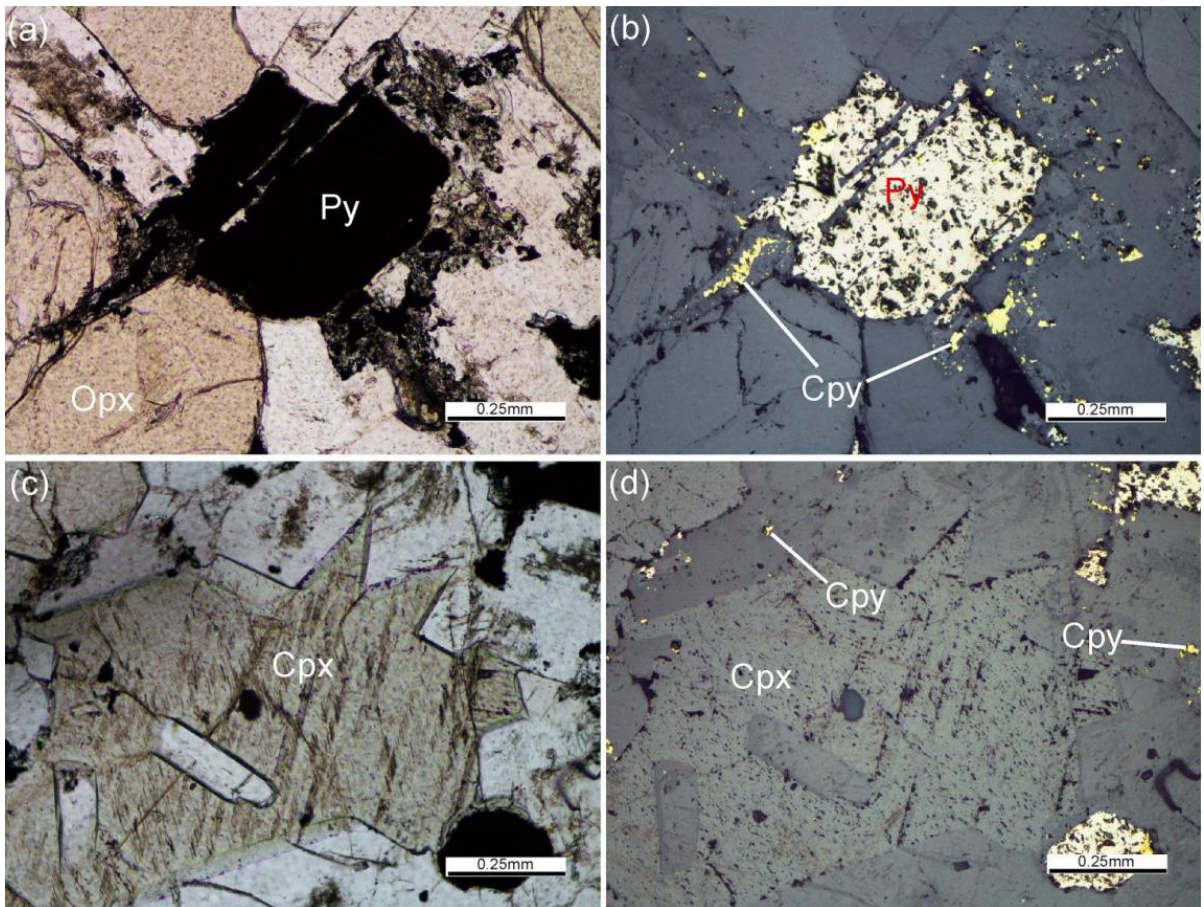


Figure 3.18. (a to d) Representative photomicrographs illustrating the minor sulphide occurrence in gabbronorite from MF9. (a), (c) – PPL; (b), (d) – reflected light.

In comparison to the gabbronorites, norites from MF9 are altered (Fig. 3.19). Cumulate texture is prevalent. Like gabbronorites, plagioclase is subhedral to euhedral (Fig. 3.19). However, the plagioclase is saussuritised in the norite. Poikilitic texture occurs, but is less obvious, due to alteration (Fig. 3.19). Minor clinopyroxene occurs. Like in the gabbronorites, inverted pigeonite is prominently preserved in norites (Fig. 3.19). With increase in the degree of alteration (as one moves up MF9), plagioclase becomes anhedral with rounded grain margins (Figs. 3.19e, f and 3.20a, b). Veins with fibrous minerals cut across (Figs. 3.20c, d). Chlorite replaces orthopyroxene (Figs. 3.20a, b).

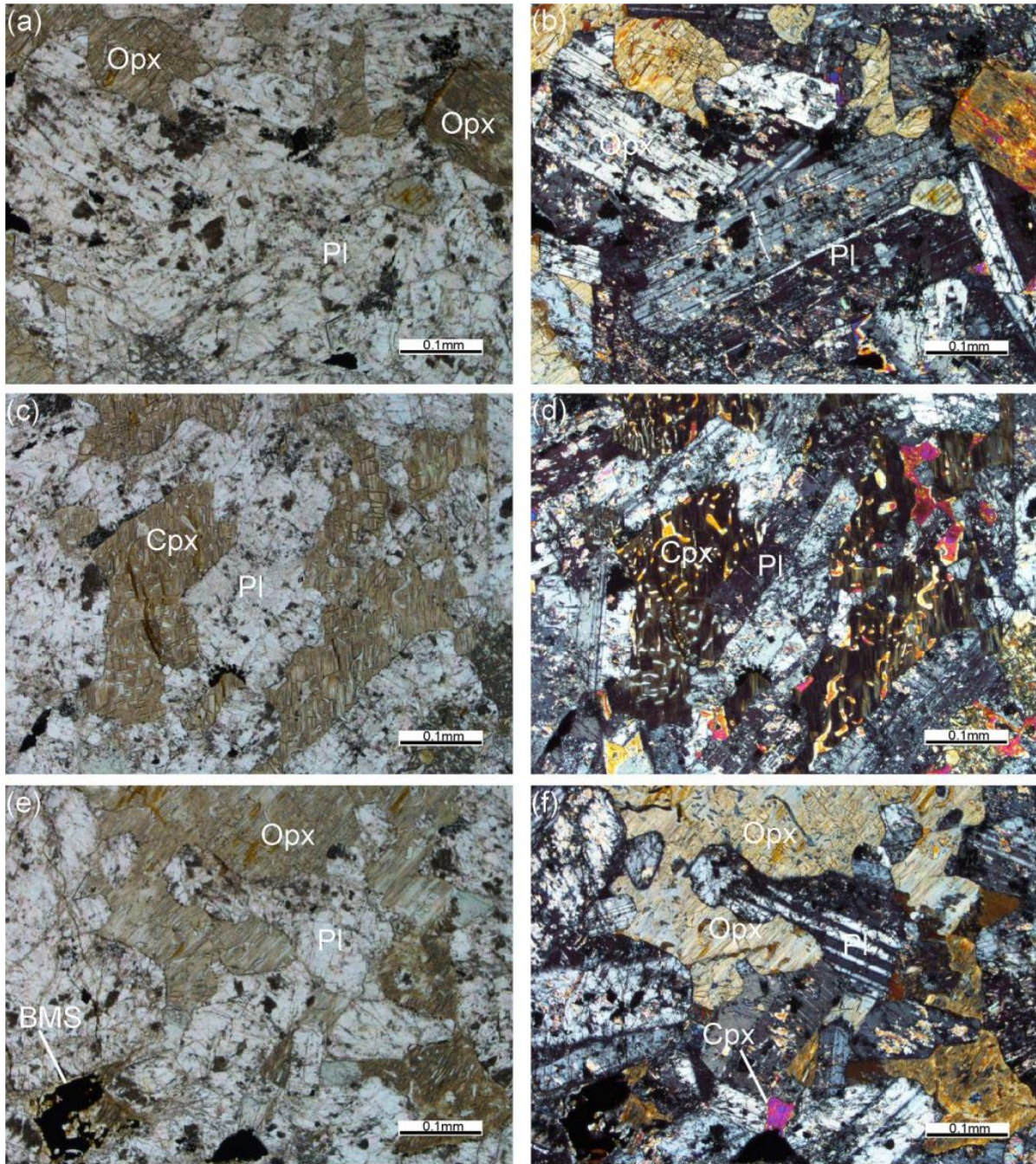


Figure 3.19. (a to f) Representative photomicrographs illustrating the norite from MF19. Notice the textural similarity in comparison with gabbro-norites (see Figs. 3.15 and 3.16). However, alteration is prominent in the norites. (a), (c), (e) – PPL; (b), (d), (f) – XPL.

Minor amounts of sulphide is present in norite too, and are conspicuous among the altered silicates (Figs. 3.20e, f). They do not appear to be resorbed as they have curved

regular grain boundaries with the surrounding silicates (Figs. 3.20e, f), likely indicating that they formed before the hydrothermal alteration.

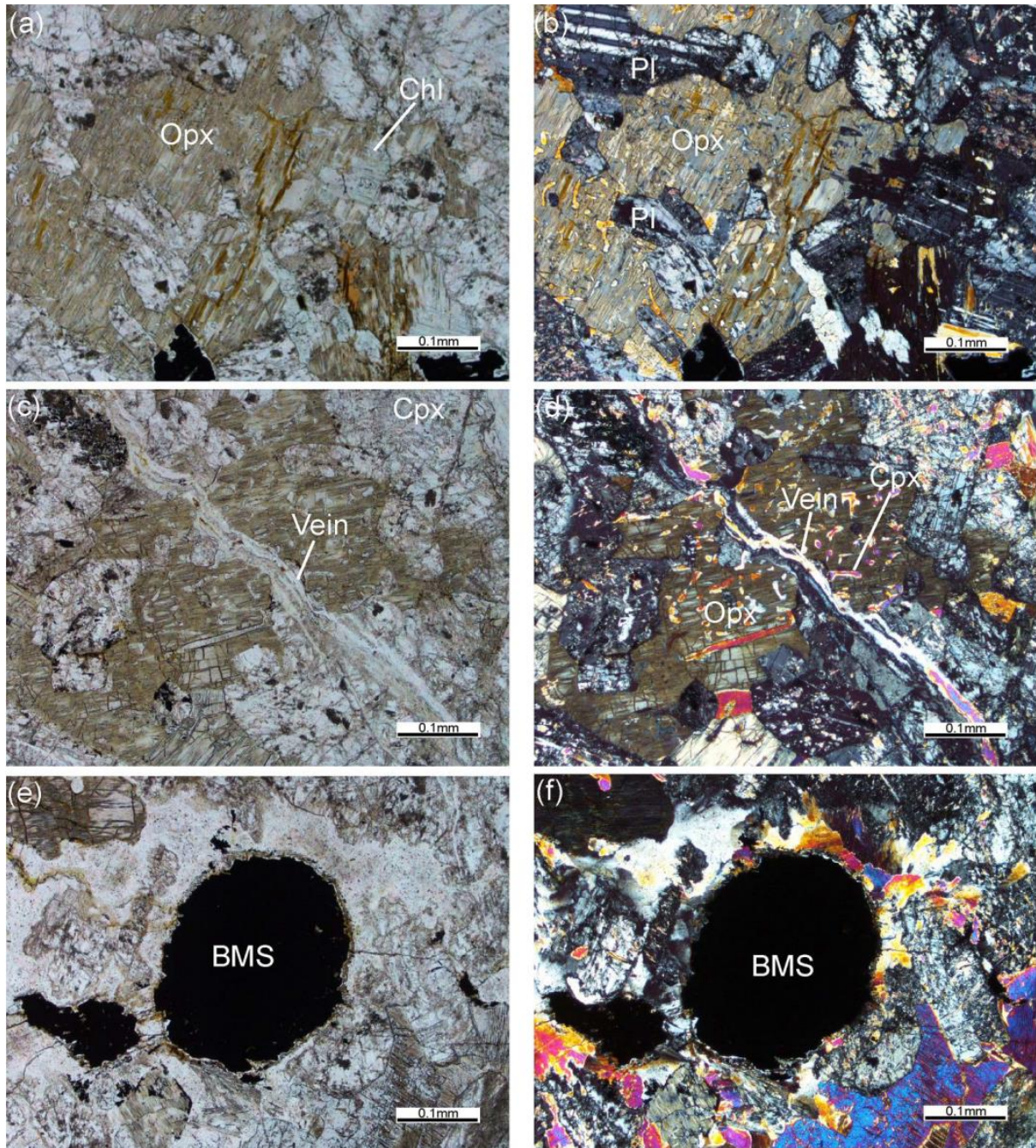


Figure 3.20. (a to f) Representative photomicrographs illustrating the norite from MF9. Notice the alteration, rounded grain margins of plagioclase and conspicuous sulphide among the altered grains. BMS – base metal sulphide; (a), (c), (e) – PPL; (b), (d), (f) – XPL.

Pyrite is the dominant sulphide and occurs as interstitial grains to silicates (Figs. 3.21a to d). It is altered to marcasite (Figs. 3.21e, f).

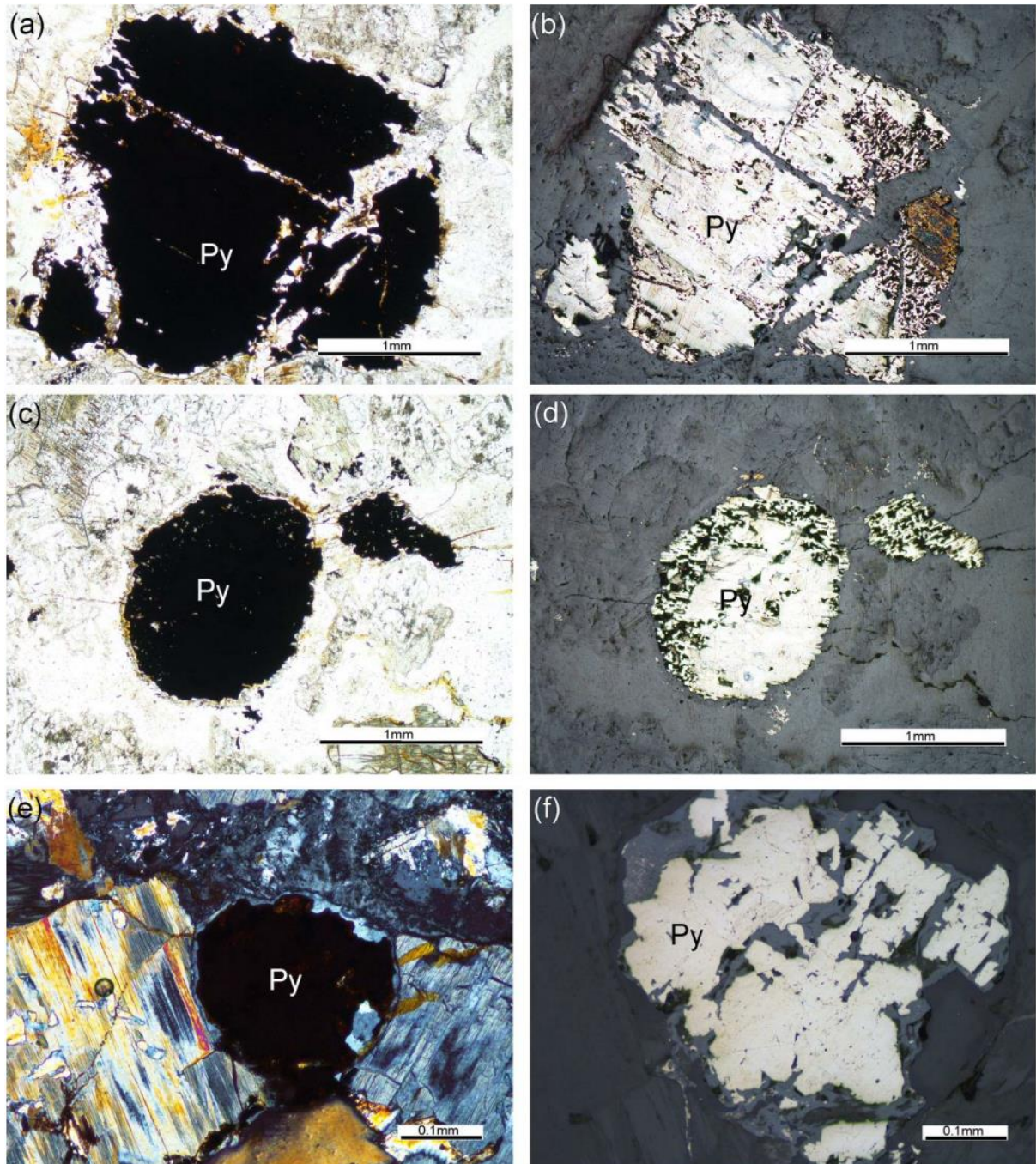


Figure 3.21. (a to f) Representative photomicrographs illustrating the minor (but conspicuous) occurrence of sulphide in norite from MF9. (a), (c) – PPL; (e) – XPL; (b), (d), (f) – reflected light.

Chapter 4

Mineral chemical characteristics

4.1. Introduction

This chapter presents mineral chemical characteristics of prominent minerals from selected units of relevance to the main objective of the study. These include the marginal facies norite and (altered) medium-grained pyroxenite from drill core MF38, and gabbro-norite from drill core MF9. Description is given for minerals from each rock type. Electron microprobe analyses of minerals are given in tables. Representative BSE-SEM images obtained during analyses are included as part of this chapter. After evaluating the compositional characteristics, results of application of available geothermobarometers on the rocks are presented.

4.2. Marginal facies norite from MF38

The quench-textured marginal norite from MF38 is characterized by elongate orthopyroxene and plagioclase (Fig. 4.1). Orthopyroxenes are Mg-rich [molar $Mg\# = 100.Mg/(Mg+Fe^{2+}) = \sim 75-85$] with compositional ranges of 0.15 to 0.37 wt.% MnO, 0.03 to 0.26 wt.% TiO₂, 0.34 to 1.81 wt.% Al₂O₃, 0.04 to 0.60 wt.% Cr₂O₃, 0.04 to 0.22 wt.% NiO and 0.54 to 7.39 wt.% CaO (Tables 4.1a, b). Compositional zoning is observed, varying from Mg-rich ($Mg\# = \sim 79-85$) core to moderately Mg-rich ($Mg\# = \sim 75-82$) rim portion (Fig. 4.2). Although there is overlap, difference in elemental concentrations can be delineated

between the core and rim compositions, with the core having lower MnO (0.15-0.36 wt.%), TiO₂ (0.06-0.15 wt.%) and FeO (8.1-15.89 wt.%), and higher CaO (1-7.4 wt.%), Al₂O₃ (1.02-1.81 wt.%), Cr₂O₃ (0.4-0.6 wt.%) and NiO (0.04-0.22 wt.%) than the rim portion of orthopyroxene (MnO = 0.21-0.37 wt.%; TiO₂ = 0.03-0.26 wt.%; FeO = 12.49-15.93 wt.%; CaO = 0.67-1.87 wt.%; Al₂O₃ = 0.34-1.4 wt.%; Cr₂O₃ = 0.04-0.5 wt.%; NiO = 0.05-0.13 wt.%). Orthopyroxenes from the marginal facies norite lie within the enstatite field of the pyroxene quadrilateral [nomenclature after Morimoto (1988); Fig. 4.3].

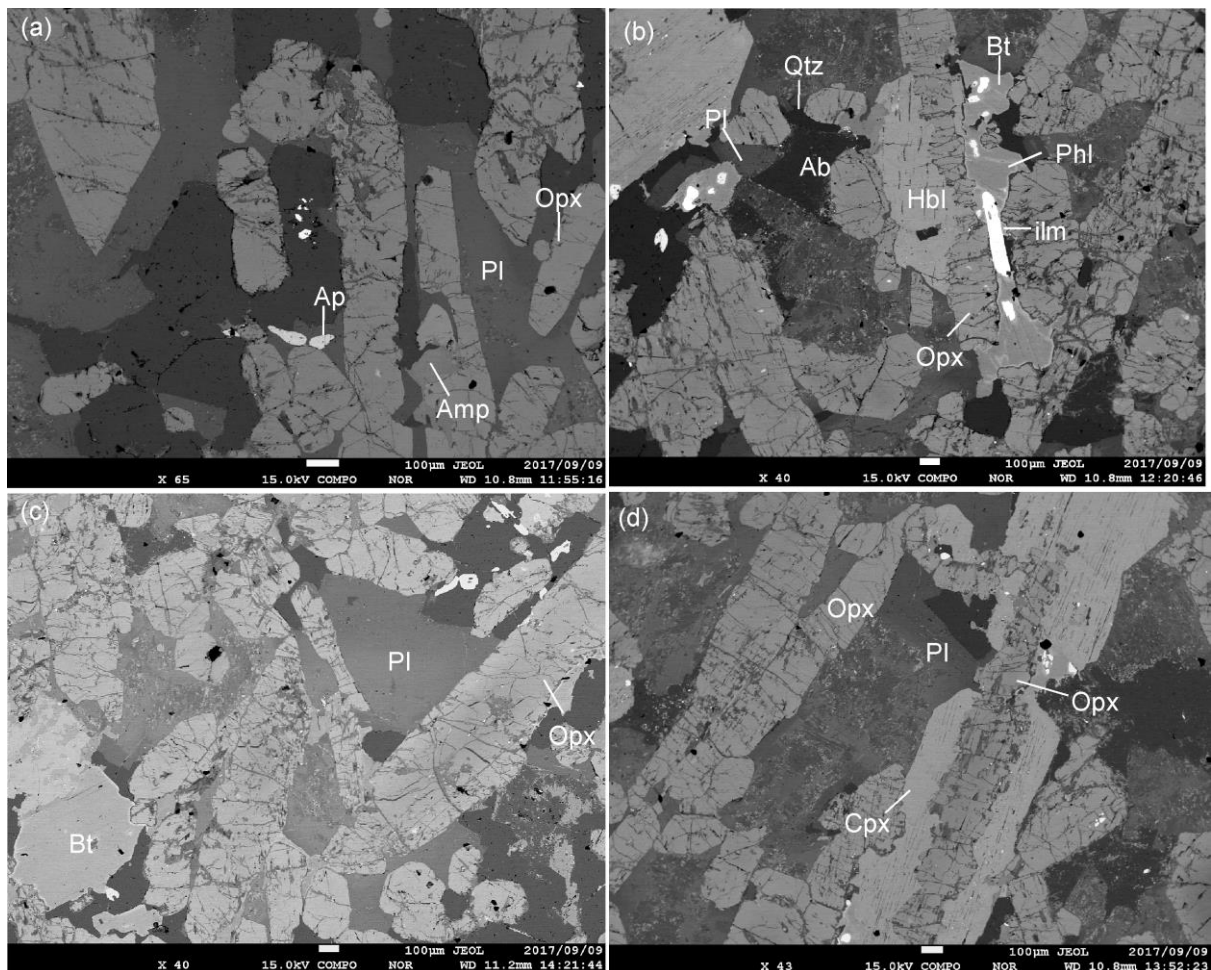


Figure 4.1. Representative BSE-SEM images illustrating the occurrence of elongate orthopyroxene (Opx), plagioclase (Pl), clinopyroxene (Cpx), phlogopite (Phl), amphibole (Hbl), biotite (Bt), quartz (Qtz), albite (Ab), and apatite (Ap) in the quench-textured marginal facies norite from MF38.

Rock	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite
Drill core	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38
Mineral	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx
SiO ₂	53,71	53,56	53,40	54,08	54,87	54,90	54,78	54,62	54,77	55,09	54,74	55,36	54,22	54,54
TiO ₂	0,15	0,14	0,22	0,26	0,00	0,09	0,03	0,00	0,12	0,06	0,17	0,15	0,08	0,08
Al ₂ O ₃	1,07	1,02	0,60	0,65	1,42	1,39	1,40	1,36	1,81	1,20	0,34	0,34	1,21	1,01
Cr ₂ O ₃	0,42	0,40	0,14	0,21	0,60	0,50	0,50	0,41	0,59	0,53	0,04	0,05	0,57	0,41
FeO	14,63	14,42	14,96	15,14	12,64	12,78	12,76	12,49	8,08	11,50	14,87	15,23	15,89	15,93
MnO	0,29	0,36	0,36	0,37	0,19	0,24	0,34	0,21	0,15	0,19	0,29	0,32	0,29	0,32
MgO	27,35	27,45	27,82	28,15	29,08	29,29	28,51	28,60	25,85	30,41	28,27	28,22	26,99	26,62
CaO	1,68	1,67	1,03	0,91	0,99	1,02	1,87	1,83	7,39	1,10	0,68	0,67	1,02	1,15
Na ₂ O	0,05	0,08	0,04	0,04	0,01	0,04	0,08	0,07	0,39	0,07		0,02	0,02	0,03
K ₂ O		0,01	0,01	0,03				0,02	0,07	0,01	0,01	0,02	0,01	0,02
NiO	0,06	0,22	0,09	0,05	0,05	0,04	0,08	0,13	0,07	0,12	0,11	0,06	0,07	0,09
Total	99,41	99,32	98,68	99,87	99,85	100,27	100,33	99,72	99,29	100,31	99,53	100,44	100,46	100,24
O=6														
Si	1,943	1,940	1,944	1,945	1,957	1,949	1,948	1,952	1,962	1,943	1,975	1,981	1,953	1,971
Ti	0,004	0,004	0,006	0,007	0,000	0,002	0,001	0,000	0,003	0,002	0,005	0,004	0,002	0,002
Al	0,045	0,043	0,026	0,027	0,060	0,058	0,059	0,057	0,076	0,050	0,014	0,014	0,051	0,043
Cr	0,012	0,011	0,004	0,006	0,017	0,014	0,014	0,011	0,017	0,015	0,001	0,001	0,016	0,012
Fe ³⁺	0,052	0,063	0,074	0,066	0,011	0,029	0,035	0,032	0,006	0,052	0,026	0,015	0,025	0,003
Fe ²⁺	0,391	0,374	0,381	0,389	0,366	0,351	0,345	0,342	0,236	0,288	0,423	0,441	0,454	0,479
Mn	0,009	0,011	0,011	0,011	0,006	0,007	0,010	0,006	0,005	0,006	0,009	0,010	0,009	0,010
Mg	1,475	1,483	1,510	1,510	1,546	1,550	1,512	1,524	1,381	1,599	1,521	1,506	1,449	1,434
Ca	0,065	0,065	0,040	0,035	0,038	0,039	0,071	0,070	0,284	0,042	0,026	0,026	0,039	0,045
Na	0,004	0,006	0,003	0,002		0,002	0,006	0,005	0,027	0,005		0,001	0,001	0,002
K			0,001	0,001				0,001	0,003	0,001		0,001		0,001
Total	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000
Mg#	79,06	79,87	79,84	79,51	80,85	81,54	81,44	81,69	85,41	84,75	78,23	77,36	76,15	74,98
En	0,76	0,77	0,78	0,78	0,79	0,80	0,78	0,79	0,73	0,83	0,77	0,76	0,75	0,73
Fs	0,20	0,19	0,20	0,20	0,19	0,18	0,18	0,18	0,12	0,15	0,21	0,22	0,23	0,24
Wo	0,03	0,03	0,02	0,02	0,02	0,02	0,04	0,04	0,15	0,02	0,01	0,01	0,02	0,02

Table 4.1. (a) Representative mineral chemical data of orthopyroxene in the marginal facies norite.

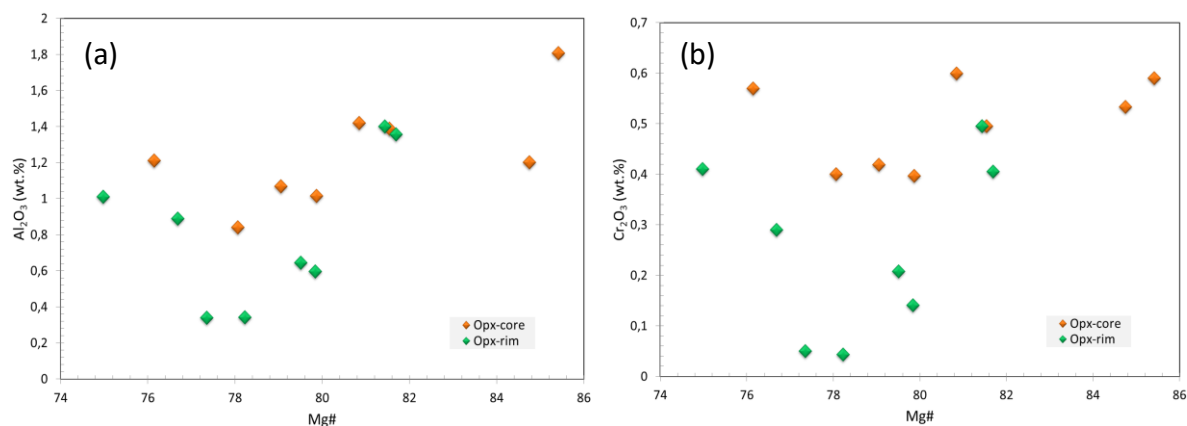


Figure 4.2. Mg# versus Al₂O₃ (wt.%) **(a)** and Cr₂O₃ (wt. %) **(b)** plots illustrating the compositional variation observed in orthopyroxene in marginal facies norite from MF38.

Rock	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite
Drill core	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38
Mineral	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx
SiO ₂	53,92	54,22	53,82	53,82	53,73	53,55	53,65	54,09	54,21	54,14	53,96	54,83	54,66
TiO ₂	0,06	0,19	0,08	0,10	0,11	0,05	0,18	0,14	0,14	0,15	0,06	0,04	0,08
Al ₂ O ₃	0,84	0,89	1,28	1,28	1,08	1,08	1,24	1,23	1,23	1,24	1,14	1,13	1,08
Cr ₂ O ₃	0,40	0,29	0,45	0,47	0,45	0,47	0,42	0,47	0,49	0,49	0,52	0,45	0,44
FeO	14,81	15,59	14,19	14,37	15,05	14,65	14,92	14,99	14,66	14,34	16,01	15,34	14,93
MnO	0,26	0,30	0,33	0,31	0,24	0,32	0,28	0,32	0,26	0,36	0,24	0,25	0,28
MgO	27,49	26,81	27,64	28,01	27,63	27,95	28,04	27,75	27,42	27,14	26,72	27,19	27,41
CaO	1,06	1,75	1,53	0,86	1,39	1,45	0,54	1,04	1,57	1,53	1,20	1,09	1,39
Na ₂ O	0,03	0,03	0,06	0,02	0,02	0,06	0,03	0,03	0,06	0,09	0,03	0,05	0,02
K ₂ O			0,02	0,01	0,03	0,00	0,02	0,03		0,01	0,02	0,01	0,02
NiO	0,11	0,06	0,08	0,06	0,04	0,11	0,06	0,10	0,10	0,04	0,06	0,07	0,08
Total	98,98	100,22	99,47	99,31	99,77	99,69	99,37	100,19	100,13	99,52	100,01	100,55	100,53
O=6													
Si	1,960	1,957	1,942	1,943	1,937	1,928	1,938	1,942	1,948	1,957	1,952	1,969	1,961
Ti	0,002	0,005	0,002	0,003	0,003	0,001	0,005	0,004	0,004	0,004	0,002	0,001	0,002
Al	0,036	0,038	0,054	0,055	0,046	0,046	0,053	0,052	0,052	0,053	0,049	0,048	0,046
Cr	0,011	0,008	0,013	0,013	0,013	0,013	0,012	0,013	0,014	0,014	0,015	0,013	0,012
Fe3+	0,032	0,032	0,050	0,041	0,064	0,086	0,053	0,045	0,034	0,018	0,032	0,004	0,017
Fe2+	0,418	0,438	0,378	0,392	0,389	0,355	0,397	0,405	0,406	0,416	0,453	0,457	0,431
Mn	0,008	0,009	0,010	0,010	0,007	0,010	0,008	0,010	0,008	0,011	0,007	0,008	0,009
Mg	1,490	1,442	1,487	1,507	1,485	1,500	1,510	1,485	1,469	1,462	1,441	1,455	1,466
Ca	0,041	0,068	0,059	0,033	0,054	0,056	0,021	0,040	0,061	0,059	0,047	0,042	0,053
Na	0,002	0,002	0,004	0,001	0,001	0,004	0,002	0,002	0,004	0,006	0,002	0,003	0,001
K			0,001	0,001	0,001		0,001	0,001	0,000		0,001		0,001
Total	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000
Mg#	78,07	76,69	79,71	79,34	79,23	80,86	79,17	78,58	78,33	77,86	76,09	76,10	77,29
En	0,76	0,74	0,77	0,78	0,77	0,78	0,78	0,77	0,76	0,75	0,74	0,74	0,75
Fs	0,21	0,23	0,20	0,20	0,20	0,19	0,21	0,21	0,21	0,21	0,23	0,23	0,22
Wo	0,02	0,03	0,03	0,02	0,03	0,03	0,01	0,02	0,03	0,03	0,02	0,02	0,03

Table 4.1. (b) Representative mineral chemical data of orthopyroxene in the marginal facies norite.

Clinopyroxenes in the marginal facies norite are dominantly Na- (Na₂O >0.2 wt.%) and Ca-rich (CaO >20 wt.%), with minor Ca-poor (CaO <20 wt.%) compositions. All Ca-rich clinopyroxene compositions plot within the diopside field of the pyroxene quadrilateral (Fig. 4.3), and have higher Mg# (~82-90) than Ca-poor clinopyroxenes (~81-82). Other than this, their compositional ranges are comparable and include 0.01 to 0.53 wt.% TiO₂, 0.2 to 1.92

wt.% Al₂O₃, 0.07 to 0.25 wt.% MnO and 0.22 to 0.71 wt.% Cr₂O₃ (Table 4.2). NiO contents are low (<0.09 wt.%).

Plagioclase composition in the marginal facies norite show quite a bit of variation with anorthite [An (= Ca/Ca+Na+K)] contents varying from An₃₂ to An₆₆ (Fig. 4.4). Na₂O content ranges from 3.87 to 7.59 wt.%, while K₂O content ranges from 0.12 to 0.58 wt.% (Table 4.3). Minor albite occurs (An_{0.88-1.09}; Na₂O = ~12 wt.%; K₂O = 0.05-0.07 wt.%).

Rock	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite
Drill core	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38
Mineral	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Amp	Amp	Amp	Amp
SiO ₂	52,54	53,10	52,55	52,79	51,57	53,40	53,31	52,67	52,48	53,02	51,91	53,89	50,44	50,78	52,96	52,84
TiO ₂	0,23	0,14	0,53	0,43	0,28	0,09	0,35	0,27	0,39	0,32	0,45	0,01	0,89	0,81	0,23	0,17
Al ₂ O ₃	1,92	1,75	1,16	1,19	1,83	0,58	1,71	1,71	1,75	1,71	1,66	0,20	4,91	4,97	1,61	1,68
Cr ₂ O ₃	0,71	0,53	0,36	0,37	0,65	0,15	0,53	0,57	0,54	0,51	0,40	0,22	0,57	0,58	0,59	0,66
FeO	6,79	9,53	6,72	6,60	6,52	6,01	8,06	6,92	7,07	7,08	7,12	4,87	7,71	7,59	5,88	6,15
MnO	0,17	0,19	0,15	0,25	0,19	0,17	0,20	0,19	0,17	0,14	0,20	0,12	0,07	0,08	0,20	0,22
MgO	16,45	19,96	16,41	16,30	15,30	15,78	18,30	16,94	16,78	16,64	15,06	15,95	18,72	18,71	16,05	16,07
CaO	20,84	14,43	21,38	21,48	22,73	23,46	17,58	20,34	20,16	20,32	22,82	24,69	11,90	11,93	22,15	22,29
Na ₂ O	0,30	0,20	0,31	0,31	0,34	0,28	0,31	0,34	0,31	0,32	0,32	0,24	0,84	0,88	0,34	0,37
K ₂ O	0,02	0,05	0,01	0,01	0,02	0,01	0,01	0,02	0,02	0,01	0,01		0,51	0,44		
NiO	0,00	0,10	0,02	0,04	0,02	0,05	0,08		0,07		0,07		0,12	0,12		0,07
Total	99,99	99,96	99,61	99,76	99,63	100,15	100,43	99,96	99,73	100,06	100,15	100,31	96,67	96,87	100	100,52
O=6																
Si	1,931	1,940	1,940	1,947	1,912	1,966	1,945	1,933	1,934	1,947	1,919	1,974	7,147	7,175	7,479	7,366
Ti	0,006	0,004	0,015	0,012	0,008	0,002	0,010	0,007	0,011	0,009	0,013	0,000	0,095	0,086	0,024	0,056
Al	0,083	0,075	0,051	0,052	0,080	0,025	0,074	0,074	0,076	0,074	0,072	0,009	0,820	0,825	0,267	0,552
Cr	0,021	0,015	0,011	0,011	0,019	0,004	0,015	0,017	0,016	0,015	0,012	0,006	0,063	0,065	0,065	0,067
Fe ³⁺	0,044	0,037	0,052	0,042	0,088	0,054	0,024	0,055	0,043	0,023	0,076	0,053	0,700	0,655		
Fe ²⁺	0,165	0,254	0,156	0,161	0,114	0,131	0,221	0,157	0,175	0,195	0,145	0,096	0,214	0,242	0,695	0,813
Mn	0,005	0,006	0,005	0,008	0,006	0,005	0,006	0,006	0,005	0,004	0,006	0,004	0,008	0,010	0,024	0,017
Mg	0,901	1,087	0,903	0,896	0,845	0,866	0,995	0,927	0,922	0,911	0,830	0,871	3,954	3,941	3,378	3,689
Ca	0,821	0,565	0,846	0,849	0,903	0,925	0,687	0,799	0,796	0,800	0,904	0,969	1,806	1,806	3,351	2,602
Na	0,022	0,014	0,022	0,022	0,024	0,020	0,022	0,024	0,022	0,023	0,023	0,017	0,230	0,241	0,094	0,168
K	0,001	0,002	0,001	0,001	0,001	0,000	0,001	0,001	0,001	0,001	0,000	0,000	0,091	0,078	0,000	0,043
Total	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	15,362	15,344	15,410	15,373
Mg#	84,56	81,06	85,29	84,75	88,08	86,88	81,80	85,48	84,07	82,39	85,16	90,03	81,23	81,46	82,94	81,94
En	0,48	0,57	0,47	0,47	0,45	0,45	0,52	0,49	0,49	0,48	0,44	0,45				
Fs	0,09	0,13	0,08	0,08	0,06	0,07	0,12	0,08	0,09	0,10	0,08	0,05				
Wo	0,43	0,30	0,44	0,45	0,48	0,48	0,36	0,42	0,42	0,42	0,48	0,50				

Table 4.2. Representative mineral chemical data of clinopyroxene and amphibole in the marginal facies norite.

Rock	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Norite
Drill core	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38
Mineral	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl
SiO ₂	52,80	52,53	59,15	58,79	53,81	54,20	60,02	59,81	58,17	58,13	66,71	66,76	51,34	51,51	60,87	58,70	51,76	62,73	59,42
TiO ₂	0,03	0,00	0,01	0,00	0,09	0,05	0,05	0,03	0,00	0,07	0,00	0,02	0,01	0,03	0,02	0,05	0,03	0,04	0,03
Al ₂ O ₃	29,61	29,60	24,98	24,98	28,90	28,94	24,47	24,61	25,73	25,87	19,50	19,57	29,47	29,31	24,44	26,29	29,37	24,28	25,10
FeO	0,27	0,27	0,20	0,32	0,28	0,23	0,29	0,30	0,23	0,28	0,06	0,06	0,27	0,37	0,23	0,25	0,25	0,43	0,27
MnO	0,00	0,02	0,02	0,00	0,02	0,02	0,04	0,05	0,00	0,00	0,00	0,02	0,00	0,00	0,00	0,00	0,00	0,04	0,01
MgO	0,03	0,00	0,01	0,14	0,00	0,02	0,00	0,03	0,02	0,04	0,02	0,01	0,01	0,00	0,01	0,01	0,02	0,01	0,00
CaO	12,28	12,05	7,09	7,23	11,19	11,30	6,61	6,66	7,70	8,04	0,24	0,19	13,95	13,94	7,45	9,19	13,77	7,52	8,48
Na ₂ O	4,45	4,52	7,59	7,39	5,18	5,21	7,43	7,49	7,05	6,79	11,86	12,00	3,91	3,87	7,35	6,06	3,95	7,46	6,67
K ₂ O	0,22	0,24	0,38	0,40	0,25	0,23	0,58	0,58	0,53	0,46	0,07	0,05	0,15	0,14	0,53	0,44	0,12	0,23	0,44
TOTAL	99,68	99,24	99,43	99,25	99,71	100,20	99,48	99,57	99,41	99,66	98,47	98,67	99,11	99,17	100,90	100,99	99,27	102,74	100,42
O=8																			
Si	2,402	2,400	2,660	2,651	2,442	2,447	2,693	2,684	2,622	2,615	2,968	2,966	2,362	2,369	2,696	2,606	2,374	2,723	2,651
Al	1,587	1,594	1,324	1,328	1,546	1,540	1,294	1,301	1,367	1,371	1,023	1,024	1,598	1,589	1,276	1,376	1,588	1,242	1,320
Ti	0,001	0,000	0,000	0,000	0,003	0,002	0,002	0,001	0,000	0,002	0,000	0,001	0,000	0,001	0,001	0,002	0,001	0,001	0,001
Fe	0,010	0,010	0,007	0,012	0,010	0,009	0,011	0,011	0,008	0,010	0,002	0,002	0,010	0,014	0,009	0,009	0,010	0,016	0,010
Mn	0,000	0,001	0,001	0,000	0,001	0,001	0,002	0,002	0,000	0,000	0,000	0,001	0,000	0,000	0,000	0,000	0,000	0,001	0,000
Mg	0,002	0,000	0,001	0,009	0,000	0,002	0,000	0,002	0,001	0,003	0,002	0,000	0,001	0,000	0,001	0,001	0,001	0,001	0,000
Ca	0,598	0,590	0,342	0,349	0,544	0,546	0,318	0,320	0,372	0,387	0,011	0,009	0,688	0,687	0,354	0,437	0,677	0,350	0,405
Na	0,392	0,400	0,662	0,647	0,456	0,456	0,646	0,652	0,616	0,592	1,023	1,033	0,349	0,345	0,631	0,522	0,351	0,628	0,577
K	0,013	0,014	0,022	0,023	0,014	0,013	0,033	0,033	0,030	0,026	0,004	0,003	0,009	0,008	0,030	0,025	0,007	0,013	0,025
Total	5,006	5,010	5,019	5,019	5,017	5,016	4,998	5,007	5,017	5,007	5,033	5,040	5,017	5,013	4,996	4,978	5,010	4,975	4,989
Or	1,25	1,37	2,13	2,25	1,43	1,30	3,33	3,32	2,98	2,61	0,36	0,27	0,84	0,79	2,95	2,53	0,68	1,29	2,49
Ab	39,09	39,87	64,57	63,46	44,92	44,92	64,81	64,82	60,51	58,88	98,55	98,85	33,37	33,18	62,21	53,03	33,94	63,40	57,28
An	59,66	58,76	33,31	34,28	53,65	53,78	31,85	31,86	36,50	38,52	1,09	0,88	65,79	66,04	34,84	44,44	65,38	35,32	40,24

Table 4.3. Representative mineral chemical data of plagioclase in the marginal facies norite.

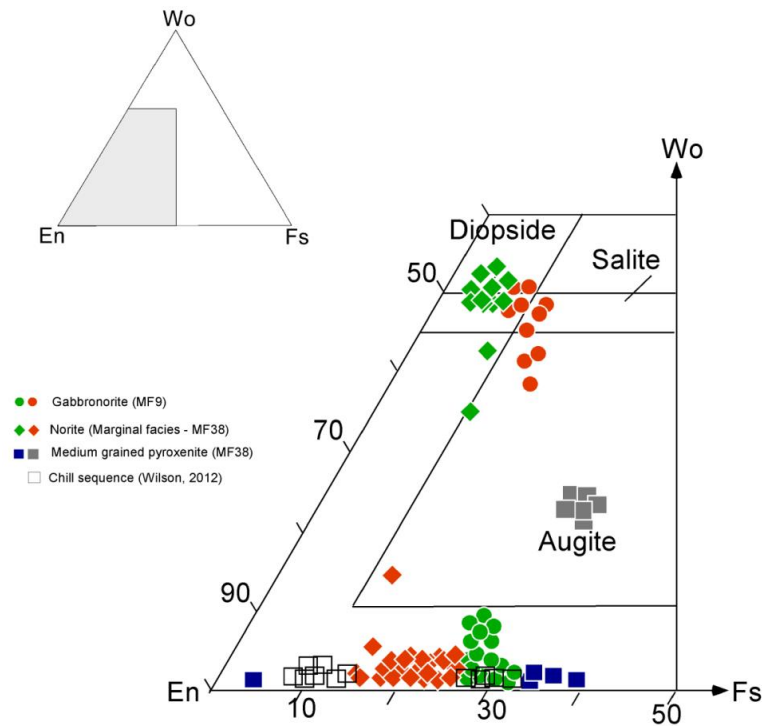


Figure 4.3. Mineral chemistry based compositional diagrams for pyroxenes from the marginal facies norite (MF38), altered medium-grained pyroxenite (MF38) and gabbronorite (MF9) in the pyroxene classification quadrilateral. Similar data from the Bushveld chill sequence is included for comparison.

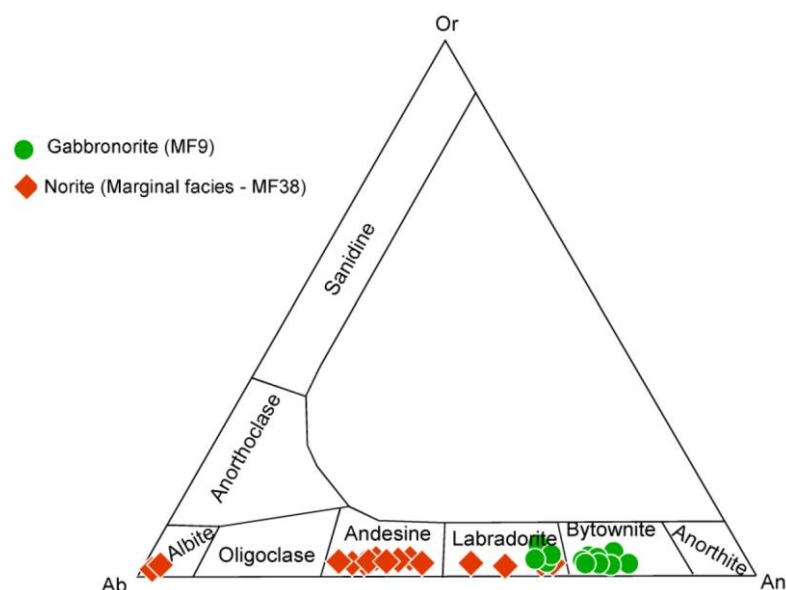


Figure 4.4. Mineral chemistry based compositional diagram for plagioclase in the marginal facies norite from MF38 and gabbro norite from MF9 in the ternary feldspar classification diagram.

Following the nomenclature scheme of Leake et al. (1997), amphiboles in the marginal facies norite are magnesio-hornblendes (Fig. 4.5), with $Mg\#$ of ~ 81 to 83 , Ca_B of 1.81 to 3.35 atoms per formula unit (apfu), Si of 7.15 to 7.48 apfu, $(Na+K)_A$ of 0.09 to 0.32 apfu, $Al(IV)$ of 0.27 to 0.83 apfu, $Fe(III)$ of 0.66 to 0.7 apfu, $Fe(II)$ of 0.21 to 0.81 apfu, Mg of 3.38 to 3.95 apfu, Ti of 0.02 to 0.1 apfu and NiO contents of 0.07 to 0.12 wt.% (Table 4.2).

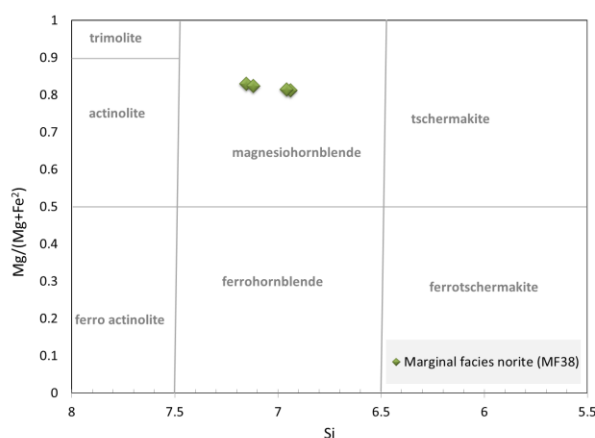


Figure 4.5. Mineral chemistry based compositional diagrams for amphiboles in the marginal facies norite from MF38 in the amphibole classification diagram of Leake et al. (1997).

Mg# of phlogopite varies from ~76 to 78, with compositional ranges of 3.53 to 5.01 wt.% TiO₂, 12.61 to 13.3 wt.% Al₂O₃, 0.27 to 0.44 wt.% Cr₂O₃, 0.11 to 0.25 wt.% NiO and 9 to 9.34 wt.% K₂O (Fig. 4.6; Table 4.4).

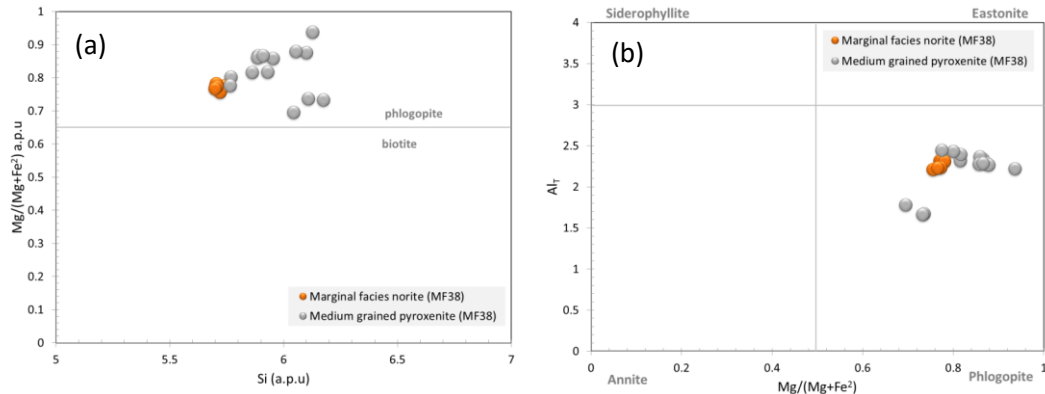


Figure 4.6. (a, b) Mineral chemistry based compositional diagrams for phlogopite in the marginal facies norite and medium-grained pyroxenite from MF38 in the mica classification diagrams of Deer et al. (1992).

4.3. Medium-grained pyroxenite from MF38

In spite of the highly altered nature of medium-grained pyroxenite, an attempt was made to see if any primary mineral chemical composition was preserved. This rock was considered for further study because of its orthocumulate nature, presence of phlogopite and prominent sulphides, the latter two similar to the marginal facies norite from the same drill core.

Other than phlogopite (Table 4.4), no reliable mineral chemical analyses (low totals) were obtained on other prominent minerals like orthopyroxene, clinopyroxene (Table 4.5) and minor intercumulus plagioclase. Nevertheless, the *obtained* compositional characteristics of the pyroxenes are compared with those from the marginal facies norite.

Rock	Norite	Norite	Norite	Norite	Norite	Norite	Norite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite
Drill core	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38
Mineral	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl
SiO ₂	38,90	38,44	38,48	38,41	38,76	38,84	38,71	41,31	42,83	41,36	42,49	43,76	40,09	42,61	42,68	42,36	43,86	44,20	40,42	41,17	44,21	
TiO ₂	3,53	3,66	5,01	3,54	3,73	4,36	4,33	0,39	2,27	0,42	3,47	0,63	0,33	0,21	3,94	3,56	0,08	0,37	0,14	0,09	0,05	
Al ₂ O ₃	13,16	13,24	12,61	13,19	13,30	12,88	12,84	13,85	14,41	14,15	14,46	13,86	14,31	13,53	13,82	13,89	10,17	13,58	14,52	10,27	10,08	
FeO	9,80	9,93	10,07	9,68	9,45	9,74	10,08	9,19	6,07	8,63	6,12	5,77	9,84	5,80	6,09	5,98	15,27	3,01	11,71	16,94	15,27	
MnO	0,01				0,02	0,05		0,07	0,10	0,01	0,06	0,02	0,02	0,13	0,04	0,00	0,01	0,27	0,03	0,20	0,32	0,28
MgO	18,85	18,76	17,52	18,74	18,97	18,55	18,53	22,89	22,02	21,63	21,03	22,74	22,24	23,58	20,65	21,68	23,92	25,02	22,71	21,70	23,49	
CaO								0,00	0,01	0,15	0,01	0,02	0,00	0,01	0,02	0,00	0,23	0,06	0,03	0,20	0,18	
Na ₂ O	0,15	0,19	0,15	0,17	0,14	0,37	0,34	0,35	0,32	0,35	0,33	0,29	0,30	0,42	0,38	0,37	1,51	0,42	0,23	0,18	0,88	
K ₂ O	9,30	9,03	9,28	9,27	9,34	9,21	9,00	5,90	8,08	5,80	7,26	6,56	6,22	6,98	7,05	7,11	1,07	6,97	4,62	1,52	1,53	
Cr ₂ O ₃	0,31	0,27		0,35	0,29	0,30	0,44	1,10	1,69	1,11	1,32	1,30	0,94	0,33	0,98	0,64	0,91	0,79	0,37	0,87	0,94	
NiO			0,11	0,11	0,25	0,16		0,12	0,01	0,08	0,03	0,01	0,07	0,04	0,08	0,05	0,06	0,01	0,04	0,01	0,02	
F								0,08	0,08	0,16	0,01	0,12	0,09	0,13	0,12	0,13	0,10	0,10	0,13	0,14	0,00	
Cl	0,28	0,29						0,37	0,36	0,36	0,32	0,48	0,30	0,47	0,40	0,37	0,01	0,40	0,28	0,00	0,00	
Total	94,23	93,74	93,65	93,41	94,28	94,55	94,45	95,64	98,44	94,34	97,03	95,80	94,96	94,26	96,30	96,27	97,51	95,00	95,51	93,48	97,10	
O=22																						
Si	5,739	5,702	5,722	5,708	5,704	5,709	5,699	5,863	5,889	5,931	5,887	6,101	5,769	6,055	5,955	5,911	6,109	6,129	5,766	6,046	6,176	
Al _{iv}	2,261	2,298	2,211	2,292	2,296	2,231	2,228	2,137	2,111	2,069	2,113	1,899	2,231	1,945	2,045	2,089	1,670	1,871	2,234	1,778	1,660	
Al _{vi}	0,028	0,017	0,000	0,019	0,010	0,000	0,000	0,180	0,224	0,322	0,249	0,379	0,197	0,321	0,227	0,195		0,348	0,208			
Al	2,289	2,315	2,211	2,310	2,306	2,231	2,228	2,317	2,335	2,392	2,361	2,278	2,427	2,266	2,273	2,285	1,670	2,219	2,442	1,778	1,660	
Ti	0,392	0,408	0,560	0,396	0,412	0,482	0,479	0,042	0,235	0,045	0,362	0,066	0,036	0,022	0,413	0,374	0,008	0,039	0,015	0,010	0,005	
Cr	0,036	0,031	0,041	0,034	0,035	0,051	0,051	0,123	0,184	0,126	0,145	0,143	0,107	0,037	0,108	0,071	0,100	0,087	0,042	0,101	0,104	
Fe	1,209	1,232	1,253	1,203	1,163	1,197	1,241	1,091	0,698	1,035	0,709	0,673	1,184	0,689	0,711	0,698	1,779	0,349	1,397	2,080	1,784	
Mn	0,001	0,000	0,008	0,002	0,006	0,000	0,008	0,012	0,001	0,007	0,002	0,002	0,016	0,005	0,000	0,001	0,032	0,004	0,024	0,040	0,033	
Mg	4,146	4,147	3,883	4,153	4,161	4,063	4,067	4,843	4,513	4,624	4,344	4,726	4,771	4,995	4,295	4,510	4,966	5,171	4,830	4,750	4,891	
Ni	0,000	0,000	0,013	0,014	0,029	0,019	0,014	0,001	0,009	0,003	0,001	0,008	0,005	0,009	0,006	0,007	0,001	0,001	0,005	0,001	0,002	
Ca	0,000	0,000	0,000	0,000	0,000	0,000	0,000		0,001	0,023	0,001	0,003		0,002	0,003		0,034	0,009	0,005	0,001	0,007	
Na	0,041	0,054	0,042	0,048	0,039	0,106	0,098	0,096	0,085	0,097	0,089	0,078	0,084	0,116	0,103	0,100	0,408	0,113	0,064	0,051	0,238	
K	1,750	1,708	1,761	1,757	1,754	1,727	1,690	1,068	1,417	1,061	1,283	1,167	1,142	1,265	1,255	1,265	0,190	1,233	0,841	0,285	0,273	
TOTAL	19,603	19,598	19,493	19,626	19,609	19,585	19,576	19,457	19,368	19,344	19,184	19,245	19,541	19,461	19,120	19,221	19,297	19,353	19,429	19,173	19,193	

Table 4.4. Representative mineral chemical data of phlogopite in the marginal facies norite and medium-grained pyroxenite from MF38.

Rock	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite	Pyroxenite
Drill core	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38	MF38
Mineral	Opx	Opx	Opx	Opx	Opx	Opx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx
SiO ₂	63,95	63,61	62,19	63,40	62,93	57,1	56,54	55,91	56,86	55,92	56,57	56,03
TiO ₂	0,00	0,01	0,02	0,04	0,00	0,08	0,03	0,06	0,01	0,01	0,02	
Al ₂ O ₃	0,23	0,15	0,88	0,74	0,14	0,27	0,3	0,48	0,17	0,39	0,36	0,43
Cr ₂ O ₃	0,02	0,02	0,00	0,01	0,00		0,03	0,39	0,01			0,02
FeO	7,39	7,43	8,34	8,26	8,90	8,72	9,47	9,88	8,82	10,05	10,38	9,76
MnO	0,11	0,13	0,09	0,09	0,13	0,56	0,53	0,47	0,7	0,57	0,57	0,69
MgO	26,71	27,06	26,00	26,27	25,18	18,76	18,11	17,36	18,44	17,39	17,68	18,02
CaO	0,02	0,01	0,05	0,05	0,03	12,91	12,91	12,54	12,81	13,12	12,85	12,1
Na ₂ O	0,07	0,06	0,46	0,32	0,05	0,33	0,37	0,48	0,25	0,27	0,4	0,71
K ₂ O	0,03	0,01	0,02	0,03	0,03	0,02	0,03	0,03	0,02	0,01	0,01	0,04
NiO	0,04	0,06	0,04	0,00	0,12	0,16	0,05	0,02	0,1	0,03	0	0,03
Total	98,57	98,55	98,09	99,21	97,51	99,01	98,41	97,93	98,24	97,81	98,91	97,97
O=6												
Si	2,314	2,300	2,261	2,281	2,323	2,121	2,116	2,114	2,130	2,114	2,113	2,103
Ti	0,000	0,000	0,001	0,001	0,000	0,002	0,001	0,002	0,000	0,000	0,001	0,000
Al	0,010	0,006	0,038	0,031	0,006	0,012	0,013	0,021	0,008	0,017	0,016	0,019
Cr	0,001	0,001	0,000	0,000	0,000	0,000	0,001	0,012	0,000	0,000	0,000	0,001
Fe ²⁺	0,857	0,828	0,781	0,821	0,922	0,503	0,515	0,541	0,526	0,544	0,538	0,479
Mn	0,003	0,004	0,003	0,003	0,004	0,018	0,017	0,015	0,022	0,018	0,018	0,022
Mg	1,441	1,459	1,409	1,409	1,386	1,039	1,010	0,979	1,030	0,980	0,985	1,008
Ca	0,001	0,000	0,002	0,002	0,001	0,514	0,518	0,508	0,514	0,532	0,514	0,487
Na	0,005	0,004	0,032	0,022	0,004	0,024	0,027	0,035	0,018	0,020	0,029	0,052
K	0,001	0,000	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,000	0,000	0,002
Total	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000
Mg#	62,72	63,79	64,34	63,18	60,04	67,35	66,22	64,40	66,19	64,30	64,67	67,79
En	0,63	0,64	0,64	0,63	0,60	0,51	0,49	0,48	0,50	0,48	0,48	0,51
Fs	0,37	0,36	0,36	0,37	0,40	0,24	0,25	0,27	0,25	0,26	0,26	0,24
Wo	0,00	0,00	0,00	0,00	0,00	0,25	0,25	0,25	0,25	0,26	0,25	0,25

Table 4.5. Representative mineral chemical data of orthopyroxene and clinopyroxene in the medium-grained pyroxenite from MF38.

Mg# of orthopyroxenes varies from ~60 to 64, with compositional ranges of 0.09 to 0.13 wt.% MnO, 0.01 to 0.04 wt.% TiO₂, 0.15-0.88 wt.% Al₂O₃, 0.01-0.02 wt.% Cr₂O₃, 0.04 to 0.12 wt.% NiO and 0.01-0.05 wt.% CaO (Table 4.5). Comparison with the mineral chemical characteristics of orthopyroxene from the marginal facies norite is illustrated in Fig. 4.7.

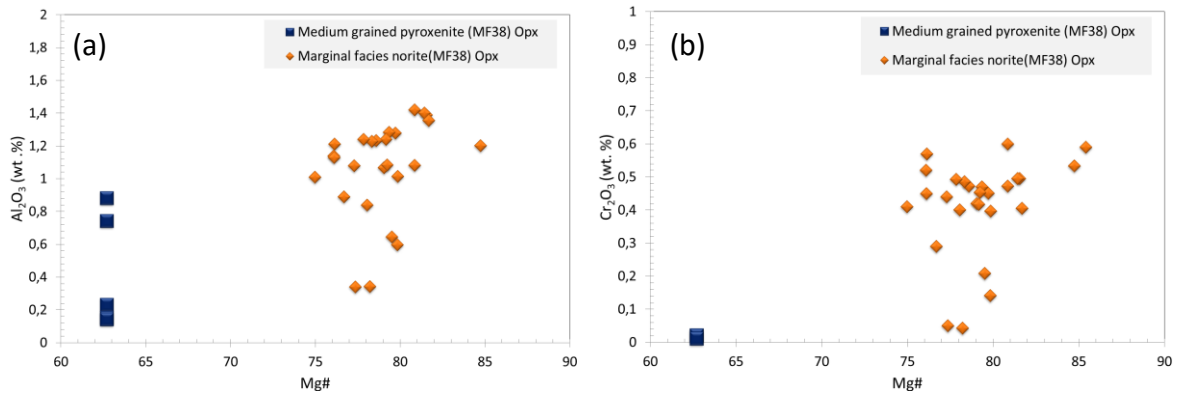


Figure 4.7. Mg# versus Al₂O₃ (wt.%) (a) and Cr₂O₃ (wt.%) (b) mineral chemical plots comparing orthopyroxene of altered medium grained pyroxenite and marginal facies norite from MF38.

Mg# of clinopyroxenes from the altered medium grained pyroxenite varies from ~64 to 68, with compositional ranges of 0.47 to 0.7 wt.% MnO, 0.01 to 0.08 wt.% TiO₂, 0.17-0.48 wt.% Al₂O₃, 0.01-0.39 wt.% Cr₂O₃, 0.02 to 0.16 wt.% NiO and 12.1-13.12 wt.% CaO (Table 4.5). Comparison with clinopyroxene from the marginal facies norite is illustrated in Fig. 4.8.

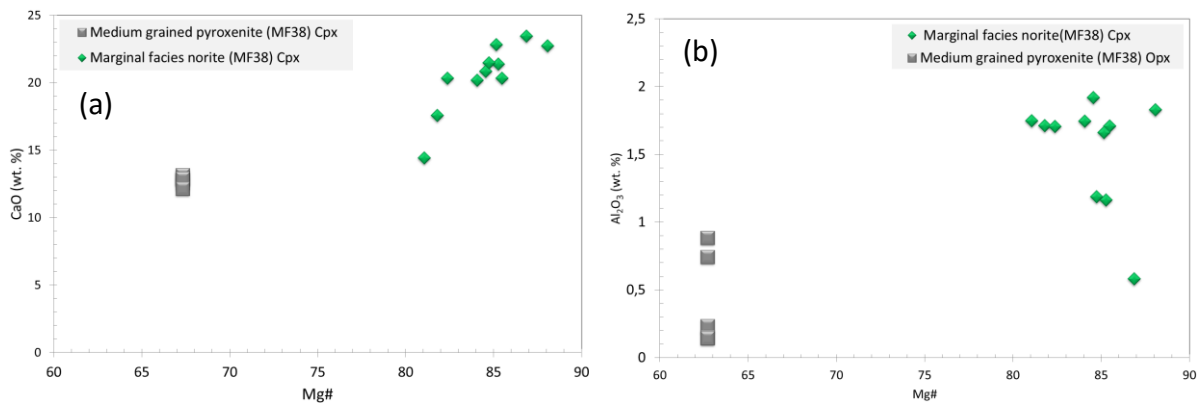


Figure 4.8. Mg# versus CaO (wt.%) (a) and Al₂O₃ (wt.%) (b) mineral chemical plots comparing clinopyroxene of altered medium grained pyroxenite and marginal facies norite from MF38.

Unlike the phlogopite in the marginal facies norite, those in the medium-grained pyroxenite have higher Mg# (~80-94) and Cr₂O₃ (0.33-1.69 wt.%), lower TiO₂ (0.05-3.94 wt.%), NiO (0.01-0.08 wt.%) and K₂O (1.52-7.26 wt.%), and comparable Al₂O₃ (10.08-14.52 wt.%) (Fig. 4.6; Table 4.4).

4.4. Gabbronorite from MF9

The gabbronorite from MF9 is the least altered of the studied mafic rock types and contain orthopyroxene, clinopyroxene and plagioclase (Fig. 4.7).

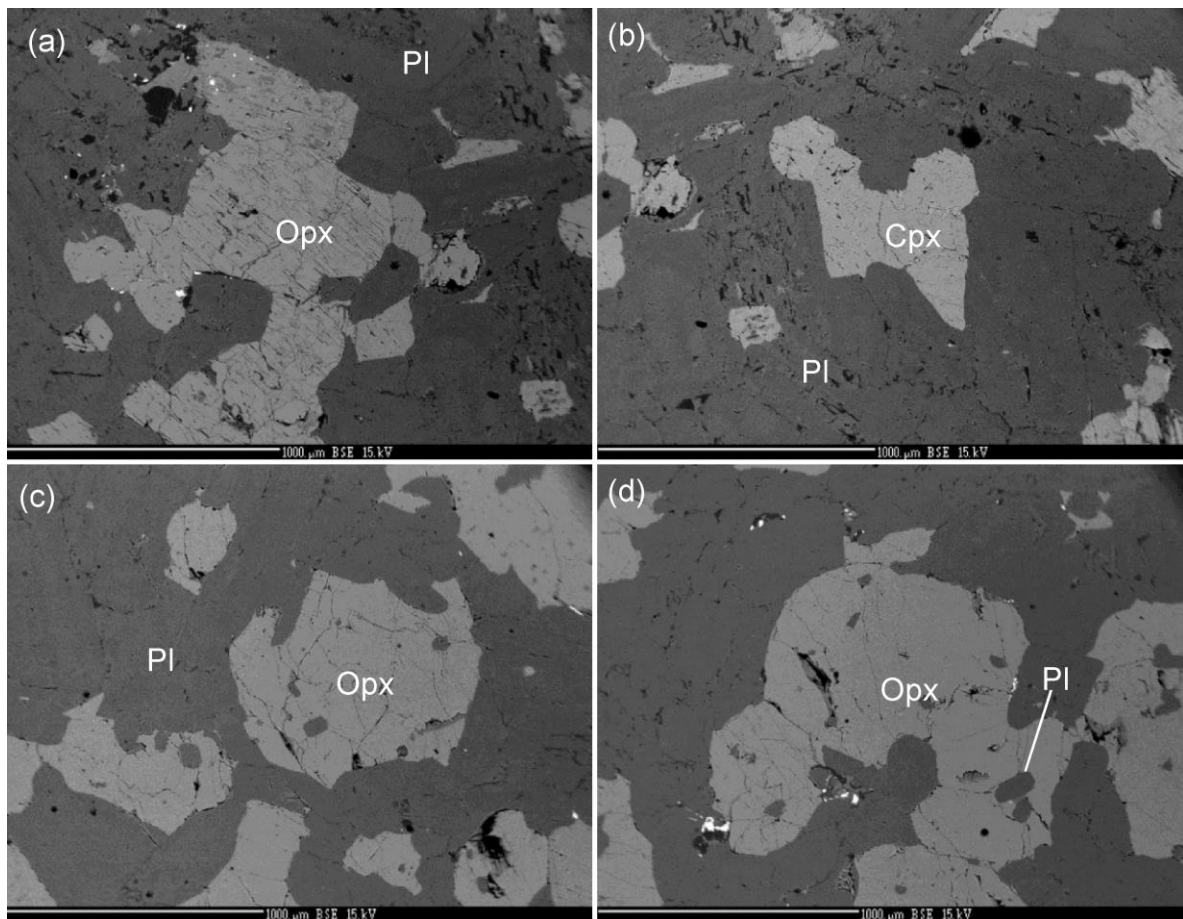


Figure 4.7. Representative BSE-SEM images illustrating the occurrence of orthopyroxene, clinopyroxene and plagioclase in gabbronorite from drill core MF9.

Orthopyroxenes in gabbronorite from MF9 have uniform composition and are less Mg-rich (Mg# = ~68-72) compared to those in norites from MF38 (Mg# = ~75-85). They are characterized by compositional ranges of 0.35 to 0.46 wt.% MnO, 0.11 to 0.17 wt.% TiO₂, ~16 to 20 wt.% FeO, 0.75 to 3.92 wt.% CaO, 0.59 to 0.93 wt.% Al₂O₃, 0.01 to 0.09 wt.% Cr₂O₃ and 0.01 to 0.06 wt.% NiO (Table 4.6). The orthopyroxenes fall in the enstatite field of the pyroxene quadrilateral (Fig. 4.3).

Rock	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN
Drill core	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9
Mineral	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx
SiO ₂	54,46	53,69	54,15	54,14	54,29	54,09	54,39	54,42	54,37	54,43	54,20	54,29	54,58	54,10	54,49	54,24	54,12
TiO ₂	0,17	0,17	0,16	0,17	0,14	0,17	0,11	0,11	0,11	0,13	0,14	0,15	0,13	0,16	0,12	0,14	0,14
Al ₂ O ₃	0,69	0,63	0,59	0,68	0,90	0,76	0,89	0,93	0,85	0,86	0,86	0,89	0,86	0,90	0,88	0,89	0,92
Cr ₂ O ₃	0,02	0,01	0,04	0,03	0,09	0,07	0,06	0,05	0,06	0,09	0,07	0,07	0,06	0,05	0,06	0,07	0,08
FeO	19,83	19,79	20,17	19,66	17,92	17,65	16,80	17,85	17,28	16,39	17,56	17,00	17,21	16,76	17,21	17,01	16,87
MnO	0,41	0,45	0,46	0,45	0,35	0,37	0,36	0,38	0,37	0,39	0,39	0,35	0,35	0,40	0,35	0,35	0,37
MgO	24,55	24,11	24,42	24,49	25,62	24,66	25,04	25,36	25,23	24,16	24,82	24,60	24,69	23,76	24,63	24,49	24,43
CaO	0,99	1,35	0,78	0,75	0,87	1,74	2,45	1,29	1,97	3,20	1,84	2,95	2,41	3,92	2,48	2,97	3,18
Na ₂ O	0,01	0,02	0,01			0,02	0,04	0,01	0,02	0,05	0,01	0,03	0,03	0,07	0,01	0,02	0,06
K ₂ O			0,02	0,01						0,01	0,01	0,00	0,01	0,01			0,01
NiO	0,01	0,02	0,03	0,01	0,04	0,04	0,04	0,01	0,02	0,06	0,05	0,04	0,04	0,02	0,06	0,07	0,03
Total	101,26	100,27	100,83	100,47	100,28	99,69	100,23	100,47	100,36	99,88	100	100,48	100,43	100,24	100,38	100,34	100,26
O=6																	
Si	1,980	1,972	1,977	1,982	1,975	1,987	1,979	1,977	1,977	1,994	1,982	1,976	1,987	1,977	1,986	1,978	1,972
Ti	0,005	0,005	0,004	0,005	0,004	0,005	0,003	0,003	0,003	0,004	0,004	0,004	0,004	0,004	0,003	0,004	0,004
Al	0,030	0,027	0,025	0,029	0,039	0,033	0,038	0,040	0,036	0,037	0,037	0,038	0,037	0,039	0,038	0,038	0,040
Cr	0,001	0,000	0,001	0,001	0,003	0,002	0,002	0,001	0,002	0,003	0,002	0,002	0,002	0,001	0,002	0,002	0,002
Fe3+	0,001	0,021	0,012		0,000		0,000		0,004			0,002		0,002			0,010
Fe2+	0,601	0,586	0,604	0,606	0,545	0,558	0,511	0,543	0,521	0,532	0,546	0,515	0,541	0,510	0,542	0,521	0,504
Mn	0,013	0,014	0,014	0,014	0,011	0,012	0,011	0,012	0,011	0,012	0,012	0,011	0,011	0,012	0,011	0,011	0,011
Mg	1,331	1,320	1,329	1,337	1,390	1,350	1,358	1,374	1,367	1,319	1,353	1,335	1,340	1,295	1,338	1,331	1,327
Ca	0,039	0,053	0,031	0,029	0,034	0,068	0,095	0,050	0,077	0,126	0,072	0,115	0,094	0,154	0,097	0,116	0,124
Na	0,001	0,001	0,001	0,000	0,000	0,001	0,003	0,001	0,001	0,004	0,001	0,002	0,002	0,005	0,001	0,001	0,004
K	0,000	0,000	0,001	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Total	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000
Mg#	68,87	69,24	68,75	68,81	71,84	70,75	72,64	71,66	72,40	71,25	71,24	72,15	71,25	71,72	71,17	71,88	72,48
En	0,68	0,67	0,68	0,68	0,71	0,68	0,69	0,70	0,70	0,67	0,69	0,68	0,68	0,66	0,68	0,68	0,68
Fs	0,31	0,30	0,31	0,31	0,28	0,28	0,26	0,28	0,27	0,27	0,28	0,26	0,27	0,26	0,27	0,26	0,26
Wo	0,02	0,03	0,02	0,01	0,02	0,03	0,05	0,03	0,04	0,06	0,04	0,06	0,05	0,08	0,05	0,06	0,06

Table 4.6. Representative mineral chemical data of orthopyroxene in gabbronorite (GN) from MF9.

Like the clinopyroxenes in the marginal facies norite from MF38 (Mg# = ~82-90), those in the gabbronorite from MF9 (Mg# = ~75-82) are also Na-rich (Na₂O >0.2 wt.%), with a dominant population of Ca-rich (CaO >20 wt.%) and relatively minor Ca-poor (CaO <20 wt.%) compositions. All Ca-rich clinopyroxene compositions plot near the dividing line of diopside-salite fields of the pyroxene quadrilateral (Fig. 4.3), and have higher Mg# (~80-82) than Ca-poor clinopyroxenes (Mg# = ~75-76). Other than this, their compositional ranges are comparable and include 0.21 to 0.31 wt.% TiO₂, 1.17 to 1.56 wt.% Al₂O₃, 0.2 to 0.31 wt.% MnO and 0.04 to 0.12 wt.% Cr₂O₃ (Table 4.7). NiO contents are low (<0.05 wt.%).

Rock	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN
Drill core	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9
Mineral	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx	Cpx
SiO ₂	52,71	52,72	53,01	52,83	52,47	52,62	52,62	52,52	52,85	52,82	52,69
TiO ₂	0,26	0,24	0,27	0,28	0,29	0,21	0,27	0,31	0,26	0,27	0,30
Al ₂ O ₃	1,35	1,23	1,23	1,22	1,48	1,33	1,29	1,56	1,17	1,36	1,46
Cr ₂ O ₃	0,08	0,06	0,07	0,05	0,05	0,08	0,04	0,06	0,08	0,07	0,12
FeO	10,17	11,45	9,77	7,84	8,06	7,99	8,29	8,27	8,50	8,11	7,21
MnO	0,26	0,31	0,24	0,20	0,22	0,25	0,21	0,25	0,24	0,24	0,22
MgO	15,93	16,41	15,68	15,26	14,68	14,84	14,77	14,69	15,34	14,84	14,90
CaO	19,30	18,49	20,10	22,54	22,72	22,72	22,49	22,59	21,75	22,84	22,88
Na ₂ O	0,24	0,14	0,25	0,22	0,24	0,21	0,22	0,24	0,24	0,23	0,25
K ₂ O		0,01	0,01				0,01	0,01	0,01		0,01
NiO	0,02		0,01	0,02	0,03	0,02	0,03	0,04	0,01	0,02	0,03
Total	100,45	101,19	100,80	100,58	100,35	100,40	100,47	100,63	100,53	100,96	100,21
O=6											
Si	1,949	1,938	1,954	1,946	1,942	1,946	1,948	1,939	1,949	1,944	1,948
Ti	0,007	0,007	0,007	0,008	0,008	0,006	0,008	0,009	0,007	0,007	0,008
Al	0,059	0,053	0,053	0,053	0,065	0,058	0,056	0,068	0,051	0,059	0,064
Cr	0,002	0,002	0,002	0,001	0,001	0,002	0,001	0,002	0,002	0,002	0,004
Fe3+	0,044	0,065	0,039	0,053	0,052	0,052	0,047	0,053	0,051	0,053	0,038
Fe2+	0,271	0,287	0,262	0,189	0,198	0,195	0,209	0,202	0,211	0,196	0,185
Mn	0,008	0,010	0,007	0,006	0,007	0,008	0,007	0,008	0,007	0,007	0,007
Mg	0,878	0,899	0,862	0,838	0,810	0,818	0,815	0,808	0,843	0,814	0,821
Ca	0,765	0,728	0,794	0,890	0,901	0,900	0,892	0,894	0,860	0,900	0,907
Na	0,017	0,010	0,018	0,016	0,017	0,015	0,016	0,017	0,017	0,016	0,018
K	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Total	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000
Mg#	76,42	75,84	76,69	81,63	80,38	80,72	79,58	79,98	80,01	80,58	81,60
En	0,46	0,47	0,45	0,44	0,42	0,43	0,43	0,42	0,44	0,43	0,43
Fs	0,14	0,15	0,14	0,10	0,10	0,10	0,11	0,11	0,11	0,10	0,10
Wo	0,40	0,38	0,41	0,46	0,47	0,47	0,47	0,47	0,45	0,47	0,47

Table 4.7. Representative mineral chemical data of clinopyroxene in gabbronorite (GN) from MF9.

Plagioclase in the gabbronorite (An₆₇-An₇₄) exhibit less variation in comparison to those in the marginal facies (An₃₂-An₆₆) (Fig. 4.4). Na₂O content ranges from 2.64 to 3.64 wt.%, while K₂O content ranges from 0.11 to 0.32 wt.% (Table 4.8).

Rock	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN	GN
Drill core	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9	MF9
Mineral	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl	Pl
SiO ₂	51,55	50,83	49,89	50,62	51,07	50,41	50,77	50,97	50,49	50,46	50,44	49,70	49,68	49,58	49,75	48,75	49,43	49,21	49,51
TiO ₂	0,02	0,01	0,01	0,02	0,06	0,00	0,03	0,01	0,03	0,02	0,03	0,02	0,02	0,01	0,02	0,03	0,01	0,03	0,02
Al ₂ O ₃	29,68	30,10	30,72	30,38	28,92	30,51	30,32	30,08	30,45	31,01	30,30	30,77	31,06	30,82	31,11	31,47	31,35	31,47	31,13
FeO	0,46	0,56	0,56	0,55	0,62	0,46	0,54	0,57	0,58	0,53	0,49	0,54	0,50	0,50	0,49	0,47	0,46	0,47	0,46
MnO	0,00	0,00	0,00	0,02	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,03	0,01	0,00	0,01	0,01	0,00	0,01	0,00
MgO	0,05	0,04	0,04	0,03	0,09	0,03	0,04	0,05	0,04	0,03	0,04	0,03	0,03	0,02	0,02	0,03	0,01	0,03	0,02
CaO	14,06	14,64	15,28	15,06	13,60	14,86	14,79	14,45	14,85	15,27	14,84	14,99	15,41	15,21	15,33	16,10	15,60	15,87	15,53
Na ₂ O	3,64	3,20	2,97	3,14	3,59	3,14	3,24	3,38	3,16	2,92	3,14	2,98	2,84	2,84	2,88	2,44	2,66	2,64	2,74
K ₂ O	0,28	0,17	0,18	0,20	0,32	0,16	0,15	0,21	0,18	0,16	0,17	0,16	0,12	0,16	0,18	0,12	0,11	0,16	0,13
Total	99,77	99,62	99,76	100,10	98,33	99,63	99,93	99,77	99,84	100,58	99,59	99,30	99,72	99,16	99,86	99,47	99,71	99,93	99,61
O=8																			
Si	2,359	2,333	2,294	2,317	2,371	2,314	2,324	2,336	2,315	2,299	2,319	2,293	2,283	2,289	2,283	2,250	2,272	2,260	2,278
Al	1,601	1,628	1,665	1,639	1,583	1,651	1,636	1,625	1,645	1,666	1,642	1,673	1,682	1,677	1,683	1,712	1,698	1,703	1,688
Ti	0,001	0,000	0,000	0,001	0,002	-	0,001	0,000	0,001	0,001	0,001	0,001	0,001	0,000	0,001	0,001	0,000	0,001	0,001
Fe	0,018	0,021	0,022	0,021	0,024	0,018	0,021	0,022	0,022	0,020	0,019	0,021	0,019	0,019	0,019	0,018	0,018	0,018	0,018
Mn	-	-	-	0,001	0,000	-	-	-	-	-	-	0,001	0,000	-	0,000	0,000	-	0,000	-
Mg	0,003	0,003	0,003	0,002	0,006	0,002	0,003	0,003	0,003	0,002	0,003	0,002	0,002	0,001	0,001	0,002	0,001	0,002	0,001
Ca	0,689	0,720	0,753	0,738	0,677	0,731	0,725	0,709	0,729	0,746	0,731	0,741	0,759	0,752	0,754	0,796	0,768	0,781	0,766
Na	0,323	0,285	0,265	0,279	0,323	0,280	0,288	0,300	0,281	0,258	0,280	0,267	0,253	0,254	0,256	0,218	0,237	0,235	0,244
K	0,016	0,010	0,011	0,012	0,019	0,009	0,009	0,012	0,011	0,009	0,010	0,009	0,007	0,009	0,011	0,007	0,006	0,009	0,008
Total	5,010	5,000	5,011	5,009	5,006	5,005	5,006	5,008	5,007	5,001	5,004	5,008	5,006	5,004	5,008	5,006	5,000	5,010	5,003
Or	1,59	0,98	1,03	1,13	1,86	0,92	0,86	1,20	1,03	0,92	0,98	0,93	0,69	0,93	1,03	0,69	0,64	0,91	0,75
Ab	31,40	28,07	25,75	27,08	31,73	27,41	28,15	29,38	27,52	25,47	27,42	26,21	24,84	25,02	25,11	21,37	23,43	22,93	24,02
An	67,02	70,95	73,22	71,78	66,41	71,67	71,00	69,42	71,45	73,61	71,61	72,86	74,47	74,05	73,86	77,93	75,93	76,16	75,23

Table 4.8. Representative mineral chemical data of plagioclase in gabbronorite (GN) from MF9.

4.5. Thermobarometric constraints

For the marginal facies norite from MF38, the two-pyroxene thermometer calibrated by Wood and Banno (1973) yielded temperatures of 863 to 1139°C, that of Wells (1977) yielded 813 to 1189°C, and that of Putirka (2008), which utilizes the Brey and Köhler (1990) thermometer with a new global regression based on the partitioning of enstatite and ferrosilite between clinopyroxene and orthopyroxene, yielded 861 to 1081°C. Pressure estimates using the clinopyroxene barometer of Nimis (1999), and non-pressure sensitive

two-pyroxene temperatures, range from 5.2 to 8.1 kbars for the marginal facies norite from MF38. The close correspondence between the different thermometer estimates attest to their reliability. In comparison to the marginal facies norite, gabbro-norites from MF9 yielded slightly higher temperatures, with the two-pyroxene thermometer calibrated by Wood and Banno (1973) yielding temperatures of 940 to 1294°C, that of Wells (1977) yielding 880 to 1267°C, and that of Putirka (2008) yielding 942 to 1173°C. Pressure estimates using the clinopyroxene barometer of Nimis (1999) range from 6.6 to 8.9 kbars for the gabbro-norites from MF9.

Chapter 5

Whole-rock geochemical characteristics

5.1. Introduction

This chapter presents whole-rock geochemical characteristics of selected rock units of relevance to the main objective of the study. These include the marginal facies norite and medium grained pyroxenite from drill core MF38, and gabbro-norite from drill core MF9. In addition, pyroxenite from MF38, harzburgite from drill core MF11 and norite from MF9 were also subjected to whole-rock geochemical analyses. Major, trace and rare-earth element bulk chemical compositions obtained for all the rock samples are given in Table 5.1. Available whole-rock geochemical data on harzburgite, pyroxenite and gabbro-norite from the Molopo Farms Complex presented in Gould et al. (1987) and Reichhardt (1994) are included for comparison in the different geochemistry-based plots.

5.2. Effect of alteration

Loss on ignition (LOI) value is a good indicator of effect of alteration. Mafic rock (gabbro-norite, norite) samples have LOI values <5 wt.% (Table 5.1), suggesting that the rocks have not been strongly hydrated or carbonated. On the other hand, ultramafic rocks (harzburgite, pyroxenite) have higher LOI values [5.3-14 wt.% (harzburgite); 5-13 wt.% (pyroxenite)] (Table 5.1).

Drill core	MF11	MF11	MF11	MF11	MF38	MF38	MF38	MF38	MF9	MF9	MF9
Rock	Harzburgite	Harzburgite	Harzburgite	Harzburgite	Norite	Norite	Pyroxenite	Pyroxenite	Gabbronorite	Gabbronorite	Norite
					Marginal facies	Marginal facies	Medium grained				
Sample_id	JMF11-59	JMF11-50c	JMF11-33	JMF11-20	M38-61	MF38-51	MF38-28d	MF38-16b	JMF9-27	JMF9-17	JMF9-10a
Depth (m)	592	520	390	311	570	517	330	256	370	270	210
SiO ₂ (wt. %)	44,92	35,64	41,37	44,46	56,61	56,51	55,24	42,90	50,98	50,44	46,72
TiO ₂	0,08	0,03	0,02	0,03	0,33	0,29	0,16	0,05	0,10	0,09	0,10
Al ₂ O ₃	2,12	1,14	1,11	0,83	9,83	8,88	3,58	1,57	16,61	20,85	17,47
Fe ₂ O _{3t}	11,91	12,37	11,40	10,83	9,53	9,48	10,77	6,52	9,48	5,69	9,66
MnO	0,18	0,14	0,17	0,16	0,16	0,16	0,15	0,09	0,15	0,10	0,15
MgO	32,33	34,78	33,90	35,63	14,21	16,21	22,28	33,99	11,71	6,68	9,64
CaO	1,33	0,14	0,61	0,59	4,92	4,48	0,55	0,02	9,17	13,71	9,68
Na ₂ O	0,08	<0,01	0,03	0,02	1,54	1,37	0,45	<0,01	1,38	1,98	1,51
K ₂ O	0,13	<0,01	<0,01	<0,01	1,00	0,82	0,84	<0,01	0,16	0,14	0,69
NiO	0,19	0,24	0,20	0,21	0,04	0,05	0,10	0,31	0,03	0,01	0,03
Cr ₂ O ₃	0,86	0,95	0,54	0,78	0,20	0,25	0,40	0,85	0,04	0,02	0,01
P ₂ O ₅	0,01	<0,01	<0,01	<0,01	0,05	0,05	0,02	<0,01	<0,01	<0,01	<0,01
LOI	5,30	14,00	10,10	5,90	1,20	1,10	5,00	13,10	-0,10	0,10	4,00
Sum	99,44	99,39	99,42	99,38	99,69	99,66	99,53	99,41	99,73	99,83	99,75
Mg#	82,88	83,37	84,13	85,43	72,67	75,30	78,67	90,29	68,77	67,67	64,02
Ba (ppm)	55	2	3	4	280	221	96	1	63	69	221
Be	<1	<1	<1	1,00	<1	<1	<1	<1	1,00	<1	<1
Ce	5,9	1,1	0,6	0,1	24,2	21	15,4	3	4,8	3,3	5,8
Co	125,5	152,3	152,5	117,3	57,2	60,7	82,7	103,9	67,4	36,3	87,4
Cs	0,20	<0,1	<0,1	<0,1	2,8	2,1	6,80	<0,1	<0,1	<0,1	0,8
Dy	0,23	0,11	<0,05	0,06	1,68	1,58	0,78	0,22	0,59	0,57	0,5
Er	0,12	<0,03	<0,03	<0,03	1,09	0,88	0,51	0,14	0,24	0,3	0,29
Eu	0,07	0,03	<0,02	<0,02	0,57	0,51	0,18	0,05	0,36	0,23	0,46
Ga	4,5	4	2,1	2,5	8,9	7,4	4,5	0,9	14,6	15,5	13,7
Gd	0,44	0,09	0,06	0,06	1,88	1,69	0,91	0,25	0,46	0,56	0,49
Hf	0,20	<0,1	<0,1	<0,1	1,7	1,5	1,20	0,20	<0,1	0,2	0,4
Ho	0,04	0,02	0,02	0,02	0,39	0,27	0,17	0,04	0,05	0,08	0,1
La	3,10	0,90	0,60	0,40	12,8	10,6	8,20	1,70	2,3	2	4,1
Lu	0,01	0,01	0,01	0,01	0,15	0,15	0,11	0,03	0,03	0,01	0,05
Nb	<0,1	<0,1	<0,1	<0,1	2,4	2,1	1,30	0,40	0,2	<0,1	0,7
Nd	2,50	1,10	0,30	0,30	10,5	9,5	5,80	1,20	1,7	1,4	2,5
Ni	1505	1895	1574	1639	348	375	806	2474	203	92	197
Pr	0,65	0,13	<0,02	<0,02	2,78	2,5	1,64	0,30	0,48	0,36	0,67
Rb	6,20	0,90	0,50	0,30	43	33,9	45,10	0,50	3,3	2,3	31,8
Sn	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Sc	17	6	14	12	29	29	25	9	26	28	26
Sm	0,62	<0,05	<0,05	<0,05	2,01	1,71	0,92	0,23	0,38	0,49	0,45
Sr	17,3	3	2,5	1	153,2	144,4	40,2	0,6	270,6	344,5	327,9
Ta	<0,1	<0,1	0,10	<0,1	0,2	0,2	<0,1	<0,1	<0,1	<0,1	<0,1
Tb	0,04	<0,01	<0,01	<0,01	0,28	0,24	0,13	0,03	0,04	0,05	0,07
Th	0,50	0,20	0,20	0,20	3,2	2,6	3,30	0,20	0,3	0,2	0,6
Tm	0,02	0,01	0,01	0,01	0,16	0,14	0,08	0,02	0,02	0,02	0,04
U	<0,1	<0,1	<0,1	<0,1	0,8	0,6	1,40	<0,1	0,1	<0,1	0,1
V	71,00	42,00	42,00	56,00	145	149	228,00	35,00	90	102	147
Y	2,2	0,5	0,2	0,2	9,8	8,8	4,7	1,5	2,9	2,6	2,4
Yb	0,14	0,05	0,05	0,05	1,02	0,96	0,62	0,16	0,24	0,23	0,33
Zr	11,8	3,1	1,5	1	64	55,1	43,9	6,6	8,6	8,7	11,6
t - total Fe as Fe ₂ O ₃											

Table 5.1. Representative major, trace and rare earth element data for harzburgites from MF11, norite and pyroxenite from MF38, and gabbronorite and norite from MF9 of the Molopo Farms Complex layered intrusion.

Deer et al. (1992) proposed a graphical plot to assess alteration by serpentine-chlorite-tremolite-talc in mafic to ultramafic rocks using LOI values and MgO contents; MgO considered with respect to the Mg-rich nature of the concerned alteration minerals (Fig. 5.1). Stoichiometric composition of typical Mg-chlorites, Mg-serpentine, Mg-tremolite and talc are indicated in Fig. 5.1. All the studied samples fall below the filtering line (Fig. 5.1), considered as benchmark for delineating altered versus unaltered samples. A serpentinized harzburgite and pyroxenite falls closer to the serpentine filtering line. The rest of the ultramafic rocks, including the medium grained pyroxenite (from MF38), fall well below the serpentine filtering line in Fig. 5.1.

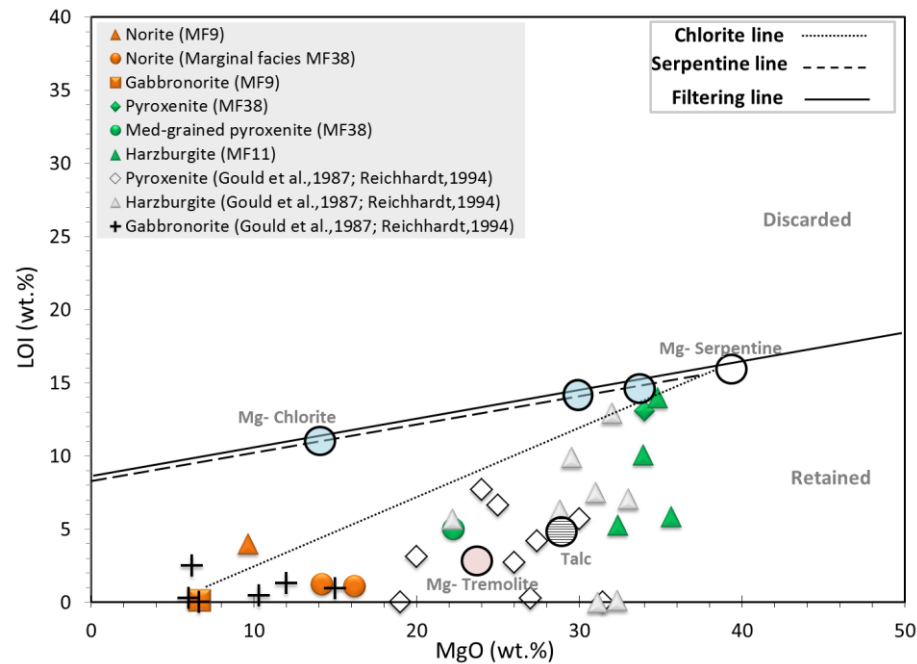


Figure 5.1. MgO vs. LOI (wt.%) addressing the alteration in the studied samples. All the studied samples fall below the filtering line, considered as benchmark for delineating altered versus unaltered samples. Data on rocks from the Molopo Farms Complex compiled from Gould et al. (1987) and Reichhardt (1994) are included for comparison. Blue filled circles on the chlorite line represent stoichiometric Mg-Chlorites; Mg-serpentine composition is indicated by unfilled circle; pink filled circle below serpentine line represent Mg-tremolite; talc is indicated by the striped circle. Dividing lines and mineral compositions are from Deer et al. (1992).

The effect of alteration was further tested using the MFW diagram of Ohta and Arai (2007), which is designed to show the effects of differentiation and alteration on mafic rocks, by combining several indicators; M corresponds to mafic rocks, F to felsic rocks and W to weathered compositions. In an 'MFW' plot unaltered rocks define an igneous trend ranging from mafic (M) to felsic compositions (F) (Fig. 5.2). For example, for the ~3.8 Ga mafic supracrustal lithologies from Nuvvuagittuq greenstone belt, Canada, O'Neil et al. (2011) considered samples falling closer to the igneous trend (samples within the dotted-line field in Fig. 5.2a) as least altered. On the other hand, samples falling away towards the W apex (Fig. 5.2a) were clearly affected by alteration [see O'Neil et al. (2011) for more details].

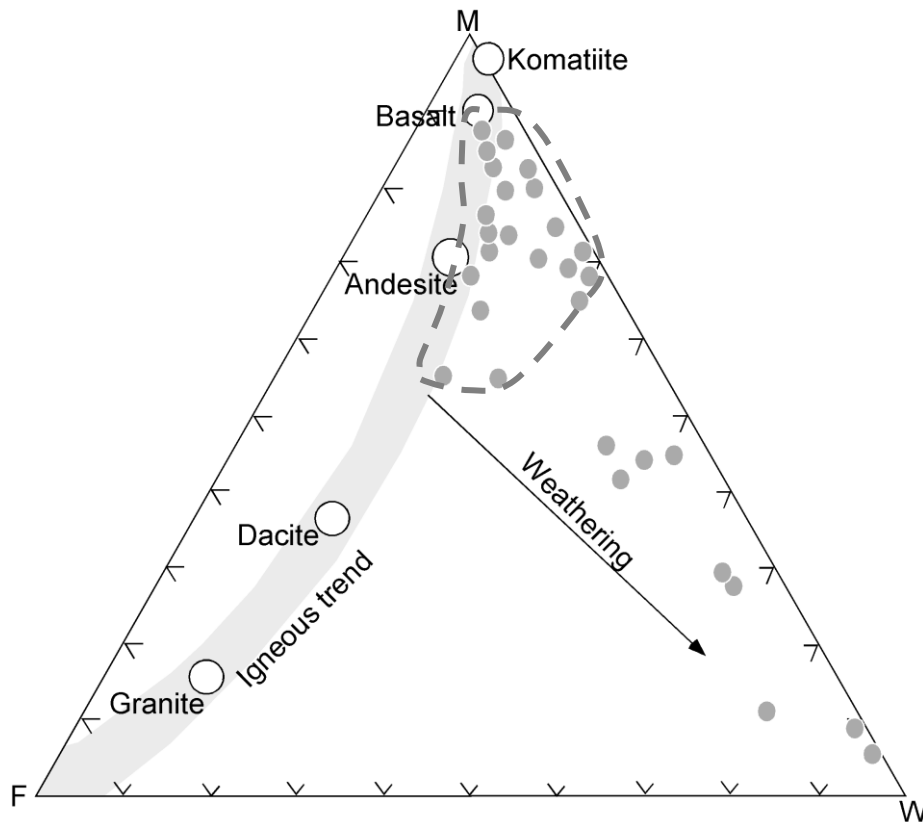


Figure 5.2. (a) ~3.8 Ga mafic supracrustal lithologies from the Nuvvuagittuq greenstone belt, Canada [data from O'Neil et al. (2011)] in the MFW diagram of Ohta and Arai (2007). See Fig. 5.2 (b) for details on M, F and W.

Thus the MFW diagram can be used to discriminate the chemical elements representing original igneous chemical features from elements remobilized during post-magmatic alteration. All the mafic rocks, including the marginal facies norite (from MF38), fall within the igneous trend in the MFW diagram (Fig. 5.2b). Among the ultramafic rocks, the serpentinized harzburgite and pyroxenite, which fall closer to the serpentine filtering line in Fig. 5.1, falls towards the W corner (Fig. 5.2b). The rest of the harzburgites fall closer to the igneous trend. Significantly, the altered medium-grained pyroxenite falls away from the igneous trend (Fig. 5.2b).

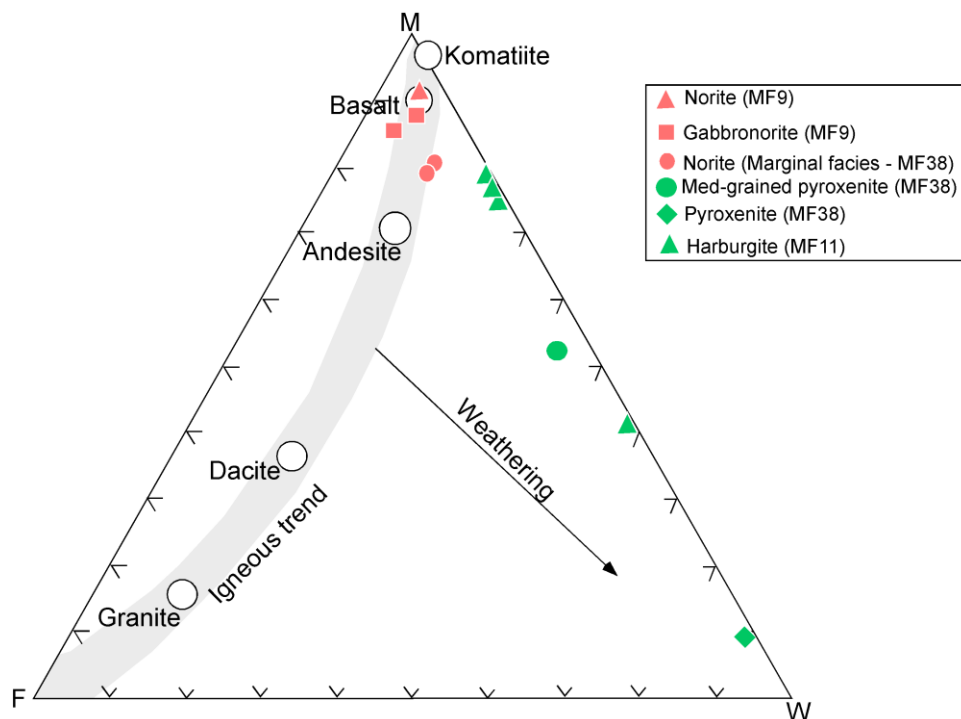


Figure 5.2. (b) Mafic and ultramafic rocks of the Molopo Farms Complex in the MFW diagram of Ohta and Arai (2007). Values plotted in the MFW diagram are: $\exp(M)$, $\exp(F)$, $\exp(W)$, re-totaled to 100. Values for M, F and W calculation are normalized to 100 wt %. $M = -0.395 \ln(\text{SiO}_2) + 0.206 \ln(\text{TiO}_2) - 0.316 \ln(\text{Al}_2\text{O}_3) + 0.160 \ln(\text{Fe}_2\text{O}_3) + 0.246 \ln(\text{MgO}) + 0.368 \ln(\text{CaO}) + 0.073 \ln(\text{Na}_2\text{O}) - 0.342 \ln(\text{K}_2\text{O}) + 2.266$. $F = 0.191 \ln(\text{SiO}_2) - 0.397 \ln(\text{TiO}_2) + 0.020 \ln(\text{Al}_2\text{O}_3) - 0.375 \ln(\text{Fe}_2\text{O}_3) - 0.243 \ln(\text{MgO}) + 0.079 \ln(\text{CaO}) + 0.392 \ln(\text{Na}_2\text{O}) + 0.333 \ln(\text{K}_2\text{O}) - 0.892$. $W = 0.203 \ln(\text{SiO}_2) + 0.191 \ln(\text{TiO}_2) + 0.296 \ln(\text{Al}_2\text{O}_3) + 0.215 \ln(\text{Fe}_2\text{O}_3) - 0.002 \ln(\text{MgO}) - 0.448 \ln(\text{CaO}) - 0.464 \ln(\text{Na}_2\text{O}) + 0.008 \ln(\text{K}_2\text{O}) - 1.374$ (Ohta and Arai, 2007).

5.3. Major element characteristics

Harzburgite is characterized by SiO₂ contents of 35.64 to 44.92 wt.%, MgO of 32.33 to 35.63 wt.%, Al₂O₃ of 0.83 to 2.12 wt.%, Fe₂O₃ of 10.83 to 12.37 wt.%, TiO₂ of 0.02 to 0.08 wt.% and CaO of 0.14 to 1.33 wt.%. Mg# ($100 \cdot \text{Mg} / (\text{Mg} + \text{Fe}^{2+})$) varies from 82.9 to 85.4 (Table 5.1).

The medium-grained pyroxenite (from MF38) has higher SiO₂ (55.24 wt.%), TiO₂ (0.16 wt.%), Al₂O₃ (3.58 wt.%), Fe₂O₃ (10.77 wt.%), MnO (0.15 wt.%) and CaO (0.55 wt.%), and lower MgO (22.28 wt.%; Mg# = 78.7) than normal pyroxenite (SiO₂: 42.9 wt.%; TiO₂: 0.05 wt.%; Al₂O₃: 1.57 wt.%; Fe₂O₃: 6.52 wt.%; MnO: 0.09 wt.%; CaO: 0.02 wt.%; MgO: 33.39 wt.%; Mg#: 90.3) (Table 5.1).

The marginal facies norites (from MF38) have higher SiO₂ (56.51-56.61 wt.%), TiO₂ (0.29-0.33 wt.%), MnO (0.16 wt.%), MgO (14.21-16.21 wt.%; Mg# = 72.7-75.3), and lower Al₂O₃ (8.88-9.83 wt.%) and CaO (4.48-4.98 wt.%) than normal norite (SiO₂: 46.72 wt.%; TiO₂: 0.1 wt.%; MnO: 0.15 wt.%; MgO: 9.64 wt.%; Mg#: 64; Al₂O₃: 17.47 wt.%; CaO: 9.68 wt.%) (Table 5.1).

Gabbro-norite is characterized by SiO₂ contents of 50.44 to 50.98 wt.%, MgO of 6.68 to 11.71 wt.%, Al₂O₃ of 16.61 to 20.85 wt.%, Fe₂O₃ of 5.69 to 9.48 wt.%, TiO₂ of 0.09 to 0.1 wt.% and CaO of 9.17 to 13.71 wt.%. Mg# ($100 \cdot \text{Mg} / (\text{Mg} + \text{Fe}^{2+})$) varies from 67.7 to 68.8 (Table 5.1).

To understand which mineral phases control the composition of the rocks, especially those ones which are to be used for constraining parental magma composition, average

compositions of prominent rock forming minerals were plotted together with the respective whole-rock contents (Figs. 5.3 and 5.4). Based on petrography, minerals in equilibrium were connected by tie lines in these plots (Figs. 5.3 and 5.4).

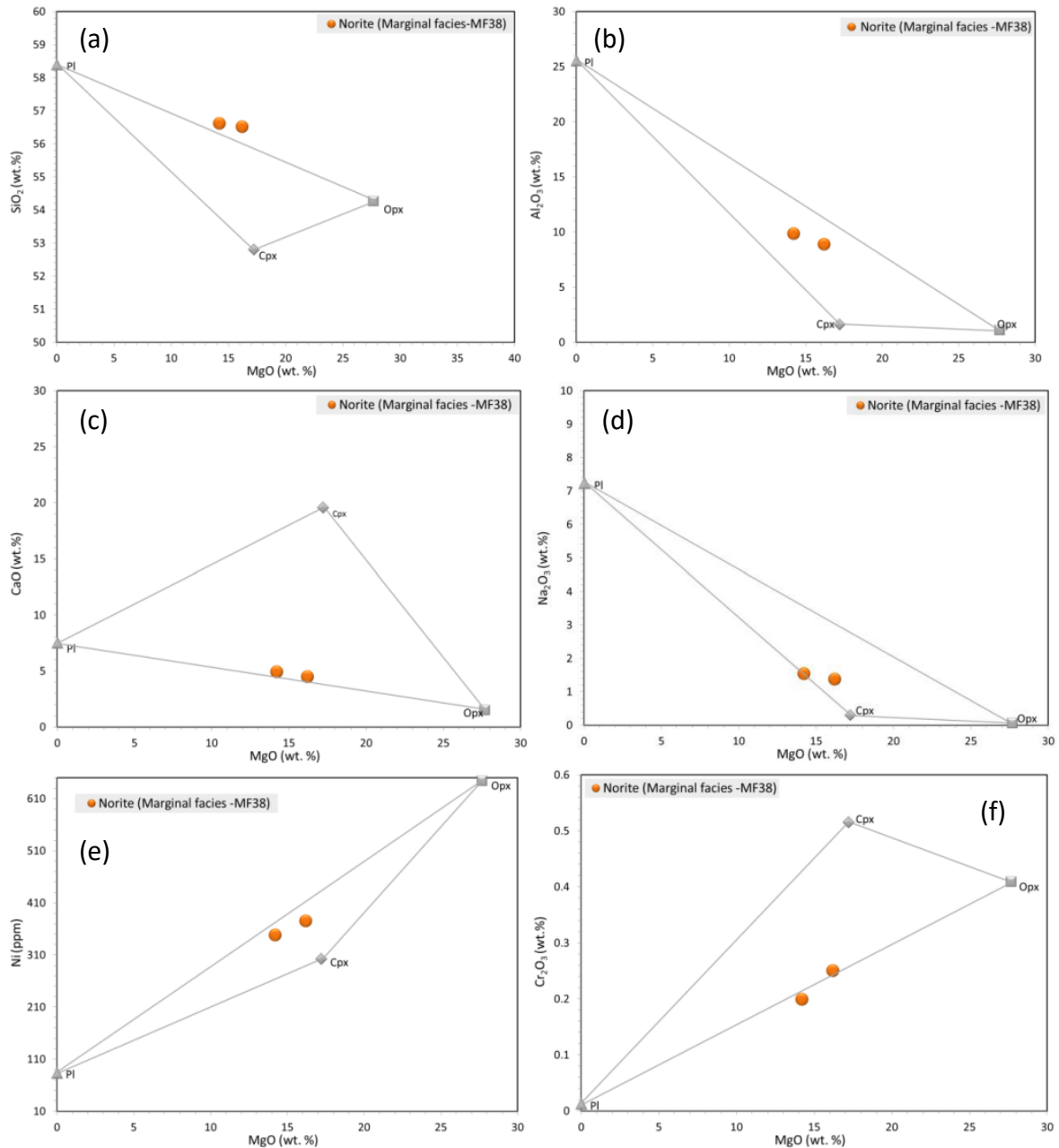


Figure 5.3. (a to f) Major element harker variation diagrams comparing the whole-rock composition of marginal facies norite from MF38, with average compositions of prominent minerals from the rock. Tie lines are connected between minerals in equilibrium and are based on petrography.

It follows that the composition of both the marginal facies norite from MF38 and the gabbronorite from MF9 is mainly controlled by orthopyroxene, plagioclase and clinopyroxene (Figs. 5.3 and 5.4). In later case, the concentration of samples towards plagioclase (Fig. 5.4), likely indicates its cumulate nature. The good correlation between mineral chemical data and whole-rock geochemical data supports petrographic observations, arguing for the general preservation of primary magmatic compositions in the studied rocks.

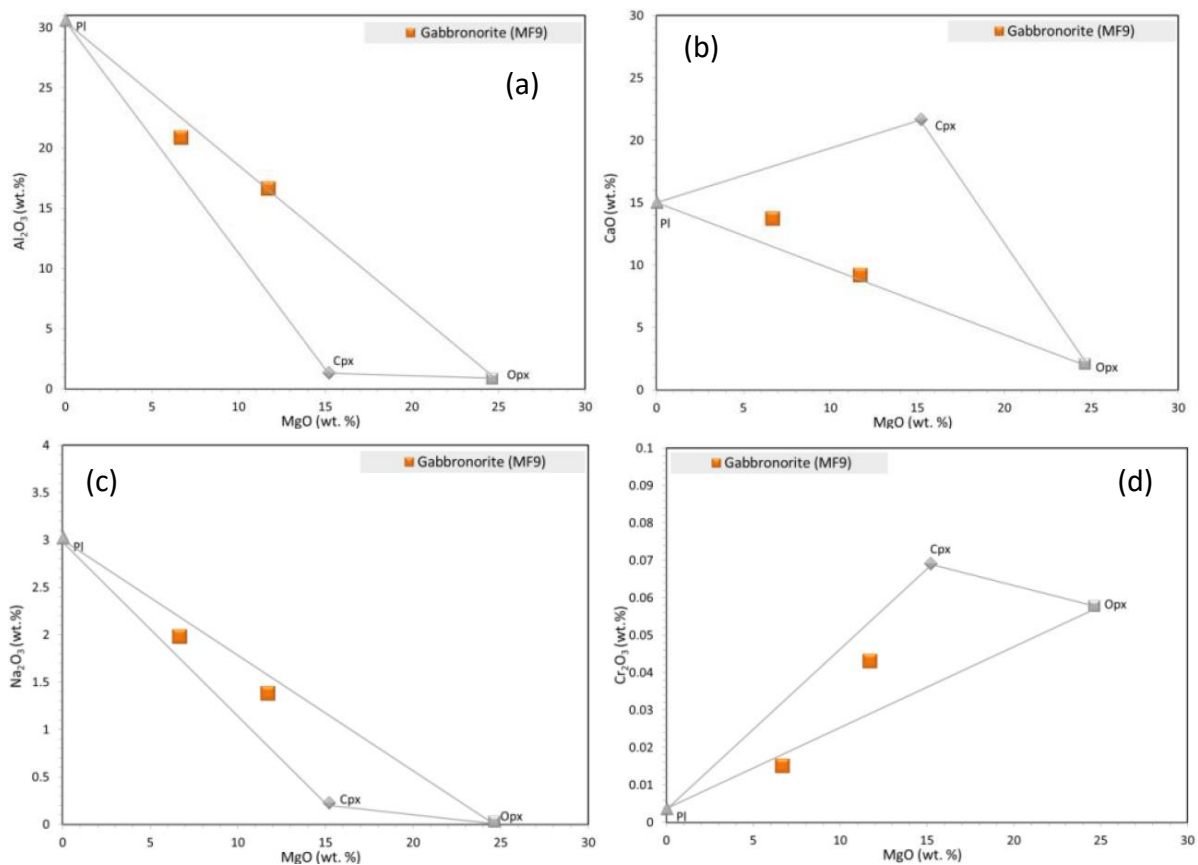


Figure 5.4. (a to d) Major element harker variation diagrams comparing the whole-rock composition of gabbronorite from MF9, with average compositions of prominent minerals from the rock. Tie lines are connected between minerals in equilibrium and are based on petrography.

5.4. Trace and rare earth element characteristics

The ultramafic rocks are characterized by high contents of Cr and Ni, with harzburgite (Cr = 3701-6486 ppm; Ni = 1505-1895 ppm) having the highest, followed by pyroxenite (Cr = 2723-5788 ppm; Ni = 806-2474 ppm). Although lower than the ultramafic rocks, marginal facies norite (from MF38) also has relatively high Cr (1361-1710 ppm) and Ni (348-375 ppm) contents. In comparison, normal norite and gabbro-norite have lower Cr [96 ppm (norite); 102-294 ppm (gabbro-norite)] and Ni [197 ppm (norite); 92-203 ppm (gabbro-norite)] contents (Table 5.1). Co is also generally higher in the ultramafic rocks [117-152 ppm (harzburgite); 83-104 ppm (pyroxenite)] than the mafic rocks [57-87 ppm (norite); 36-67 ppm (gabbro-norite)] (Table 5.1). V and Sc contents are slightly variable, but in general mafic rocks have higher V [145-149 ppm (norite); 90-102 ppm (gabbro-norite)] and Sc [26-29 ppm (norite); 26-28 ppm (gabbro-norite)] than the ultramafic rocks [V: 42-71 ppm (harzburgite), 35-228 ppm (pyroxenite); Sc: 6-17 ppm (harzburgite), 9-25 ppm (pyroxenite)] (Table 5.1). It should be pointed out that the highest V content (228 ppm) was in the medium-grained pyroxenite from MF38.

In the primitive-mantle normalized (Sun and McDonough, 1989) multi-element spidergram, all the ultramafic rocks show large ion lithophile element (LILE) enrichment, but differ in the high-field strength elements (HFSE) pattern (Fig. 5.5c). While pyroxenite exhibits a relatively constant HFSE pattern, harzburgite have variable HFSE pattern. The mafic rocks also show a similar pattern, with LILE enrichment, but different HFSE patterns (Fig. 5.5c). While the marginal facies norite (from MF38) has relatively constant HFSE pattern, that of

the normal norite is slightly depleted. Gabbronorite shows both relatively constant as well as variable HFSE patterns. All rocks exhibit negative Nb, Ta and Ti anomalies (Figs. 5.5a, c).

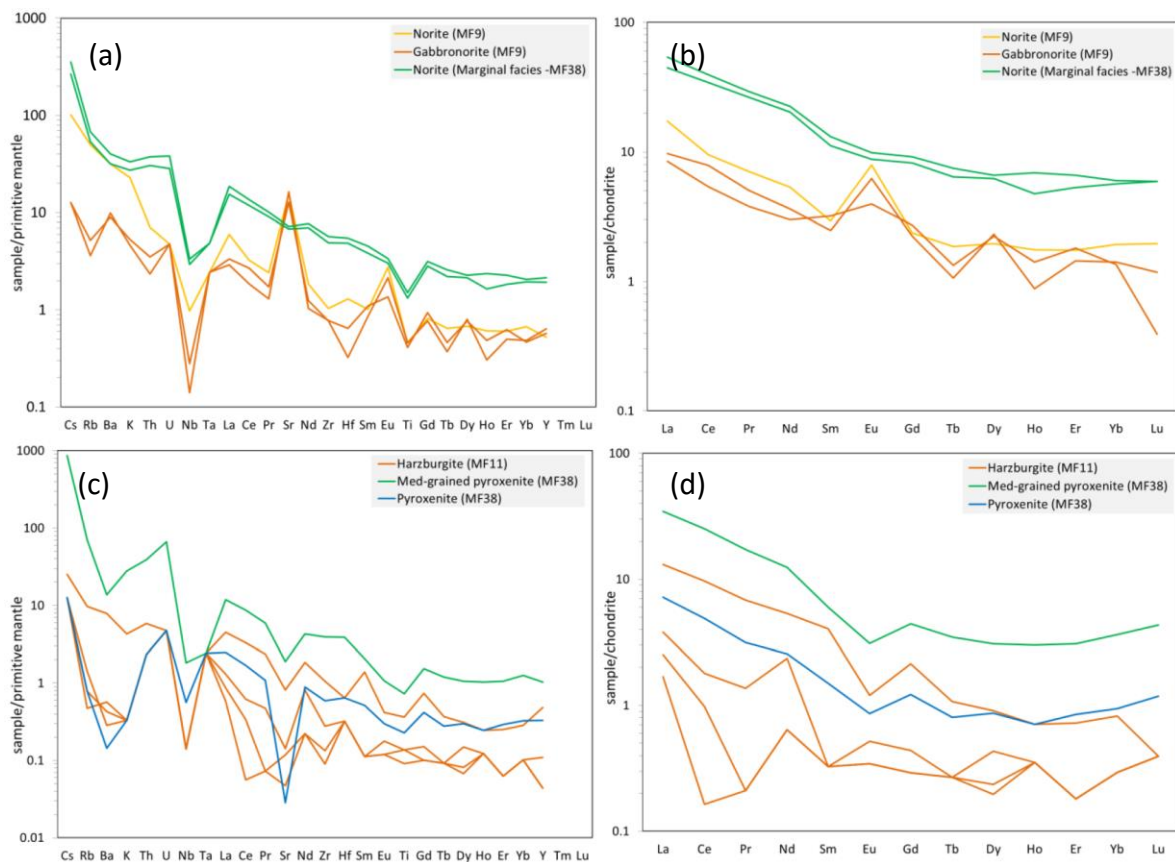


Figure 5.5. Primitive mantle-normalized trace element spider diagram (a, c) and chondrite-normalized REE diagram (b, d) of ultramafic and mafic rocks from the Molopo Farms Complex. Normalization values from Sun and McDonough (1989) for this and other similar diagrams in the thesis.

The chondrite-normalized (Sun and McDonough, 1989) REE patterns of the rocks are characterized by enrichment of light REE (LREE, e.g., La) relative to middle REE (MREE, e.g., Sm) [$(La/Sm)_N = 3.23-11.62$ (harzburgite), $4.77-5.75$ (pyroxenite), $4-5.88$ (norite), $2.63-3.91$ (gabbronorite)], relatively constant to slightly depleted heavy REE (HREE, e.g., Yb) [$(Gd/Yb)_N = 0.99-2.6$ (harzburgite), $1.21-1.29$ (pyroxenite), $1.23-1.52$ (norite), $1.59-2.01$ (gabbronorite)],

and variable Eu anomalies [$(\text{Eu}/\text{Eu}^*) = 0.39\text{-}1.35$ (harzburgite), $0.59\text{-}0.63$ (pyroxenite), $0.88\text{-}2.98$ (norite), $1.34\text{-}2.63$ (gabbro-norite)] (Figs. 5.5b, d). While the marginal facies norite (from MF 38) is characterized by negative Eu anomaly ($\text{Eu}/\text{Eu}^* = 0.88\text{-}0.91$), the normal norite and gabbro-norite have prominent positive Eu anomalies ($\text{Eu}/\text{Eu}^* = 1.34\text{-}2.98$) (Fig. 5.5b), the latter indicating cumulus plagioclase. The $(\text{La}/\text{Yb})_N$ ratios of the rocks vary from 5.74 to 15.88 for harzburgite, 7.62 to 9.49 for pyroxenite, 7.92 to 9 for norite and 6.24 to 6.87 for gabbro-norite.

Chapter 6

Discussion

6.1. Parental magma composition to the Bushveld Complex layered intrusion

Before attempting to infer the parental magma composition of the Molopo Farms Complex layered intrusion, it is important to summarize the relevant details of parental magma constraints from the Bushveld Complex layered intrusion. These include (see Fig. 1.5 for the approximate stratigraphic position):

- **B3 sills:** Fine-grained gabbro-norites in contact with the Main zone.
- **B2 sills:** Fine-grained gabbro-norites in contact with the upper Critical zone.
- **B1 sills:** Quench-textured fine-grained norites in contact with the Lower zone and lower Critical zone.
- **B1UM sills:** Orthocumulates consisting of a mixture of B1 liquid and cumulate olivine and chromite, in contact with the Lower zone.
- **Chill margins/sequences:** Quench-textured medium-grained pyroxenite/gabbro-norite against country rock followed by spinifex-textured pyroxenite/gabbro-norite at the base of the Lower zone.

Petrographically (see Fig. 1.6 for representative photomicrographs), the chill margin/sequence rocks (in the quench- and spinifex-textured portions) contain elongate, skeletal, compositionally zoned grains of orthopyroxene, olivine, clinopyroxene and zoned

plagioclase, with minor amphibole, phlogopite, K-feldspar, quartz, chromite and sulphides (Wilson, 2012; Maier et al., 2016). The quench textured B1 rocks contain elongate, skeletal, compositionally zoned grains of orthopyroxene surrounded by plagioclase, with minor clinopyroxene, chromite, biotite and sulphides (Harmer and Sharpe, 1985; Sharpe and Hulbert, 1985; Barnes et al., 2010). B1UM rocks contain granular olivine, oikocrystic orthopyroxene and interstitial plagioclase, with minor chromite, biotite and sulphides (Harmer and Sharpe, 1985; Sharpe and Hulbert, 1985; Barnes et al., 2010). Here the intercumulus material is similar to the mineralogy of B1 rocks. The B2 and B3 rocks are equigranular and consist of plagioclase, orthopyroxene, and clinopyroxene with accessory biotite and Fe-Ti oxides (Harmer and Sharpe, 1985; Sharpe and Hulbert, 1985; Barnes et al., 2010).

6.2. Rock types used to infer parental magma composition to the Molopo Farms Complex layered intrusion

The approximate stratigraphic position of the different rocks sampled as part of this study is shown in Fig. 6.1. Of the different rocks sampled, the following rocks/units were considered as useful in inferring the parental magma composition to the Molopo Farms Complex layered intrusion.

- **Marginal facies norite (MF38):** Quench-textured medium-grained norite against the country rock (Fig. 6.1). Based on the gradational contact observed between the norite and the ultramafic sequence above, with the contact marked by the presence

of a thin feldspathic pyroxenite layer, it is argued that the noritic unit could not be a sill. The occurrence of remobilized country rock at the base of the marginal facies norite has all the hallmarks of a typical chill margin. But unlike the chill margins of the Bushveld Complex, which rests on quartzite, the country rock to the marginal facies norite from MF38 is granitoid. Petrographically, the norite contains elongate, skeletal, compositionally zoned grains of orthopyroxene, and plagioclase, with minor clinopyroxene, phlogopite, amphibole, quartz, K-feldspar, biotite and sulphides (see Figs. 3.3 and 3.4). The irregular curved melt-like grain margins of quartz (see Figs. 3.3 and 3.4) are conspicuous. The marginal facies norite from MF38 has close similarities to chill margins and B1 sills of the Bushveld Complex.

- **Medium-grained pyroxenite (MF38):** Medium-grained pyroxenite within the ultramafic sequence (Fig. 6.1). Petrographically, the rock is an orthocumulate with intercumulus plagioclase+orthopyroxene+clinopyroxene, minor phlogopite and sulphides (see Fig. 3.8). The irregular round grain margins of the intercumulus material is conspicuous (see Fig. 3.8). The medium-grained pyroxenite from MF38 has similarities to B1UM of the Bushveld Complex, with the composite mineralogy of the intercumulus material resembling that of the B1 liquid.

Other sampled rocks include pyroxenite and harzburgite from MF11 (Fig. 6.1), which are typical olivine and pyroxene cumulates, and gabbro-norites and norite (Fig. 6.1) from MF9, which are typical pyroxene and plagioclase cumulates. These cumulate rocks were included in the following petrogenetic inference exercise for comparison.

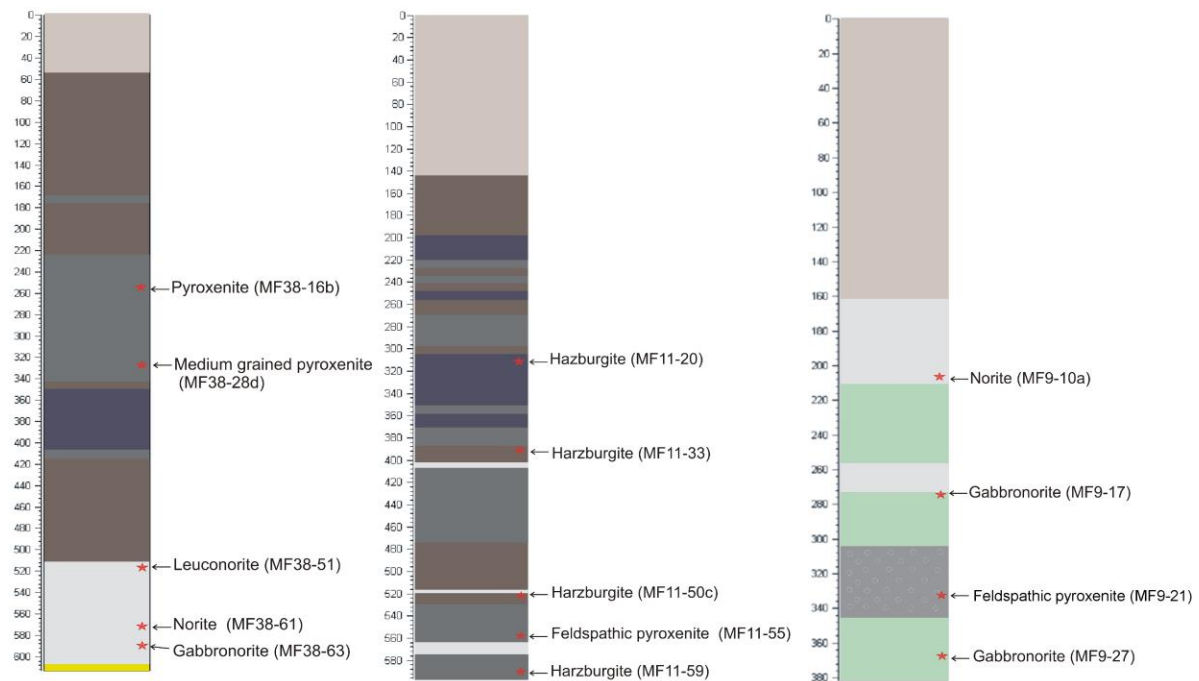


Figure 6.1. Core logs of the three drill cores studied here (from left to right MF38, MF11 and MF9) showing the approximate position of sampling of the different rock types. The sample numbers (given in parenthesis) corresponds with the sample ids in Table 5.1.

6.3. Parental magma composition to the Molopo Farms Complex layered intrusion

The *modus operandi* for inferring parental magma composition involves a comparative exercise between the selected rocks from the Molopo Farms Complex and the equivalents from the Bushveld Complex. Whole-rock geochemical data is used for the purpose.

The marginal facies norite from MF38 was compared with chill margins and B1 compositions from the Bushveld Complex. Four sets of geochemistry-based plots are used: major element harker, trace element harker, trace element spider and REE plots. In the harker diagrams (Figs. 6.2 and 6.3), the marginal facies norites from MF38 show close similarity to chill margin compositions reported by Wilson (2012) and Maier et al. (2016),

and B1 sill composition reported by Barnes et al. (2010). In the trace element spider and REE diagrams (Figs. 6.4a, b), the marginal facies norite pattern more or less superimpose on the pattern of chill margin from the eastern Bushveld Complex reported by Wilson (2012). The chill margin composition from the western Bushveld Complex reported by Maier et al. (2016) also has closely similar pattern with the marginal facies norite, but at lower contents. Further, the trace element spider and REE pattern of average B1 composition reported by Barnes et al. (2010) more or less superimpose on the pattern of the marginal facies norite (Figs. 6.4c, d). Thus it is suggested that the marginal facies norite from the drill core MF38 represents the earliest known parental magma composition to the Molopo Farms Complex layered intrusion.

The medium grained pyroxenite from MF38 was compared with B1UM and chill margin compositions from the Bushveld Complex. In the harker diagrams (Figs. 6.2 and 6.3), the medium-grained pyroxenite from MF38 show close similarity to B1UM compositions reported by Barnes et al. (2010). On the other hand, they fall away from the B1 compositions (Figs. 6.2 and 6.3). The trace element and REE patterns of the medium-grained pyroxenite more or less superimpose on the average B1UM composition reported by Barnes et al. (2010) (Figs. 6.5a, b). In terms of chill margins, the medium grained pyroxenite show close similarity to chill margin composition from the western Bushveld Complex, different to that from the eastern Bushveld Complex. This is further supported by the trace element and REE patterns of the medium-grained pyroxenite which lies closer to those of chill margin composition from the western Bushveld Complex (Figs. 6.5c, d).

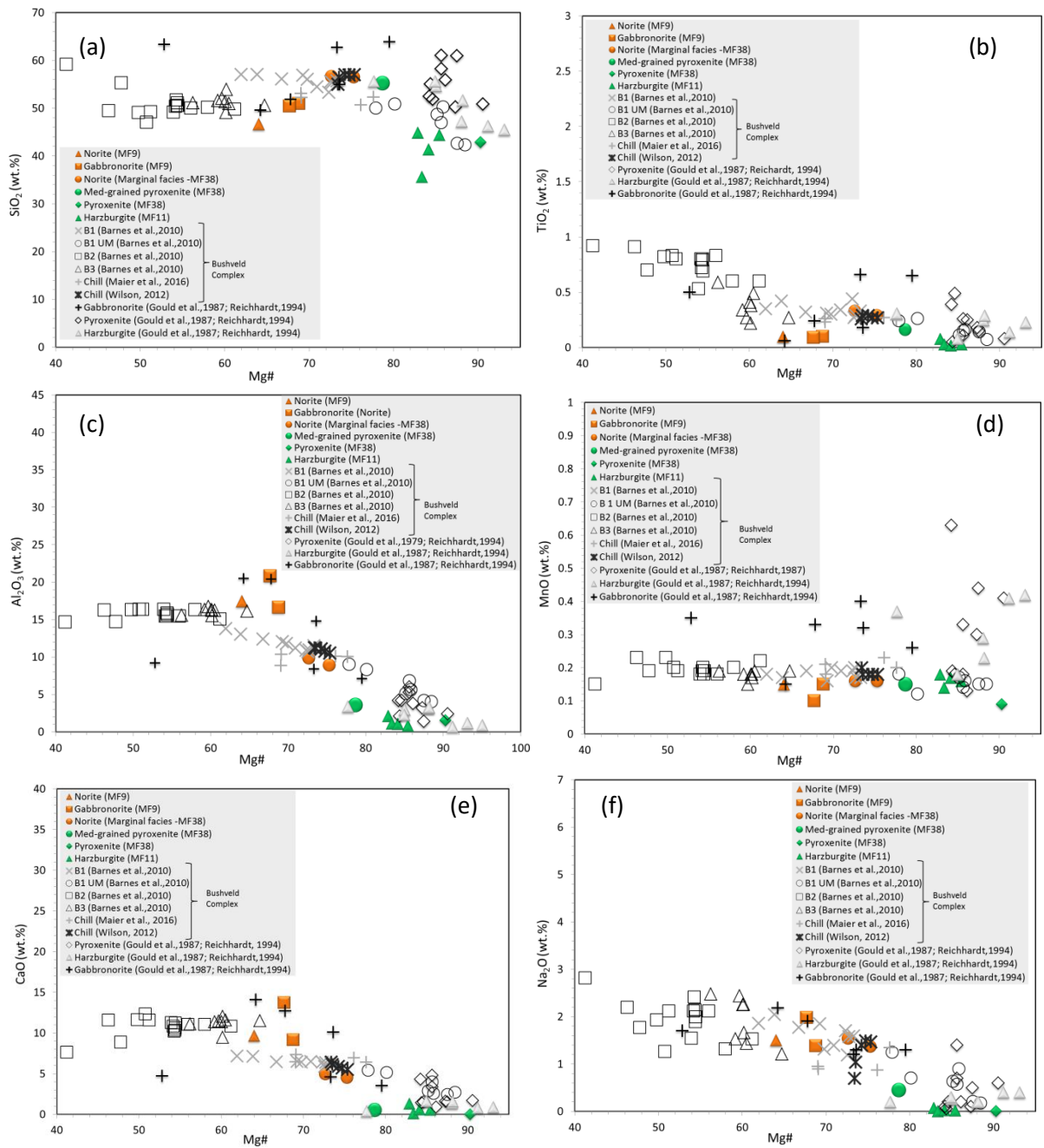


Figure 6.2. (a to f) Major element harker variation diagrams of the marginal facies norite and medium grained pyroxenite from MF38 of the Molopo Farms Complex compared to various parental magma compositions to the Bushveld Complex. Other mafic and ultramafic rocks sampled as part of the study from MF38, MF11 and MF9 are included for comparison. Data on rocks from the Molopo Farms Complex compiled from Gould et al. (1987) and Reichardt (1994) are also included.

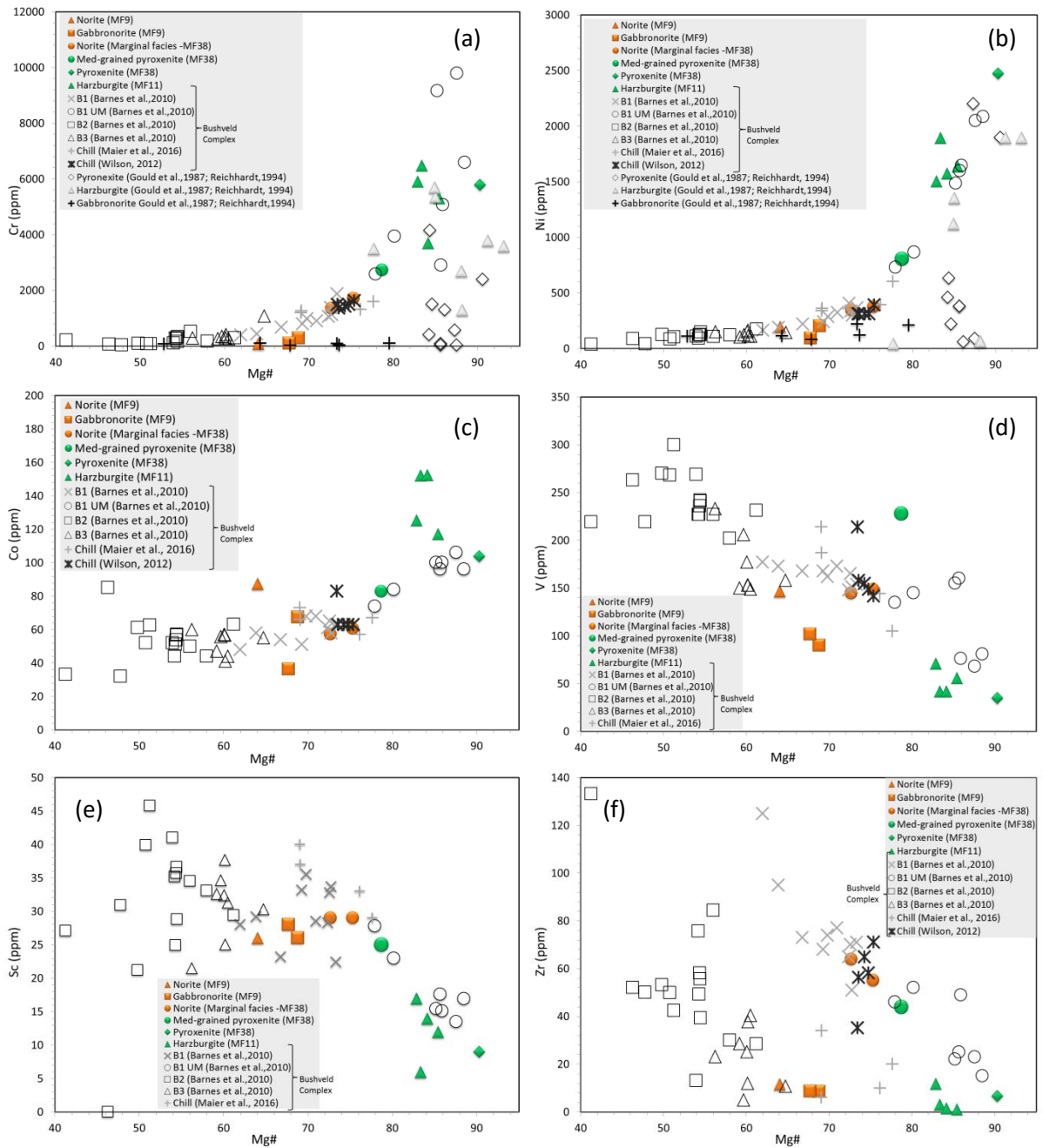


Figure 6.3. (a to f) Trace element harker variation diagrams of the marginal facies norite and medium grained pyroxenite from MF38 of the Molopo Farms Complex compared to various parental magma compositions to the Bushveld Complex. Other mafic and ultramafic rocks sampled as part of the study from MF38, MF11 and MF9 are included for comparison. Data on rocks from the Molopo Farms Complex compiled from Gould et al. (1987) and Reichardt (1994) are also included.

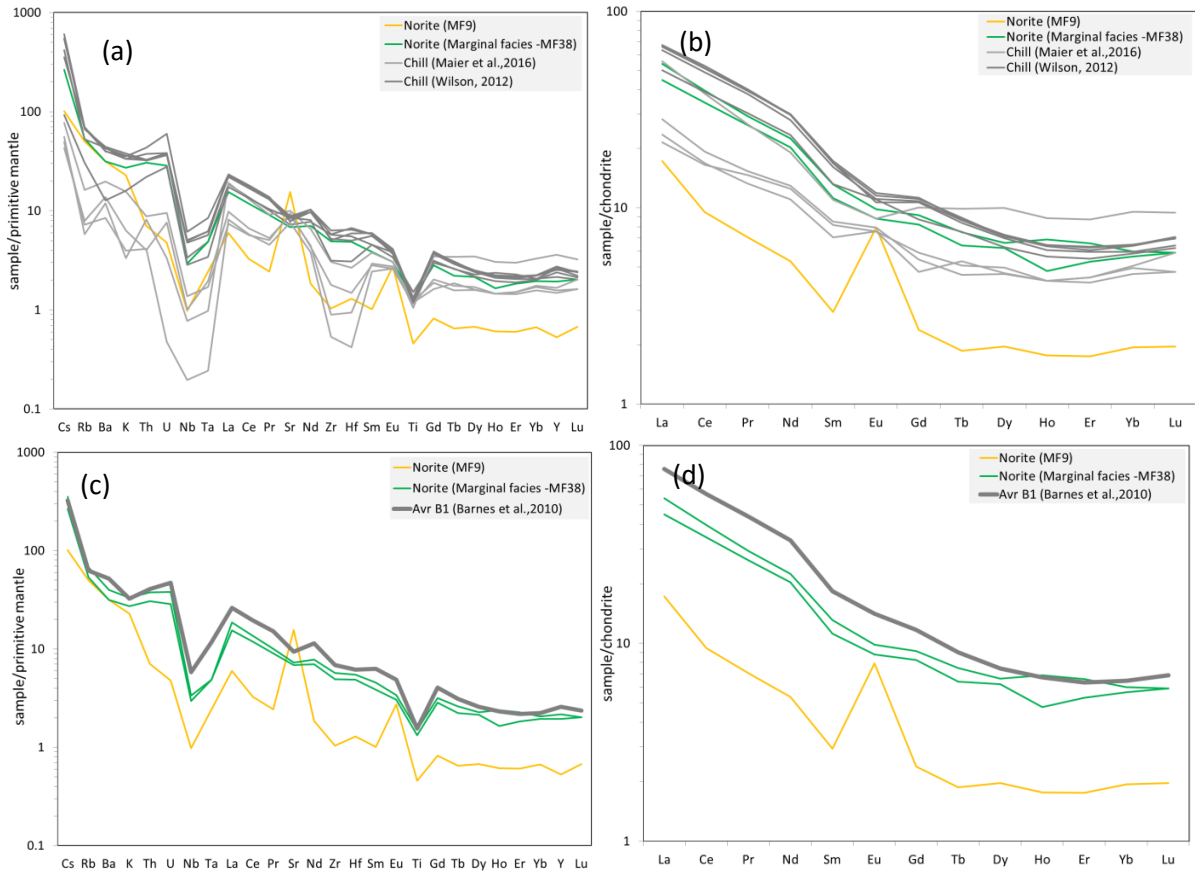


Figure 6.4. (a to d) Primitive mantle normalized trace element spider and chondrite normalized REE diagrams of the marginal facies norite from MF38 of the Molopo Farms Complex compared to chill margin compositions from the eastern (from Wilson, 2012) and western (from Maier et al., 2016) Bushveld Complex (a, b), and average B1 composition (c, d)(from Barnes et al., 2010). Norite from MF9 is included for comparison.

On the other hand, the chill margin from the eastern Bushveld Complex has comparable trace element spider and REE patterns, but at higher contents (Figs. 6.5c, d). Thus it is suggested that the medium grained pyroxenite from drill core MF38 of the Molopo Farms Complex represents a compositional equivalent to B1UM from the Bushveld Complex. The normal (cumulate) ultramafic rocks from MF38 and MF11 are different from the B1UM composition from Bushveld Complex (Fig. 6.5).

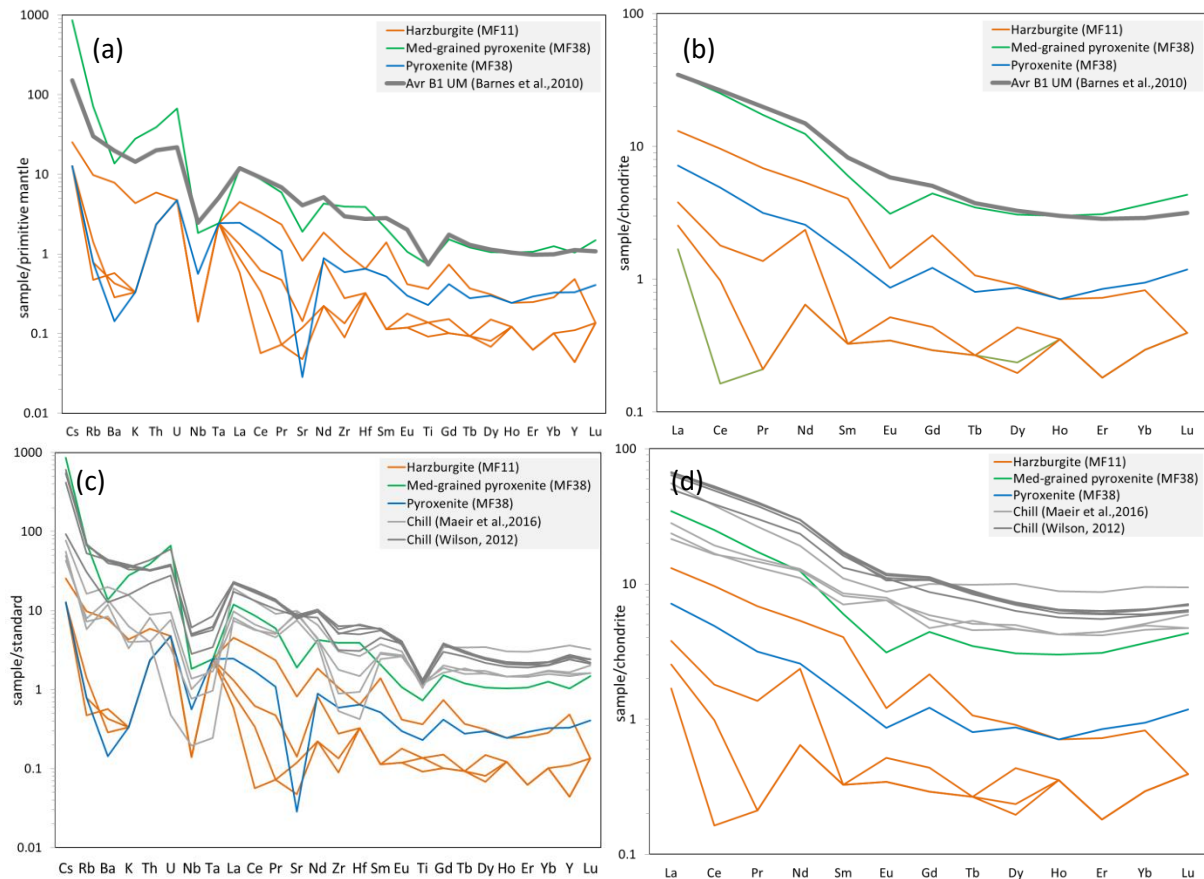


Figure 6.5. (a to d) Trace element spider and chondrite normalized REE diagrams of the medium grained pyroxenite from MF38 of the Molopo Farms Complex compared to average B1UM composition (from Barnes et al., 2010) (a, b) and chill margin compositions from the eastern (from Wilson, 2012) and western (from Maier et al., 2016) Bushveld Complex (c, d). Pyroxenite from MF38 and harzburgite from MF11 are included for comparison.

Considering the gabbronoritic nature of B2 and B3 compositions from the Bushveld Complex, a comparison was attempted with that of gabbronorites from MF9. In the harker diagrams (Figs. 6.2 and 6.3), the gabbronorites from MF9 show close similarity to B3 compositions reported by Barnes et al. (2010). B2 compositions fall away from the gabbronorites from MF9 (Figs. 6.2 and 6.3). This is further supported by the trace element and REE patterns of the gabbronorites from MF9 which shows similar (not superimposed)

pattern to average B2 composition reported by Barnes et al. (2010) (Fig. 6.6). On the other hand, the gabbronorites have no similarity to average B2 composition reported by Barnes et al. (2010) (not shown). Thus it is suggested that compositional equivalent of B3 from the Bushveld Complex do occur in the Molopo Farms Complex.

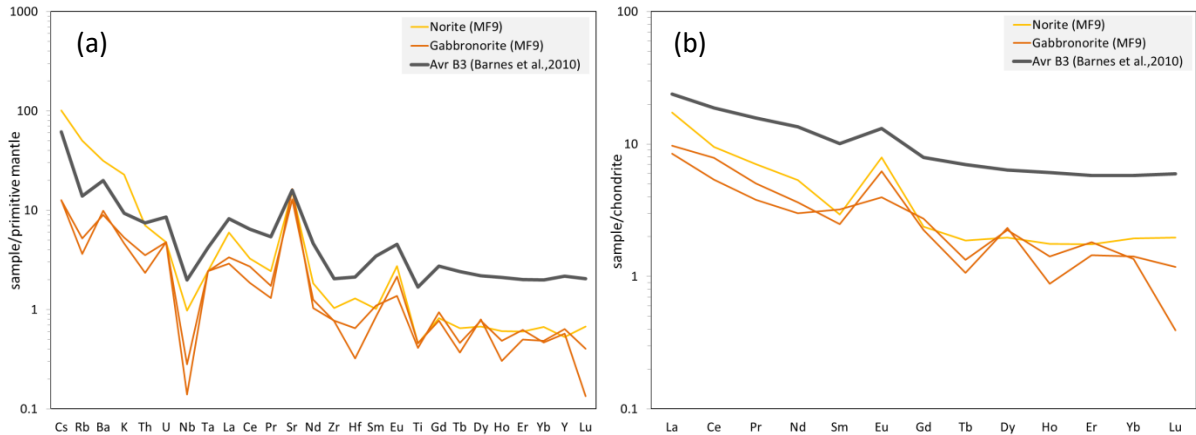


Figure 6.6. Trace element spider **(a)** and chondrite normalized REE **(b)** diagrams of gabbronorites and norite from MF9 of the Molopo Farms Complex compared to average B3 composition from Bushveld Complex (from Barnes et al., 2010).

6.4. Orthopyroxene mineral chemical constraints to the parental magma composition

Orthopyroxene is one of the prominent minerals occurring in the marginal rocks of the Bushveld Complex. Compositional zoning has been reported from elongated, skeletal orthopyroxene occurring as part of quench-textured rocks like B1 sills and chill margins (Barnes et al., 2010; Wilson, 2012; Maier et al., 2016). These studies also tried to identify the most primitive orthopyroxene related to the Bushveld magma. The highest Mg# (0.93) among Bushveld orthopyroxenes has been reported from cumulate rocks associated with chill sequence from the eastern Bushveld Complex (Fig. 6.7; Wilson, 2012). Orthopyroxene in

the marginal facies norite from MF38 of the Molopo Farms Complex is compositionally zoned and has comparable mineral chemical characteristics to those from the quench and chill margin rocks from the eastern Bushveld Complex reported by Wilson (2012) (Fig. 6.7). This further supports the inference made through whole-rock geochemical exercise on the similarity between the marginal facies norite from MF38 and chill margin from the eastern Bushveld Complex (Fig. 6.4). The highest Mg# reported in this study for orthopyroxene from the marginal facies norite of the Molopo Farms Complex is 0.85. In comparison, orthopyroxenes in gabbronorites from MF9 has a lower Mg# (Fig. 6.7).

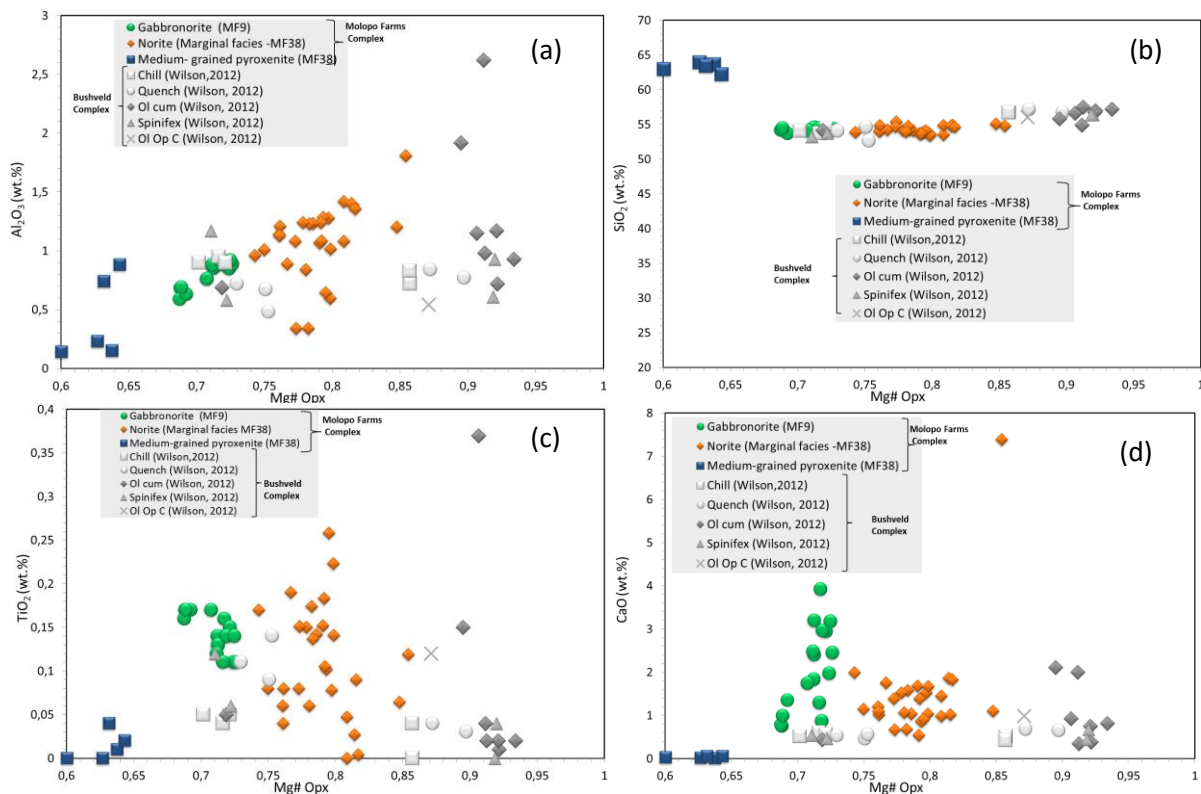


Figure 6.7. (a to d) Mineral chemistry based diagrams for orthopyroxene mineral compositions in the marginal facies norite from MF38 of the Molopo Farms Complex, compared to those in rocks of the chill sequence from eastern Bushveld Complex. Orthopyroxene compositions in gabbronorite from MF9 and altered orthopyroxene compositions from medium grained pyroxenite in MF38 are included for comparison. Orthopyroxene data from the eastern Bushveld chill sequence is from Wilson (2012).

6.5. Petrogenetic characteristics of the Molopo Farms Complex layered intrusion

The limitations of the exercise carried out in this section are acknowledged beforehand. But given the identification of marginal facies, representing the earliest known parental magma composition, and possible equivalents to Bushveld marginal sill compositions from the Molopo Farms Complex, an attempt is made to provide petrogenetic constraints, including likely setting of formation and the role of sub-continental lithosphere and crustal contamination.

While bulk of the studies on the intracratonic (see Fig. 1.2) Bushveld Complex has argued for its derivation from an asthenosphere-derived magma (e.g., Harmer and Von Gruenewaldt, 1991; Hatton, 1995; Barnes and Maier, 2002; Barnes et al., 2010; Richardson and Shirey, 2008), some studies did suggest the possible role for a subduction setting for its formation. For example, Clarke et al. (2009) argued for a back-arc type extension setting for the formation of the Bushveld magmas in relation to the convergence associated with the Paleoproterozoic Limpopo orogeny (Fig. 6.8). Significantly in Fig. 6.8, the Molopo Farms Complex is also included straddling across the Thabazimbi Murchinson lineament (TML).

Although a subjective approach, application of the four-tier immobile trace element (La, Sm, Yb, Nb and Th) based tectonic discrimination method of Agrawal et al. (2008) indicates that the marginal facies norite and medium grained pyroxenite from MF38 of the Molopo Farms Complex fall in the field of IAB, indicating the possibility of formation in a subduction setting (Fig. 6.9). With the exception of the B2 compositions, the rest of the parental magma

compositions from the Bushveld Complex also fall in the field of IAB (Fig. 6.9). B2 compositions fall towards the MORB field.

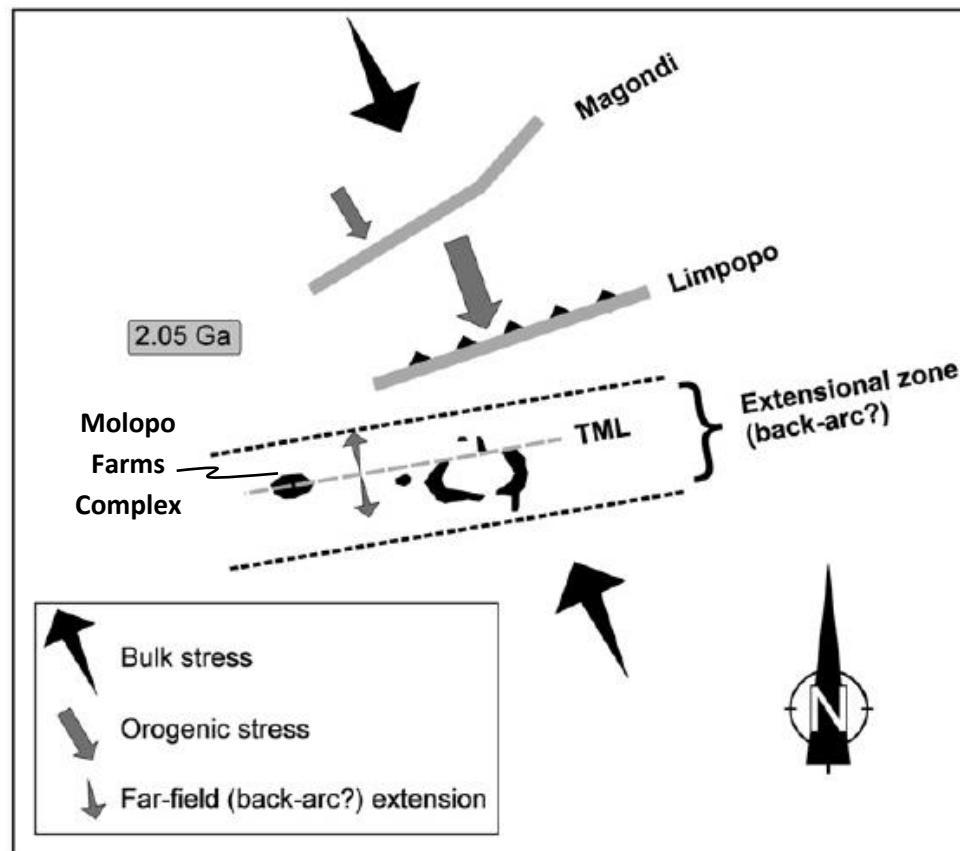


Figure 6.8. Schematic emplacement model for the Rustenburg layered suite and satellite Molopo Farms Complex, showing the Bushveld Complex sill emplaced from a dyke-like feeder that utilised the Thabazimbi Murchinson Lineament (TML) into an extensional (back-arc) zone within the overall compressive (subduction) regime at 2.05 Ga [from Clarke et al. (2009)].

Two important aspects of the prevailing petrogenetic model for Bushveld magmas include the presence of a sub-continental lithospheric mantle (SCLM) component (Hamilton, 1977; Harmer and Von Gruenewaldt, 1991; Harmer and Sharpe, 1985; Hatton and Schweitzer, 1995; Richardson and Shirey, 2008; Barnes et al., 2010) and significant amounts of crustal contamination (e.g., Kruger, 1994; Maier et al., 2000; Harris et al., 2005). The involvement of

the SCLM component is supported by the Bushveld-aged peridotite and eclogite xenoliths from the ~1.202 Ga (Kramers and Smith, 1983) Premier kimberlite on the southern margin of the Bushveld Complex, implying the scenario of an asthenosphere-derived magma incorporating variable proportions of peridotitic and eclogitic components while moving through the SCLM; the xenoliths recording the new age (Bushveld-age) (Carlson et al., 1999; Richardson and Shirey, 2008).

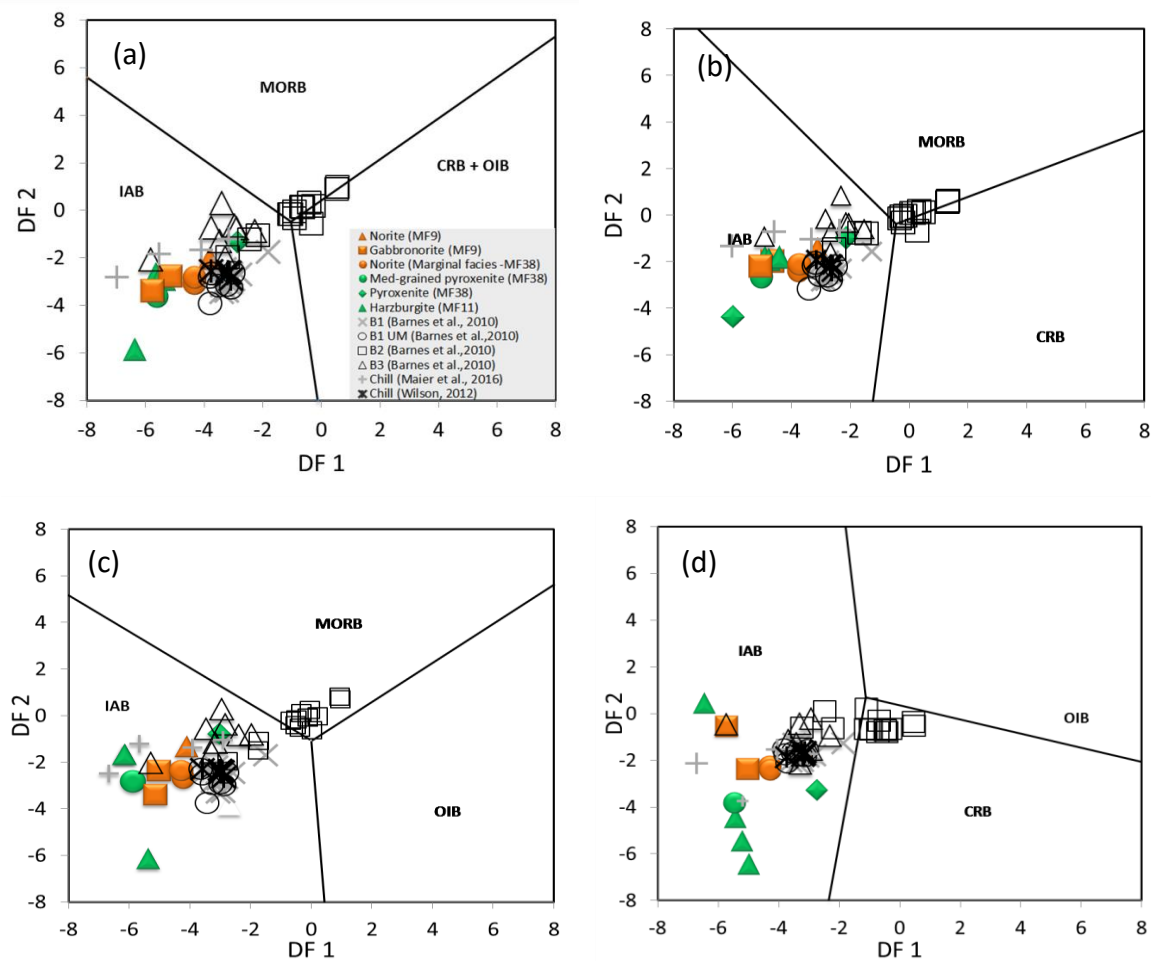


Figure 6.9. (a to d) Tectonic setting characteristics of the marginal facies norite and medium grained pyroxenite from MF38 of the Molopo Farms Complex. Various parental magma compositions to the Bushveld Complex, and other mafic and ultramafic rocks sampled as part of the study from MF38, MF11 and MF9 are included for comparison. The approach involves utilizing the immobile trace elements La, Sm, Yb, Nb and Th. Fields and discriminant scores are from Agrawal et al. (2008).

On the other hand, variably radiogenic initial Sr-, Pb- and Os-isotope ratios, crustal Sm-Nd signatures, and elevated oxygen and sulfur isotope values have long argued for significant amounts of contamination of Bushveld magmas by crustal material (Hamilton, 1977; Harmer and Sharpe, 1985; Hart and Kinloch, 1989; Schiffries and Rye, 1989; Kruger, 1994; Harmer et al., 1995; McCandless et al., 1999; Schoenberg et al., 1999; Maier et al., 2000; Curl, 2001; Mathez and Waight, 2003; Prevec et al., 2005; Harris et al., 2005; Penniston-Dorland et al., 2012).

The ratios of La, Ba and Nb, which are negligibly modified by petrogenetic processes such as partial melting or fractional crystallization, are widely used as a sensitive proxy to differentiate between the contribution of convecting and non-convecting part of the mantle to the sources of basaltic rocks (e.g., Saunders et al., 1992; Peate, 1997; Jourdan et al., 2007). The trend of marginal facies norite and medium grained pyroxenite from MF38 of the Molopo Farms Complex in the La/Ba versus La/Nb plot contrasts with the trend typical of ocean island basalts and/or asthenospheric mantle source(s) (e.g., Saunders et al., 1992), supporting a strong lithospheric contribution to their magma (Fig. 6.10a). This trend is similar to that shown by rocks of the Bushveld Complex, interpreted as progressive lithosphere contamination of asthenosphere-derived melts (e.g., Richardson and Shirey, 2008; Maier et al., 2016). Further, the high Ba/Nb (> 20) and high Ce/Nb_{PM} (normalized to primitive mantle) (> 1) ratios of the marginal facies norite and medium grained pyroxenite from MF38 are also typical of subcontinental lithosphere derived magmas like the Karoo and Paraná flood basalts (e.g., Hawkesworth et al., 1984; Ellam et al., 1992; Gallagher and

Hawkesworth, 1992; Peate, 1997; Jourdan et al., 2007). Thus like the scenario advocated for the Bushveld Complex, an interpretation in terms of a strong contribution from the SCLM to their magmas is suggested for the Molopo Farms Complex.

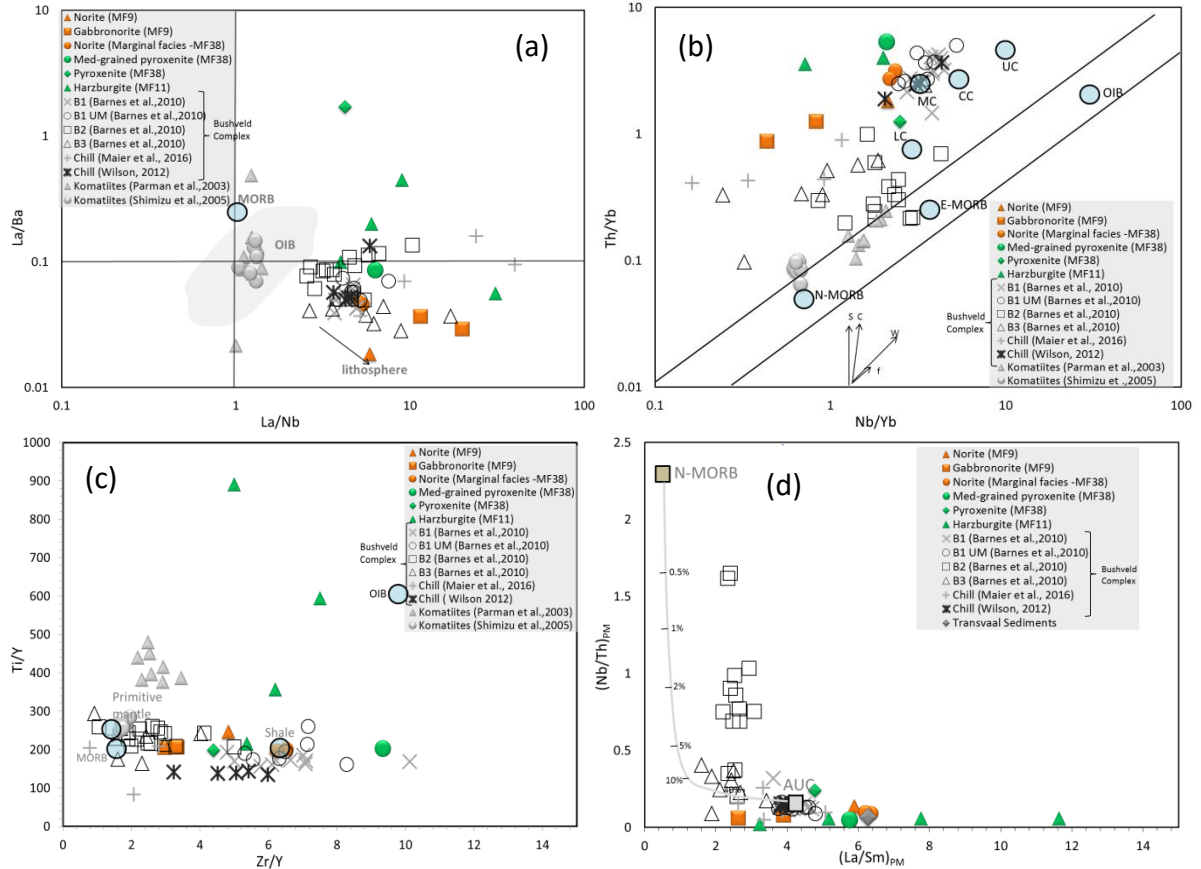


Figure 6.10. Marginal facies norite and medium grained pyroxenite from MF38 of the Molopo Farms Complex in terms of La/Ba versus La/Nb **(a)**, Th/Yb versus Nb/Yb **(b)**, Ti/Y versus Zr/Y **(c)** and (Nb/Th)_{PM} versus (La/Sm)_{PM} **(d)** plots. Various parental magma compositions to the Bushveld Complex, and other mafic and ultramafic rocks sampled as part of the study from MF38, MF11 and MF9 are included for comparison. The fields and compositions in (a) are from Saunders et al. (1992), those in (b) are Pearce (2008), and those in (c) are from Brewer et al. (1992). The mixing line between N-MORB (Sun and McDonough, 1989) and average upper continental crust (AUC; McLennan, 2001) indicates the degree of contamination based on the position of the sample relative to the line and is adapted from Richan et al. (2015). PM – Primitive mantle normalized. MORB – midocean ridge basalt (N – normal; E – enriched); OIB – ocean island basalt. In (b), s - subduction component vector, c - crustal contamination vector, w - within plate variation, f - fractional crystallization, LC – lower crust, MC – middle crust, UC – upper crust, and CC – continental crust. All the crustal values from Rudnick and Gao (2003).

On the other hand, the high Th/Ta (> 5) and Ba/Zr (> 2), and low Nb anomaly [$Nb/Nb^* = Nb_{PM}/V(Th_{PM} \times La_{PM}) = < 0.3$] values of the marginal facies norite and medium grained pyroxenite from MF38, considered as important proxies for the involvement of crustal material (e.g., Pearce, 2008), warrants the evaluation of the role of crustal contamination in their petrogenetic history. When considered in terms of typical MORB and Archean crustal compositions (Figs. 6.10b to d), the role of crustal contamination gains support. In the Ti/Y versus Zr/Y plot (Fig. 6.10c), based on the incompatible high field strength element ratios which are not significantly modified by moderate amounts of fractional crystallization or susceptible to variations in the degree of partial melting (e.g., Peate, 1997), the marginal facies norite and medium grained pyroxenite from MF38 of the Molopo Farms Complex plot towards the post-Archean shale component, supporting the role of late crustal contamination. This is further supported by petrogenetic mixing trends involving MORB and average upper crust (AUC) composition in Fig. 6.10d. Significantly, the marginal facies norite and medium grained pyroxenite from MF38 falls towards Transvaal sediment (the country rock to Bushveld and Molopo Farms complexes) compositions in Fig. 6.10d. Hence the so-called subduction setting suggested by trends in Fig. 6.9 is clearly inherited by crustal contamination, illustrating the subjective nature of using tectonic discrimination diagrams alone to infer the likely tectonic setting of formation. Thus the geochemical characteristics of the marginal facies norite and medium grained pyroxenite from MF38 and considered as parental magma compositions to the Molopo Farms Complex can be explained in terms of melting of the metasomatized subcontinental lithospheric mantle beneath the Kaapvaal

Craton, likely by the same asthenosphere-derived magma that formed the Bushveld Complex, and were subsequently contaminated by crustal material.

6.6. Significance of phlogopite

The occurrence of hydrous phases like phlogopite and amphibole in Bushveld marginal rocks was proposed to indicate the high fluid content of the Bushveld magmas (Barnes et al., 2010; Wilson, 2012; Maier et al., 2016). Their occurrence in the earlier formed rocks supports the role of metasomatism of SCLM beneath the Bushveld (Richardson and Shirey, 2008). The prominent occurrence of phlogopite in the marginal facies norite (see Figs. 3.3, 3.4, 4.1 and 4.6) and medium grained pyroxenite (Figs. 3.8 and 4.6) from MF38 of the Molopo Farms Complex further supports the inference for a common petrogenetic scenario for the different Bushveld magmas and its satellite intrusions like the Molopo Farms Complex.

6.7. Mineralization implications for the Molopo Farms Complex

Although Bushveld Complex and Molopo Farms Complex layered intrusions are considered to have formed from the same magma, the ultramafic and mafic sequences from the Molopo Farms Complex have a total estimated thickness that is considerably less than that of the Rustenburg layered suite of the Bushveld Complex (see Fig. 1.8; Grould et al., 1987; Von Gruenewaldt et al., 1989; Reichhardt, 1994; Prendergast, 2012). Nevertheless, as shown in this study, the marginal facies norite and medium grained pyroxenite from MF38 of

the Molopo Farms Complex are respectively compositionally equivalent to chill margin/B1 and B1UM from the Bushveld Complex (Figs. 6.4 and 6.5). Similarly, the compositional characteristics of gabbro-norites from MF9 of the Molopo Farms Complex (Fig. 6.6) indicate the preservation of composition equivalent to B3 from the Bushveld Complex. No compositional equivalent of B2 from the Bushveld Complex has been identified. However, as indicated in Fig. 1.8, equivalents of most of the Critical zone and whole of the Upper zone of the Rustenberg layered suite of the Bushveld Complex does not occur in the Molopo Farms Complex. Thus based on the preservation of the equivalents to the earliest [chill/B1/B1UM – Bushveld; marginal facies norite/medium grained pyroxenite – Molopo] and latest [B3 – Bushveld; gabbro-norites from MF9 – Molopo] parental magma compositions, and the lesser thickness of the Molopo ultramafic-mafic sequences with respect to the Rustenberg layered suite, it is inferred that magma that formed the Molopo Farms Complex likely differentiated faster. Therefore the chances of encountering prominent chromitite layers, as in the Critical zone of the Bushveld Complex (see Fig. 1.4), are likely nil for the Molopo Farms Complex. Minor chromite-rich intervals do occur in places (Gould et al., 1987; Reichhardt, 1994), but they are never comparable to those in the Bushveld Complex. Instead, Molopo Farms Complex could be a target for exploring sulphide mineralization. The rocks studied here from the Molopo Farms Complex do host a prominent sulphide assemblage of pyrrhotite, pentlandite and chalcopyrite with traces of pyrite and sphalerite (Figs. 3.2, 3.6, 3.9, 3.17, 3.18 and 3.21), an assemblage typically found in layered mafic to ultramafic rocks.

Chapter 7

Concluding remarks

- A rare marginal facies (in drill core MF38) is reported from the base of the ultramafic sequence of the Molopo Farms Complex layered intrusion. It consists of remobilized country rock and quench textured norite, the later exhibiting a gradational contact with the ultramafic sequence.
- Mineral chemical composition of elongated, skeletal, compositionally zoned orthopyroxene in the marginal facies norite is similar to that reported for orthopyroxene in chill sequence to the Bushveld Complex.
- Geochemical characteristics of the marginal facies norite are closely comparable to chill margin and B1 from the Bushveld Complex, arguing for it to represent the earliest known parental magma composition to the Molopo Farms Complex.
- A medium grained phlogopite-bearing pyroxenite (in drill core MF38) is considered as the compositional equivalent to B1UM of the Bushveld Complex.
- Gabbro-norites and norite from the drill core MF9 are considered to preserve compositions comparable to B3, considered parental to differentiated end members of the Bushveld Complex. No compositional equivalent of B2 was observed in the studied Molopo Farms Complex rocks.

- Petrogenetic characterization suggests that the geochemical characteristics of the marginal facies norite and medium grained pyroxenite can be explained in terms of melting of the metasomatized subcontinental lithospheric mantle beneath the Kaapvaal Craton, likely by the same asthenosphere-derived magma that formed the Bushveld Complex, and were subsequently contaminated by crustal material.
- The prominent occurrence of phlogopite in the marginal facies norite and medium grained pyroxenite is similar to that observed in Bushveld marginal rocks, and supports the role of metasomatism of subcontinental lithospheric mantle beneath Bushveld-Molopo Farms complexes.
- Considering the fact that the Molopo Farms Complex is not as thick as the Bushveld Complex, and it preserves mafic and ultramafic rocks showing similarity to the earliest magma (B1, B1UM and chill margins) as well as the most differentiated of the Bushveld magma (B3), it is argued that the Molopo Farms Complex evolved faster and likely did not form rocks of the Bushveld Complex, which hosts the chromite-bearing layers (known for PGE mineralization).
- Instead, it is argued that the Molopo Farms Complex is a better target for Cu-Ni sulphide mineralization. The studied samples, including the rare mafic chill sequence, hosts a sulphide assemblage of pyrrhotite, pentlandite and chalcopyrite with traces of pyrite and sphalerite, the association similar to that typically found in layered mafic to ultramafic rocks..

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