

**ARCHEAN BONINITE-LIKE MAFIC-ULTRAMAFIC ROCKS FROM THE LECHANA
LAYERED INTRUSION, MOTLOUTSE COMPLEX, BOTSWANA**

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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December, 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: Archean boninite-like mafic-ultramafic rocks from the Lechana layered intrusion, Motloutse Complex, Botswana, in fulfilment of the requirements for the degree of Master of Science in Geology of the BIUST.



.....
Prof. Rajesh Hariharan

Date: ...05/12/2017.....

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Abstract

Mafic to ultramafic rocks occurring in the Lechana area forms part of the Archean high-grade Motloutse Complex terrane in eastern Botswana. Their occurrence as inclusions (displaced fragments) within ~2.6 Ga tonalite gneiss indicates that they are older than ~2.6 Ga. The ultramafic rocks – peridotite and pyroxenite – are widespread in the mapped area as layers, with some layers rich in pyroxenite, others rich in peridotite, and a third type of layer made up of peridotite with patchy pyroxenite domains. Anorthosite occurs to the northern part of the Lechana area and is gneissic. Both the layered mafic (anorthosite) and ultramafic (peridotite-pyroxenite) rocks are prominently associated with amphibolites. Together they are considered as part of an Archean layered intrusion – referred here as the Lechana layered intrusion. In addition to olivine, orthopyroxene (ultramafic rocks) and plagioclase (anorthosite), both the mafic and ultramafic rocks are characterized by the prominent occurrence of primary magmatic amphibole implying hydrous conditions during their formation. Amphibole mineral chemical characteristics indicate preservation of primary magmatic compositions in the anorthosite, with minor effect of sericitization, while amphiboles in the peridotite exhibit the effect of serpentinization. Isocon analyses applied to the amphibole mineral chemistry helped to understand which elements were gained and lost during hydrothermal alteration. In terms of whole-rock geochemical characteristics, all the studied mafic to ultramafic rocks are characterized by high SiO₂ and MgO contents, similar to boninites. Significantly, a peridotite sample with patchy pyroxenite domains gave the unique chondrite-normalized U-shaped boninite-like REE pattern. Trace element

modeling indicated the possible role played by crustal contamination to account for the *boninite-like* signature. Similar primitive mantle normalized multi element and chondrite normalized REE patterns of the layered mafic to ultramafic rocks indicate likely derivation from a common parental magma. Amphibolites indicate formation in a transitional setting with MORB-like and arc-like characteristics, while the layered mafic to ultramafic rocks indicate formation in an active continental margin setting. Combining together, it can be suggested that the original magma formed in a MORB setting and then moved to an arc setting – much like in a suprasubduction setting. The peridotite-pyroxenite-anorthosite are related in terms of differentiation of the original magma. Comparison with mafic to ultramafic rocks occurring in the mineralized Selebi-Phikwe belt (within the high-grade Phikwe Complex terrane) helps to evaluate the Cr-Ni-V mineralization potential of the rocks of the Lechana layered intrusion.

Chapter 1

Introduction, geologic setting and objectives

1.1 Introduction – Boninites

Boninites are a distinctive style of subduction-related magmatic rocks that are interpreted to result from the melting of strongly depleted mantle that is variably metasomatized by slab-derived fluids or melts (Crawford et al., 1989; Pearce et al., 1992). The depleted mantle source is different from that of ambient mantle which forms MORB-like rocks (Fig. 1.1). They were first reported from the Bonin Island in the Izu-Bonin-Mariana arc, which is an excellent example of a modern intra-oceanic convergent margin system. These primitive arc rocks have distinctive geochemical characteristics, including intermediate SiO_2 contents (>52 wt.%), high MgO (>8 wt.%), Mg# $[(100 \times \text{Mg}/\text{Mg} + \text{Fe}^{2+}) = \sim 55-83]$, compatible element contents (Ni, Cr, Co) and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios, low TiO_2 (<0.5 wt.%), U-shaped rare-earth element (REE) patterns, extreme high-field strength element (HFSE) depletions, and commonly, but not always, Zr and Hf enrichments relative to the middle REE (Crawford et al., 1989; Pearce et al., 1992; Le Bas, 2000; Le Maitre et al., 1989). Here the high MgO, low Ti and U-shaped REE pattern (Fig. 1.1) is unique. Thus the classical definition of boninites is based more on chemistry than on mineralogy or petrography. They commonly occur in ophiolite complexes and are considered as indicators of subduction-related settings in oceanic island arcs – better termed as suprasubduction (SSZ) setting (Crawford et al., 1989; Pearce et al., 1984; Shervais, 2001). A fore-arc environment is ideal for boninite genesis, with

the high magnesium and very low titanium content attained via high degrees of partial melting within the convecting mantle wedge (Ishikawa et al., 2002; Dilek et al., 2008).

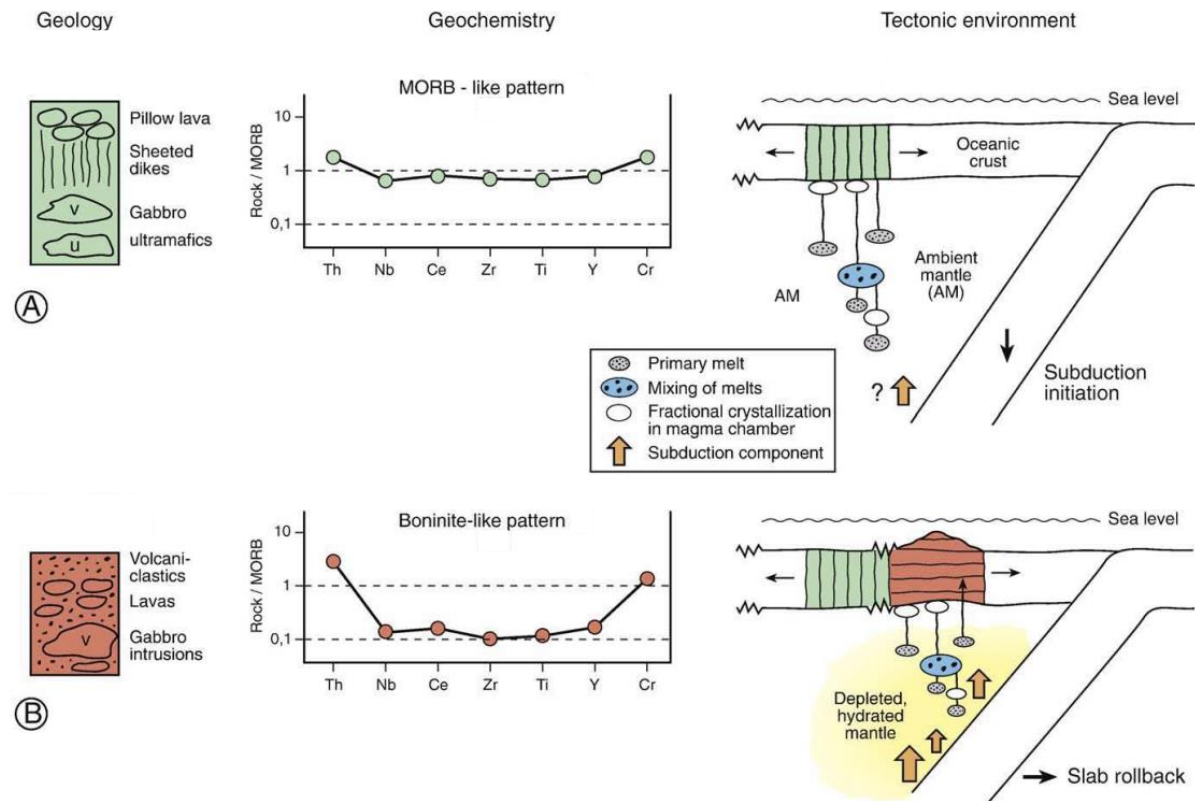


Figure 1.1. Schematic model comparing the typical tectonic environment for the generation of mid-ocean ridge basalt (MORB)-like (a) and boninite-like (b) rocks, and their geochemical and geological characteristics [from Furnes et al. (2009)].

1.2. Boninite-like rocks in Archean terranes

Unlike the widely reported boninites from Phanerozoic ophiolites [see reviews in Kusky (2004), Furnes et al. (2014)], boninite-like rocks constitute minor constituents of mafic- to ultramafic-rock assemblages in Archean greenstone sequences (e.g., Polat et al., 2002; Furnes et al., 2009; Hoffmann et al., 2010; Manikyamba et al., 2015). Here the usage *boninite-like* acknowledges the fact that boninites *sensu stricto* are typically found in

younger ophiolites (e.g., Tethyan ophiolites; Ishikawa et al., 2002; Tamura and Arai, 2006), and that finding similar rocks in Archean rock record (which is fragmental and deformed in nature) has some degree of skepticism associated with it. The later skepticism is justified considering the implications on finding boninite-like rocks in Archean (Dilek and Polat, 2008), and the volume of literature devoted to arguing for and against the operation of plate tectonics in the early Earth (e.g., Hamilton, 2003; Stern, 2005; Bédard, 2006; Brown, 2006; Cawood et al., 2006; Rollinson, 2007). Understanding this situation, Dilek and Polat (2008) pointed out that the mafic- to ultramafic-rock assemblages (considered as suprasubduction ophiolite-like sequences) which host boninite-like rocks in Archean greenstone belts have a slight different internal structure and thicker stratigraphy than the Phanerozoic counterparts (Fig. 1.2).

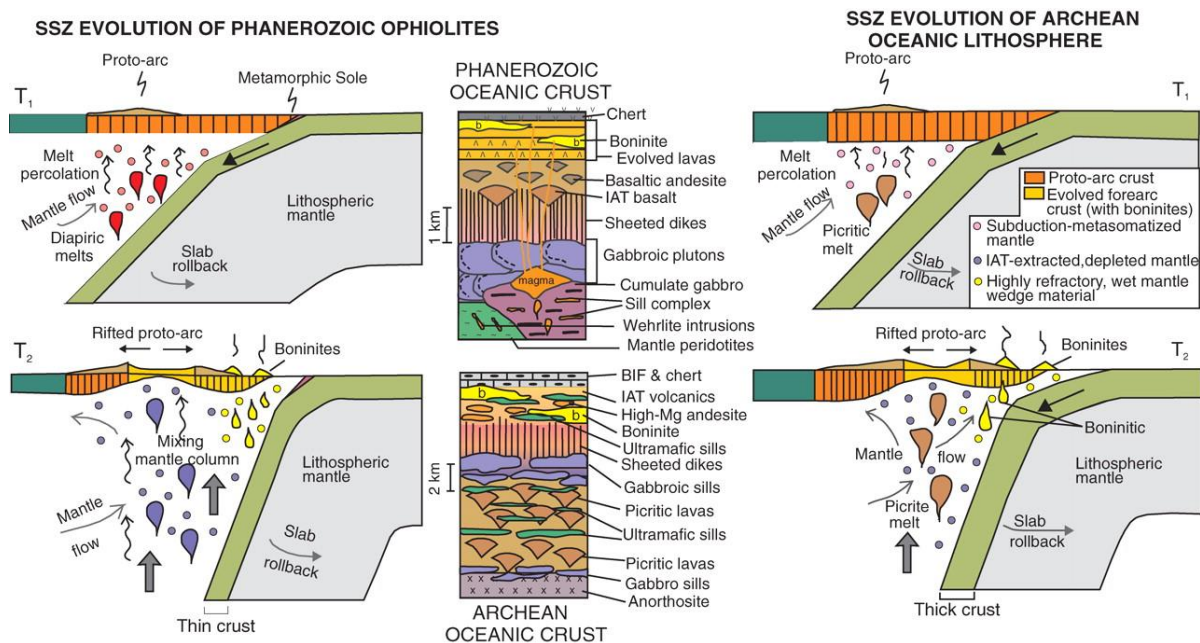


Figure 1.2. Reconstructed stratigraphy of the inferred Archean (thick) and Phanerozoic (thin) oceanic crust and their sequential (T1 to T2) petrogenetic evolution in suprasubduction zone (SSZ) environments. BIF-banded iron formation; IAT-island arc tholeiite [from Dilek and Polat (2008)].

Importantly, these Archean rocks exhibit a hybrid mixture of MORB-like and arc-like elemental signatures, reflecting repeated melting of a MORB mantle source in a subarc-forearc wedge that has been modified by fluids released from subducting oceanic slab and sediment-derived melts (Dilek and Polat, 2008). The mixed elemental pattern is similar to that found in Phanerozoic ophiolites. Hence whole-rock geochemical characteristics of related mafic- to ultramafic-rock assemblages are important to identify boninite-like rocks from Archean terranes.

A prominent mode of occurrence of mafic- to ultramafic- rocks in Archean terranes is as part of layered intrusions. Unlike the better exposed Proterozoic (~2.5-2.0 Ga) counterparts (e.g., Bushveld Complex layered intrusion in South Africa, Great Dyke layered intrusion in Zimbabwe), ultramafic- to mafic-rocks occurring as part of Archean layered intrusions are dominantly exposed as dismembered fragments in high-grade (amphibolite- to granulite-facies) metamorphic terrains (e.g., Fig. 1.3). In spite of the overprint events, these ultramafic- to mafic-intrusions often preserve primary magmatic features including layering at various scales (from centimeter- to meter- to kilometer-scale), cumulate textures, minerals of magmatic origin in an equant or inequigranular granoblastic-polygonal textured framework, and whole-rock geochemical characteristics. One of the best-preserved and well exposed Archean layered intrusions is the ~2.97 Ga Fiskensæset layered intrusion in SW Greenland (Windley et al., 1973). This layered intrusion has been extensively studied in recent years (Polat et al., 2009, 2011, 2012; Huang et al., 2014) and has provided important constraints in characterizing subduction-related mafic-ultramafic rocks from other Archean high-grade terranes.

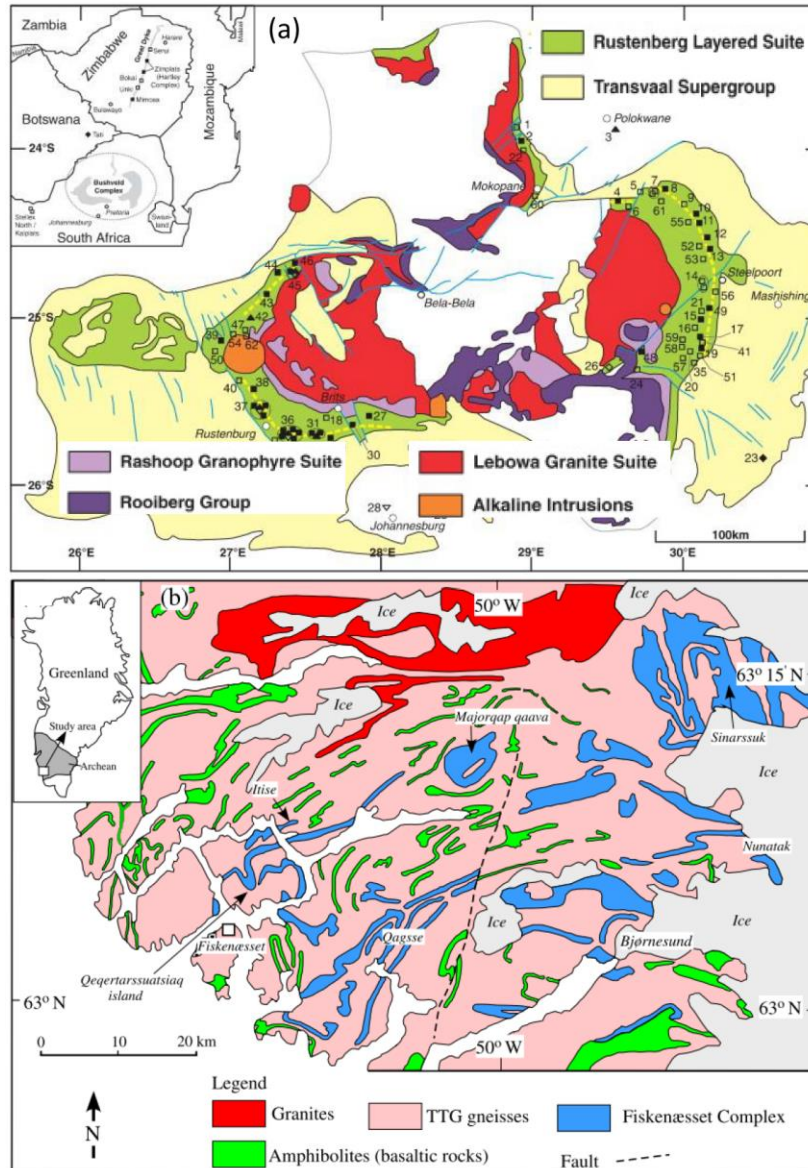


Figure 1.3. Comparison of the mode of occurrence of a typical Proterozoic (a) and Archean layered intrusion (b). **(a)** Simplified geologic map of the Bushveld Complex layered intrusion in South Africa [from Maier et al. (2013)]. **(b)** Simplified geologic map of the Fiskensæset region in Greenland, showing the fragmental distribution of Fiskensæset Complex layered intrusion in TTG gneisses, amphibolites (meta-basalts), and granites [from Polat et al. (2011)].

Eastern Botswana exposes two prominent mafic- to ultramafic sequences, one within the Phikwe Complex and another in the Motloutse Complex. The former, part of the Selebi-Phikwe belt of mafic- to ultramafic intrusions have attracted few studies (Maier et al., 2008; Fiorentini et al., 2012), primarily due to the Ni-Cu-(PGE) sulphide deposits hosted by these

intrusions, which have been mined (e.g., BCL mine). Other than the studies by Green (1963) and Lear (1971), carried out as part of exploration programs, no study exists in recent literature on similar rocks from the Motloutse Complex. The present study focuses on ultramafic- to mafic-rocks occurring in the southern Motloutse Complex.

1.3. Geologic setting of the Motloutse Complex

Motloutse Complex constitutes an Archean terrane to the southwest of the Zimbabwe Craton and west of the Limpopo Complex (Figs. 1.4, 1.5). Unlike the granitoid-greenstone terranes of the Zimbabwe Craton where dominantly low-grade (greenschist-facies) metamorphic conditions prevail, the Limpopo Complex is a high-grade (amphibolite- to granulite-facies) metamorphic terrain occurring between the Archean Kaapvaal and Zimbabwe cratons (e.g., Van Reenen et al., 1990; Fig. 1.4). It is primarily subdivided into three zones – the Northern Marginal Zone occurring along the southern margin of the Zimbabwe Craton, the Central Zone occupying the central and largest area of the complex, and the Southern Marginal Zone occurring along the northern margin of the Kaapvaal Craton (Fig. 1.4). The three zones are separated from one another and also from the adjacent cratons by kilometre-scale shear zones (see reviews in Blenkinsop, 2011; Smit et al., 2011; Van Reenen et al., 2011). The Central Zone is further subdivided into the Beit Bridge Complex, Phikwe Complex and the Mahalapye Complex (Fig. 1.4; Aldiss, 1991). The Motloutse Complex, which occurs to the west of the Phikwe Complex (Fig. 1.5), preserves a higher grade of metamorphism than the adjacent cratonic terranes, but lacks the granulites of the Limpopo Complex (Aldiss, 1991; Carney et al., 1994; Holzer et al., 1999).

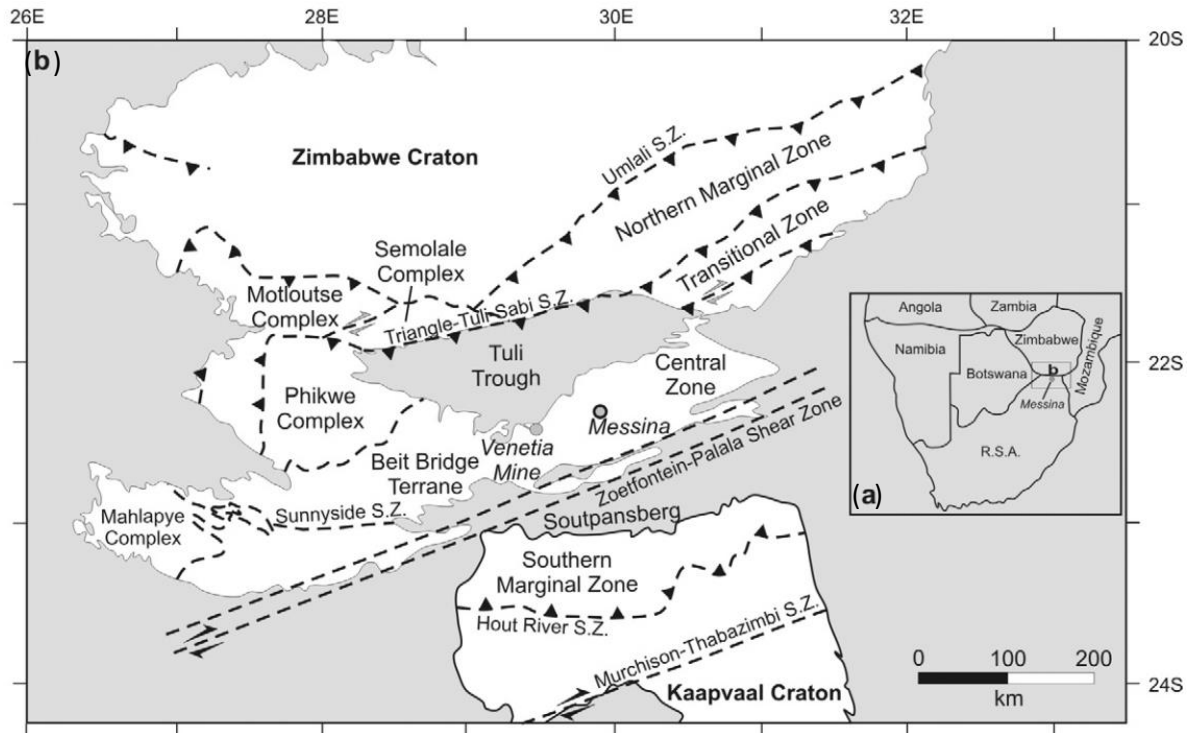


Figure 1.4. Generalized geological map of the Limpopo Complex showing the three zones and adjacent Archean cratons, separated by shear zones (S.Z.) **(b)**. Inset **(a)** shows the area covered in **(b)** from a southern African point of view. [from Barton et al. (2003)].

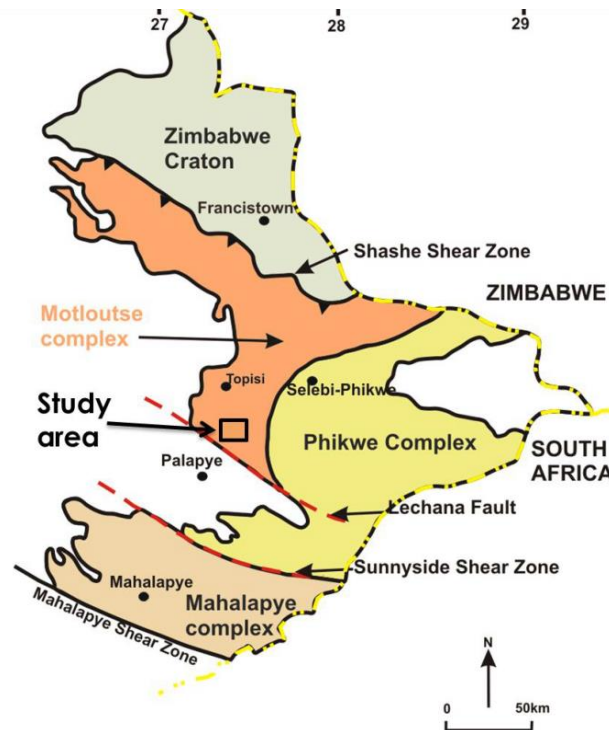


Figure 1.5. The Archean to Paleoproterozoic terranes of eastern Botswana. The present study area occurs in the southern part of the Motloutse Complex [from McCourt et al. (2004)].

The Motloutse Complex is made up of granitoid gneisses, meta-supracrustal rocks and mafic to ultramafic intrusions (Aldiss, 1991; Smith and Phofuestsile, 1985; Carney et al., 1994; Key et al., 1994). Granitoid gneiss variants include migmatitic gneiss, grey banded orthogneiss, tonalitic gneiss and porphyritic granite gneiss. Amphibolites interlayered with granitoid gneiss can be locally traced for several kilometres. Metasedimentary rocks prominently occur as a lithostratigraphic unit (Shashe Group) right across the northern part of the complex and consist of quartzite, quartz-mica schist, marble and calc-silicate rocks, with minor metapelite and iron formation (Key, 1976; Aldiss, 1989; Smith and Phofuestsile, 1985; Carney et al., 1994). Ultramafic (peridotite, pyroxenite) and mafic (anorthosite) intrusions occur as lens-shaped bodies commonly associated with amphibolites, and are widespread with better exposures in the southern part of the Motloutse Complex (Green, 1963; Lear, 1971; Carney et al., 1994; Key et al., 1994).

The Shashe shear zone forms the northern boundary of the Moutloutse Complex and constitutes a thrust sense ductile shear zone along which the Motloutse Complex has been emplaced over the Zimbabwe Craton (Aldiss, 1991; Carney et al., 1994; Key et al., 1994; Paya, 1996; Ranganai et al., 2002; McCourt et al., 2004). The ENE to WSW trending Magogaphate shear zone and the N-S trending Dikalate thrust sense shear zone separates the eastern margin of the Motloutse Complex from the Phikwe Complex (Aldiss, 1991; Key et al., 1994; Paya et al., 1997; McCourt et al., 2004). To the west and southwest the contacts are buried below Proterozoic and younger cover rocks.

Available geochronologic data brackets the granitoid magmatism in Motloutse Complex to ~2.7-2.62 Ga (U-Pb zircon; Holzer et al., 1999; Zeh et al., 2009). Quartzites within the Motloutse Complex were deposited between 2661 and 2647 Ma with the provenance being the granitoid-greenstone terranes from the southwestern Zimbabwe Craton (U-Pb zircon; McCourt et al., 2004). McCourt et al. (2004) suggested a NE-directed subduction below the Zimbabwe protocontinent at 2.65 Ga, with the Motloutse Complex as part of the lower plate. The 2645 ± 22 Ma granitoid gneiss sample dated by Zeh et al. (2009) preserves evidence for a 2056 ± 12 Ma overprint event. Thus the available geochronologic data indicate evidence for a Paleoproterozoic overprint event (Zeh et al., 2009; this study); no Neoarchean overprint event has been reported. Amphibolite-facies metamorphic conditions (~600 to 690°C and ~5 kbar) related to anatectic overprint have been reported (Smith and Phofuetsile, 1985; Aldiss, 1989). Unlike the Phikwe Complex or other Limpopo Complex terranes, no granulite-facies conditions are reported from the Motloutse Complex.

1.4. Objectives and approach

The prime objective of the study is to characterize and understand the origin of the mafic-ultramafic rocks occurring in the Lechana area in the southern part of the Motloutse Complex. Considering the mineralized nature of similar rocks occurring in the Selebi-Phikwe belt in the adjacent Phikwe Complex, evaluating the mineralization potential of the studied rocks was an obvious addendum. After going through available literature on ultramafic- to mafic-rocks occurring as part of Archean layered intrusions, especially those in high-grade metamorphic terrains, the following objectives and related approach were laid out.

- Field geologic mapping of the study area to identify, delineate and demarcate the various rock types, as well as understand the effect of overprint event(s).
- Petrographic characterization of representative samples collected from the field to identify the minerals present and understand their mutual relation. Complementing the petrographic characterization with backscattered electron imaging helps to understand the mutual textural relation between the different rock forming minerals, and the effect of overprint event(s).
- Mineral chemical characterization of petrographically characterized samples to study the chemical composition of prominent minerals. Mineral chemical characteristics can be used to better understand the igneous versus metamorphic (or secondary) nature of the minerals, with the application of geothermometers providing temperature and water content constraints.
- Whole-rock geochemical characterization of petrographically characterized samples, which can give a plethora of information including the likely origin of the rock and its tectonic setting.

1.5. Sampling and analytical methods

Since starting the project in late 2014, a number of field sessions were carried out in the study area; the proximity of the study area to BIUST providing easy access. A detailed geologic map (including structural information) was prepared. Sample locations and

structural measurements were imported onto a satellite image of the area, on which the georeferenced geologic map was overlain using ArcGIS.

Representative bulk rock samples of the different rock types were collected from the field 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 analyses 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 field geologic mapping-petrography-mineral chemistry-whole-rock geochemistry approach mentioned above. A brief introduction to the geologic setting of the Motloutse Complex is given in chapter 1. The thesis commences with first addressing and evaluating the field relations of rocks exposed in the study area (chapter 2). From chapter 3 onwards, the study focuses on the ultramafic to mafic rocks occurring in the study area. Chapter 3 details the petrographic characteristics. Chapter 4 addresses the role of mineral chemical characteristics in addressing the nature of composition of minerals (preserved) in the studied ultramafic to mafic rocks. Whole-rock geochemical characteristics of the 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 the likely tectonic setting of formation, and the resulting concluding remarks are given in chapter 7.

Chapter 2

Field relations

2.1 Introduction

This chapter presents description of field relations between rock types exposed in the study area from the southern part of the Motloutse Complex. The study area, referred as Lechana area, covers the area around Maope, Mokobjwe and Tamasane hills (Fig. 2.1a). The geologic map prepared as part of the study is given in Fig. 2.1b. Tonalite gneiss constitutes the dominant rock type exposed in the mapped area (Fig. 2.1). Mafic (amphibolite, anorthosite) and ultramafic (peridotite-pyroxenite) rocks occur as inclusions in tonalite gneiss in the Lechana area (Fig. 2.1). The description given below follows the order in which one encounters the different rock types from northern to southern part of the study area.

2.2. Rock types

2.2.1. Tonalite gneiss

The occurrence of biotite-bearing tonalitic gneiss varies from foliated gneiss to banded variant to relatively minor porphyritic gneiss (Fig. 2.2). It is typically light grey, with pinkish appearance on weathered surfaces (Figs. 2.2a, b). Intrusive relation with amphibolite is well exposed (Figs. 2.2c, d). All the tonalitic gneiss variants, especially those occurring towards the eastern part of the study area, exhibit evidence for local shear deformation (Figs. 2.2e, f).

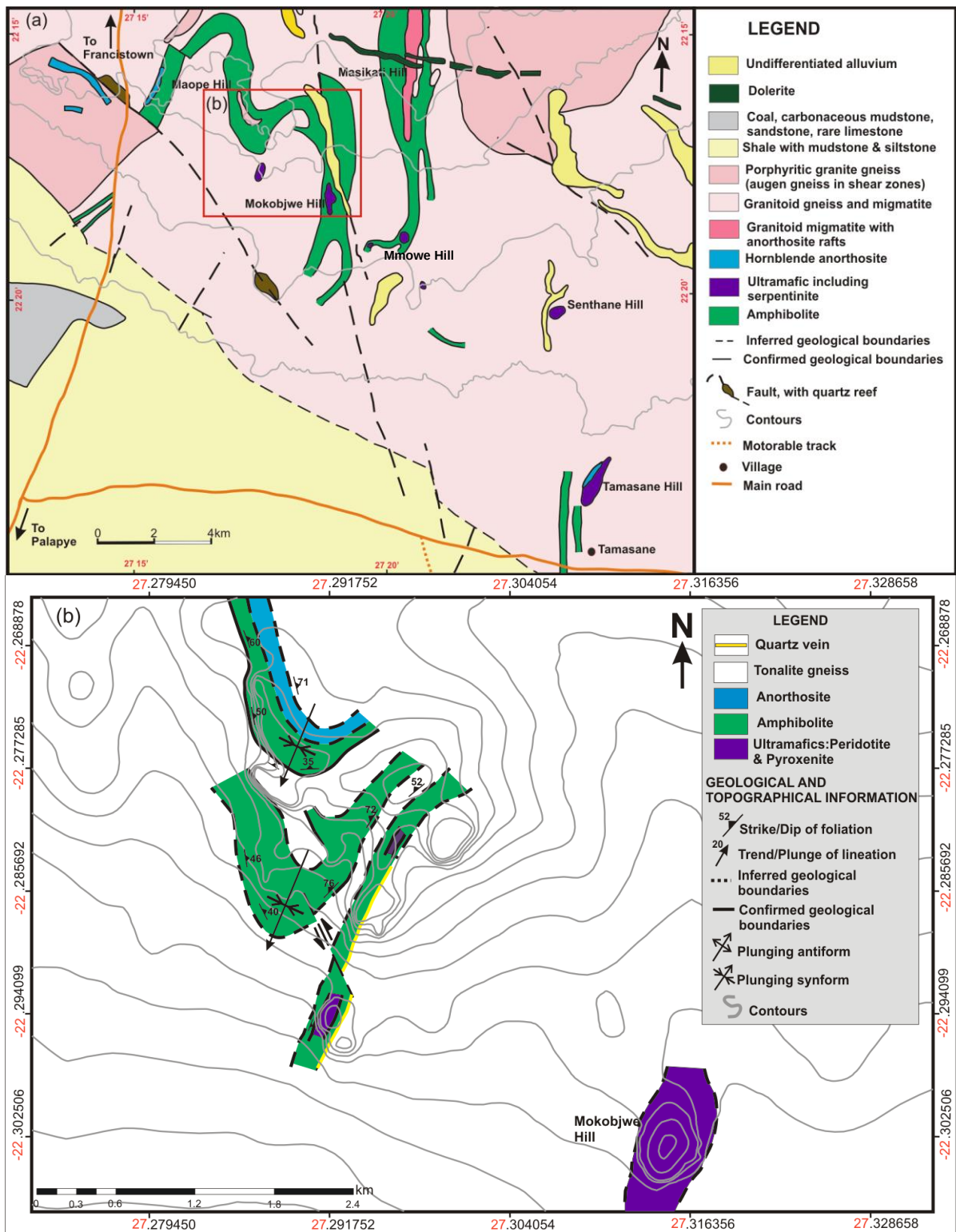


Figure 2.1. (a) Geological map of the southern part of Motloutse Complex showing the study area (modified from Key et al., 1994). **(b)** Geological map of Maope-Mokobjwe areas [rectangle in (a)] prepared as part of the study.



Figure 2.2. Field photographs illustrating the typical occurrence of tonalite gneiss in the Lechana area. (a) pinkish appearance on weathered surface; (b) typical light grey color of *fresh* tonalite gneiss; (c), (d) tonalite intruding into amphibolite; (e), (f) K-feldspar (Kfs) metasomatic overprint imparting pinkish color. Note the asymmetric nature of Kfs augens.

Locally, the light-grey tonalitic gneiss exhibit K-feldspar metasomatic overprint, imparting a pinkish color, and is associated with shear deformation. Asymmetric K-feldspar augens are conspicuous of such exposures (Fig. 2.2f). Possibility of local anatexis overprint is not discounted, but no garnet-bearing portions were found during the field mapping.

2.2.2. Amphibolite

Amphibolite occupies prominent hills around Maope in the northern part of the study area (Fig. 2.1). It is dominantly gneissic in appearance (Fig. 2.3a). A banded variant also occurs and is due to the layer parallel intrusion of granitoid gneiss into the amphibolite (Fig. 2.3b). Boudinage structures are seen associated with the banded variant (Fig. 2.3b). Rare pillow-like structures occur associated with a massive variant, suggesting that the protolith of the amphibolite could have been volcanic. Locally amphibolite inclusions occur in tonalite gneiss (Fig. 2.3c). In terms of relative proportion of minerals, two varieties of amphibolite occur – an amphibole-rich variant and a plagioclase-rich one, with both variants often occurring in proximity. Dark appearance on weathered surface does not help to delineate the mineralogic difference easily. Like tonalitic gneiss, amphibolite is also locally overprinted by pinkish K-feldspar metasomatism and is associated with shear deformation (Fig. 2.3d). Garnet-bearing leucocratic patches and veins occur locally in the amphibolite, with garnet sometimes forming large grains up to 3 cm (Figs. 2.3e, f). No garnet-bearing amphibolite was sampled as part of the study.

2.2.3. Anorthosite

Anorthosite occurrence is restricted to the northern part of the study area, and is closely associated with amphibolite (Fig. 2.1). It is amphibole-bearing, and occurs dominantly as a

gneissic variant (Fig. 2.4a) and less dominantly as a massive variant without any gneissic fabric (Fig. 2.4b).

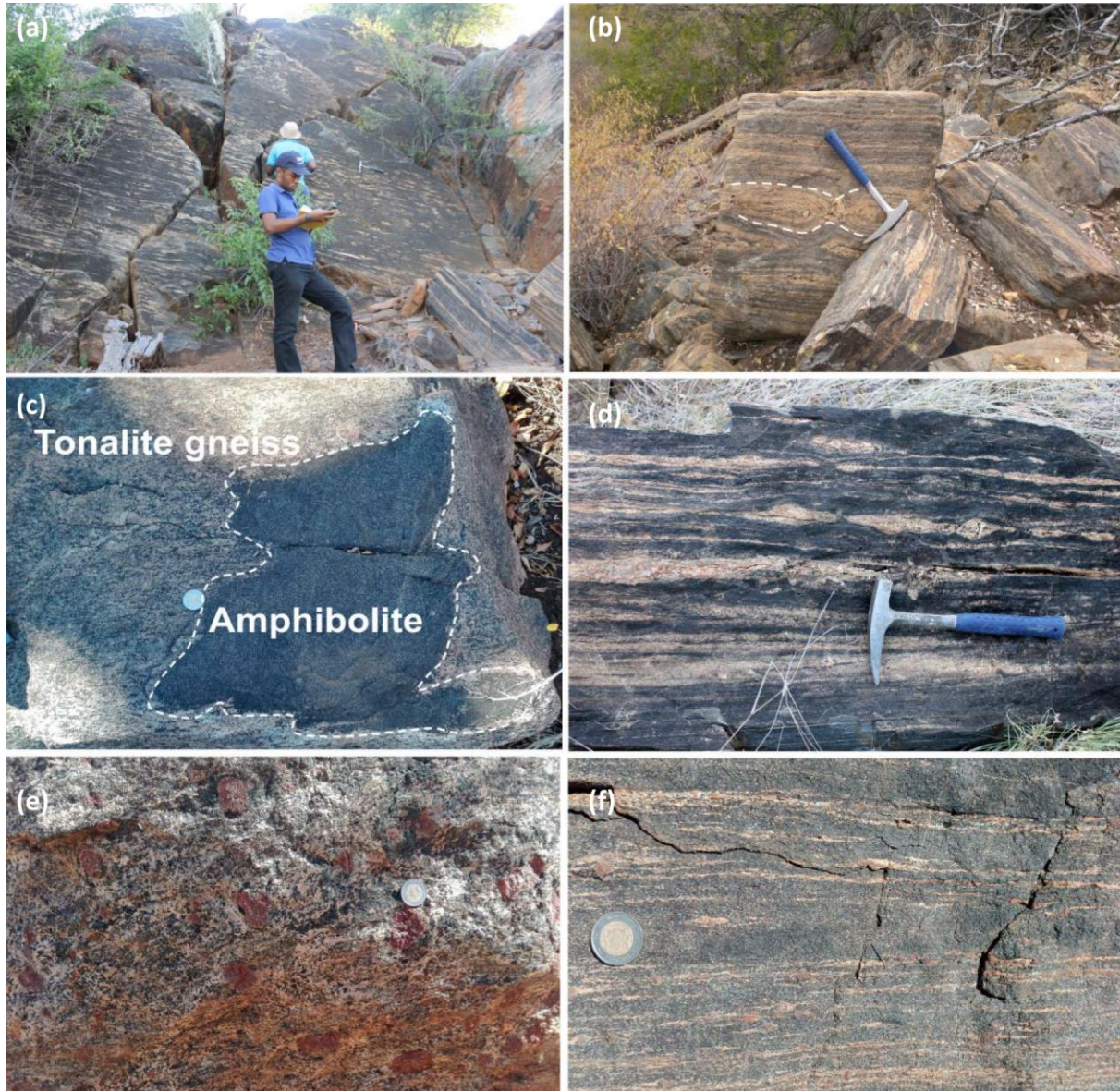


Figure 2.3. Field photographs illustrating the typical occurrence of amphibolite in the Lechana area. (a) dark gneissic amphibolite; (b) banded amphibolite with boudinage structure; (c) massive amphibolite inclusion in tonalite gneiss; (d) Kfs metasomatic overprint on dark amphibolite. Note the asymmetric structures; (e), (f) Locally garnet-bearing patches and veins occur in amphibolite indicating an anatectic overprint.

Locally the anorthosite exhibit intrusive relation with amphibolite, with rare enclaves of amphibolite within the anorthosite, indicating that the amphibolites are older. Although not easily visible, hand specimen examination indicates the presence of quartz grains in anorthosite, indicating the effect of deformation. Garnet occurs locally in the anorthosite, and is related to the anatectic overprint that affected parts of the Motloutse Complex. No garnet-bearing anorthosite was sampled as part of this study.

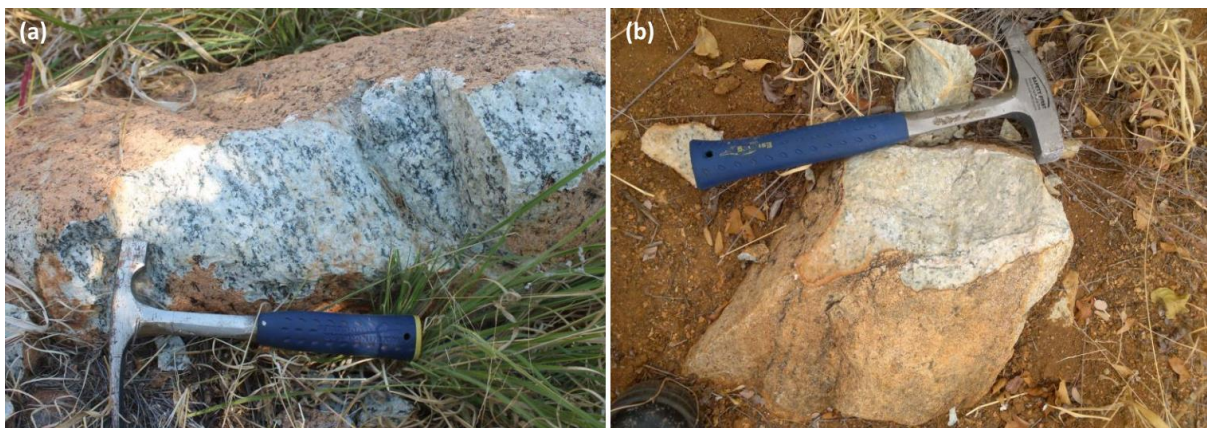


Figure 2.4. Field photographs illustrating the typical occurrence of anorthosite in the Lechana area. (a) gneissic variant; (b) massive variant.

2.2.4. Peridotite-pyroxenite

Ultramafic rocks are widely distributed in the study area, occurring as lens-shaped bodies up to a kilometer in length occupying low-lying ridges (Fig. 2.5a) and hills (Maope, Mokobjwe, Senthane, Mmowe and Tamasane hills; Fig. 2.1). Like anorthosite, they are closely associated with amphibolite (Fig. 2.1). The ultramafic rocks vary from a dominant serpentized peridotite to relatively minor pyroxenite. These several metre thick bodies are

characterized by centimeter- to meter-scale layering (Fig. 2.5), which can be traced for the entire outcrop.

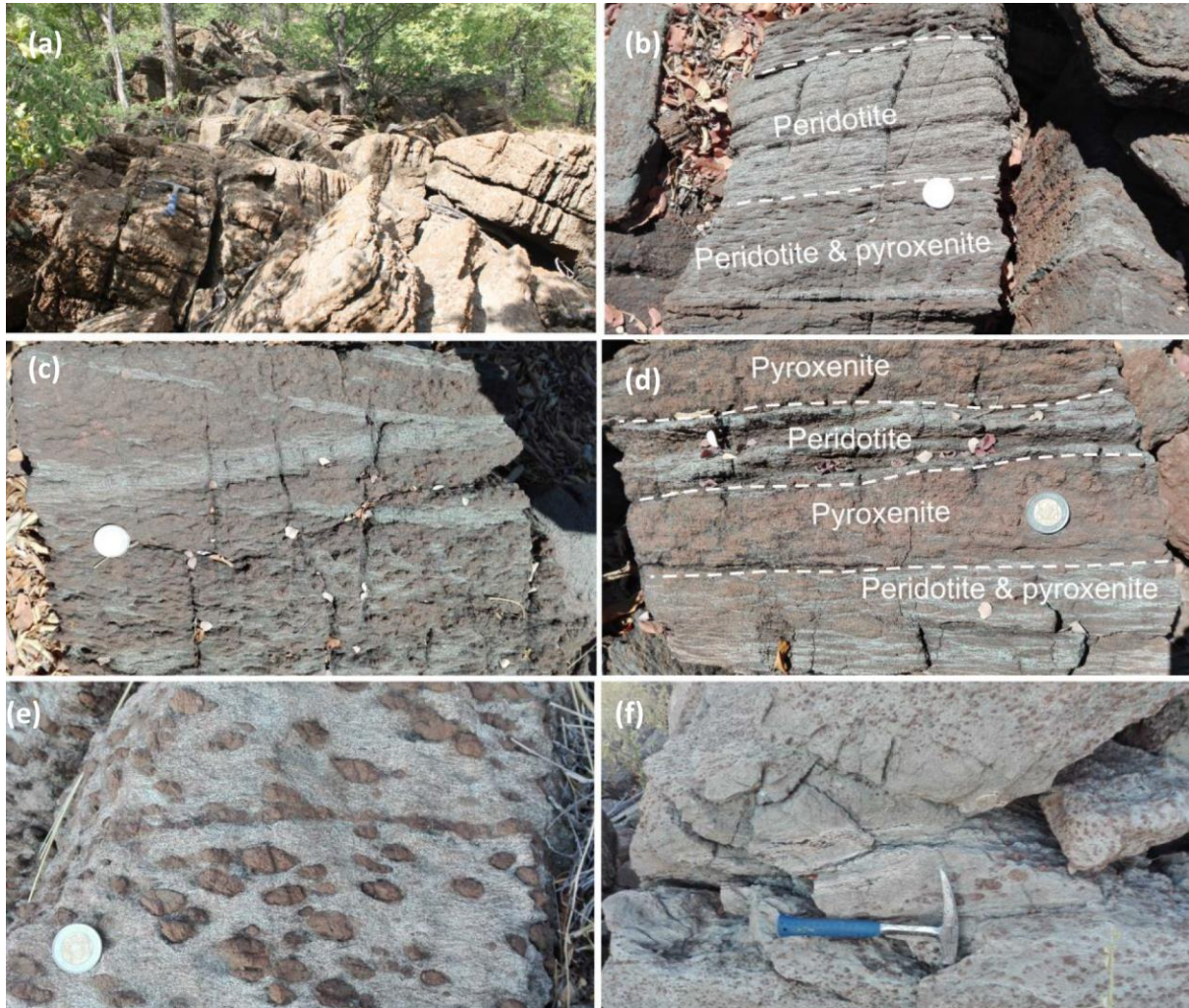


Figure 2.5. Field photographs illustrating the typical occurrence of ultramafic rocks in the Lechana area. (a) brownish layered ultramafic rocks occupying a low-lying ridge; (b) to (d) the conspicuous peridotite (greenish on weathered surface) and pyroxenite (brownish) layering observed in the ultramafic rocks; (e) pyroxenite patches in peridotite. Note the asymmetric nature of the patches; (f) prominent magnetite-rich layers (in the middle of the figure) associated with peridotite-pyroxenite association from the Mokobjwe Hill.

Three types of layers occur, and are characterized by their pale-greenish (peridotite) to pale-greenish-brownish (peridotite with pyroxenite patches) to brownish (pyroxenite)

appearance on weathered surface (Figs. 2.5b to d). The conspicuous peridotite-pyroxenite association often occurs as thick monotonous layers of pale-greenish peridotite (dark on fresh surface) with millimeter to centimeter-sized brownish symmetric to asymmetric pyroxenite patches (Fig. 2.5e). Locally, adjacent pyroxenite patches coalesce to form larger patches to veins. Prominent magnetite-rich layers are associated with the peridotite-pyroxenite association (Fig. 2.5f). These mineralized layers can be traced for the entire outcrop length. On fresh surfaces, the peridotite is dark and pyroxenite patches are lighter (greyish) (Fig. 2.6). Magnetite-rich layers occur from mm to cm scale.

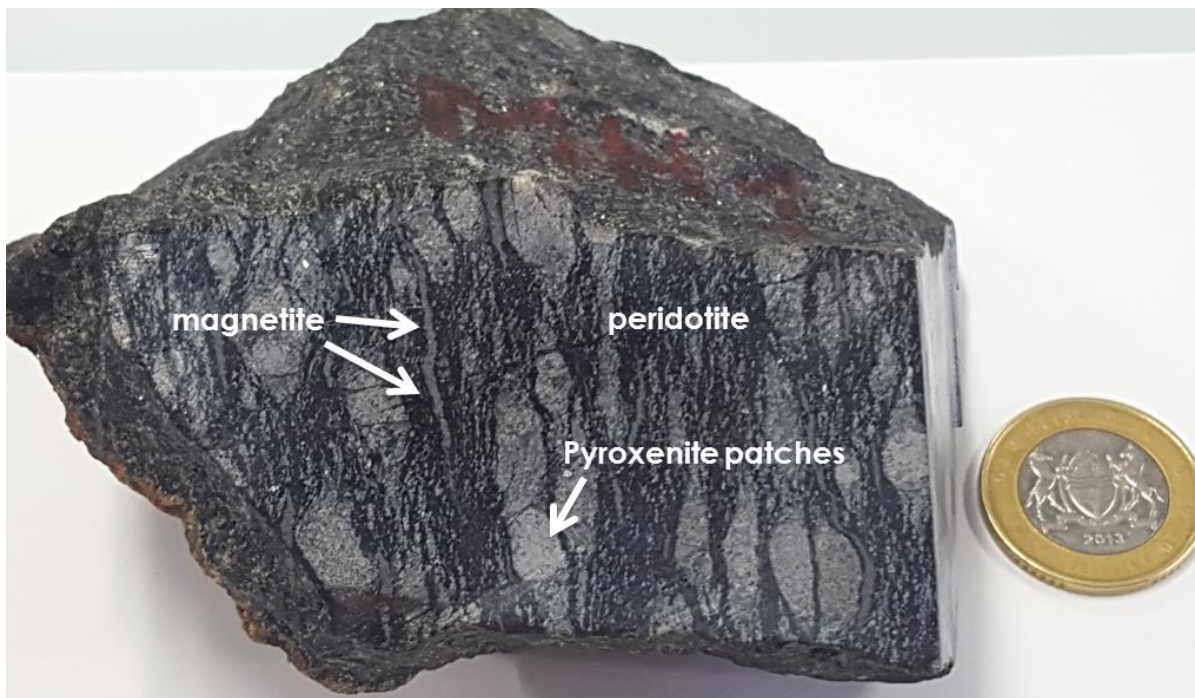


Figure 2.6. Polished hand specimen illustrating the occurrence of pyroxenite patches in peridotite and their association with magnetite-rich layers. On fresh surface, the peridotite is dark, while pyroxenite is lighter (greyish).

No garnet-bearing overprint occurs in the ultramafic intrusions. But there is evidence for the effect of shear deformation in exposures towards the eastern part of the mapped area. For

e.g., pyroxenite patches are asymmetric (Fig. 2.5e), mimicking smaller asymmetric Kfs augens in tonalite gneiss and amphibolite.

2.3. Relative chronology of events

The peridotite, pyroxenite and anorthosite occurring in the Lechana area is considered to be part of a layered intrusion – referred as the Lechana layered intrusion. Their consistent association with amphibolites indicates that the metabasalts likely formed the earliest phase of the magmatic event that formed the Lechana layered intrusion. Based on field relations, the peridotite, pyroxenite and anorthosite, all part of the Lechana layered intrusion, and the associated amphibolites are intruded by the tonalite gneiss. Zeh et al. (2009) presented a U-Pb zircon age of 2645 ± 22 Ma for tonalitic gneiss from the Lechana area. Thus the mafic to ultramafic rocks of the Lechana layered intrusion has to be older than 2.6 Ga. The magmatic zircon domains from the granitoid gneiss contain xenocryst cores of >2.8 Ga and locally show overgrowths formed at 2056 ± 12 Ma (Zeh et al., 2009). The overprint events – anatectic overprint, shear deformation, K-feldspar metasomatism – in the Lechana area seem to be concomitant, and are likely Paleoproterozoic. The shear deformation is prominent in tonalite gneiss and amphibolite exposures towards the eastern part of the mapped area, and is related to the N-S trending Dikalate shear zone, which together with the ENE-WSW trending Magogaphate shear zone separates Motloutse Complex from the adjacent Phikwe Complex (Fig. 1.5b; Key et al., 1994; Paya et al., 1997; Holzer et al., 1999; McCourt et al., 2004).

Chapter 3

Petrographic characteristics

3.1. Introduction

The chapter presents petrographic characteristics of mafic to ultramafic rocks occurring in the Lechana area. The main focus is on petrographically characterizing rocks part of the Lechana layered intrusion. 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 and oxide mineral(s), when prominently present are illustrated together with the aid of reflected light photomicrographs.

3.2. Amphibolite

The studied amphibolite samples have a prominent fabric defined by amphibole and plagioclase (Fig. 3.1a). Granoblastic polygonal texture is preserved. Irregular curved grain margin relation between the two dominant minerals is conspicuous (Fig. 3.1b). Significantly, these curved grain margins protrude each other, especially plagioclase protruding into amphibole (Fig. 3.1b), likely indicating the effect of anatectic overprint. Inclusion host relations include plagioclase inclusions in amphibole (Fig. 3.1b). Plagioclase is sericitised (Fig. 3.1), while amphibole is locally replaced by chlorite. Minor sulphides occur interstitial to sericitised plagioclase, and include pyrrhotite, chalcopyrite and pyrite (Figs. 2.1e, f). Chalcopyrite and pyrite often occur along the margin of pyrrhotite (Fig. 2.1f).

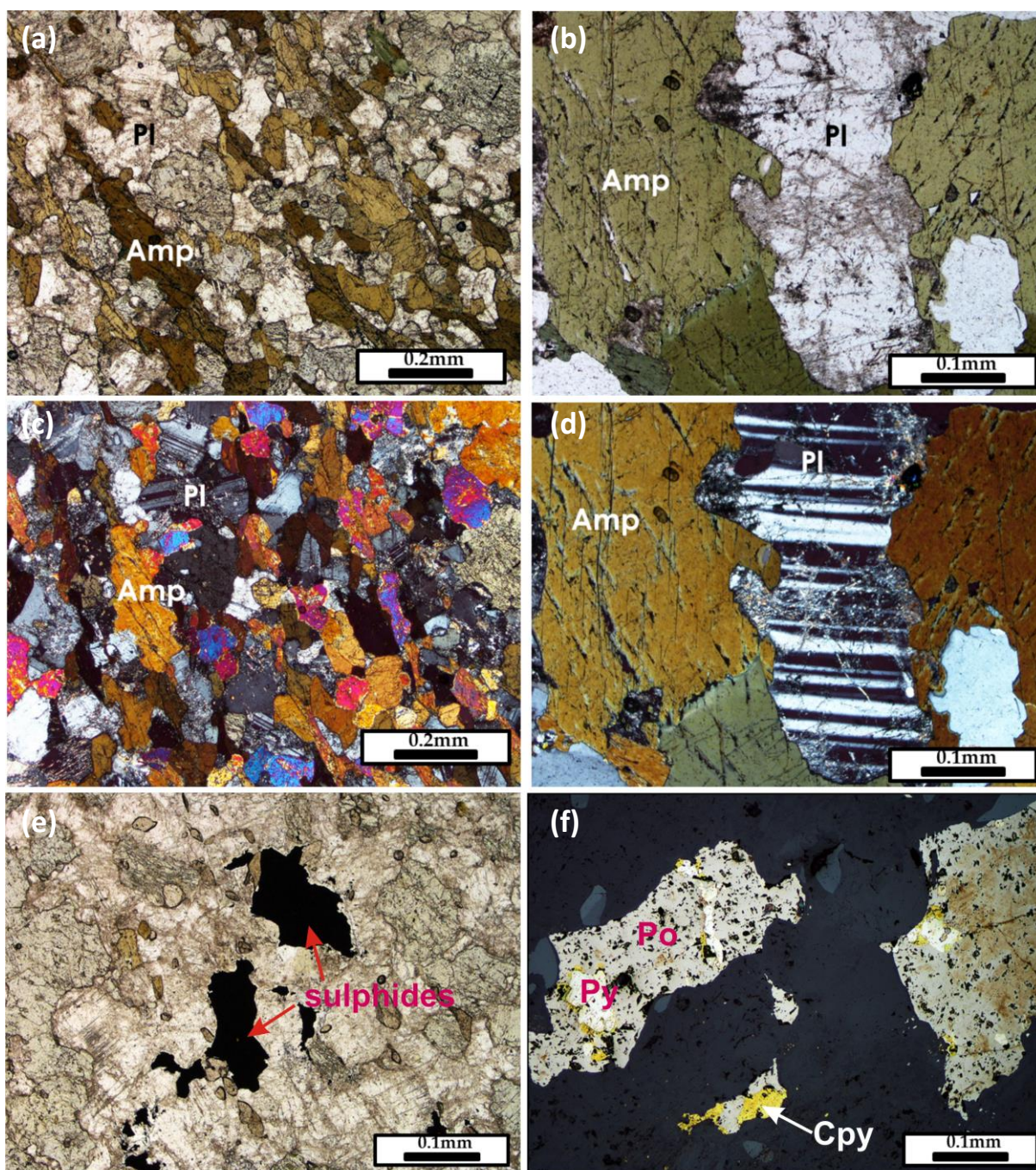


Figure 3.1. Representative photomicrographs illustrating the petrographic characteristics of amphibolite from the Lechana area. (a), (b) – prominent fabric defined by amphibole and plagioclase; (c), (d) – irregular curved grain margin relation between amphibole and plagioclase; (e), (f) – typical occurrence of sulphides interstitial to sericitized plagioclase. Amp – amphibole; Pl – plagioclase; Po – pyrrhotite; Cpy – chalcopyrite; Py – pyrite; (a), (c), (e) – plane polarized light; (b), (d) – cross polarized light; (f) – reflected light.

3.3. Anorthosite

Anorthosite is medium- to coarse-grained, with amphibole content varying from ~ 1 to 10 modal percentages. Plagioclase dominant samples are essentially cumulates. Sericitization of plagioclase is widespread (Fig. 3.2). Preserved inclusion-host relations include amphibole inclusion in plagioclase and vice versa (Fig. 3.2a). No granoblastic polygonal texture is observed. Although straight line grain margins do occur, irregular curved grain margins are conspicuous and widespread between plagioclase-plagioclase and plagioclase-amphibole (Fig. 3.2). Chlorite occur locally replacing amphibole. Alteration related veins often cut across. Bent plagioclase grains and quartz grains with sutured grain margins in the studied samples indicate the effect of shear deformation (Figs. 3.2e, f).

3.4. Peridotite-pyroxenite

Peridotite is serpentinized with variable preservation of relics of olivine and orthopyroxene (Fig. 3.3). Large grains of olivine and orthopyroxene occur locally. Amphibole is a prominent mineral in the serpentinized domains and outside (Fig. 3.4), constituting up to ~40 modal%. Orthopyroxene content varies up to ~10 %. Based on modal proportions (including relics in serpentinized domains), it is an amphibole harzburgite. Magnetite is conspicuously associated with the serpentinized domains. Cr-spinel occurs as an accessory phase.

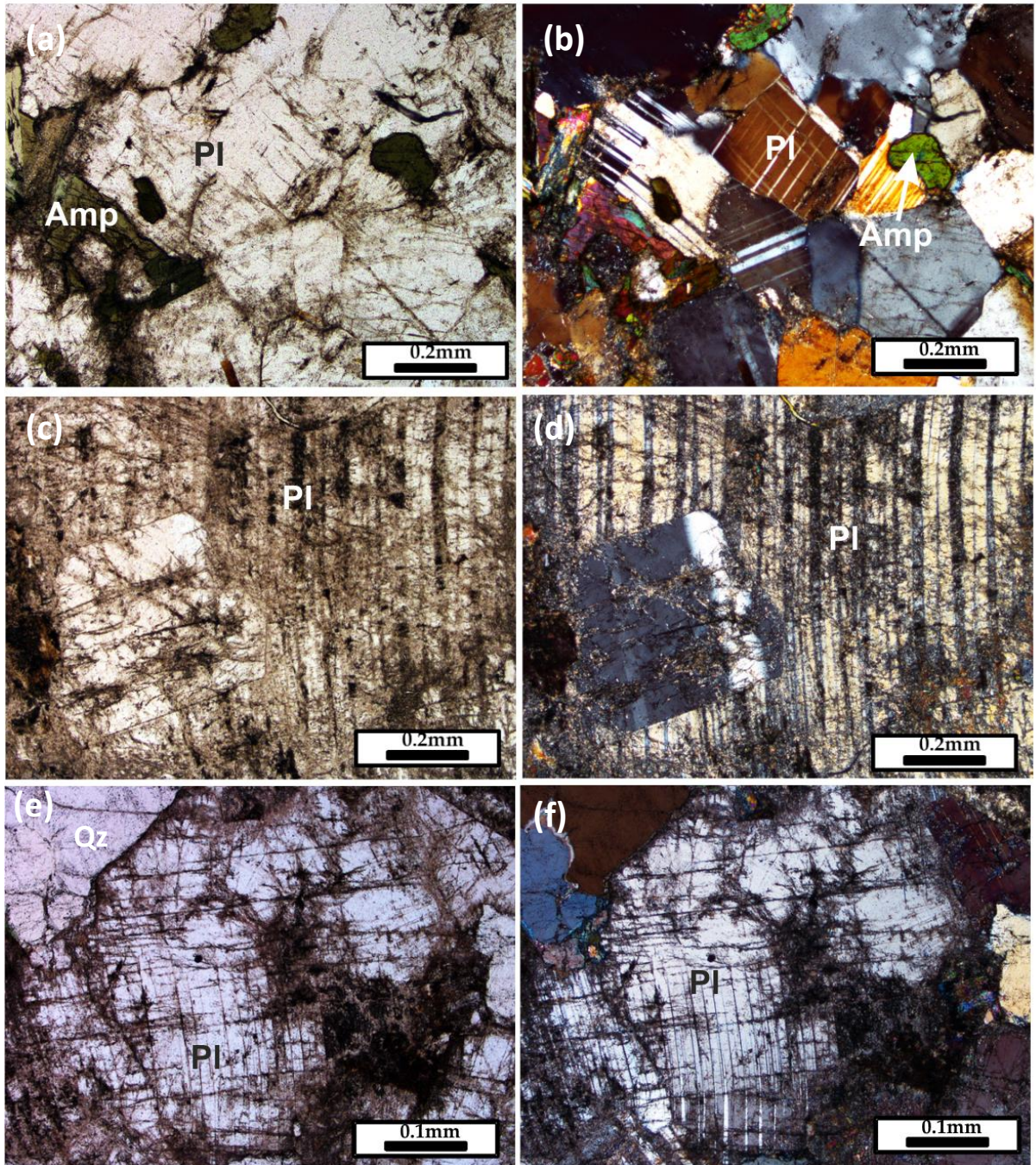


Figure 3.2. Representative photomicrographs illustrating the petrographic characteristics of anorthosite from the Lechana area. **(a), (b)** – amphibole and plagioclase occurrence as individual grains as well as inclusions within each other; **(c), (d)** – sericitization of plagioclase is widespread; **(e), (f)** – bent plagioclase and quartz grains with sutured grain margins; Qz - quartz; (a), (c), (e) – plane polarized light; (b), (d), (f) – cross polarized light.

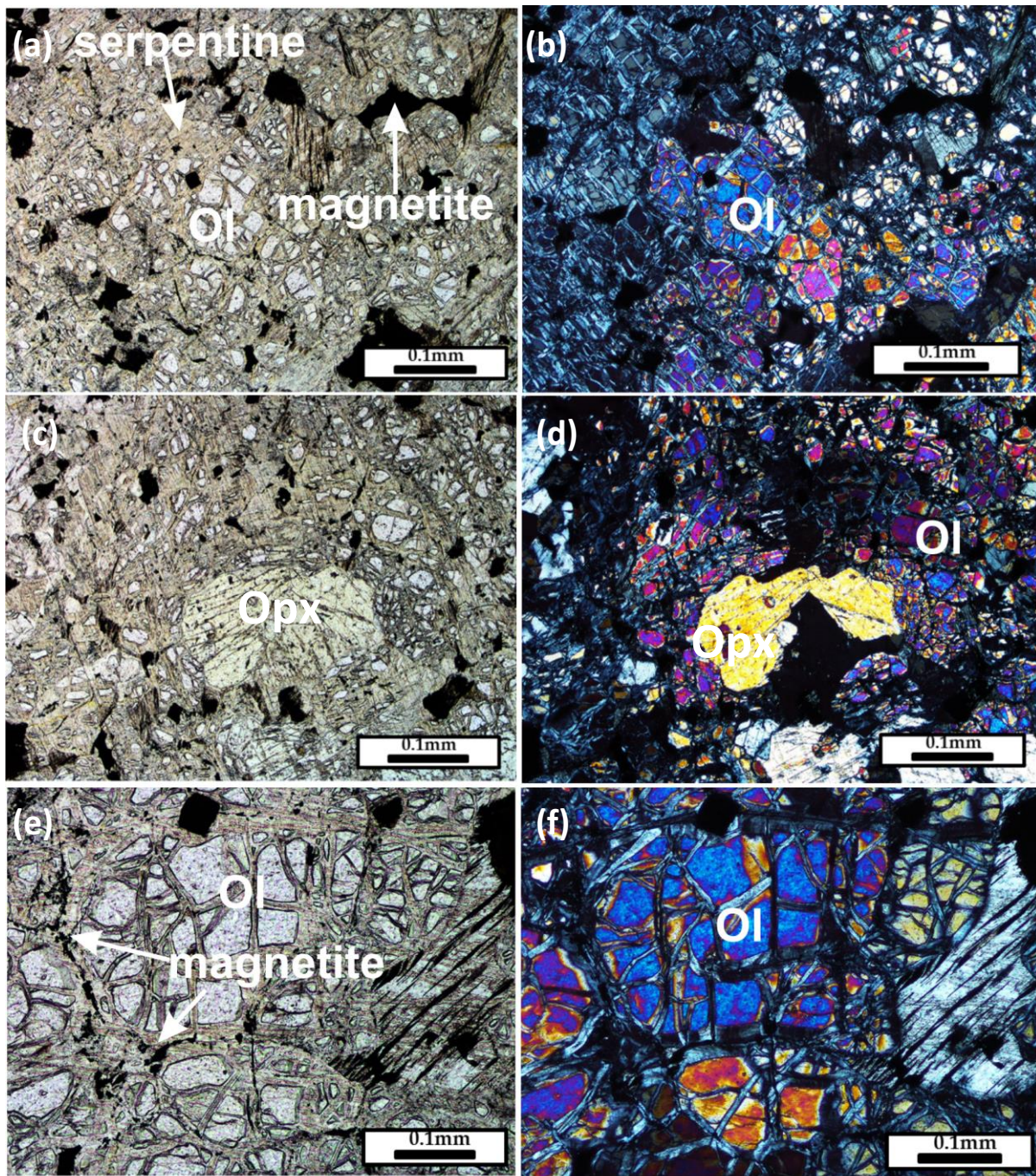


Figure 3.3. (a to f) Representative photomicrographs illustrating petrographic characteristics of peridotite from the Lechana area. It is serpentinized with variable preservation of relics of olivine and orthopyroxene with associated magnetite. Ol – olivine; Opx – orthopyroxene; (a), (c), (e) – plane polarized light; (b), (d), (f) – cross polarized light.

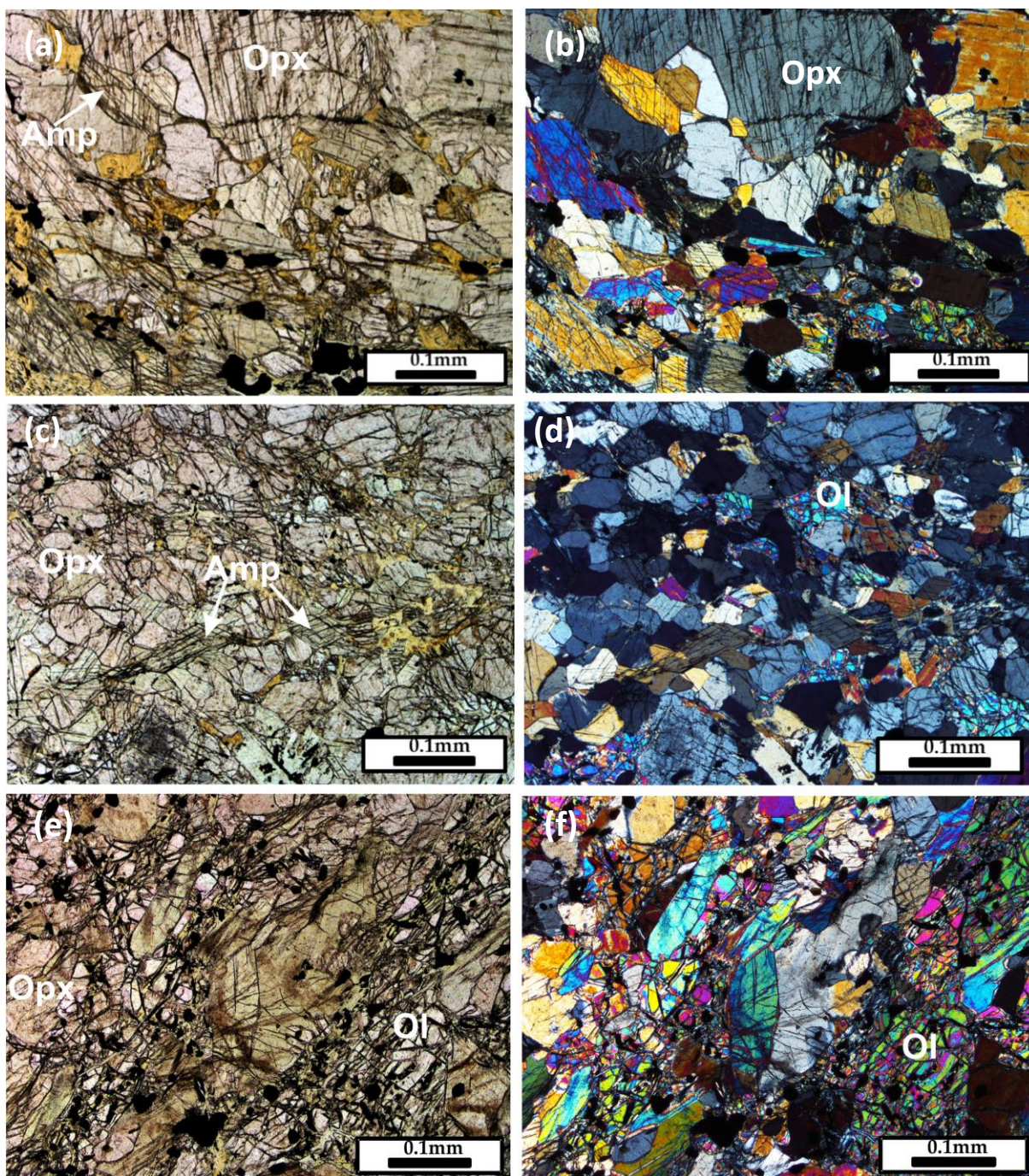


Figure 3.4. (a to f) Representative photomicrographs illustrating petrographic characteristics of peridotite with prominent amphibole associated with orthopyroxene and olivine. Variable degree of serpentinization can be seen. (a), (c), (e) – plane polarized light; (b), (d), (f) – cross polarized light.

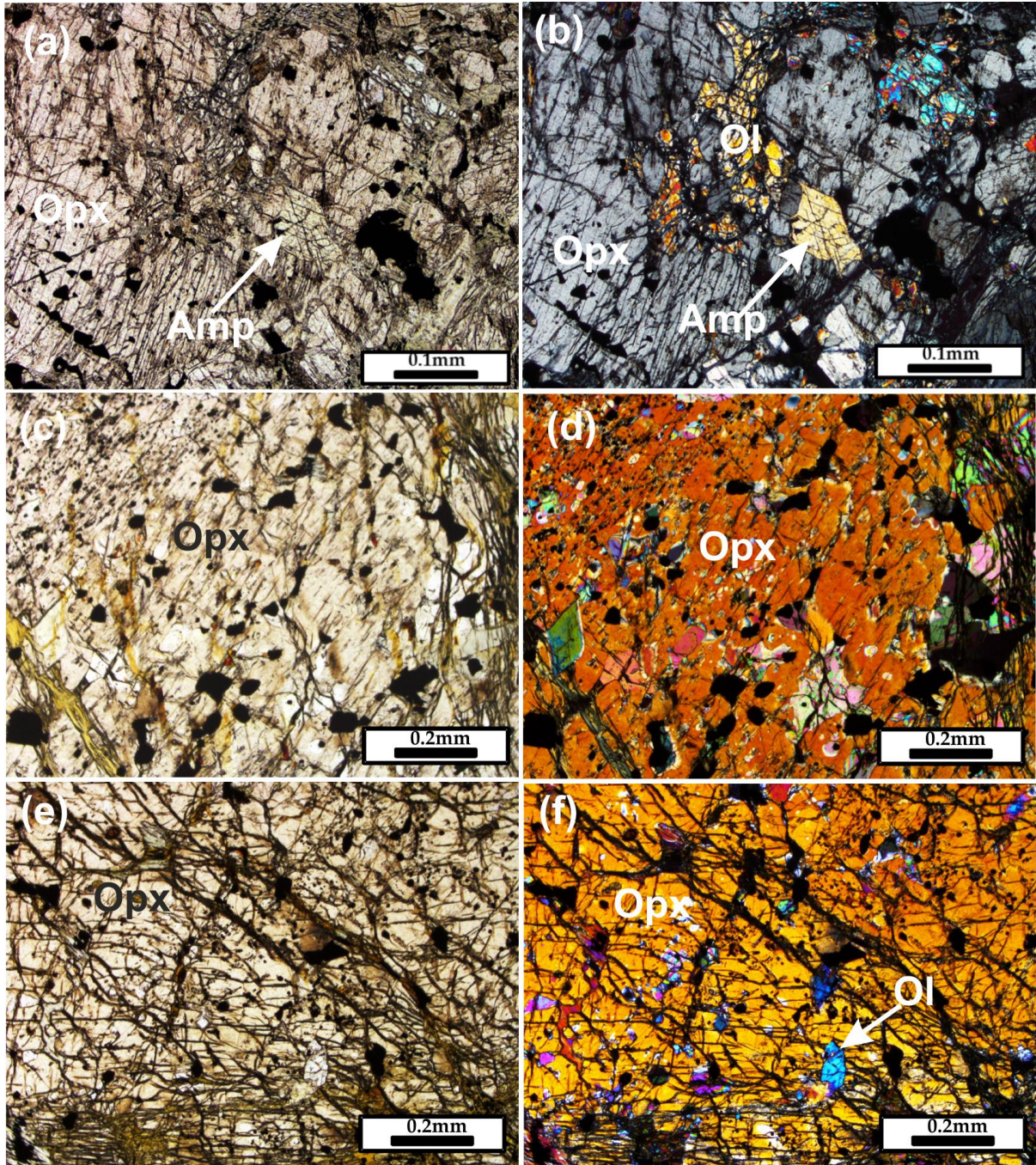


Figure 3.5. (a to f) Representative photomicrographs illustrating the petrographic characteristics of pyroxenite from the Lechana area. Pyroxenite prominently occurs as patchy domains in peridotite. Amphibole and olivine occurs within large orthopyroxene. Pyroxenite is less serpentinized in comparison to the peridotite. (a), (c), (e) – plane polarized light; (b), (d), (f) – cross polarized light.

Pyroxenite prominently occurs as homogenous brownish patchy domains in serpentinized peridotite (Fig. 3.5). Orthopyroxene is the dominant mineral with minor amphibole and olivine (Fig. 3.5), and is essentially an orthopyroxenite. In general, the contact between peridotite and pyroxenite domains is sharp (Fig. 3.5), with local penetration of serpentine veins into the pyroxenite (Fig. 3.5).

Preserved inclusion-host relations in the ultramafic rocks include amphibole inclusions in orthopyroxene, and orthopyroxene and olivine inclusions in amphibole (Figs. 3.5, and 3.6a, b). Curved irregular grain margins are widespread between prominent minerals in the non-serpentinized domains of ultramafic rocks (Figs. 3.6c, d). However, unlike the anorthosite, no protruding grain margin relations are observed. Straight line grain margins do occur in ultramafic rocks from the Lechana layered intrusion, but do not form 120° triple junctions (Figs. 3.6c, d). Amphibole grains within serpentinized domains are characterized either by straight line or rounded grain margins (Figs. 3.6e, f).

Various stages of progression of serpentinization is well preserved in the ultramafic rocks (Fig. 3.7). Mesh, hourglass and bastitic textures characterize the serpentinization. Magnetite start to occur as subhedral to anhedral grains associated with olivine and orthopyroxene. With the progress of serpentinization, the occurrence of magnetite varies from elongated adjointed grains to veins to layers (Fig. 3.7). Layers become prominent with widening of the fluid pathways associated with serpentinization. Magnetite-rich domains associated with serpentinization are prominently seen in the peridotite portion of peridotite-pyroxenite

associations (Fig. 3.8). Magnetite occurrence in the patchy pyroxenite domains is relatively minor, associated with thin serpentine veins that penetrate them (Fig. 3.8).

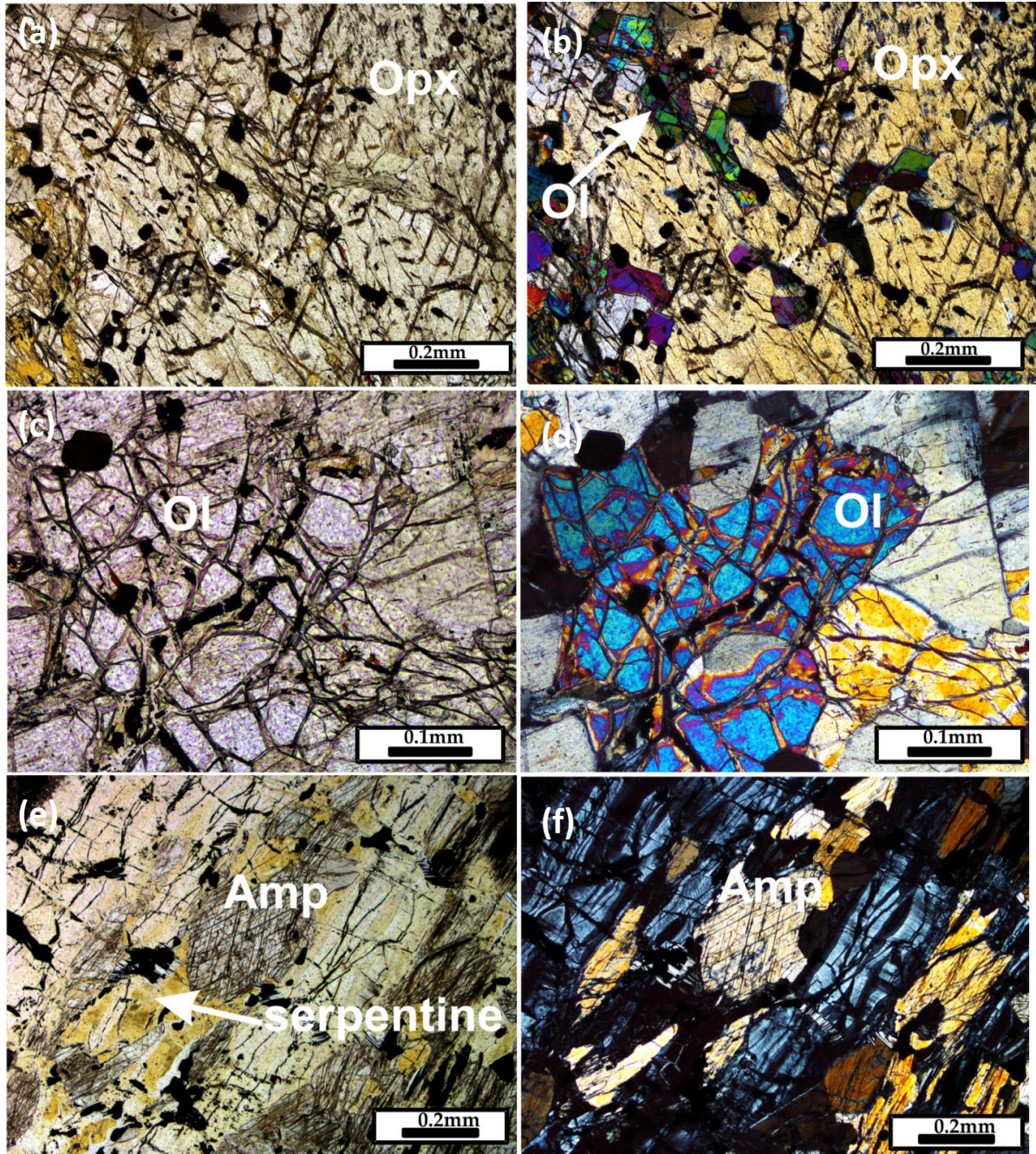


Figure 3.6. Representative photomicrographs from ultramafic rocks of the Lechana area illustrating olivine inclusions in orthopyroxene (**a, b**), curved irregular grain margins of prominent minerals (**c, d**), and occurrence of amphibole within serpentine (**e, f**). (**a**), (**c**), (**e**) – plane polarized light; (**b**), (**d**), (**f**) – cross polarized light.

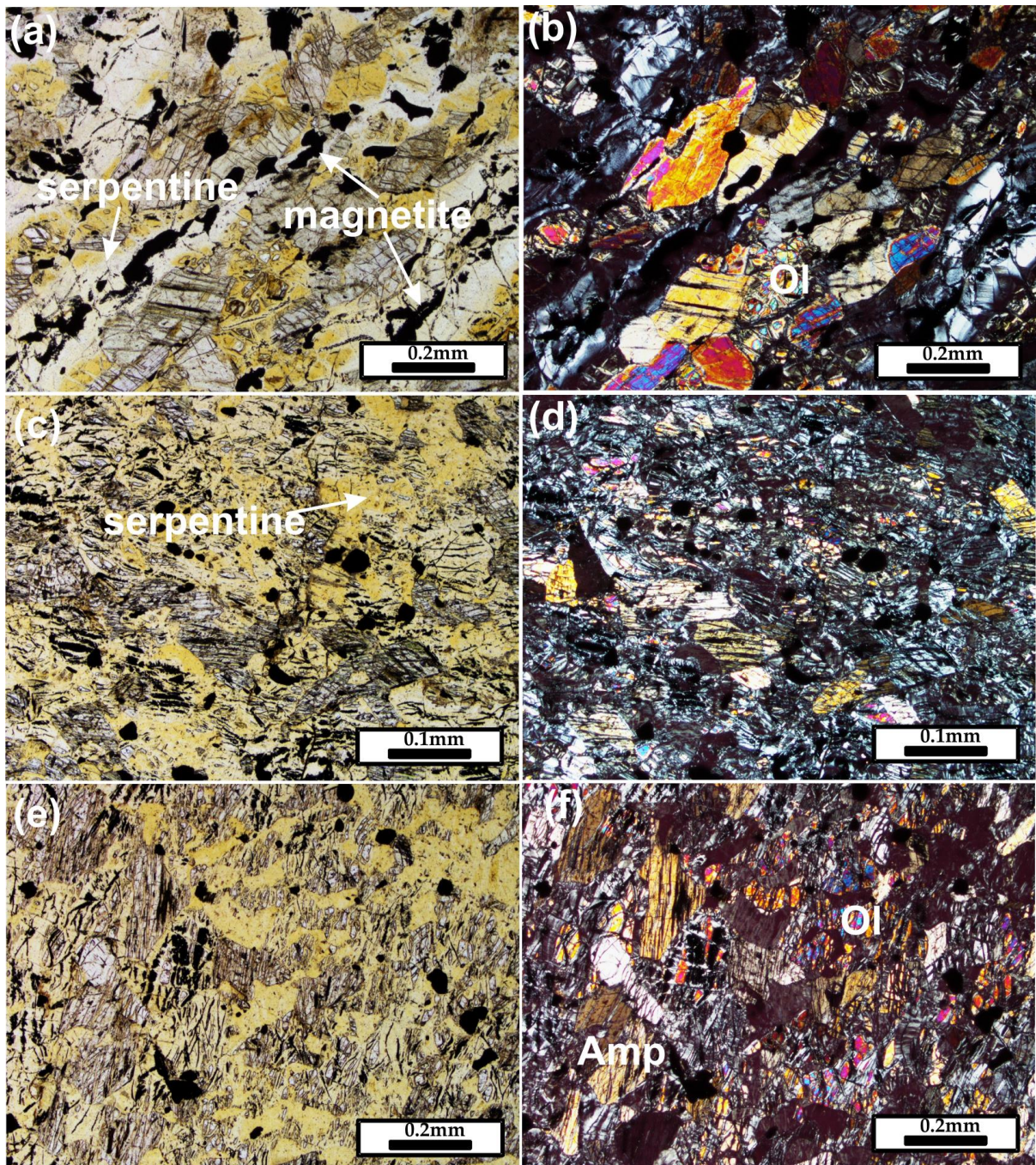


Figure 3.7. (a to f) Representative photomicrographs illustrating the various stages of serpentinization preserved in ultramafic rocks of the Lechana area. With progression of serpentinization, subhedral magnetite grains become elongated grains to veins to layers. (a), (c), (e) – plane polarized light; (b), (d), (f) – cross polarized light.

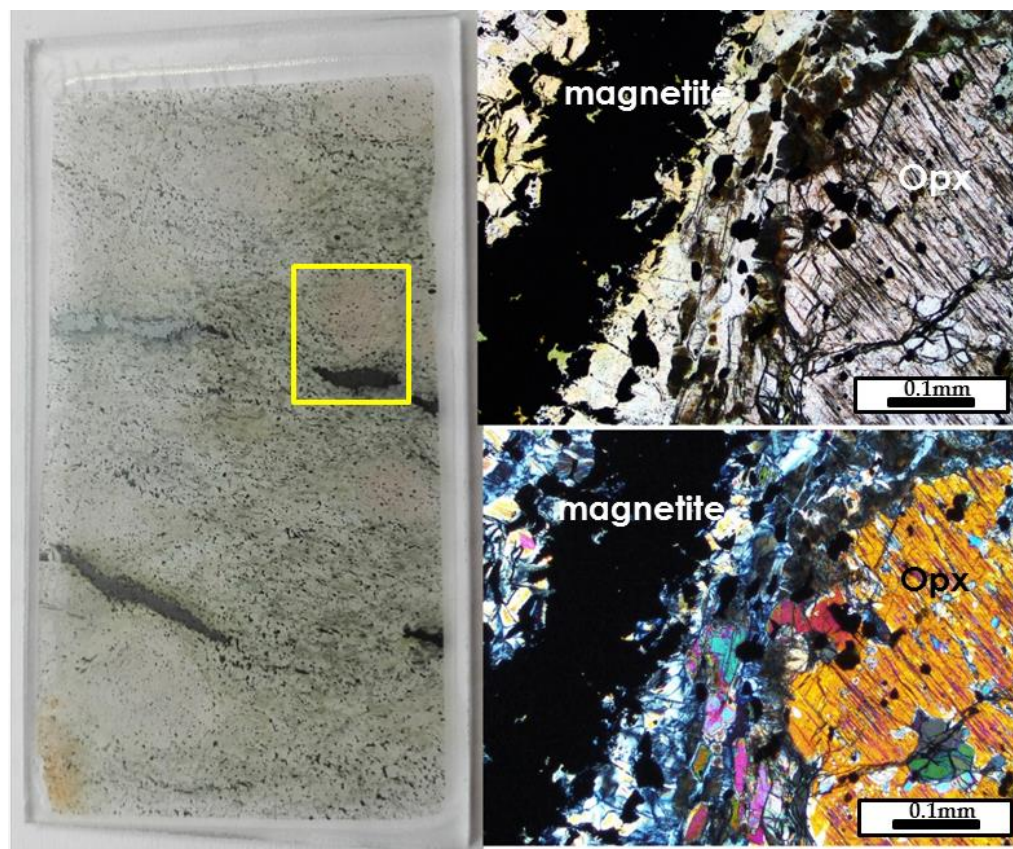


Figure 3.8. Representative thin section and photomicrographs illustrating the occurrence of magnetite-rich domains within the serpentinized peridotite portion of peridotite-pyroxenite associations. Magnetite occurrence in the pyroxenite patchy domains is relatively minor. The box indicates the area covered by the photomicrographs. Top photomicrograph – plane polarized light; Bottom photomicrograph – cross polarized light.

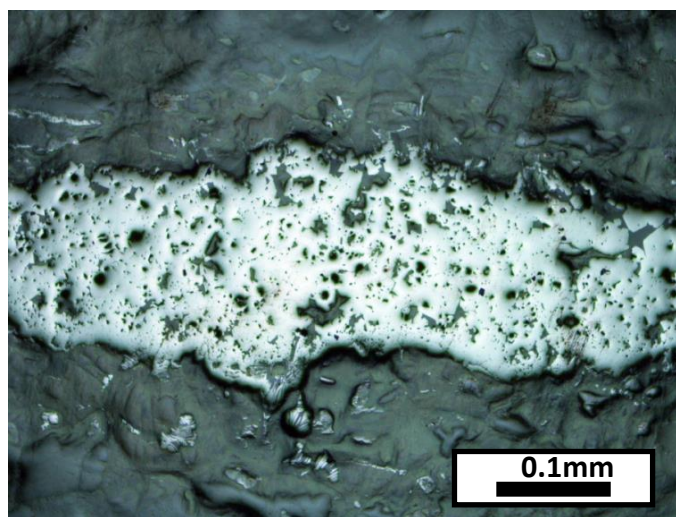


Figure 3.8. (continued) Reflected light photomicrograph indicating the prominent occurrence of magnetite-rich layers associated with serpentinization in the peridotite.

Chapter 4

Mineral chemical characteristics

4.1. Introduction

This chapter presents chemical characteristics of prominent minerals from peridotite, pyroxenite and anorthosite, belonging to the Lechana layered intrusion. As amphibole is a prominent rock-forming mineral in the different rocks, the modifier 'amphibole' is implied and hereafter not separately mentioned (i.e., for e.g., peridotite is used instead of amphibole peridotite). Electron microprobe analyses of minerals in the rocks are given in tables. Representative BSE-SEM images obtained during analyses are included as part of this chapter. Compositional characteristics of similar minerals from different rocks are presented in a comparative way. Where the compositional characteristics are modified by alteration (serpentinization, sericitization), isocon mass balance (Grant, 1986, 2005) exercise was carried out. After evaluating the compositional characteristics, results of application of available geothermometers on the rocks are presented.

4.2. Olivine

Olivine in the peridotite show effect of serpentinization (Fig. 4.1), with rare preservation of original olivine composition ($Mg\# = \sim 81-82$; $MnO = 0.22-0.3 \text{ wt.}\%$; $NiO = 0.26-0.31 \text{ wt.}\%$; $MgO = 43.39-44.03 \text{ wt.}\%$; $FeO = 16.58-17 \text{ wt.}\%$; Fig. 4.2; Table 4.1a) in peridotite with patchy pyroxenite domains. In comparison, most mineral chemical analyses of olivine relics in

peridotite have low totals (Table 4.1b), due to the effect of serpentinization. Nevertheless, the olivine relics are characterized by similar Mg# (~82-83), MnO (0.23-0.27 wt.%), and lower NiO (0.14-0.23 wt.%), MgO (37.52-42.91 wt.%) and FeO (13.81-15.91 wt.%) contents than the primary olivine (Fig. 4.2; Table 4.1b).

Rock	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte
Mineral	OI	OI	OI	OI	OI	OI	OI	OI
SiO ₂	39,53	39,67	39,56	39,22	39,16	38,72	36,25	36,30
FeO	16,88	16,87	16,70	17,00	16,93	16,61	16,61	16,58
MnO	0,28	0,24	0,27	0,30	0,26	0,23	0,22	0,23
MgO	43,61	43,67	43,44	43,36	44,00	44,03	43,39	43,75
NiO	0,26	0,29	0,28	0,29	0,31	0,30	0,29	0,35
Total	100,77	100,85	100,48	100,37	100,75	100,04	96,93	97,39
O=4								
Si	0,996	0,998	1,000	0,994	0,988	0,984	0,957	0,954
Fe(II)	0,356	0,355	0,353	0,360	0,357	0,353	0,367	0,364
Mn	0,006	0,005	0,006	0,006	0,006	0,005	0,005	0,005
Mg	1,639	1,638	1,636	1,639	1,655	1,668	1,708	1,714
Ni	0,005	0,006	0,006	0,006	0,006	0,006	0,006	0,007
Total	3,004	3,002	3,001	3,006	3,012	3,016	3,043	3,046
Mg#	82,16	82,19	82,26	81,97	82,25	82,54	82,32	82,47
Fo	81,92	81,98	82,02	81,71	82,02	82,33	82,13	82,27
Fa	17,78	17,76	17,69	17,97	17,70	17,42	17,63	17,49
Tp	0,30	0,26	0,29	0,32	0,28	0,24	0,24	0,25

Table 4.1. (a) Representative mineral chemical data of olivine primary olivine composition preserved in peridotite with pyroxenite patchy domains (Perd-Pxynte) from the Lechana layered intrusion.

Rock	Peridotite	Peridotite	Peridotite	Peridotite	Peridotite	Peridotite	Peridotite	Peridotite	Peridotite
Mineral	OI	OI	OI	OI	OI	OI	OI	OI	OI
SiO ₂	34,37	33,46	32,82	31,33	30,38	28,63	28,39	27,89	24,86
FeO	15,82	15,84	15,91	15,5	15,45	14,96	14,98	14,49	13,81
MnO	0,24	0,24	0,26	0,25	0,27	0,24	0,24	0,23	0,23
MgO	42,91	42,5	42,25	41,22	40,7	39,5	39,4	39,6	37,52
NiO	0,23	0,16	0,16	0,21	0,16	0,17	0,14	0,17	0,15
Total	93,66	92,33	91,5	88,62	87,1	83,62	83,34	82,5	76,69
O=4									
Si	0,939	0,930	0,923	0,912	0,902	0,888	0,884	0,876	0,846
Fe(II)	0,361	0,368	0,374	0,377	0,384	0,388	0,390	0,381	0,393
Mn	0,006	0,006	0,006	0,006	0,007	0,006	0,006	0,006	0,007
Mg	1,748	1,761	1,771	1,788	1,802	1,826	1,830	1,855	1,903
Ni	0,005	0,004	0,004	0,005	0,004	0,004	0,004	0,004	0,004
Total	3,060	3,070	3,077	3,089	3,098	3,113	3,116	3,123	3,154
Mg#	82,86	82,71	82,56	82,58	82,45	82,48	82,42	82,97	82,89
Fo	82,65	82,49	82,32	82,35	82,19	82,24	82,19	82,74	82,65
Fa	17,09	17,24	17,39	17,37	17,50	17,47	17,53	16,98	17,06
Tp	0,26	0,26	0,29	0,28	0,31	0,28	0,28	0,27	0,29

Table 4.1. (b) Representative mineral chemical data of olivine relics in peridotite, affected by serpentinization, from the Lechana layered intrusion.

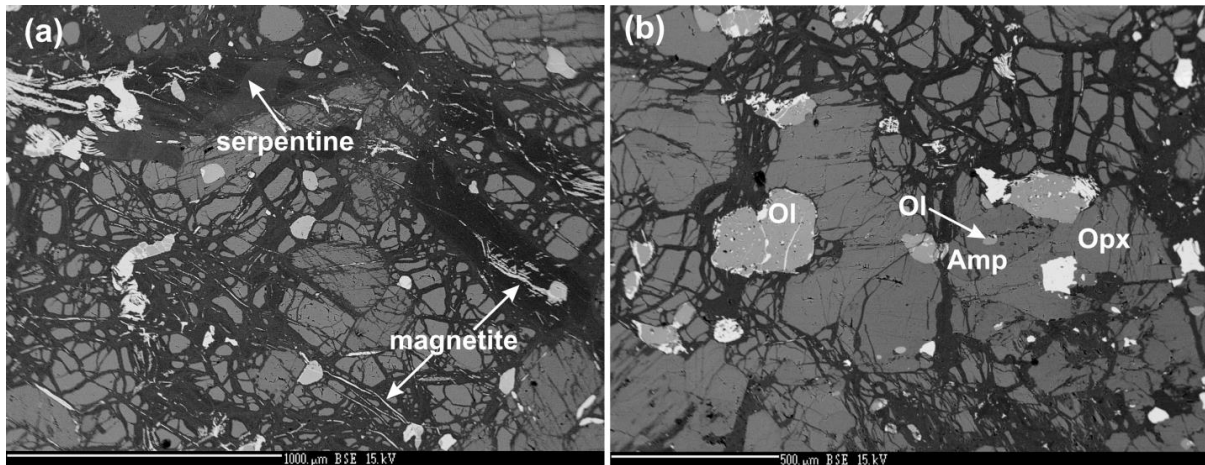


Figure 4.1. Representative BSE images illustrating the effect of serpentinization on olivine in peridotite from the Lechana layered intrusion. Notice the olivine inclusion in amphibole.

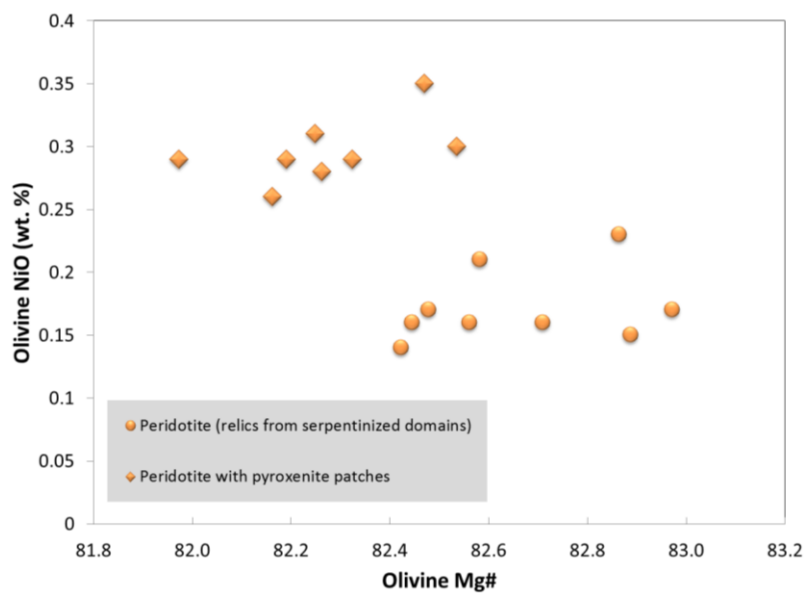


Figure 4.2. Mg# versus NiO (wt.%) plot for olivine compositions from the Lechana layered intrusion.

The mobility/immobility of elements and the gains and losses of material (Gresens, 1967) can be evaluated using the isocon mass balance method (Grant, 1986, 2005). Grant's isocon exercise involves first computation using the equation, $C_a = (m_0/m_a)C_0$, where m_0 is the reference mass of the original sample and m_a is the mass of the altered sample. This is

followed by calculating the mass change (m_0/m_a) graphically by representing the concentrations in the altered rock against those in the original and connecting, by means of a straight line through the origin (isocon line), the components that show no relative gain or loss of mass (immobile elements) (Fig. 4.3). The results can be complimented with representative elemental histograms to illustrate which elements are gained and which are lost (e.g., Whitbread and Moore, 2004). Although typically carried out on whole-rock geochemical data from altered rocks, the mass balance exercise have also been used while dealing with altered mineral chemical compositions; albeit rarely (e.g., Fiorentini et al., 2007).

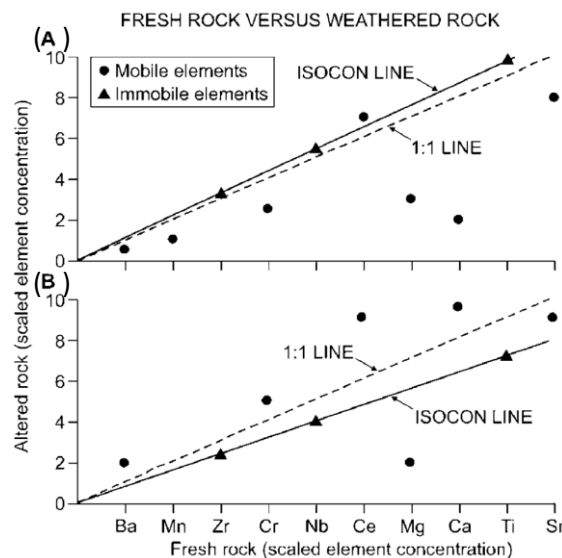


Figure 4.3. Representative illustration of isocon plots of an altered sample plotted against a parent sample showing: **(A)** mass loss and **(B)** mass gain (from Whitbread and Moore, 2004).

Application of isocon mass balance exercise to the serpentinized olivine compositions indicates that Cr_2O_3 and CoO were gained, while V_2O_3 , K_2O , CaO , NiO , TiO_2 , ZnO , SiO_2 , Cl , Na_2O , FeO , MgO and MnO (in decreasing order) were lost (Fig. 4.4); likely due to serpentinization.

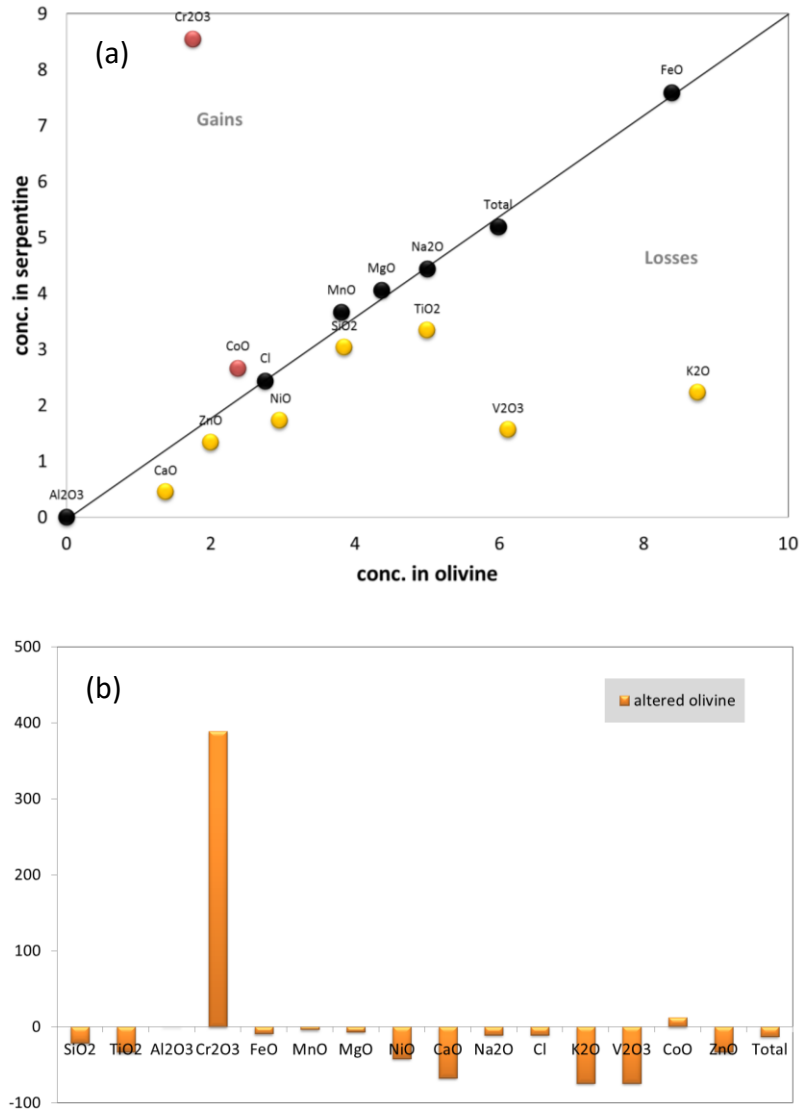


Figure 4.4. Representative isocon plot **(a)** and elemental histogram **(b)** illustrating elements gained and lost from olivine compositions affected by serpentinization.

4.3. Orthopyroxene

Orthopyroxenes are Mg-rich, with peridotite with patchy pyroxenite domains having higher Mg# (~86-87) and NiO (0.08-0.12 wt.%), and lower Cr₂O₃ (0.05-0.09 wt.%) and MnO (0.18-0.24 wt.%) contents than peridotite (Mg# = ~83-84; NiO = 0.03-0.07 wt.%; Cr₂O₃ = 0.11-0.17 wt.%; MnO = 0.21-0.27 wt.%) (Fig. 4.5; Table 4.2a).

The compositional range of Al_2O_3 [1.74-2.48 wt.% (peridotite with pyroxenite patchy domains); 1.73-2.2 wt.% (peridotite)] and TiO_2 [0.08-0.11 wt.% (peridotite with pyroxenite patchy domains); 0.07-0.11 wt.% (pyroxenite)] are comparable. Like olivine, the mineral chemical analyses of orthopyroxene relics in peridotite are also characterized by low totals (Table 4.2b), due to the effect of serpentinization (Fig. 4.6). Mg# of these orthopyroxenes vary from ~83 to 84, with compositional ranges of 0.02 to 0.03 wt.% NiO, 0.04 to 0.13 wt.% Cr_2O_3 , 0.25 to 0.31 wt.% MnO, 1.15 to 1.83 wt.% Al_2O_3 and 0.01 to 0.1 wt.% TiO_2 (Fig. 4.5; Table 4.2b). Application of isocon mass balance exercise to the serpentinized olivine compositions indicates that Cl, Na_2O , CoO and MgO were gained, while Cr_2O_3 , V_2O_5 , TiO_2 , Al_2O_3 , NiO, ZnO, CaO, K_2O , SiO_2 , FeO and MnO (in decreasing order) were lost (Fig. 4.7); likely due to serpentinization. All the orthopyroxenes in peridotite-pyroxenite lie within the enstatite field of the pyroxene quadrilateral [nomenclature after Morimoto (1988); Fig. 4.8].

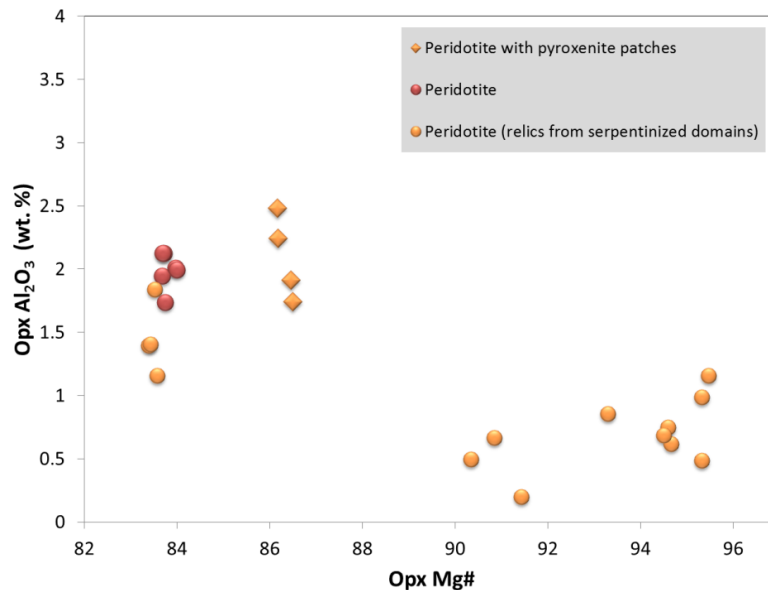


Figure 4.5. Mg# versus Al_2O_3 (wt.%) plot for orthopyroxene compositions from the Lechana layered intrusion.

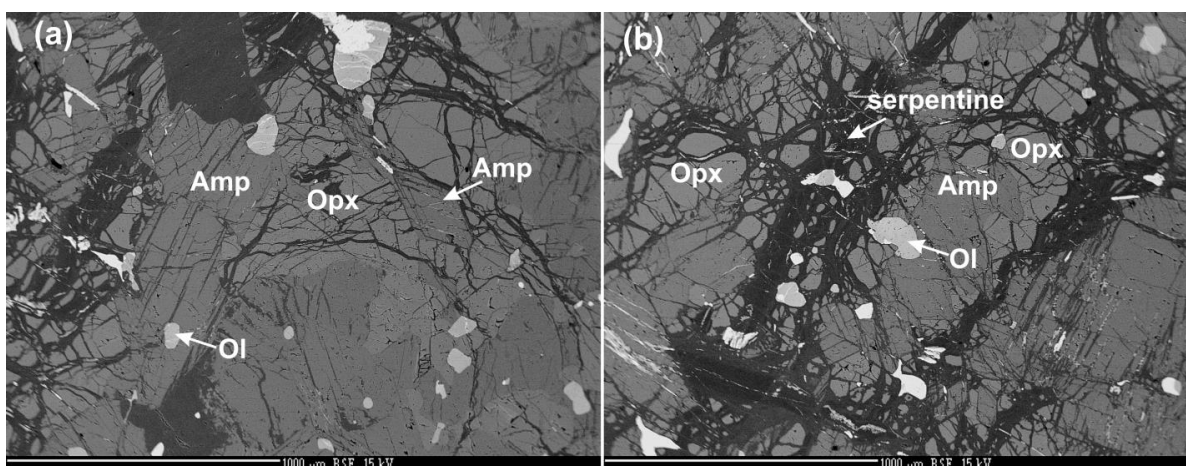


Figure 4.6. Representative BSE images illustrating the effect of serpentinization on orthopyroxene and amphibole in peridotite. Notice the olivine inclusion in amphibole.

Rock	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Peridotite	Peridotite	Peridotite	Peridotite	Peridotite	Peridotite
Mineral	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx	Opx
SiO ₂	55,49	56,38	56,09	56,04	55,54	55,33	54,57	55,13	55,22	54,75
TiO ₂	0,08	0,11	0,1	0,11	0,07	0,08	0,09	0,09	0,07	0,11
Al ₂ O ₃	2,48	1,74	2,24	1,91	2,12	2,12	1,94	1,73	2	1,99
FeO	9,02	9,02	9,12	8,94	10,85	10,87	10,87	10,88	10,68	10,62
MnO	0,23	0,18	0,24	0,18	0,27	0,23	0,25	0,24	0,26	0,21
MgO	31,54	32,42	31,92	32,03	31,35	31,35	31,29	31,48	31,43	31,32
CaO	0,26	0,27	0,25	0,29	0,16	0,17	0,23	0,2	0,25	0,29
NiO	0,11	0,08	0,08	0,12	0,07	0,03	0,08	0,04	0,03	0,05
Total	99,34	100,39	100,21	99,75	100,69	100,54	99,59	99,98	100,17	99,61
O=6										
Si	1,952	1,962	1,956	1,962	1,945	1,942	1,936	1,945	1,943	1,939
Ti	0,002	0,003	0,003	0,003	0,002	0,002	0,002	0,002	0,002	0,003
Al	0,103	0,071	0,092	0,079	0,088	0,088	0,081	0,072	0,083	0,083
Fe(II)	0,265	0,263	0,266	0,262	0,318	0,319	0,323	0,321	0,314	0,315
Mn	0,007	0,005	0,007	0,005	0,008	0,007	0,008	0,007	0,008	0,006
Mg	1,654	1,682	1,659	1,671	1,637	1,641	1,655	1,656	1,648	1,653
Ca	0,010	0,010	0,009	0,011	0,006	0,006	0,009	0,008	0,009	0,011
Total	3,994	3,999	3,994	3,995	4,007	4,010	4,019	4,015	4,012	4,014
Mg#	86,17	86,50	86,19	86,46	83,74	83,72	83,69	83,76	83,99	84,02
En	0,85	0,86	0,85	0,85	0,84	0,85	0,86	0,85	0,85	0,85
Fs	0,15	0,14	0,14	0,14	0,15	0,15	0,14	0,14	0,14	0,14
Wo	0,01	0,01	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,01

Table 4.2. (a) Representative mineral chemical data of primary orthopyroxene composition preserved in peridotite with pyroxenite patchy domains (Perd-Pxynte) and peridotite from the Lechana layered intrusion.

Rock Mineral	Peridotite Opx	Peridotite Opx	Peridotite Opx	Peridotite Opx	Peridotite Opx	Peridotite Opx	Peridotite Opx	Peridotite Opx	Peridotite Opx	Peridotite Opx	Peridotite Opx	Peridotite Opx	Peridotite Opx	Peridotite Opx	Peridotite Opx
SiO ₂	39,7	38,47	36,7	31,86	43,19	39,23	39,49	47,53	45,22	45,91	46,69	46,32	45,4	50,01	
TiO ₂	0,02	0,03	0,03	0	0,06	0,04	0,06	0,03	0,02	0,04	0	0,01	0,02	0,1	
Al ₂ O ₃	0,85	0,66	0,49	0,19	1,15	1,39	1,4	0,74	0,98	1,15	0,48	0,61	0,68	1,83	
FeO	4,75	6,6	6,85	5,49	10,05	9,7	9,67	4,04	3,47	3,39	3,5	3,91	4,09	10,86	
MnO	0,11	0,13	0,1	0,18	0,31	0,26	0,25	0,1	0,09	0,08	0,1	0,1	0,1	0,28	
MgO	37,2	36,84	36,02	32,94	28,71	27,36	27,35	39,76	39,79	40,22	40,1	39,02	39,52	30,92	
CaO	0,09	0,07	0,06	0,15	0,16	0,2	0,2	0,05	0,06	0,06	0,04	0,07	0,09	0,18	
NiO	0,03	0,06	0,02	0,05	0,02	0,02	0,03	0,28	0,2	0,15	0,25	0,26	0,29	0,03	
Total	82,85	82,93	80,39	71,06	83,78	78,45	78,7	92,61	89,98	91,16	91,31	90,39	90,32	94,44	
O=6															
Si	1,695	1,663	1,645	1,618	1,848	1,805	1,809	1,791	1,755	1,756	1,783	1,789	1,762	1,885	
Ti	0,001	0,001	0,001	0,000	0,002	0,001	0,002	0,001	0,001	0,001	0,000	0,000	0,001	0,003	
Al	0,043	0,034	0,026	0,011	0,058	0,075	0,076	0,033	0,045	0,052	0,022	0,028	0,031	0,081	
Fe(II)	0,170	0,239	0,257	0,233	0,360	0,373	0,371	0,127	0,113	0,108	0,112	0,126	0,133	0,342	
Mn	0,004	0,005	0,004	0,008	0,011	0,010	0,010	0,003	0,003	0,003	0,003	0,003	0,003	0,009	
Mg	2,367	2,374	2,406	2,494	1,832	1,876	1,868	2,234	2,302	2,293	2,283	2,247	2,286	1,738	
Ca	0,004	0,003	0,003	0,008	0,007	0,010	0,010	0,002	0,002	0,002	0,002	0,003	0,004	0,007	
Total	4,284	4,319	4,341	4,377	4,121	4,154	4,150	4,191	4,223	4,218	4,206	4,197	4,222	4,070	
Mg#	93,32	90,87	90,36	91,45	83,59	83,41	83,45	94,61	95,34	95,49	95,33	94,68	94,51	83,54	

Table 4.2. (b) Representative mineral chemical data of orthopyroxene relics in peridotite, affected by serpentinization, from the Lechana layered intrusion.

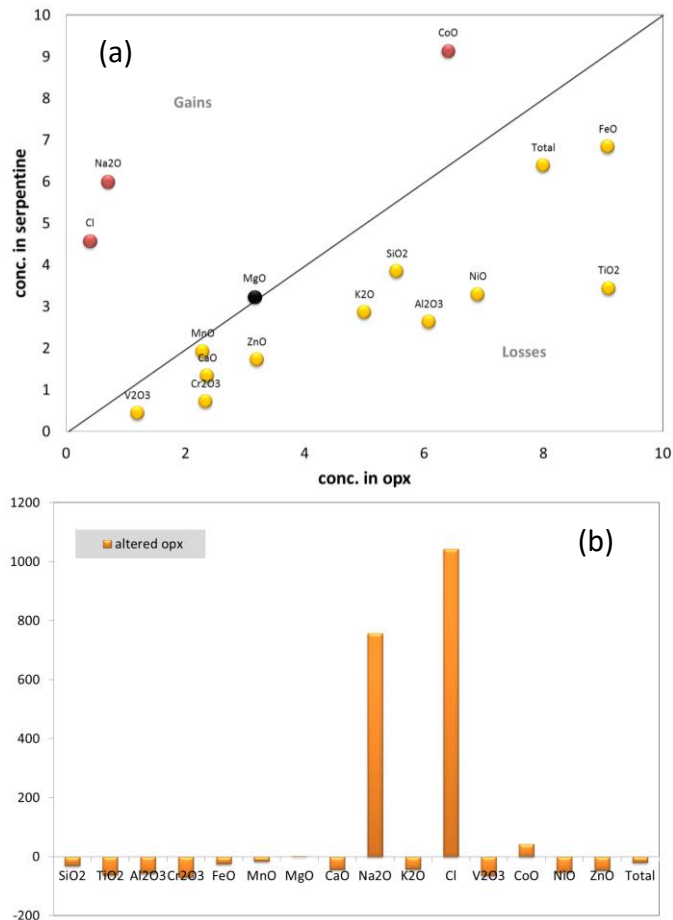


Figure 4.7. Representative isocon plot (a) and elemental histogram (b) illustrating elements gained and lost from orthopyroxene compositions affected by serpentinization.

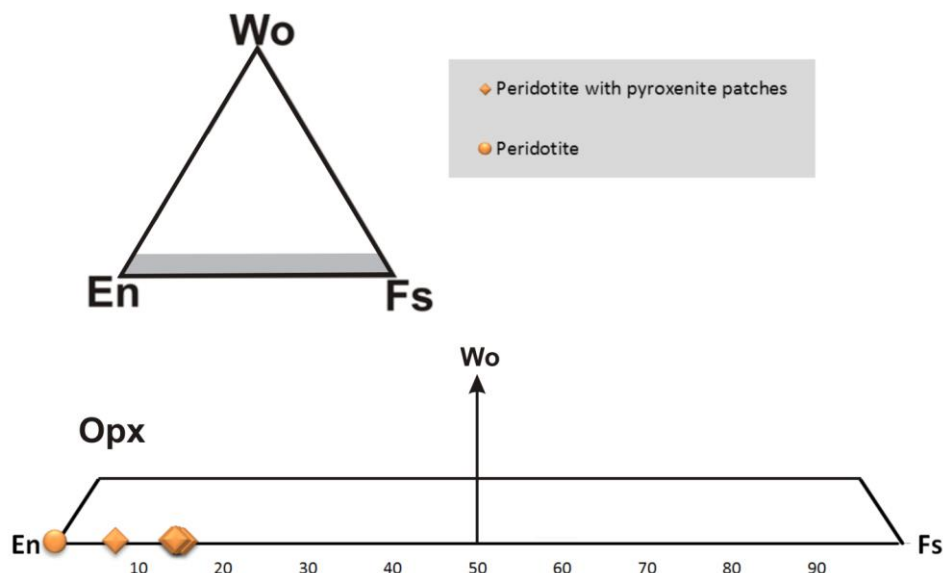


Figure 4.8. Mineral chemistry (mol.%) based compositional diagrams for pyroxenes from peridotite with patchy pyroxenite domains and peridotite in the pyroxene classification quadrilateral.

4.4. Amphibole

Amphiboles are Mg-rich richer in ultramafic (peridotite-pyroxenite) than in mafic rocks (anorthosite) from the Lechana layered intrusion. Primary amphibole compositions were preserved in peridotite with patchy pyroxenite domains and anorthosite (Fig. 4.9), and are edenitic (Fig. 4.10). The former is characterized by Mg# of ~85, Ca_B of 1.82 to 1.86 apfu, (Na+K)_A of 0.4 to 0.43 apfu, Ti of 0.08 to 0.09 apfu, Al(IV) of 1.31 to 1.39 apfu, Al(VI) of 0.32 to 0.4 apfu, Fe(III) of 0.58 to 0.7 apfu and F+Cl content of 0.04 to 0.12 wt.% (Table 4.3a). In comparison, amphiboles in anorthosite have lower Mg# (~55-57) and Fe(III) (0.33-0.51 apfu), and higher Ca_B (1.87-1.92 apfu), (Na+K)_A (0.47-0.63 apfu), Al(IV) (1.25-1.51 apfu), Al(VI) (0.39-0.51 apfu) and F+Cl content of 0.09 to 0.18 wt.% (Table 4.3b). Amphibole from a heavily altered (sericitized) anorthosite has a slightly different composition [Mg# (~58); Ca_B

(1.87 apfu), (Na+K)_A (0.33 apfu), Al(IV) (0.97 apfu), Al(VI) (0.33 apfu) Fe(III) (0.46 apfu), F+Cl (0.21 wt.%); Table 4.3b], showing the local effect of alteration.

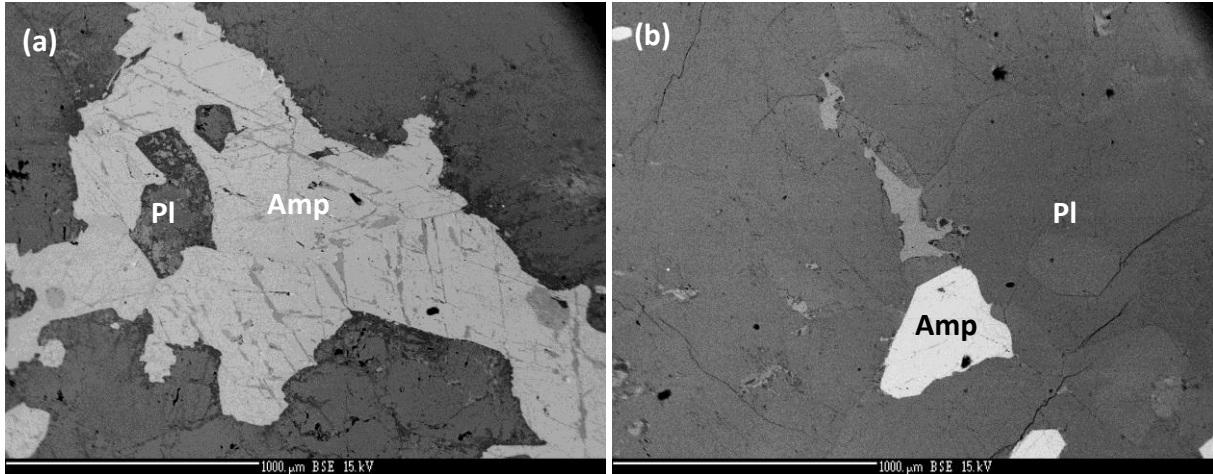


Figure 4.9. Representative BSE-SEM images illustrating the better preservation of primary magmatic amphibole in anorthosite, relative to ultramafic rocks, from the Lechana layered intrusion. The textural relation of amphibole with plagioclase inclusion **(a)** and vice versa **(b)** supports the primary magmatic nature of amphibole.

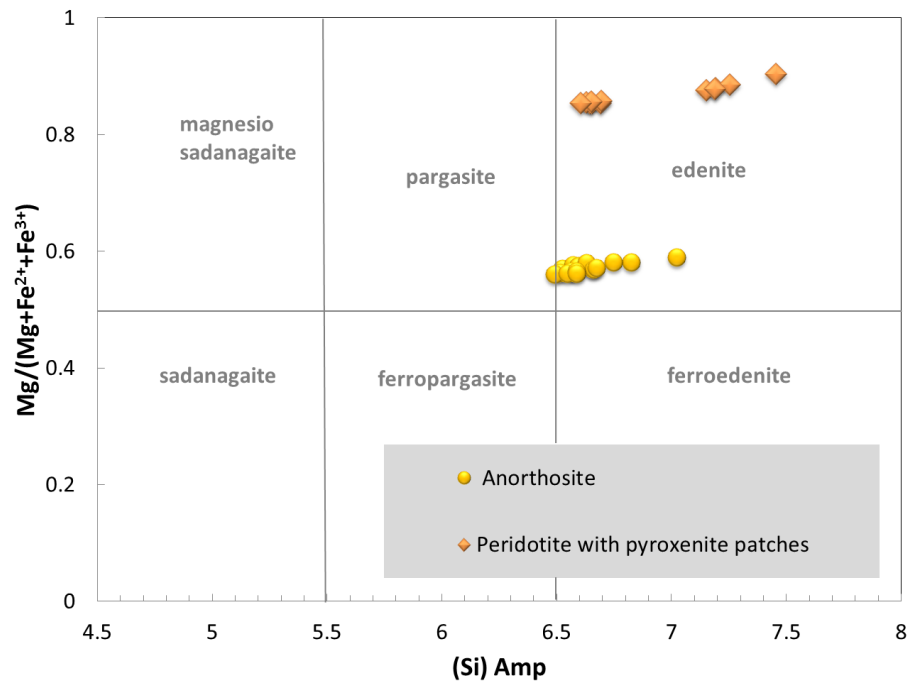


Figure 4.10. Mineral chemistry based compositional diagram for primary amphiboles from anorthosite and peridotite with pyroxenite patchy domains in the amphibole classification diagram of Leake et al. (1997). x-axis is in per formula unit. y-axis is in mole ratio.

Rock	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte	Perd-Pxynte
mineral	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp
SiO ₂	54,02	51,54	52,54	51,44	51,99	47,34	46,99	47,92	48,09	48	47,2	47
TiO ₂	0,43	0,65	0,65	0,78	0,73	0,8	0,75	0,78	0,87	0,79	0,77	0,81
Al ₂ O ₃	4,54	6,98	6,7	7,53	7,19	10,21	10,18	10,31	10,41	10,19	10,12	10,25
Cr ₂ O ₃	0,17	0,31	0,31	0,27	0,24	0,65	0,64	0,69	0,68	0,59	0,55	0,64
FeO	3,98	4,73	4,53	4,81	4,79	5,6	5,58	5,68	5,59	5,5	5,52	5,64
MnO	0,06	0,07	0,08	0,07	0,07	0,12	0,11	0,09	0,08	0,1	0,1	0,12
MgO	20,79	19,21	19,54	18,98	19,27	18,34	18,31	18,5	18,19	18,41	18,37	18,43
CaO	12,82	13,03	12,85	13,06	12,83	12,22	12,3	12,23	12,28	12,23	12,16	12,37
Na ₂ O	0,12	0,15	0,18	0,19	0,18	1,35	1,41	1,34	1,34	1,41	1,33	1,43
K ₂ O	0,02	0,03	0,04	0,04	0,04	0,23	0,27	0,22	0,25	0,23	0,25	0,24
NiO	0,13	0,14	0,16	0,16	0,15	0,08	0,12	0,09	0,08	0,12	0,08	0,08
Total	97,26	96,93	97,66	97,52	97,61	97,04	96,77	97,99	98,03	97,77	96,57	97,17
O=23												
Si	7,455	7,193	7,254	7,153	7,190	6,645	6,632	6,655	6,693	6,695	6,653	6,606
Al (IV)	0,545	0,807	0,746	0,847	0,810	1,355	1,368	1,345	1,307	1,305	1,347	1,394
Al (VI)	0,193	0,341	0,344	0,387	0,362	0,334	0,325	0,342	0,400	0,370	0,334	0,304
Fe(III)	0,418	0,354	0,376	0,318	0,412	0,657	0,659	0,660	0,582	0,626	0,651	0,663
Ti	0,045	0,068	0,067	0,082	0,076	0,084	0,080	0,081	0,091	0,083	0,082	0,086
Cr	0,019	0,034	0,034	0,030	0,026	0,072	0,071	0,076	0,075	0,065	0,061	0,071
Fe(II)	0,042	0,198	0,147	0,241	0,142	0,000	0,000	0,000	0,068	0,015	0,000	0,000
Mn	0,007	0,008	0,009	0,008	0,008	0,014	0,013	0,011	0,009	0,012	0,012	0,014
Mg	4,277	3,997	4,022	3,935	3,973	3,838	3,852	3,830	3,774	3,828	3,860	3,862
Ca	1,895	1,948	1,901	1,946	1,901	1,838	1,860	1,820	1,831	1,828	1,836	1,863
Na	0,032	0,041	0,048	0,051	0,048	0,367	0,386	0,361	0,362	0,381	0,363	0,390
K	0,004	0,005	0,007	0,007	0,007	0,041	0,049	0,039	0,044	0,041	0,045	0,043
Total	14,931	14,994	14,956	15,004	14,956	15,246	15,294	15,219	15,237	15,250	15,245	15,295

Table 4.3. (a) Representative mineral chemical data of amphiboles in peridotite with patchy pyroxenite domains (Perd-Pxynte) from the Lechana layered intrusion.

Rock	Anorthosite	Anorthosite	Anorthosite	Anorthosite	Anorthosite	Anorthosite	Anorthosite	Anorthosite	Anorthosite	Anorthosite	Anorthosite	Anorthosite	Anorthosite	Anorthosite	Anorthosite	Anorthosite
Mineral	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp	Amp
SiO ₂	44,01	44,58	44,5	45,34	43,91	44,8	45,02	45,24	45,18	44,79	44,12	45,55	44,75	44,55	46,41	46,07
TiO ₂	0,76	0,81	0,79	0,75	0,82	0,75	0,73	0,78	0,79	0,85	0,79	0,74	0,83	0,76	0,69	0,69
Al ₂ O ₃	11,06	10,67	11,22	10,27	11,57	10,87	10,92	10,35	10,33	11,16	10,99	10,13	10,93	10,75	9,3	9,5
Cr ₂ O ₃	0,01	0,02	0	0	0	0,03	0,02	0,01	0,02	0,03	0,01	0	0,02	0,02	0	0,01
FeO	15,36	15,32	15,81	15,65	15,57	15,23	15,38	15,31	15,47	15,59	15,64	15,64	15,54	15,68	15,19	15,43
MnO	0,24	0,27	0,3	0,23	0,25	0,25	0,25	0,26	0,28	0,26	0,26	0,26	0,25	0,3	0,27	0,27
MgO	11,37	11,63	11,36	11,56	11,07	11,48	11,53	11,8	11,4	11,29	11,14	11,64	11,26	11,2	11,77	11,93
CaO	11,79	12,03	12,03	12,1	11,83	11,92	11,9	12,02	11,97	12,02	11,95	11,92	12,18	11,97	12,07	12,1
Na ₂ O	1,2	1,17	1,09	1,09	1,24	1,18	1,1	1,02	1,11	1,03	1,13	1,13	1,14	1,11	0,93	0,98
K ₂ O	1,33	1,29	1,34	1,15	1,45	1,26	1,21	1,1	1,15	1,25	1,34	1,19	1,32	1,23	0,98	1,01
Cl	0,06	0,04	0,07	0,06	0,06	0,08	0,06	0,05	0,06	0,05	0,07	0,04	0,06	0,05	0,06	0,05
NiO	0,03	0,01	0,02	0	0,01	0,03	0,01	0	0,01	0	0,02	0,01	0,01	0,01	0,02	0,02
Total	97,39	98	98,77	98,41	97,89	98,05	98,27	98,08	97,88	98,52	97,64	98,41	98,43	97,81	97,78	98,57
O=23																
Si	6,530	6,574	6,520	6,658	6,494	6,599	6,597	6,634	6,664	6,565	6,549	6,676	6,591	6,591	6,828	6,751
Al (IV)	1,470	1,426	1,480	1,342	1,506	1,401	1,403	1,366	1,336	1,435	1,451	1,324	1,409	1,409	1,172	1,249
Al (VI)	0,463	0,428	0,457	0,436	0,511	0,486	0,483	0,423	0,460	0,493	0,472	0,426	0,488	0,465	0,440	0,392
Fe(III)	0,491	0,438	0,512	0,407	0,434	0,410	0,482	0,496	0,381	0,450	0,422	0,448	0,317	0,427	0,326	0,437
Ti	0,085	0,090	0,087	0,083	0,091	0,083	0,080	0,086	0,088	0,094	0,088	0,082	0,092	0,085	0,076	0,076
Cr	0,001	0,002	0,000	0,000	0,000	0,003	0,002	0,001	0,002	0,003	0,001	0,000	0,002	0,002	0,000	0,001
Fe(II)	1,414	1,452	1,425	1,515	1,491	1,465	1,403	1,381	1,527	1,461	1,519	1,469	1,597	1,513	1,543	1,454
Mn	0,030	0,034	0,037	0,029	0,031	0,031	0,031	0,032	0,035	0,032	0,033	0,032	0,031	0,038	0,034	0,034
Mg	2,515	2,557	2,481	2,531	2,441	2,521	2,519	2,580	2,507	2,467	2,465	2,543	2,472	2,470	2,581	2,606
Ca	1,874	1,901	1,888	1,904	1,874	1,881	1,868	1,888	1,892	1,887	1,900	1,872	1,922	1,897	1,902	1,900
Na	0,345	0,334	0,310	0,310	0,356	0,337	0,312	0,290	0,317	0,293	0,325	0,321	0,326	0,318	0,265	0,278
K	0,252	0,243	0,250	0,215	0,274	0,237	0,226	0,206	0,216	0,234	0,254	0,222	0,248	0,232	0,184	0,189
Total	15,471	15,478	15,448	15,429	15,504	15,455	15,407	15,384	15,425	15,414	15,479	15,415	15,495	15,448	15,351	15,367

Table 4.3. (b) Representative mineral chemical data of amphiboles in anorthosite from the Lechana layered intrusion.

On the other hand, amphiboles from peridotite show variable effect of serpentinization, with wider ranges of Mg# of ~85 to 92, Ca_B of 1.9 to 2.2 apfu, (Na+K)_A of 0.04 to 0.26 apfu, Ti of 0.03 to 0.08 apfu, Al(IV) of 0.75 to 1.27 apfu, Al(VI) of 0.19 to 0.39 apfu, Fe(III) of 0.32 to

1.49 apfu, Fe(II) of 0.04 to 0.24 apfu and F+Cl content of 0.02 to 0.14 wt.% (Table 4.3c). Two groupings were found – one that is partially serpentinized and the other intensively serpentinized – in correspondence with the observed petrography. Application of isocon mass balance exercise indicates similar gain/loss pattern for partial and intensive serpentinized amphibole compositions, with gain of Cr₂O₃, NiO and MgO, and loss of K₂O, Cl, V₂O₃, MnO, FeO, ZnO, Na₂O, Al₂O₃, TiO₂ and SiO₂ (in decreasing order) (Fig. 4.11).

Rock mineral	Peridotite Amp	Peridotite Amp	Peridotite Amp	Peridotite Amp	Peridotite Amp	Peridotite Amp	Peridotite Amp	Peridotite Amp	Peridotite Amp	Peridotite Amp	Peridotite Amp	Peridotite Amp	Peridotite Amp	Peridotite Amp	Peridotite Amp
SiO ₂	42,93	43,46	42,31	41,68	43,26	41,78	41,34	40,92	37,91	38,58	39,19	35,12	35,42	31,85	32,14
TiO ₂	0,54	0,54	0,47	0,52	0,5	0,48	0,44	0,49	0,5	0,45	0,5	0,49	0,43	0,43	0,41
Al ₂ O ₃	6,32	6,98	6,59	6,97	6,63	5,8	6,06	6,27	5,92	5,82	6,46	5,96	5,89	5,4	4,99
Cr ₂ O ₃	0,38	0,5	0,46	0,5	0,43	0,38	0,4	0,43	0,35	0,38	0,4	0,43	0,39	0,4	0,37
FeO	5,24	5,7	5,4	5,58	5,39	4,9	5,08	5,22	5,17	5,12	5,5	5,11	5,05	4,81	4,7
MnO	0,12	0,11	0,09	0,09	0,12	0,12	0,1	0,11	0,11	0,09	0,09	0,07	0,08	0,1	0,1
MgO	18,35	18,05	18,05	17,97	18,19	18,13	18,11	17,95	17,01	17,12	17,21	16,25	16,24	15,36	15,71
CaO	12,2	12	11,83	11,98	11,98	11,98	11,81	11,72	11,39	11,28	11,67	10,91	10,98	10,57	10,14
Na ₂ O	0,54	0,52	0,53	0,59	0,52	0,46	0,49	0,54	0,54	0,52	0,56	0,54	0,54	0,54	0,51
K ₂ O	0,16	0,27	0,24	0,24	0,24	0,18	0,21	0,22	0,23	0,22	0,21	0,24	0,22	0,22	0,21
NiO	0,05	0,06	0,06	0,06	0,09	0,05	0,07	0,08	0,06	0,04	0,04	0,06	0,06	0,05	0,02
Total	86,88	88,31	86,07	86,24	87,42	84,27	84,24	84,01	79,26	79,75	82,01	75,2	75,34	69,85	69,42
O=23															
Si	6,730	6,706	6,684	6,591	6,734	6,747	6,679	6,630	6,544	6,603	6,546	6,393	6,440	6,287	6,325
Al (IV)	1,168	1,269	1,227	1,299	1,216	1,104	1,154	1,197	1,204	1,174	1,272	1,279	1,262	1,256	1,157
Al (VI)	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	0,000
Fe(III)	0,687	0,735	0,713	0,738	0,702	0,662	0,686	0,707	0,746	0,733	0,768	0,778	0,768	0,794	0,773
Ti	0,064	0,063	0,056	0,062	0,059	0,058	0,053	0,060	0,065	0,058	0,063	0,067	0,059	0,064	0,061
Cr	0,047	0,061	0,057	0,063	0,053	0,049	0,051	0,055	0,048	0,051	0,053	0,062	0,056	0,062	0,058
Fe(II)	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	0,000
Mn	0,016	0,014	0,012	0,012	0,016	0,016	0,014	0,015	0,016	0,013	0,013	0,011	0,012	0,017	0,017
Mg	4,289	4,152	4,251	4,236	4,221	4,365	4,362	4,336	4,377	4,368	4,286	4,410	4,402	4,520	4,609
Ca	2,049	1,984	2,002	2,029	1,998	2,073	2,044	2,034	2,106	2,068	2,088	2,128	2,139	2,235	2,138
Na	0,164	0,156	0,162	0,181	0,157	0,144	0,153	0,170	0,181	0,173	0,181	0,191	0,190	0,207	0,195
K	0,032	0,053	0,048	0,048	0,048	0,037	0,043	0,045	0,051	0,048	0,045	0,056	0,051	0,055	0,053
Total	15,245	15,192	15,213	15,259	15,202	15,254	15,241	15,249	15,338	15,289	15,314	15,374	15,380	15,497	15,385

Table 4.3. (c) Representative mineral chemical data of amphiboles in peridotite (serpentinized) from the Lechana layered intrusion.

4.4.1. Primary versus secondary nature of amphibole

The primary versus secondary (metamorphic) nature of the amphiboles present in the peridotite-pyroxenite-anorthosite was evaluated using their mineral chemical characteristics. In the Ca+Na+K versus Si diagram of Giret et al. (1980), amphibole compositions from anorthosite and peridotite with patchy pyroxenite domains fall in the

field of primary magmatic amphiboles (Fig. 4.12a). Amphiboles from peridotite fall in the field of secondary amphiboles (Fig. 4.12a).

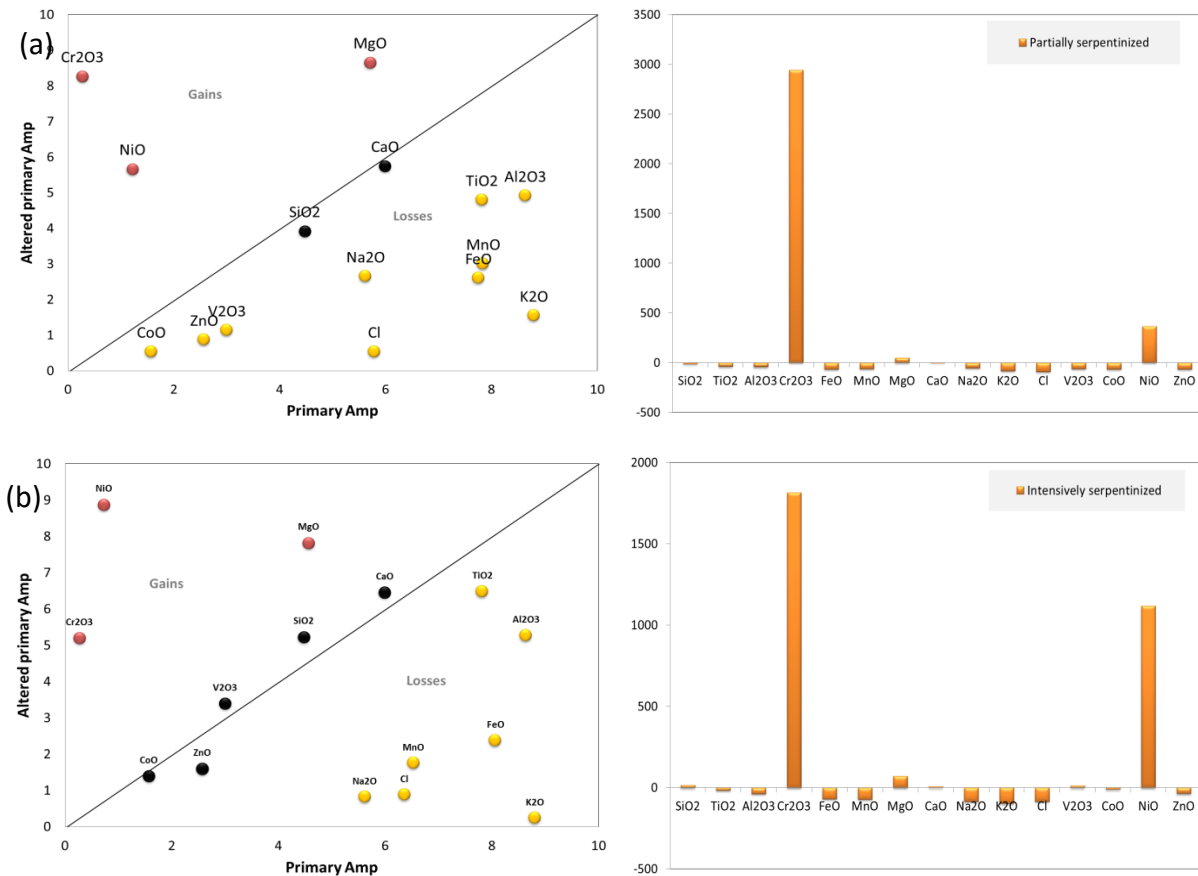


Figure 4.11. Representative isocon plots (left) and elemental histograms (right) illustrating elements gained and lost from amphibole affected by partial (a) and intensive (b) serpentinization.

As the complex mineral structure of amphibole often makes it difficult to distinguish unambiguously if it is of magmatic, metamorphic, hydrothermal or metasomatic origin (e.g., Martin, 2007; Schumacher, 2007), the limitations of the discrimination fields in Fig. 4.12a needs to be acknowledged. The different trends of amphibole compositions were further explored with plots using TiO_2 , $(\text{Na}+\text{K})_A$, Al(IV) , $(\text{Na}/\text{Ca}+\text{Na})$ and $(\text{Al}/\text{Si}+\text{Al})$; the element concentrations generally considered sensitive to temperature (Gilbert et al., 1982). In Figs.

4.12b to d, amphibole compositions from anorthosite and peridotite with patchy pyroxenite domains fall closer to the primary trend. In comparison, amphibole compositions from the highly altered (sericitized) anorthosite and peridotite affected by serpentinization fall along the trend of secondary amphiboles in Figs. 4.12a to d. This shift in trend is likely due to the effect of alteration.

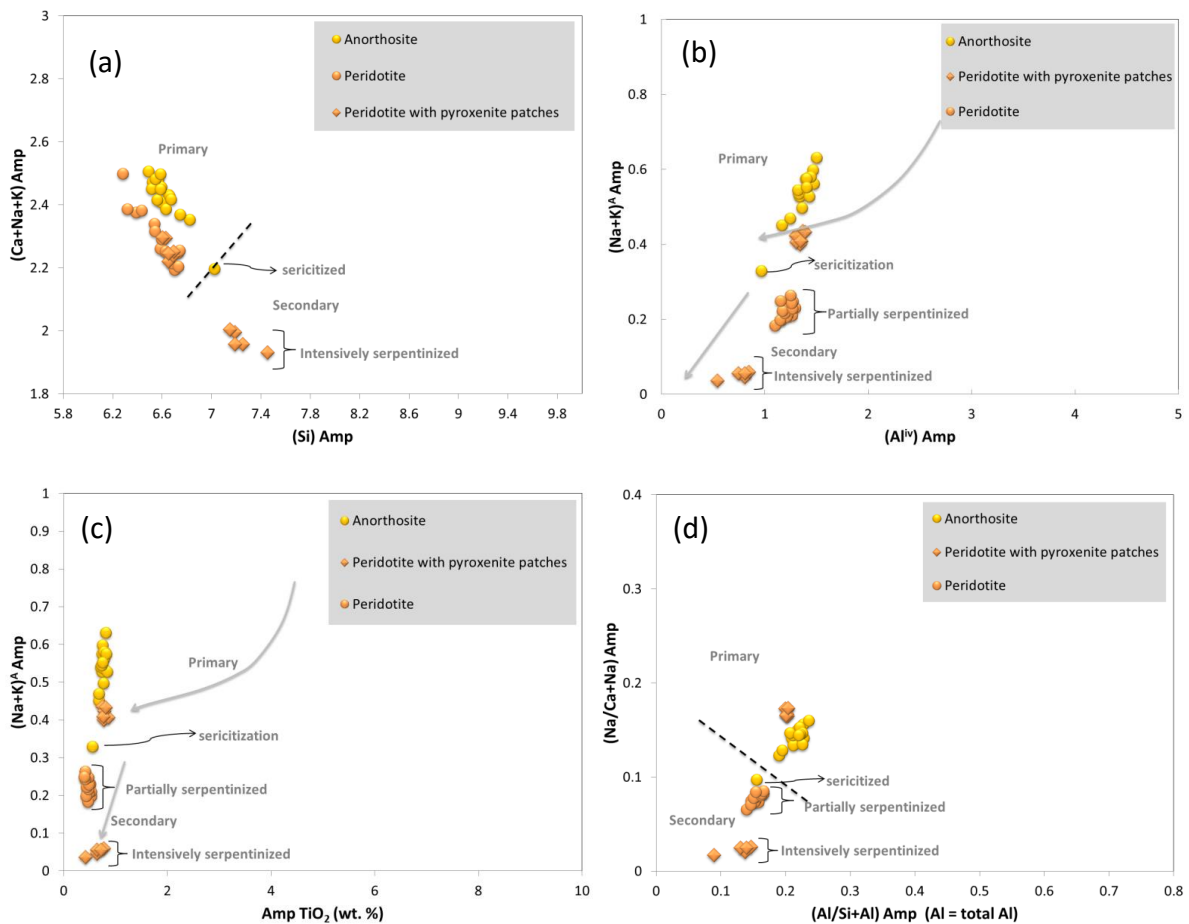


Figure 4.12. Mineral chemistry based diagrams evaluating the primary versus secondary trend of amphiboles in peridotite with patchy pyroxenite domains, peridotite affected by serpentinization, and anorthosite from the Lechana layered intrusion. Amphibole composition affected by sericitization is indicated separately. Ca+Na+K (apfu) versus Si (apfu) (a); Occupancy of Na+K in A-site versus occupancy of Al in tetrahedral site (b), and TiO₂ content (wt.%) (c); (Na/Ca+Na) versus Al/(Si+Al) (d). The fields in (a) are modified from Giret et al. (1980), while the trend lines in (b) and (c) are modified from Molina et al. (2009). The dividing line in (d) is drawn based on the trends observed in (a) to (c).

4.5. Plagioclase

Plagioclase composition in anorthosite from the Lechana layered intrusion has anorthite [An (=Ca/(Ca+Na+K))] contents varying from An₅₂ to An₆₃ (Fig. 4.13). The Ca-rich compositions were obtained from plagioclase inclusions in amphibole (Fig. 4.9b). Na₂O content ranges from 4.2 to 5.41 wt.%, while K₂O content ranges from 0.12 to 0.33 wt.% (Table 4.4).

Rock mineral	Anorthosite PI	Anorthosite PI	Anorthosite PI	Anorthosite PI	Anorthosite PI	Anorthosite PI	Anorthosite PI	Anorthosite PI	Anorthosite PI	Anorthosite PI
SiO ₂	56,18	56,36	56,61	54,68	55,41	55,43	55,08	55,78	55,82	52,65
TiO ₂	0	0,01	0	0	0,02	0	0	0	0	0,02
Al ₂ O ₃	28	27,97	28,09	28,62	28,33	28,35	28,51	28,43	28,51	29,43
FeO	0,1	0,08	0,11	0,1	0,11	0,12	0,1	0,08	0,13	0,16
MnO	0,02	0	0	0	0,01	0,01	0	0	0,01	0
MgO	0,01	0,01	0,01	0,02	0,01	0,01	0	0,01	0,01	0,01
CaO	10,91	10,95	11	11,79	11,45	11,35	11,58	11,41	11,51	13,12
Na ₂ O	5,31	5,41	5,39	4,83	5,07	5,07	4,92	5,17	5,02	4,2
K ₂ O	0,33	0,28	0,12	0,29	0,33	0,26	0,31	0,22	0,27	0,22
Total	100,97	101,09	101,44	100,36	100,78	100,68	100,61	101,13	101,36	99,83
O=8										
Si	2,510	2,513	2,515	2,463	2,484	2,486	2,475	2,489	2,487	2,396
Al	1,475	1,470	1,471	1,520	1,497	1,499	1,510	1,495	1,497	1,579
Ti	0,000	0,000	0,000	0,000	0,001	0,000	0,000	0,000	0,000	0,001
Fe	0,004	0,003	0,004	0,004	0,004	0,005	0,004	0,003	0,005	0,006
Mn	0,001	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Mg	0,001	0,001	0,001	0,001	0,001	0,001	0,000	0,001	0,001	0,001
Ca	0,522	0,523	0,524	0,569	0,550	0,546	0,558	0,546	0,550	0,640
Na	0,460	0,468	0,464	0,422	0,441	0,441	0,429	0,447	0,434	0,371
K	0,019	0,016	0,007	0,017	0,019	0,015	0,018	0,013	0,015	0,013
Total	4,992	4,994	4,985	4,996	4,997	4,992	4,993	4,993	4,989	5,006
Or	1,88	1,58	0,68	1,65	1,87	1,49	1,77	1,25	1,54	1,25
Ab	45,95	46,46	46,68	41,87	43,65	44,04	42,70	44,49	43,43	36,22
An	52,17	51,96	52,64	56,48	54,48	54,48	55,53	54,26	55,03	62,53

Table 4.4. Representative mineral chemical data of plagioclase feldspar in anorthosite from the Lechana layered intrusion.

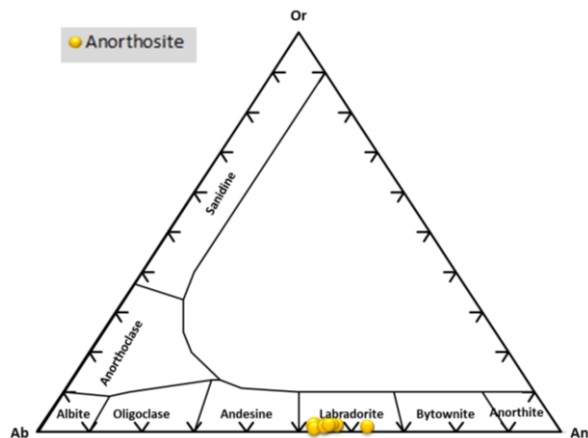


Figure 4.13. Mineral chemistry based compositional diagram for plagioclase from anorthosite in the ternary feldspar classification diagram.

4.6. Cr-spinel and Cr-magnetite

Spinel group minerals in the ultramafic rocks of the Lechana layered intrusion are represented by Cr-spinel and Cr-magnetite. Their mineral chemistry were respectively characterized with the consideration of the possible use of Cr-spinel compositions to infer likely tectonic setting of the rocks, and the occurrence of prominent magnetite-bearing layers associated with peridotite-pyroxenite associations (see Fig. 2.5f and 3.8).

Spinel in peridotite has higher Cr₂O₃ (11.88-16.68 wt.%) contents, Cr# (molar Cr# = 100 X Cr/(Cr+Al)) (~19-25) and Fe³⁺# (molar Fe³⁺# = 100 X Fe³⁺/(Fe³⁺+Cr+Al)) (~13-17) values than those in peridotite with patchy pyroxenite domains (Cr₂O₃ = 8.49-9.99 wt.%, Cr# = ~10-12; Fe³⁺# = ~7-9 (Fig. 4.14a; Table 4.5). The Cr-spinels from the two ultramafic rocks also differ in the contents of other elements, with peridotite having higher Ti (0.03-0.05 apfu), Mn (0.05-0.06 apfu), Fe(III) (2.09-2.66 apfu) and Fe(II) (3.76-4.29 apfu), and lower Al (10.09-11.05 apfu) and Mg (3.62-4.18 apfu) than peridotite with patchy pyroxenite domains (Ti = 0.01-0.02 apfu, Al = 13.03-13.52 apfu, Mn = 0.03-0.04 apfu, Fe(III) = 0.97-1.3 apfu, Fe(II) = 2.81-3.13 apfu, Mg = 4.76-5.11 apfu) (Table 4.5). In terms of Cr³⁺ – Fe³⁺ – Al³⁺ systematics, the Cr-spinels from the Lechana layered intrusion falls in the field of spinels whose composition was affected by high-grade metamorphism (Fig. 4.14b).

The Cr₂O₃ contents and Fe³⁺# values of magnetite in peridotite (6.46-10.83 wt.%; ~78-86) and peridotite with patchy pyroxenite domains (6.69-10.83 wt.%; ~78-83) are comparable. In comparison, Cr# values are higher in peridotite with patchy pyroxenite domains (~73-89) than in the peridotite (~68-72) (Fig. 4.14a; Table 4.6). The Cr-magnetites from the two

ultramafic rocks also differ in the contents of other elements, with peridotite having higher Ti (0.62-0.84 apfu), Al (0.76-1.29 apfu), Fe(II) (7.81-8.15 apfu) and Mg (0.52-1.33 apfu), and lower Mn (0.08 apfu) and Fe(III) (9.27-12.06 apfu) than peridotite with patchy pyroxenite domains (Ti = 0.12-0.34 apfu, Al = 0.25-0.75 apfu, Mn = 0.04-0.1 apfu, Fe(III) = 11.86-13.43 apfu, Fe(II) = 7.74-7.96 apfu, Mg = 0.18-0.5 apfu) (Table 4.6).

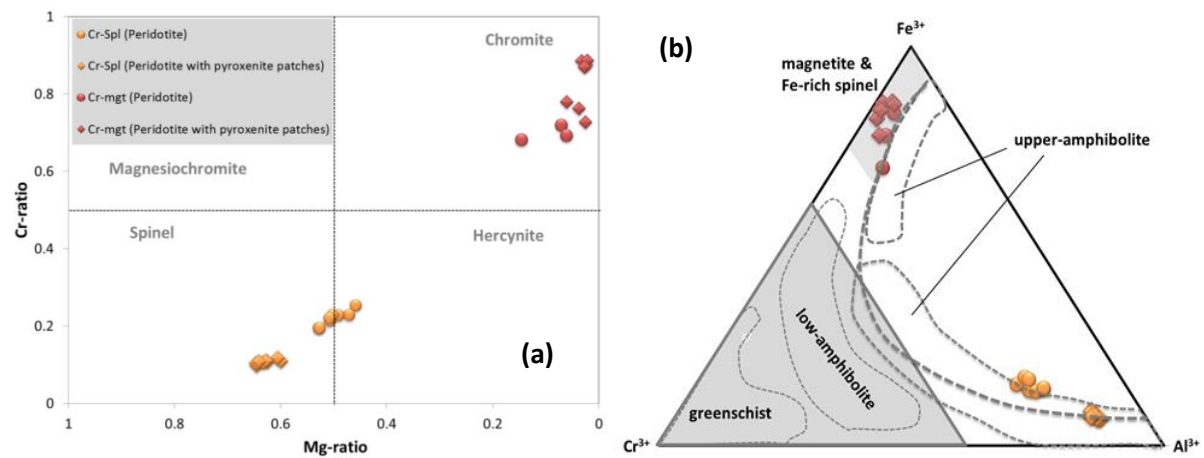


Figure 4.14. Cr-spinel and Cr-magnetite compositions from the peridotite-pyroxenite of the Lechana layered intrusion in terms of $\text{Cr}\#[\text{Cr}/(\text{Cr}+\text{Al})]$ versus $\text{Mg}\#[\text{Mg}/(\text{Mg}+\text{Fe}^{+2})]$ mole ratio plot **(a)** and the $\text{Cr}^{3+} - \text{Fe}^{3+} - \text{Al}^{3+}$ ternary diagram **(b)**. Fields in (a) are from Dick and Bullen (1984), and those in (b) indicating the likely effect of different metamorphic-facies overprint conditions on the spinel composition is from Saumur and Hattori (2013) and references therein.

4.7. Primary igneous assemblages in rocks of the Lechana layered intrusion

Based on the observed inclusion-host textural relations, and their compositional characteristics, the following assemblages are inferred for the different rocks.

Peridotite: olivine-orthopyroxene-amphibole-Cr-spinel-Cr-magnetite

Pyroxenite: olivine-orthopyroxene-amphibole

Anorthosite: plagioclase-amphibole

Sample mineral	Perd-Pxynte Cr-Spl	Perd-Pxynte Cr-Spl	Perd-Pxynte Cr-Spl	Perd-Pxynte Cr-Spl	Perd-Pxynte Cr-Spl	Perd-Pxynte Cr-Spl	Perd-Pxynte Cr-Spl	Perd-Pxynte Cr-Spl	Peridotite Cr-Spl	Peridotite Cr-Spl	Peridotite Cr-Spl	Peridotite Cr-Spl	Peridotite Cr-Spl	Peridotite Cr-Spl	Peridotite Cr-Spl	Peridotite Cr-Spl	Peridotite Cr-Spl
SiO ₂	0,01	0,03	0,01	0,02	0,02	0	0,02	0,01	0,04	0,03	0,03	0,02	0,02	0,03	0,03	0,03	0,05
TiO ₂	0,09	0,04	0,05	0,07	0,12	0,07	0,07	0,06	0,23	0,2	0,2	0,16	0,13	0,22	0,2	0,13	0,13
Al ₂ O ₃	50,48	52,42	52,4	51,46	49,65	50,48	50,83	50,61	35,48	33,17	35,25	35,59	33,49	30,81	31,7	33,18	33,18
Cr ₂ O ₃	9,08	8,49	9,03	9,05	9,06	9,33	9,19	9,99	15,63	16,68	15,47	14,36	12,05	13,61	13,34	11,88	11,88
FeO	22,85	20,67	20,89	21,39	24,11	23,15	21,45	22,68	30,95	30,94	28,94	27,69	25,43	28,27	27,91	25,34	25,34
MnO	0,18	0,18	0,16	0,17	0,18	0,2	0,16	0,19	0,27	0,29	0,26	0,23	0,19	0,25	0,24	0,19	0,19
NiO	0,57	0,68	0,59	0,5	0,74	0,68	0,58	0,49	0,2	0,15	0,16	0,21	0,18	0,17	0,19	0,18	0,18
MgO	15,06	15,67	15,76	15,27	14,33	15,2	15,43	14,57	9,96	9,41	10,18	10,37	10,01	9,52	9,72	9,9	9,9
ZnO	0,35	0,32	0,39	0,38	0,26	0,31	0,32	0,35	0,42	0,36	0,39	0,37	0,34	0,23	0,2	0,34	0,34
V ₂ O ₃	0,07	0,11	0,03	0,07	0,1	0,08	0,05	0,09	0,1	0,1	0,11	0,12	0,04	0,1	0,07	0,07	0,07
CaO	0,01	0,01	0,01	0,01	0	0	0	0	0	0	0,04	0,02	0	0	0,02	0,02	0,02
Total	98,8	98,74	99,44	98,45	98,64	99,5	98,19	99,14	93,35	91,4	91,1	89,21	82,03	83,28	83,69	81,33	81,33
O=4																	
Si	0,002	0,007	0,002	0,004	0,004	0,000	0,004	0,002	0,010	0,008	0,008	0,005	0,006	0,008	0,008	0,014	0,014
Ti	0,015	0,007	0,008	0,012	0,020	0,012	0,012	0,010	0,043	0,039	0,038	0,031	0,027	0,046	0,042	0,028	0,028
Al	13,125	13,518	13,429	13,351	13,035	13,051	13,239	13,160	10,483	10,093	10,610	10,867	11,047	10,185	10,384	11,030	11,030
Cr	1,584	1,469	1,552	1,575	1,596	1,618	1,606	1,743	3,098	3,405	3,124	2,941	2,667	3,018	2,931	2,649	2,649
Fe(III)	1,245	0,968	0,992	1,029	1,302	1,294	1,114	1,057	2,292	2,388	2,151	2,095	2,211	2,664	2,568	2,221	2,221
Fe(II)	2,971	2,814	2,806	2,908	3,189	2,953	2,850	3,127	4,196	4,292	4,029	3,904	3,741	3,967	3,919	3,756	3,756
Mn	0,034	0,033	0,029	0,032	0,034	0,037	0,030	0,036	0,057	0,063	0,056	0,050	0,045	0,059	0,056	0,045	0,045
Mg	4,953	5,112	5,109	5,012	4,759	4,971	5,084	4,793	3,723	3,622	3,876	4,005	4,177	3,981	4,028	4,163	4,163
Zn	0,057	0,052	0,063	0,062	0,043	0,050	0,052	0,057	0,078	0,069	0,074	0,071	0,070	0,048	0,041	0,071	0,071
Total	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000
Cr#	0,11	0,10	0,10	0,11	0,11	0,11	0,11	0,12	0,23	0,25	0,23	0,21	0,19	0,23	0,22	0,19	0,19
Mg#	0,63	0,64	0,65	0,63	0,60	0,63	0,64	0,61	0,47	0,46	0,49	0,51	0,53	0,50	0,51	0,53	0,53
Fe ³⁺ #	0,08	0,07	0,07	0,07	0,09	0,09	0,07	0,07	0,15	0,15	0,14	0,13	0,14	0,17	0,16	0,14	0,14

Table 4.5. Representative mineral chemical data of Cr-spinel in peridotite with patchy pyroxenite domains (Perd-Pxynte) and peridotite from the Lechana layered intrusion.

Sample mineral	Perd-Pxynte Cr-mgt	Perd-Pxynte Cr-mgt	Perd-Pxynte Cr-mgt	Perd-Pxynte Cr-mgt	Perd-Pxynte Cr-mgt	Perd-Pxynte Cr-mgt	Perd-Pxynte Cr-mgt	Peridotite Cr-mgt	Peridotite Cr-mgt	Peridotite Cr-mgt
SiO ₂	0,07	0,03	0,05	0,06	0,03	0,04	0,06	2,14	0,02	0,03
TiO ₂	0,53	0,82	0,71	0,69	1,45	0,7	0,6	2,55	3,41	2,81
Al ₂ O ₃	0,7	0,97	0,77	0,9	2,07	1,42	1,69	3,4	2,32	1,93
Cr ₂ O ₃	8,06	10,05	8,89	8,89	10,9	6,8	6,69	10,83	8,81	6,46
V ₂ O ₃	0,22	0,24	0,22	0,26	0,21	0,23	0,3	0,24	0,29	0,22
FeO	82,37	80,15	81,81	81,39	76,31	82,4	81,83	63,38	69,7	72,53
MnO	0,17	0,21	0,15	0,18	0,38	0,25	0,2	0,31	0,29	0,28
MgO	0,56	0,42	0,39	0,48	1,09	0,66	0,44	2,77	1,25	1,05
CaO	0,04	0,02	0,02	0,02	0	0	0	0,22	0,01	0
NiO	0,38	0,36	0,36	0,38	0,69	0,61	0,52	0,26	0,25	0,25
Total	93,16	93,37	93,39	93,34	93,23	93,21	92,39	86,68	86,41	85,64
O=32										
Si	0,022	0,009	0,015	0,019	0,009	0,012	0,019	0,690	0,007	0,010
Ti	0,123	0,190	0,165	0,160	0,335	0,162	0,140	0,618	0,844	0,703
Al	0,255	0,352	0,280	0,327	0,749	0,515	0,618	1,292	0,900	0,757
Cr	1,967	2,450	2,167	2,167	2,647	1,656	1,642	2,760	2,292	1,699
V	0,054	0,059	0,054	0,064	0,052	0,057	0,075	0,062	0,077	0,059
Fe(III)	13,434	12,740	13,139	13,084	11,863	13,423	13,347	9,270	11,030	12,060
Fe(II)	7,829	7,924	7,955	7,904	7,739	7,802	7,900	7,814	8,153	8,113
Mn	0,044	0,055	0,039	0,047	0,099	0,065	0,053	0,085	0,081	0,079
Mg	0,258	0,193	0,179	0,221	0,499	0,303	0,204	1,331	0,613	0,521
Ca	0,013	0,007	0,007	0,007	0,000	0,000	0,000	0,076	0,004	0,000
Total	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000
Cr#	0,89	0,87	0,89	0,87	0,78	0,76	0,73	0,68	0,72	0,69
Mg#	0,03	0,02	0,02	0,03	0,06	0,04	0,03	0,15	0,07	0,06
Fe ³⁺ #	0,86	0,82	0,84	0,84	0,78	0,86	0,86	0,70	0,78	0,83

Table 4.6. Representative mineral chemical data of Cr-magnetite in peridotite with patchy pyroxenite domains (Perd-Pxynte) and peridotite from the Lechana layered intrusion.

4.8. Thermometric constraints

In the studied rocks, amphibole is the only primary mineral that is least affected by alteration. The use of amphibole composition as a geothermometer is generally accepted, while its potential as a geobarometer is often limited and continues to be debated (e.g., Erdmann et al., 2014). Temperature estimates from amphibole compositions were attempted using the formulations given in Ridolfi et al. (2010), which is recommended for amphiboles crystallized from hydrous magmas (see discussion in chapter 6). The equation for estimating temperature is,

$$T (^{\circ}\text{C}) = -151.487\text{Si}^* + 2041; \text{Si}^* = \text{Si} + ([^{4}\text{Al}]/15) - (2[^{4}\text{Ti}] - ([^{6}\text{Al}]/2) - ([^{6}\text{Ti}]/1.8) + (\text{Fe}^{3+}/9) + (\text{Fe}^{2+}/3.3) + (\text{Mg}/26) + ([^{\text{B}}\text{Ca}]/5) + ([^{\text{B}}\text{Na}]/1.3) - ([^{\text{A}}\text{Na}]/15) + ([^{\text{A}}]/2.3)$$

while that for estimating melt H₂O content is,

$$\text{H}_2\text{O melt (wt.\%)} = 5.215[^{6}\text{Al}^*] + 12.28; [^{6}\text{Al}^*] = ([^{4}\text{Al}]/13.9) - ((\text{Si} + [^{6}\text{Ti}])/5) - ([^{\text{C}}\text{Fe}^{2+}]/3) - (\text{Mg}/1.7) + (([^{\text{B}}\text{Ca}] + [^{\text{A}}]/1.2)) + ([^{\text{A}}\text{Na}]/2.7) - 1.56 \text{ K} - (\text{Fe}\# / 1.6) \text{ [from Ridolfi et al. (2010)]}.$$

Calculated temperatures using amphibole compositions from peridotite with patchy pyroxenite domains range from 892 to 902°C (±22°C). The corresponding calculated water contents in the melt vary from 6.4 to 6.9 (± 0.4) wt.%. Calculated temperatures using amphibole compositions from anorthosite are lower, ranging from 833 to 887°C (±22°C). The corresponding calculated water contents in the melt vary from 6.4 to 7.2 (± 0.4) wt.%.

Chapter 5

Whole-rock geochemical characteristics

5.1. Introduction

This chapter presents whole rock characteristics of the mafic (anorthosite) and ultramafic rocks (peridotite, pyroxenite), belonging to the Lechana layered intrusion. Similar data on amphibolite, which is closely associated with peridotite-pyroxenite-anorthosite and considered as the earliest phase of the magmatic event that formed the layered intrusion, is also presented. Considering the prominent peridotite-pyroxenite association and its association with magnetite mineralization, a number of composite rocks (peridotite with patchy pyroxenite domains) were also subjected to geochemical analyses. Major, trace and rare-earth element data obtained for all the rock samples are given in Table 5.1.

5.2. Effect of alteration

Considering the sericitized/serpentinized nature of the studied rocks, it is important to first assess the effect of alteration on the chemistry. Loss on ignition (LOI) values is a good indicator of effect of alteration. Mafic rock (amphibolite, anorthosite) samples have LOI values <3 wt.% (Table 5.1), suggesting that the rocks have not been strongly hydrated or carbonated. On the other hand, ultramafic rocks (peridotite, pyroxenite) have higher LOI values [5.7-10.2 wt.% (peridotite); 3.7-8.7 (pyroxenite); 4.7-7.5 (peridotite with pyroxenite patchy domains)] (Table 5.1).

Rock type:	Peridotite					Peridotite with pyroxenite patches				Pyroxenite	
Sample ID	TH1	MK1	LH1	LP1	LP3	MH1	MH2	MPD1	MPD2	LP1b	LP3b
SiO ₂	42,9	39,4	39,03	39,86	38,67	42,47	46,61	45,95	44,43	46,69	38,68
Al ₂ O ₃	4,7	3,68	3,31	4,67	4,92	4,18	1,78	5,33	4,86	4,15	4,71
Fe ₂ O ₃	12,4	14	11,82	12,64	12,95	12,23	11,54	10,88	10,53	12,44	14,08
MgO	29,1	30,9	31,46	28,22	29,16	29,17	32,11	28,09	29,96	28,7	29,88
CaO	3,16	2,95	2,17	3,77	3,13	2,71	1,86	2,33	1,63	2,65	2,19
Na ₂ O	0,29	0,1	0,14	0,09	0,08	0,05	0,13	0,03	0,01	0,06	0,05
K ₂ O	0,05	0,05	0,04	0,06	0,05	0,02	0,04	0,01	0,01	0,04	0,03
TiO ₂	0,24	0,18	0,17	0,28	0,29	0,22	0,08	0,25	0,18	0,24	0,27
P ₂ O ₅	0,01	0,01	0,01	0,01	0,02	0,01	0,05	0,02	0,01	0,01	0,01
MnO	0,16	0,17	0,16	0,14	0,14	0,15	0,17	0,15	0,15	0,22	0,16
Cr ₂ O ₃	0,62	0,6	0,785	0,478	0,472	0,667	0,641	0,646	0,595	0,479	0,516
LOI	5,7	7,2	10,2	9,1	9,4	7,5	4,7	5,6	6,9	3,7	8,7
Sum	99,5	99,4	99,44	99,49	99,47	99,47	99,92	99,49	99,47	99,48	99,46
Mg#	80,66	79,74	82,59	79,92	80,06	80,96	83,22	82,15	83,53	80,44	79,10
Ba	4	24	14	10	14	2	5	29	5	36	14
Ni	1262	1058	1270	1193	1272	1258	1514	1750	1736	845	1289
Sc	16	12	12	18	16	15	19	18	13	13	13
Be	<1	<1	<1	<1	3	<1	<1	<1	<1	<1	<1
Co	117	136	128,5	126	128	112,9	113,4	105,2	110,4	108,6	128,3
Cs	0,1	0,1	0,1	0,3	0,1	0,1	0,1	0,2	0,2	0,3	0,3
Ga	2,7	6,7	5,1	6,6	6,6	2,6	2,5	4,7	4,6	6,5	7,3
Hf	0,6	0,4	0,3	0,5	0,4	0,4	0,1	0,5	0,3	0,3	0,4
Nb	0,3	0,2	0,2	0,8	0,6	0,3	0,4	0,7	0,4	0,1	0,2
Rb	0,1	1,7	2,1	1,6	0,9	0,1	1,7	1,7	1,2	1,4	1,4
Sn	<1	<1	<1	<1	<1	<1	<1	<1	<1	1	1
Sr	35,5	9,7	6,7	29,4	27,5	14,3	5,1	3,3	2,1	23,4	17,6
Ta	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Th	0,3	0,3	0,4	0,7	1	0,3	0,2	0,3	0,3	0,7	0,3
U	0,1	0,1	0,1	0,2	0,2	0,1	0,1	0,1	0,1	0,1	0,1
V	99	84	74	101	99	90	77	108	84	100	103
W	0,5	0,5	0,5	0,6	0,5	0,5	0,5	0,9	0,5	0,5	1,9
Zr	16,3	14,5	13,4	24,4	23,5	15	3,6	13,5	9,8	13,7	14,7
Y	4,8	5,5	3,2	8,1	7,5	4,8	1,2	7	3,4	4,4	5,5
La	1,9	3,1	2,9	3,6	3,5	1,8	0,7	2,2	1,5	2	2,3
Ce	3,8	4,7	3,3	7,2	6,3	3,5	0,7	4,7	2,3	3,4	5
Pr	0,5	0,51	0,31	0,9	0,65	0,43	0,08	0,64	0,3	0,39	0,42
Nd	2,4	2	1,5	3,8	3,4	2	0,4	3,4	1,5	1,2	2,6
Sm	0,65	0,5	0,2	0,94	0,76	0,52	0,11	0,87	0,41	0,3	0,67
Eu	0,2	0,25	0,16	0,43	0,26	0,19	0,05	0,11	0,1	0,15	0,17
Gd	0,91	0,86	0,49	1,23	1,32	0,7	0,2	1,21	0,53	0,68	0,83
Tb	0,14	0,12	0,07	0,16	0,18	0,12	0,04	0,2	0,1	0,09	0,11
Dy	0,87	0,95	0,59	1,57	1,33	0,91	0,25	1,34	0,63	0,84	1,04
Ho	0,21	0,21	0,12	0,3	0,29	0,16	0,05	0,27	0,12	0,16	0,19
Er	0,56	0,56	0,39	0,93	0,92	0,5	0,19	0,74	0,41	0,42	0,45
Tm	0,09	0,07	0,03	0,17	0,1	0,07	0,03	0,11	0,06	0,04	0,07
Yb	0,59	0,71	0,4	0,8	0,77	0,52	0,16	0,68	0,41	0,51	0,58
Lu	0,08	0,06	0,04	0,11	0,1	0,07	0,04	0,11	0,06	0,06	0,06

t- total Fe as Fe₂O₃

Table 5.1. Representative major, trace and rare earth element data for ultramafic (peridotite, pyroxenite) and mafic (amphibolite, anorthosite) rocks from the Lechana area.

Rock type:	Amphibolite		Anorthosite				
Sample ID	LC2	MA1	LC3	VML4	LAG1	MAG2	AG5
SiO ₂	48,22	50,94	52,24	54,35	53,85	53,13	50,47
Al ₂ O ₃	14,86	17,55	19,62	26,35	26,51	25,09	26,23
Fe ₂ O _{3t}	9,38	9,05	6,14	1,43	1,2	2,49	1,95
MgO	4,67	6,55	4,34	0,85	0,37	1,08	1,11
CaO	17,03	10,33	10,23	10,72	10,33	9,77	10,86
Na ₂ O	1,99	2,94	3,44	4,34	3,71	3,8	3,62
K ₂ O	0,63	0,63	1,32	0,74	1,69	1,84	2,35
TiO ₂	0,98	0,43	0,2	0,06	0,08	0,29	0,35
P ₂ O ₅	0,06	0,02	0,01	0,01	0,02	0,11	0,12
MnO	0,33	0,15	0,1	0,02	0,02	0,03	0,03
Cr ₂ O ₃	0,055	0,004	0,018	0,012	0,017	0,002	0,01
LOI	1,6	1,2	2,2	1,1	2,2	2,3	2,8
Sum	99,83	99,84	99,87	99,96	99,97	99,94	99,92
Mg#	47,02	56,34	55,76	51,45	35,47	43,61	50,37
Ba	124	99	158	132	220	372	377
Ni	136	62	84	<20	<20	<20	<20
Sc	37	30	18	4	2	6	6
Be	3	<1	3	<1	2	<1	<1
Co	49	43,5	29,6	5,4	2,6	10,3	9
Cs	1,4	0,4	1,2	0,7	2,3	0,8	0,5
Ga	17	13,8	15	16,9	17,9	20,4	17,4
Hf	2	0,6	1	0,3	0,6	0,4	1,3
Nb	2,6	0,2	3,8	0,7	1,7	1,7	0,5
Rb	24,7	15,7	50,6	17,1	65	70,8	68,9
Sn	<1	<1	2	<1	<1	<1	<1
Sr	135	166,7	191,5	261,7	227,6	294,4	287
Ta	0,1	0,1	0,8	0,2	0,1	0,2	0,1
Th	1	0,5	3,1	0,2	1	3	0,9
U	0,2	0,2	1,7	0,3	0,6	1,9	0,6
V	253	156	82	26	22	63	63
W	1,9	0,7	0,8	0,7	0,5	0,7	0,5
Zr	70,3	19,3	21,1	11	16,9	12,5	51,2
Y	20,2	8,2	10,8	2,5	3,8	5,5	3,5
La	5,4	3,2	5,7	3,2	3,9	7,8	6,3
Ce	12,8	5,6	12,1	4,2	6	11,2	7,9
Pr	1,77	0,67	1,46	0,46	0,63	1,12	0,78
Nd	9,2	3,6	5,7	1,8	2,5	4,3	3
Sm	2,42	0,78	1,41	0,14	0,63	0,95	0,56
Eu	0,84	0,46	0,49	0,32	0,33	0,5	0,46
Gd	3,32	1,1	1,69	0,43	0,65	1	0,73
Tb	0,52	0,2	0,29	0,06	0,11	0,17	0,1
Dy	3,67	1,38	1,62	0,39	0,75	1,02	0,7
Ho	0,77	0,31	0,4	0,09	0,14	0,23	0,14
Er	2,13	0,96	1,13	0,2	0,43	0,64	0,51
Tm	0,3	0,11	0,14	0,04	0,06	0,09	0,06
Yb	2	0,89	1,06	0,26	0,42	0,58	0,33
Lu	0,27	0,12	0,14	0,02	0,06	0,08	0,05

Table 5.1. (continued)

Whole-rock geochemistry

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 (including serpentinized ones) fall below the filtering line (Fig. 5.1), considered as benchmark for delineating altered versus unaltered samples. Significantly, all the ultramafic rocks, including the serpentinized ones, fall below the serpentine filtering line in Fig. 5.1. Mafic rocks with minor chlorite, on the other hand, are least affected by serpentinization (Fig. 5.1).

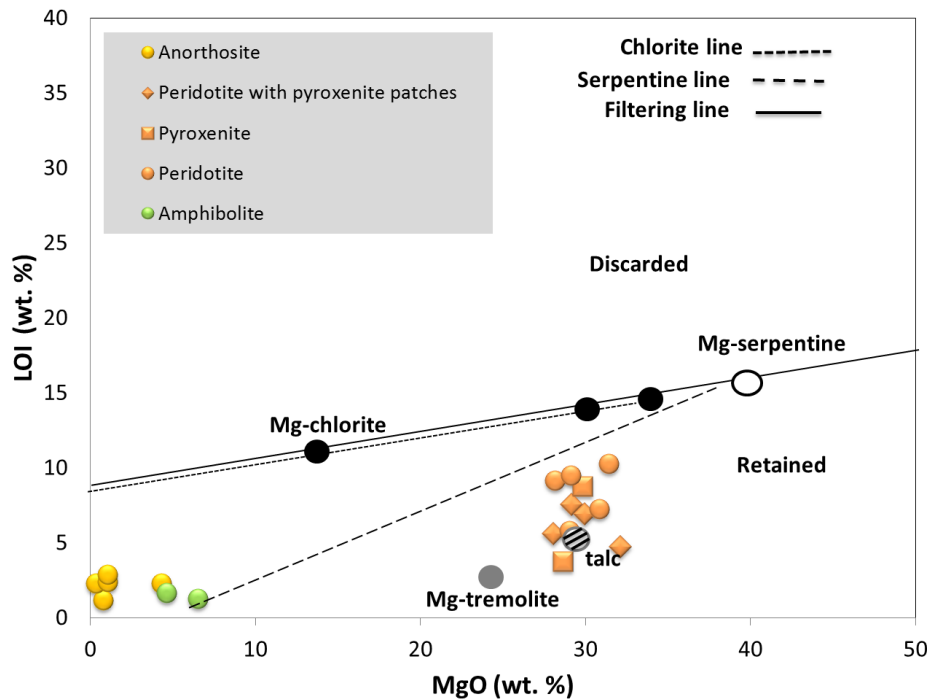


Figure 5.1. MgO vs. LOI (wt.%) addressing the alteration in the studied samples. All the studied samples fall below the filtering line, considered as benchmark for delineating altered versus unaltered samples. Black filled circles on the chlorite line represent stoichiometric Mg-Chlorites; Mg-serpentine composition is indicated by unfilled circle; grey 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).

As has been suggested by a number of studies on Archean ultramafic to mafic rocks, only samples for which the LOI is less than or equal to that in 100% serpentine $\pm$ chlorite $\pm$ talc (filtering line in Fig. 5.1; Deer et al., 1992) have been included for the geochemical characterization. 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 $\sim$ 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].

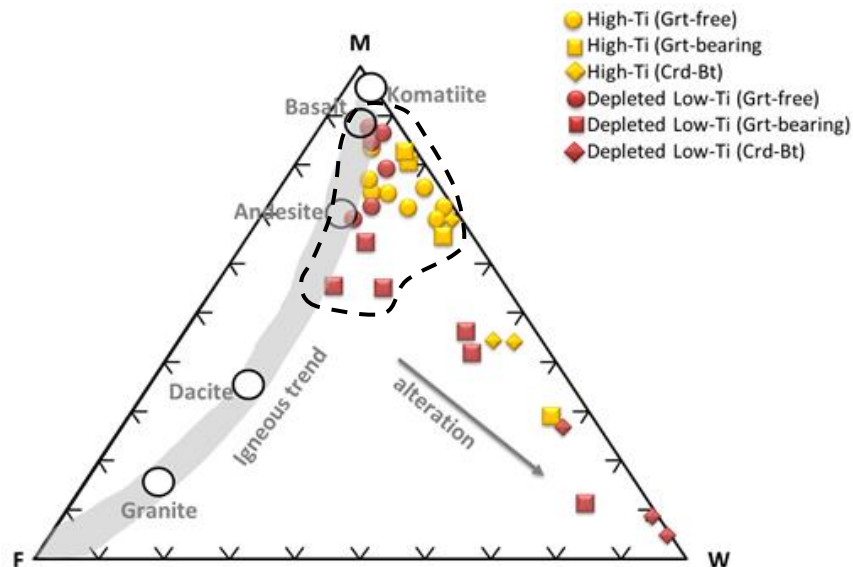


Figure 5.2. (a) $\sim$ 3.8 Ga mafic supracrustal lithologies from the Nuvvuagittuq greenstone belt, Canada [data from O’Neil et al. (2011)] in the MFW diagram of Ohta and Arai (2007). See Fig. 5.2 (b) for details on M, F and W.

Thus the MFW diagram can be used to discriminate the chemical elements representing original igneous chemical features from elements remobilized during post-magmatic alteration. Except one ultramafic sample, the rest of the studied samples from the Lechana layered intrusion fall closer to the igneous trend in the MFW diagram (Fig. 5.2b). Significantly, typical boninites (Crawford et al., 1989) fall closer to the least altered samples from the Lechana layered intrusion (Fig. 5.2b). The exercise illustrated in Figs. 5.1 and 5.2 is not fool proof and it is certainly acknowledged that alteration will have some effect on the chemistry of the rocks, especially major elements.

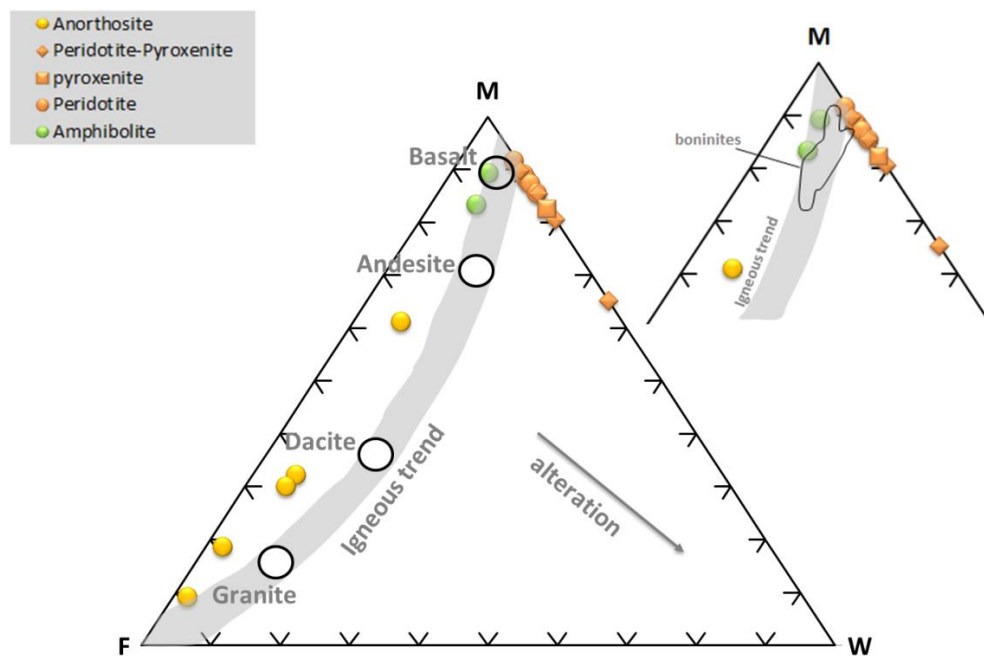


Figure 5.2. (b) Mafic and ultramafic rocks of the Lechana layered intrusion in the MFW diagram of Ohta and Arai (2007). Typical boninite field is from Crawford et al. (1989). Values plotted in the MFW diagram are: $\exp(F)$, $\exp(W)$, re-totaled to 100. Values for M, F and W calculation are normalized 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

Amphibolite is characterized by SiO₂ contents of 48.22 to 50.94 wt.%, MgO of 4.67 to 6.55 wt.%, Al₂O₃ of 14.86 to 17.55 wt.%, Fe₂O₃ of 9.05 to 9.38 wt.%, TiO₂ of 0.43 to 0.98 wt.% and CaO of 10.33 to 17.03 wt.%. Mg# ($100 \cdot \text{Mg} / (\text{Mg} + \text{Fe}^{2+})$) varies from ~47 to 56 (Table 5.1).

Anorthosite is characterized by SiO₂ contents of 50.47 to 54.35 wt.%, MgO of 0.37 to 4.34 wt.%, Al₂O₃ of 19.62 to 26.51 wt.%, Fe₂O₃ of 1.2 to 6.14 wt.%, TiO₂ of 0.06 to 0.35 wt.% and CaO of 9.77 to 10.86 wt.%. Mg# varies from ~35 to 56 (Table 5.1).

Peridotite is characterized by SiO₂ contents of 38.67 to 42.91 wt.%, MgO of 28.22 to 31.46 wt.%, Al₂O₃ of 3.31 to 4.92 wt.%, Fe₂O₃ of 11.82 to 14 wt.%, TiO₂ of 0.17 to 0.29 wt.% and CaO of 2.17 to 3.77 wt.%. Mg# varies from ~80 to 83 (Table 5.1).

Pyroxenite is characterized by SiO₂ contents of 38.68 to 46.69 wt.%, MgO of 28.7 to 29.88 wt.%, Al₂O₃ of 4.15 to 4.71 wt.%, Fe₂O₃ of 12.44 to 14.08 wt.%, TiO₂ of 0.24 to 0.27 wt.% and CaO of 2.19 to 2.65 wt.%. Mg# varies from ~79 to 80 (Table 5.1).

Peridotite with patchy pyroxenite domains is characterized by SiO₂ contents of 42.47 to 46.61 wt.%, MgO of 28.09 to 32.11 wt.%, Al₂O₃ of 1.78 to 5.33 wt.%, Fe₂O₃ of 10.53 to 12.23 wt.%, TiO₂ of 0.08 to 0.25 wt.% and CaO of 1.63 to 2.71 wt.%. Mg# varies from ~81 to 84 (Table 5.1).

To understand which mineral phases control the composition of the rock, 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).

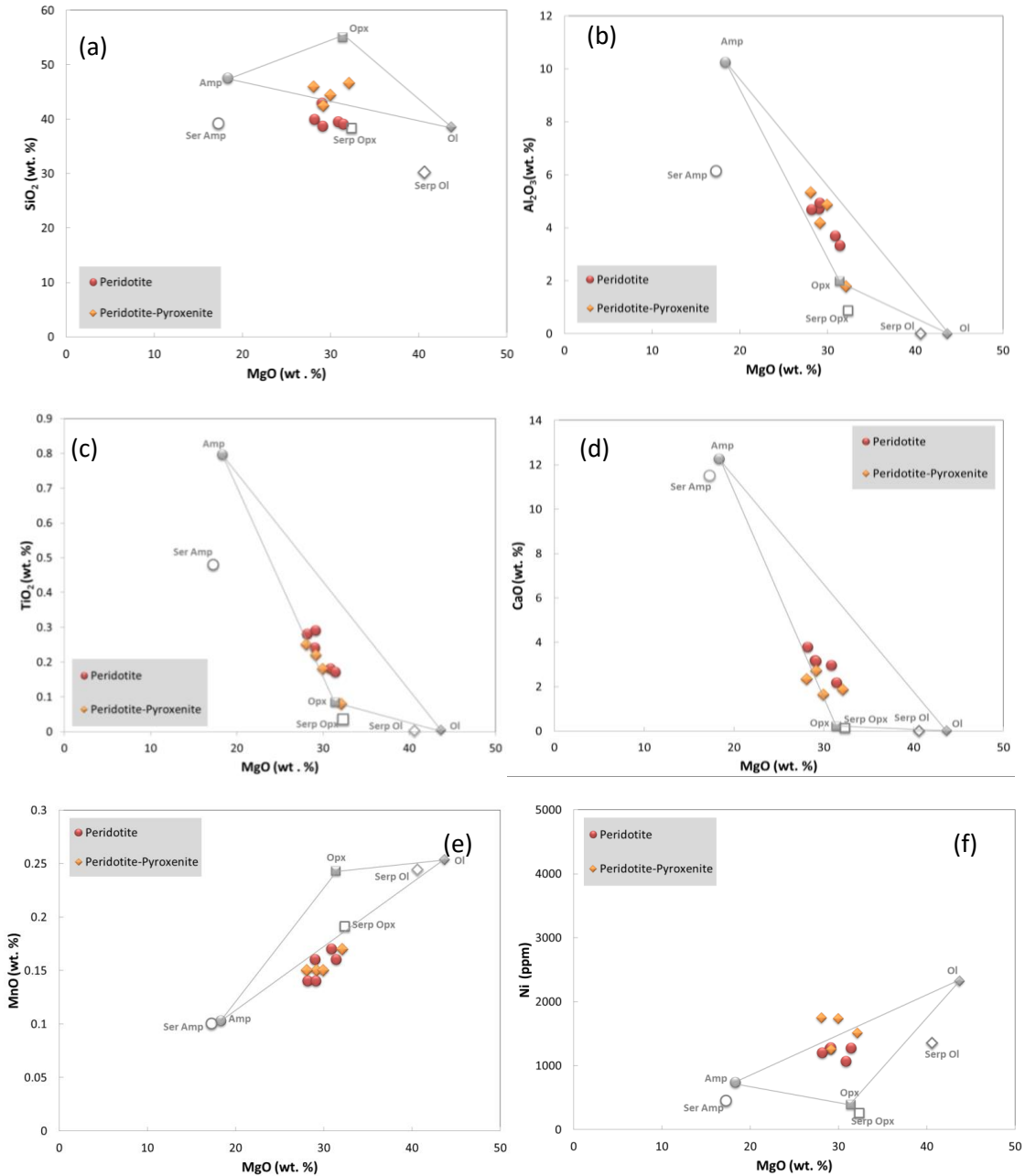


Figure 5.3. (a to f) Major element harker variation diagrams comparing the whole-rock compositions of peridotite-pyroxenite from the Lechana layered intrusion, with average compositions of prominent minerals from the respective rocks. Tie lines are connected between minerals in equilibrium and are based on petrography. Average mineral compositions affected by serpentinization (with the modifier Serp) are also included for comparison.

It follows that the composition of the ultramafic rocks (peridotite, pyroxenite) is mainly controlled by olivine, orthopyroxene and amphibole (Fig. 5.3), whereas the composition of the mafic unit (anorthosite) is mainly controlled by plagioclase and to a lesser extent by amphibole (Fig. 5.4). In later case, the concentration of samples towards plagioclase (Fig. 5.4), likely indicates its cumulate nature. Mineral compositions affected by serpentinization seem to have little control on the chemistry. 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.

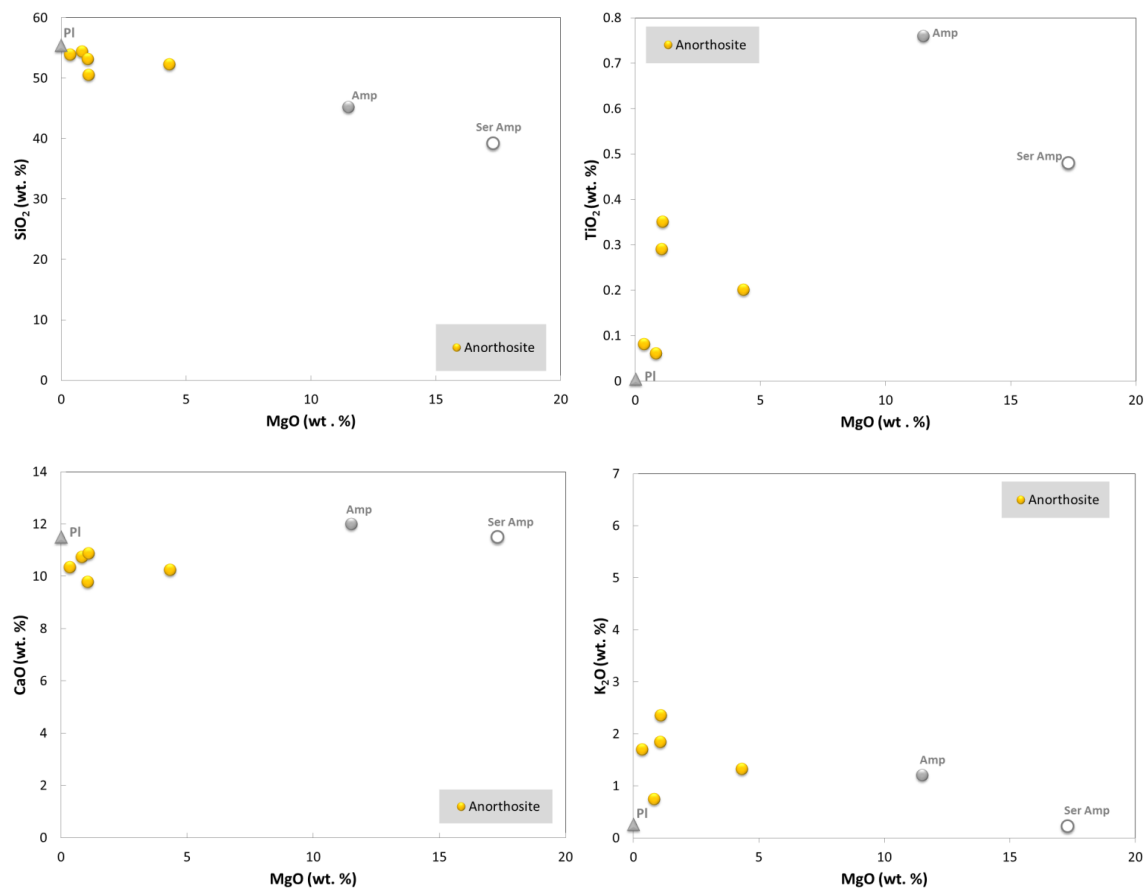


Figure 5.4. (a to d) Major element harker variation diagrams comparing the whole-rock composition of anorthosite from the Lechana layered intrusion, with average composition of prominent minerals in the rock. Amphibole composition affected by sericitization is indicated by Ser-Amp.

5.4. Trace and rare earth element characteristics

The ultramafic rocks are characterized by high contents of Cr and Ni, with peridotite with patchy pyroxenite domains (Cr = 4071-4564 ppm; Ni = 1258-1750 ppm) having the highest, followed by peridotite (Cr = 3270-4256 ppm; Ni = 1058-1272 ppm) and pyroxenite (Cr = 3277-3530 ppm; Ni = 845-1289 ppm). Amphibolite and anorthosite have lower Cr [27-376 ppm (amphibolite); 14-123 ppm (anorthosite)] and Ni [62-136 ppm (amphibolite); <20-84 ppm (anorthosite) contents (Table 5.1). Amphibolite has the highest V (156-253 ppm) and Sc (30-37 ppm) contents among the different rocks [V: 77-108 ppm, Sc: 13-19 (peridotite with patchy pyroxenite domains); V: 100-103 ppm, Sc: 13 ppm (pyroxenite); V: 74-101 ppm, Sc: 12-18 ppm (peridotite); V: 22-82 ppm, Sc: 2-18 ppm (anorthosite)].

In the primitive-mantle normalized (Sun and McDonough, 1989) multi-element spider gram, all the studied rocks show large ion lithophile element (LILE) enrichment, with relatively constant high-field strength elements (HFSE) pattern (Figs. 5.5a, c, e, g, i). Variable enrichment of LILE, with amphibolite and anorthosite having the highest content (Figs. 5.5a, c) indicates the effect of overprint event(s) on these fluid mobile elements. In comparison, the near constant HFSE pattern of the different rocks indicates the less effect of alteration on these elements. All rocks exhibit negative Nb, Ta and Ti anomalies (Figs. 5.5a, c, e, g, i). Positive Sr anomaly of anorthosite (Fig. 5.5c) correlates with its cumulus plagioclase content. Similar anomaly for one of the amphibolite sample (Fig. 5.5a) indicates dominance of plagioclase.

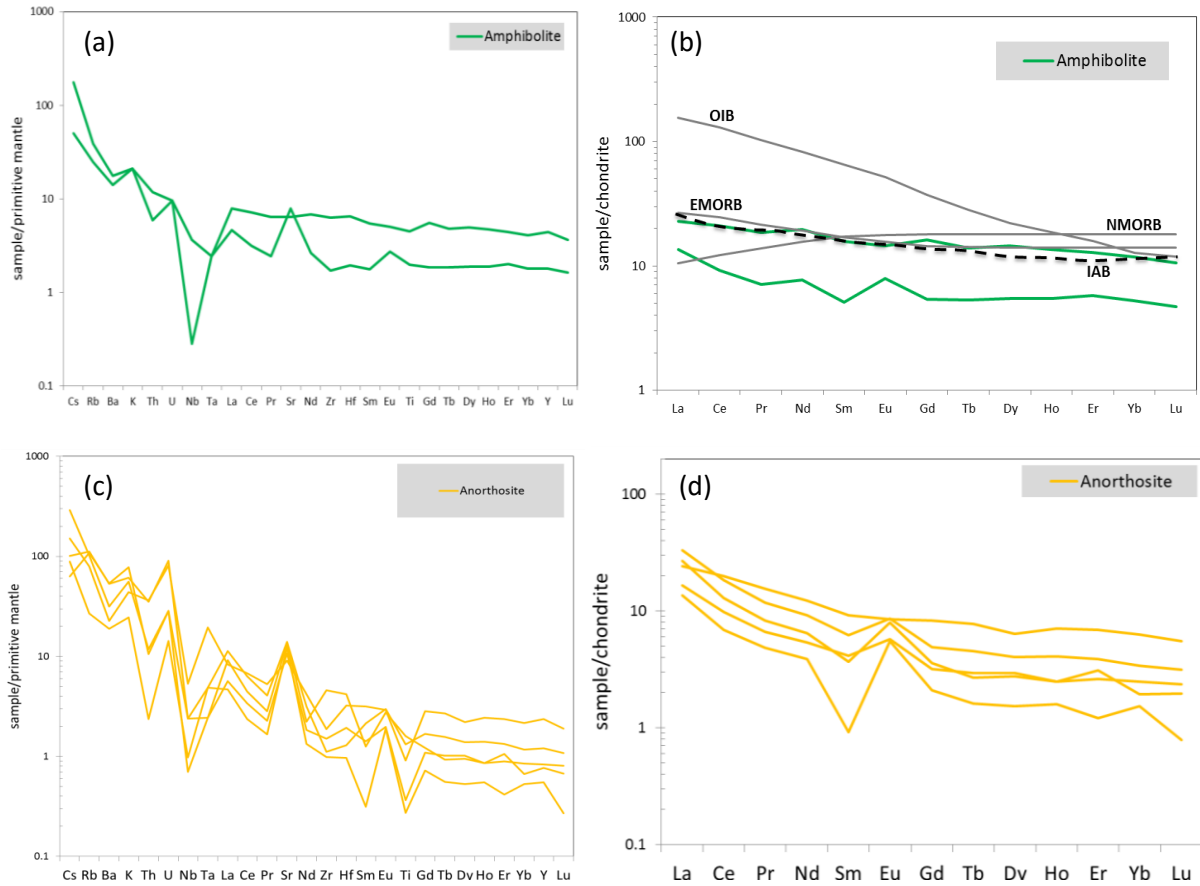


Figure 5.5. Primitive mantle-normalized trace element spider gram (a, c) and chondrite-normalized REE diagram (b, d) of amphibolite and anorthosite from the Lechana area. Typical oceanic island basalt (OIB), island arc basalt (IAB), enriched mid-oceanic ridge basalt (E-MORB), normal mid-oceanic ridge basalt (N-MORB) and primitive mantle patterns are from Sun and McDonough (1989).

The chondrite-normalized (Sun and McDonough, 1989) REE patterns of the rocks also show similar pattern with slight enrichment of light REE (LREE, e.g., La) relative to middle REE (MREE, e.g., Sm) $[(La/Sm)_N - \text{peridotite with patchy pyroxenite domains: } 1.63\text{--}4.11; \text{peridotite: } 1.89\text{--}9.36; \text{pyroxenite: } 2.22\text{--}4.3; \text{anorthosite: } 2.61\text{--}14.76; \text{amphibolite: } 1.44\text{--}2.65]$, near constant to slight depletion of heavy REE (HREE, e.g., Yb) $[(Gd/Yb)_N - \text{peridotite with patchy pyroxenite domains: } 1.03\text{--}1.47; \text{peridotite: } 1\text{--}1.42; \text{pyroxenite: } 1.1\text{--}1.18; \text{anorthosite: } 1.28\text{--}1.83; \text{amphibolite: } 1.02\text{--}1.37]$ and variable Eu anomalies $[(Eu/Eu^*) - \text{peridotite with}$

patchy pyroxenite domains: 0.33-1.02; peridotite: 0.79-1.49; pyroxenite: 0.7-0.98; anorthosite: 0.97-3.67; amphibolite: 0.91-1.52)] (Figs. 5.5b, d, f, h, j). Prominent positive Eu anomalies of most of the anorthosite samples correlate with its cumulus plagioclase nature (Fig. 5.5d). The anorthosite sample, which lacks Eu anomaly, contains more modal proportion of amphibole. The positive Eu anomaly of one of the amphibolite sample correlates with the Sr anomaly (Fig. 5.5b). The $(La/Yb)_N$ ratios vary from 2.32 to 3.14 for peridotite with patchy pyroxenite domains, 2.31 to 5.2 for peridotite, 2.81 to 2.84 for pyroxenite, 3.86 to 13.69 for anorthosite and 1.94 to 2.58 for amphibolite.

The REE pattern of amphibolite from the Lechana layered intrusion has similarity to typical island arc basalt (IAB) and enriched- mid ocean ridge basalts (E-MORB) patterns from Sun and McDonough (1989). The amphibolite sample with more plagioclase has lower REE contents (Fig. 5.5b). Significantly, a peridotite sample with patchy pyroxenite domains (sample MH2; Table 5.1) gave the unique U-shaped boninite REE pattern (Fig. 5.6).

5.5. Test of immobility

Several studies investigating element mobility during alteration have identified, however, some elements that retain approximately their original concentration (e.g., Nicollet and Andriololona, 1980; Weaver and Tarney, 1981; Polat and Hofmann, 2003). In general, the HFSE and REE are considered immobile during secondary processes whereas LILE are considered mobile (Rollinson, 1993). All the studied rocks display coherent chondrite-normalized REE (Fig. 5.5), and primitive mantle-normalized multi-element spider grams,

especially HFSE patterns (Fig. 5.5), indicating that these elements were relatively immobile during overprint events.

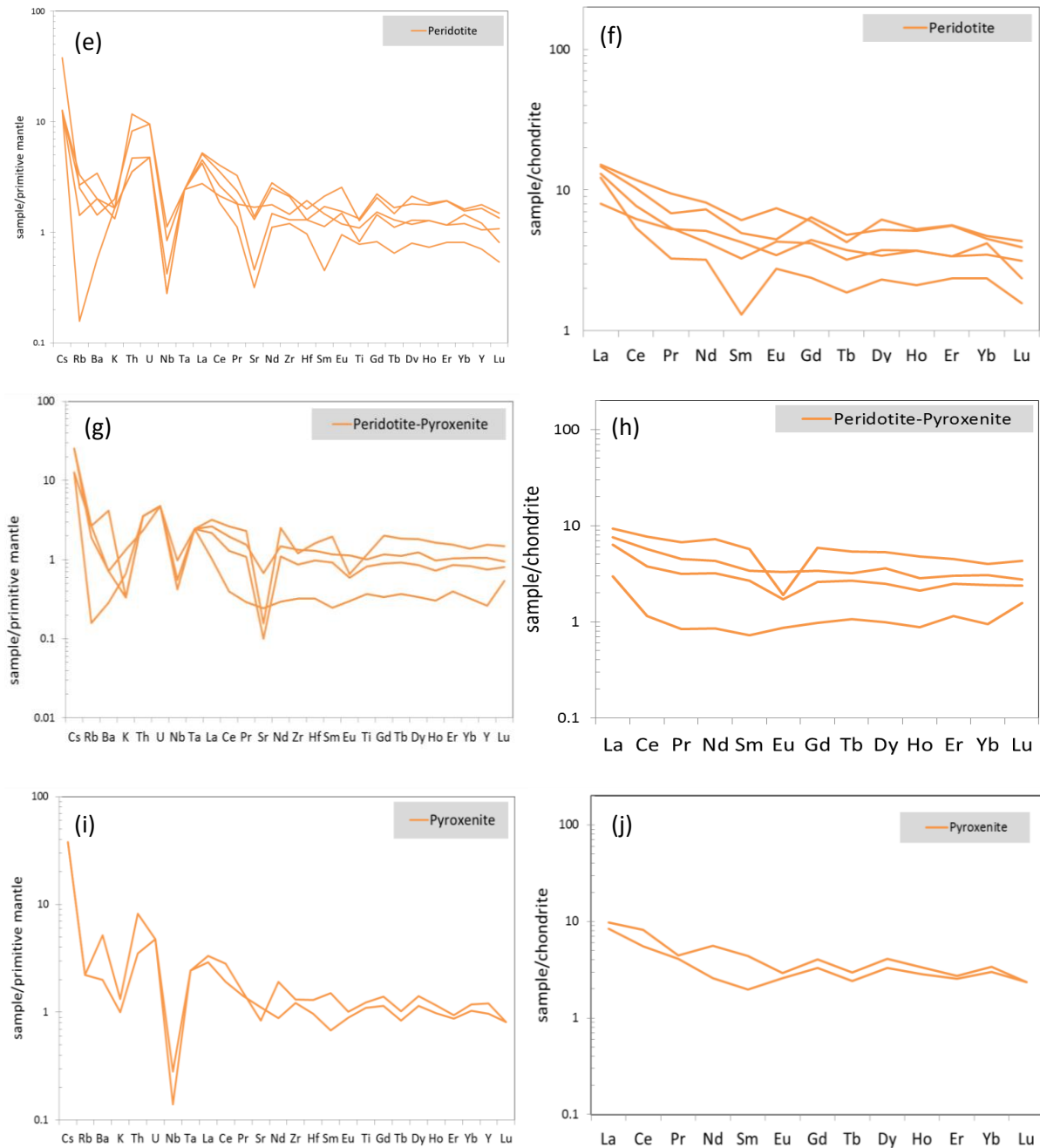


Figure 5.5. (continued) Primitive mantle-normalized trace element spider gram (e, g, i) and chondrite-normalized REE diagram (f, h, j) of peridotite, peridotite with patchy pyroxenite domains, and pyroxenite from the Lechana layered intrusion.

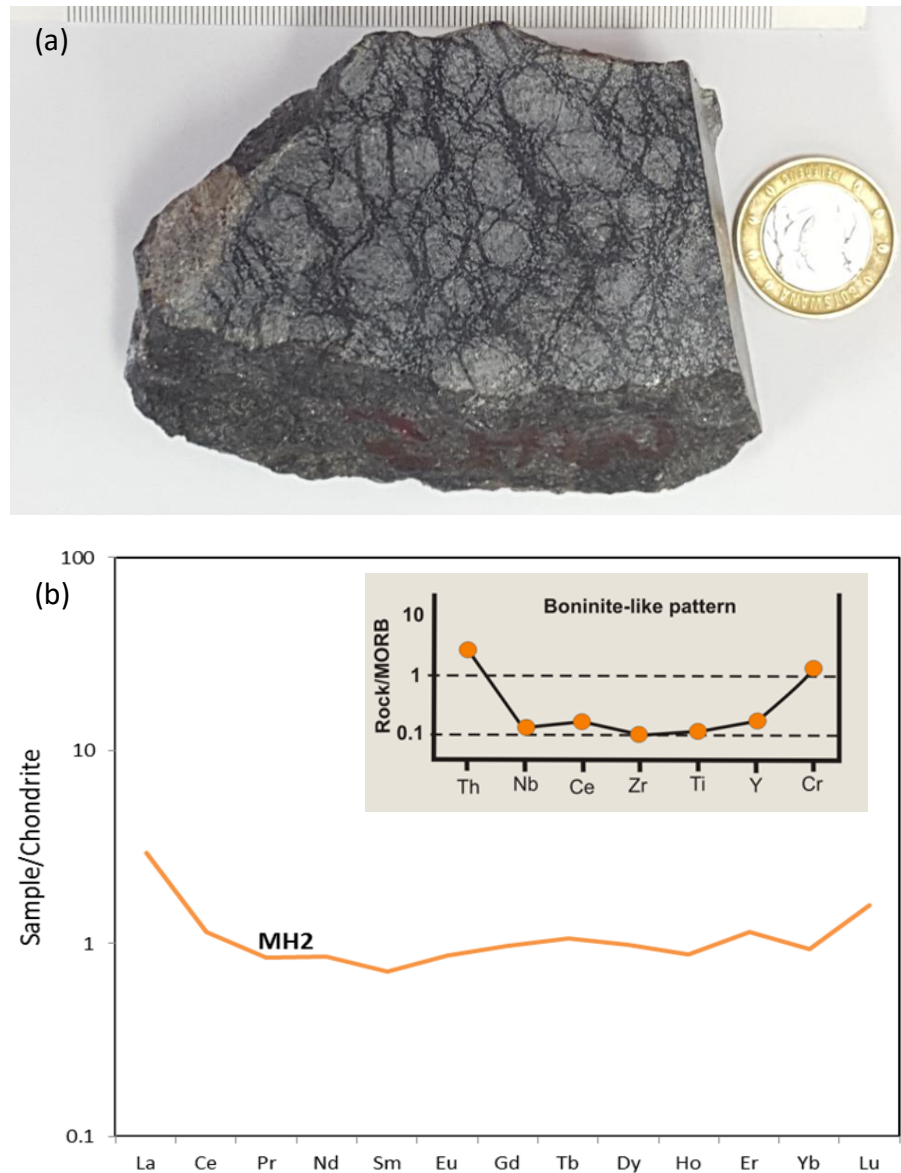


Figure 5.6. (a) Polished photograph of the composite rock (peridotite with patchy pyroxenite domains) from which the unique U-shaped boninite-like REE pattern was obtained. **(b)** Chondrite-normalized REE pattern of sample MH2. Inset in (b) shows the typical U-shaped REE pattern of boninites [from Crawford et al. (1989)].

The ultramafic to mafic rocks studied here were assessed for post-emplacement alteration by plotting Zr (a known sensitive indicator of immobility; Rollinson, 1993; Polat and Hofmann, 2003) against REE (represented by La, Ce, Sm, Nd, Gd) and HFSE (represented

by Nb) (Fig. 5.7). Except an anorthosite sample, the results show consistent positive correlation as illustrated in Fig. 5.7, suggesting that the most immobile trace elements, such as Zr, Nb, Y, Ta, V, Hf, Th, and REE, define well-correlated trends within all three rocks that are consistent with their relatively incompatible behavior during magmatic processes, thus allowing their use for purposes of drawing petrogenetic inferences.

5.6. Petrogenetic characterization

Trends of increasing SiO_2 , TiO_2 , CaO, Al_2O_3 , and decreasing Cr and Ni contents with decreasing MgO of the Lechana layered intrusion rocks are typical of ultramafic to mafic rocks related by differentiation. With Mg # of ~81 to 84, peridotite with patchy pyroxenite domains constitutes the least evolved of the studied rocks, followed by peridotite (~80-83) and pyroxenite (~79-80). Anorthosite constitutes the most differentiated rock type with Mg# of ~35 to 56. This order of differentiation among the intrusive rocks of the Lechana layered intrusion is also supported by their respective Cr and Ni contents.

Consistent trends of evolution were observed from the MgO-rich peridotite-pyroxenite rocks to the least MgO-rich anorthosite (Fig. 5.8). If this inference is correct, then the most MgO-rich peridotite with patchy pyroxenite domains represent the closest to the parental magma composition to the studied ultramafic to mafic rocks. Further, petrogenetic characteristics are given in chapter 7, as part of discussion of the results.

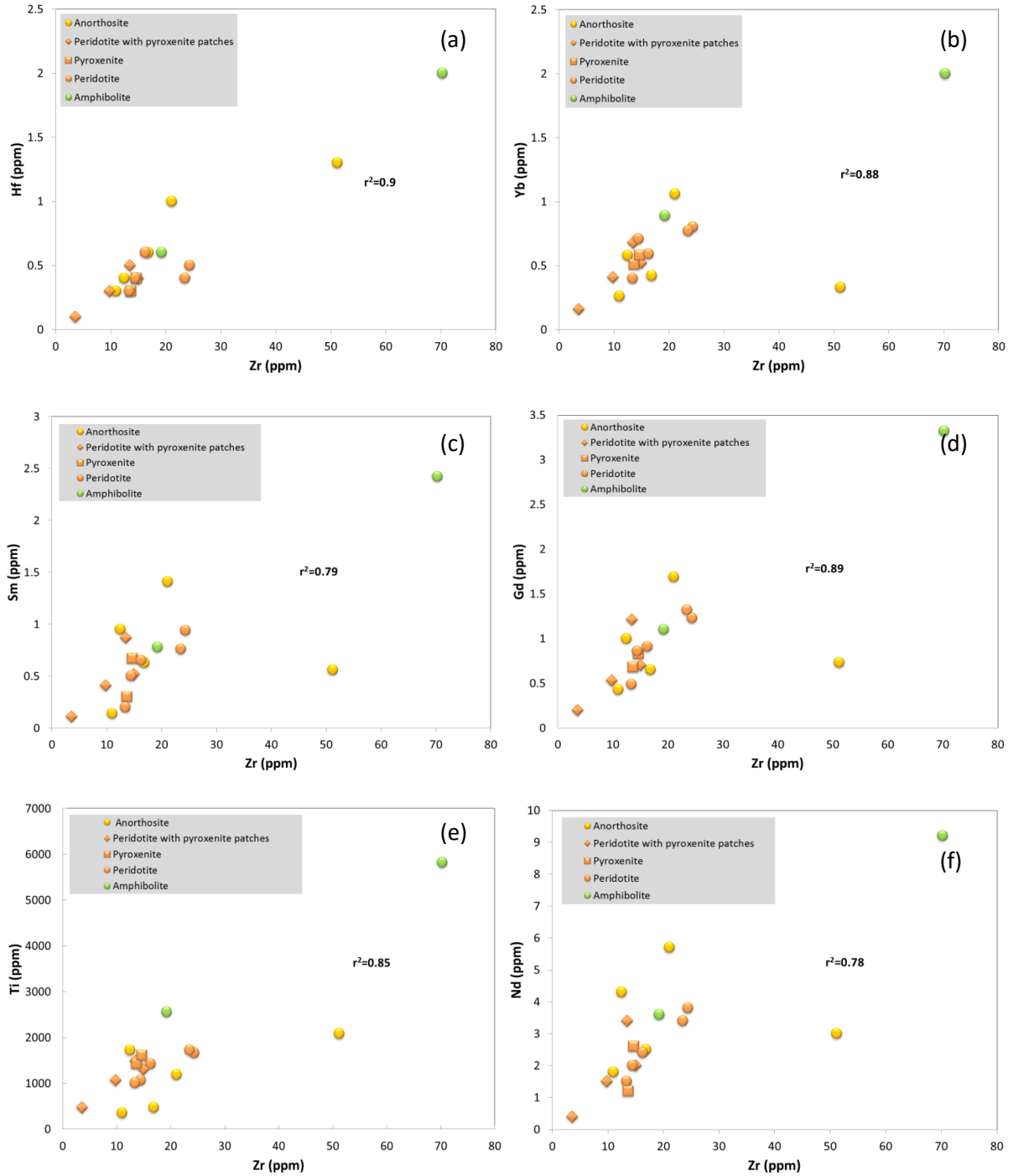


Figure 5.7. (a to f) Plots illustrating the good correlation between Zr and other trace and REE elements indicating the general immobility of these elements during secondary alteration, as indicated by their correlation coefficient (r^2), in the Lechana layered intrusion rocks. The anorthosite sample that fall away from the general trend is not used for making any petrogenetic inference, but is included in the geochemistry-based plots for reference.

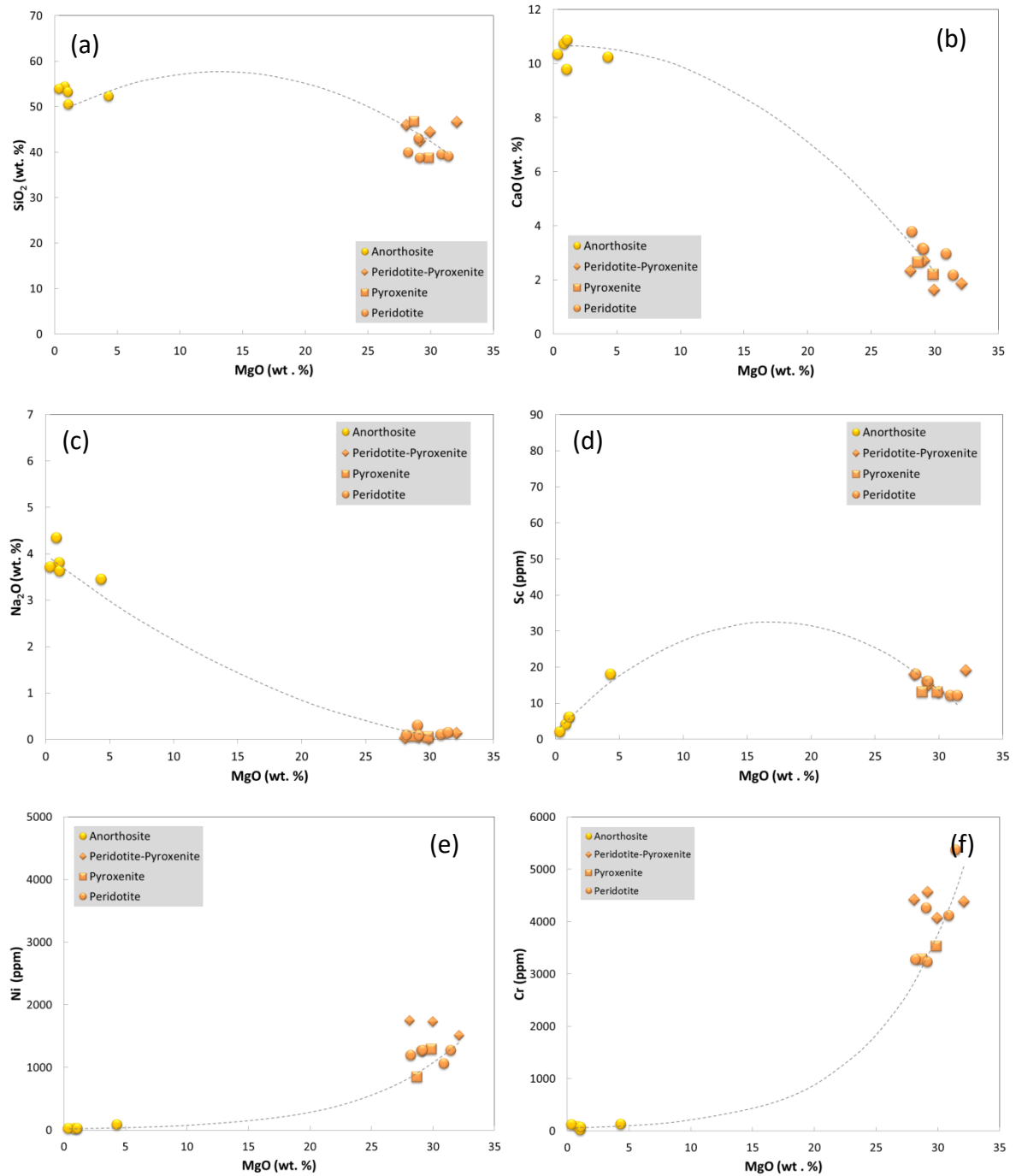


Figure 5.8. (a to f) Harker variation diagrams illustrating the consistent trend of evolution observed from ultramafic to mafic rocks. Some of the peridotite with patchy pyroxenite domains fall slightly away from the trend, and could be due to them being composite rocks. As shown in Figs. 5.5 and 5.6, not all peridotite with patchy pyroxenite domains produce the unique U-shaped REE pattern of boninites. The trend lines were approximately calculated using the TRAZAS geochemical modeling program of Cebriá and López-Riuz (1990).

Chapter 6

Discussion

6.1. Defining a new Archean layered intrusion – Lechana layered intrusion

Millimeter to centimeter-scale layering observed in the peridotite-pyroxenite rocks (see Fig. 2.5) in the Lechana area is typical of layering observed in layered intrusions. Field relations indicate that the ultramafic (peridotite-pyroxenite) and mafic (anorthosite) rocks occurring in the Lechana area are closely associated with amphibolite (see Fig. 2.1). Possible pillow-like structures preserved in the massive amphibolite can be interpreted to indicate that it is a meta-basalt. Like typical layered intrusions (e.g., ~2.06 Ga Rooiberg volcanics associated with ~2.05 Ga Bushveld Complex layered intrusion; Hatton, 1995), the earlier magma (basaltic) was likely volcanic. The subsequent magma intruded beneath this volcanic cover, the differentiation of which likely formed the ultramafic to mafic members (peridotite-pyroxenite-anorthosite) of the layered intrusion. The argument for differentiation is supported by geochemically modeled trends between these rocks (see Fig. 5.8). The mafic (amphibolite-anorthosite) to ultramafic (peridotite-pyroxenite) rocks occur as inclusions with the 2645 ± 22 Ma (Zeh et al., 2009) tonalite gneiss. Hence they should be older than ~2.6 Ga. Thus the mafic to ultramafic rocks occurring in the Lechana area constitute dismembered remnants of an Archean layered intrusion (e.g., see Fig. 1.3b) – referred here as the Lechana layered intrusion – exposed within an Archean high-grade terrain (Motloutse Complex). Although of higher-grade (amphibolite-facies) than typical lower-grade (greenschist- to amphibolite-facies) greenstone terranes in the adjacent

Zimbabwe Craton, the Motloutse Complex terrane does not strictly preserve granulite-facies conditions or evidence of polymetamorphism, as typically seen in Archean high-grade terranes (e.g., Limpopo Complex high-grade terrane).

6.2. Overprint event(s) that affected the rocks of the Lechana layered intrusion

Unlike the adjacent Phikwe Complex, which form part of the Limpopo Complex high-grade terrane (see Figs. 1.4 and 1.5), the Motloutse Complex terrane which exposes rocks of the Lechana layered intrusion has not been subjected to granulite-facies metamorphism. Petrographic studies indicate that, except amphibolite, no granoblastic polygonal texture is preserved in the mafic to ultramafic rocks of the Lechana layered intrusion. Both amphibolite and anorthosite, which occur together towards the northern part of the mapped area (see Fig. 2.1), are affected by an anatectic overprint as evidenced by the local occurrence of garnet (e.g., see Figs. 2.3e, f). No such visible anatectic overprint is seen in the ultramafic rocks. But the ultramafic rocks, especially those exposed towards the eastern part of the mapped area, show evidence for shear deformation. Both the anatectic overprint and shear deformation are related to the Paleoproterozoic (~2 Ga) event that affected the southern part of the Motloutse Complex (Zeh et al., 2009). The lack of consistent overprint metamorphic events in the mafic to ultramafic rocks of the Lechana layered intrusion, indicate that the amphibolite-facies metamorphism reported by earlier studies (Smith and Phofuetsile, 1985; Aldiss, 1989) from the Motloutse Complex is not widespread, and is rather localized. Alteration events – serpentinization in the ultramafic rocks and sericitization in

anorthosite – are typical of that observed in ultramafic to mafic rocks associated with layered intrusions.

6.3. Boninitic nature of rocks from the Lechana layered intrusion

One of the main aims of the study was to understand the possible boninitic nature of the mafic to ultramafic rocks of the Lechana layered intrusion. To evaluate the boninitic nature of the studied rocks, they were compared with typical boninite data compiled from the online GEOROC database. It can be seen from Fig. 6.1 that the major element compositions of the mafic to ultramafic rocks of the Lechana layered intrusion show close similarity to typical boninites. The combination of intermediate-silica and high-MgO contents is typical of boninites (Fig. 6.1a). Similar comparison to boninites was observed in terms of trace element compositions (Figs. 6.2 and 6.3). It should be noted that the one of the amphibolite samples fall in the MORB field, while the other, with more plagioclase, fall in the overlap region of boninite and island arc tholeiite (IAT) fields in Fig. 6.3. The relevance of this transitional behavior is evaluated in section 6.4. Significantly, one of the peridotite with patchy pyroxenite domains sample showed the unique U-shaped REE pattern of boninites (see Fig. 5.6). Not all composite rocks (peridotite with patchy pyroxenite domains) gave the typical boninite-like REE pattern (see Fig. 5.5). Hence, it seems that peridotite and pyroxenite need to be *mixed in a certain ratio* to obtain the unique boninite-like REE pattern. Thus it is argued that the mafic to ultramafic rocks of the Lechana layered intrusion forms a prominent example of Archean *boninite-like* rocks.

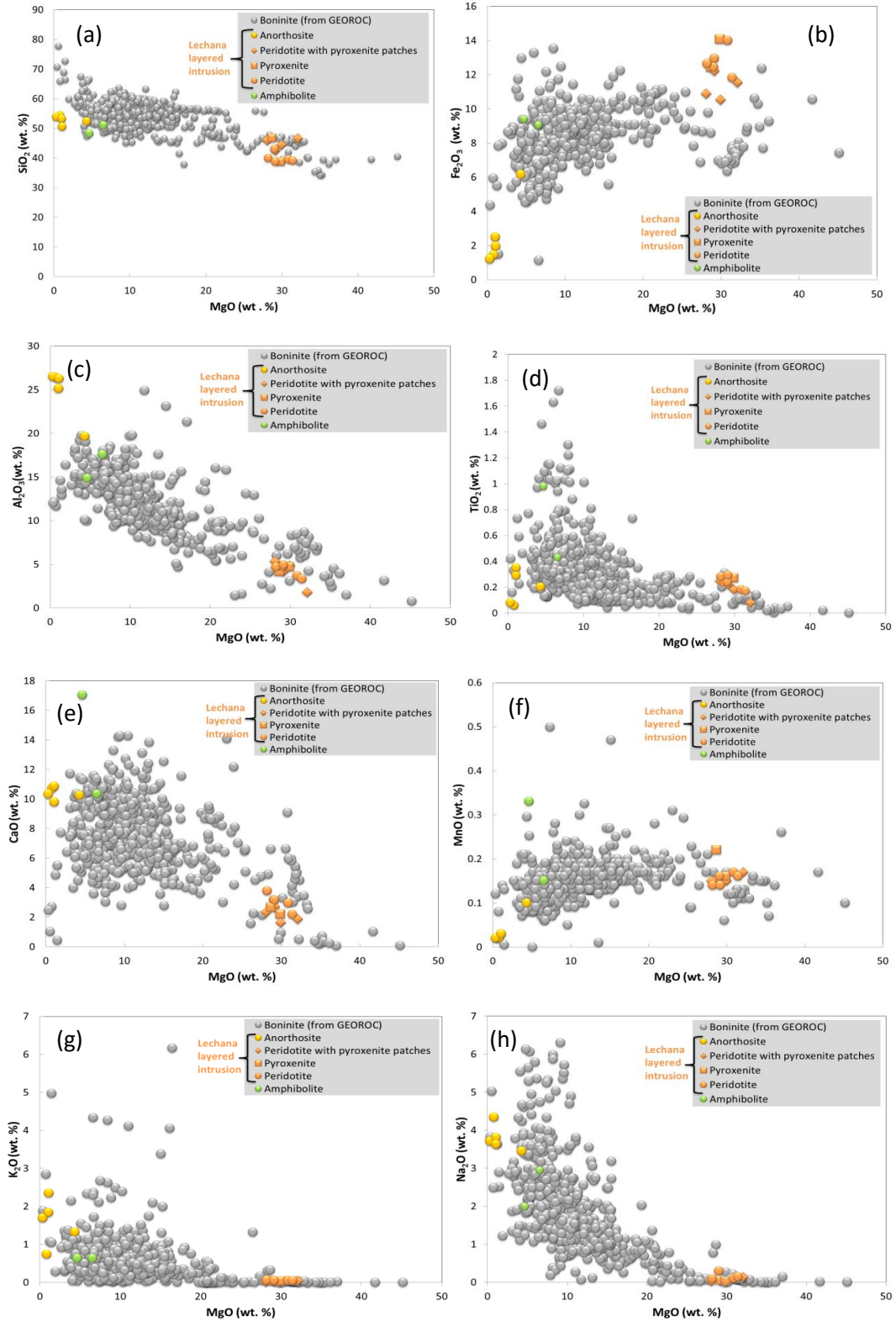


Figure 6.1. (a to h) Major element harker diagrams comparing the Lechana layered intrusion rocks to boninites. The boninite data is compiled from the GEOROC online database.

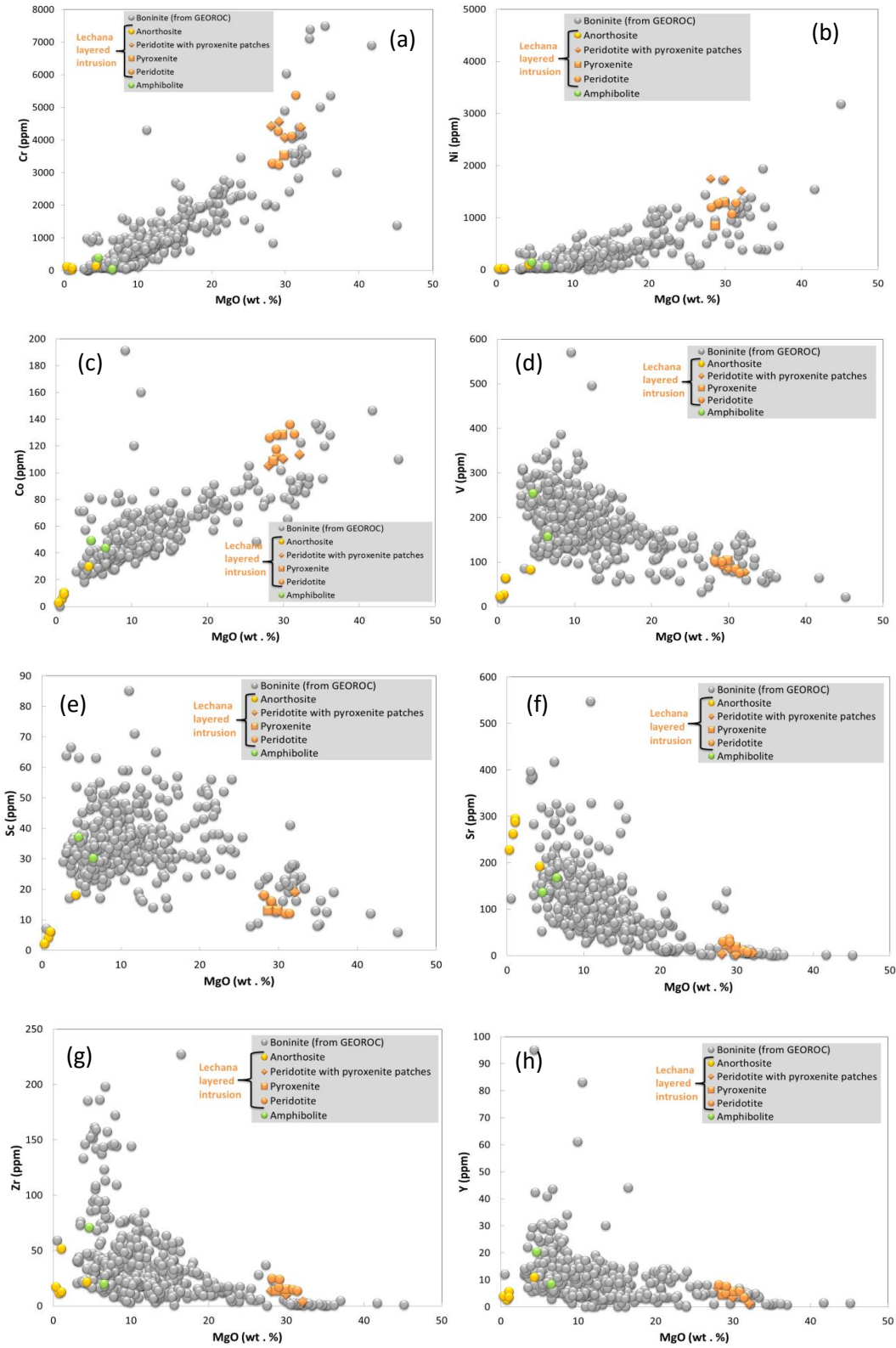


Figure 6.2. (a to h) Trace element harker diagrams comparing the Lechana layered intrusion rocks to boninites. The boninite data is compiled from the GEOROC online database.

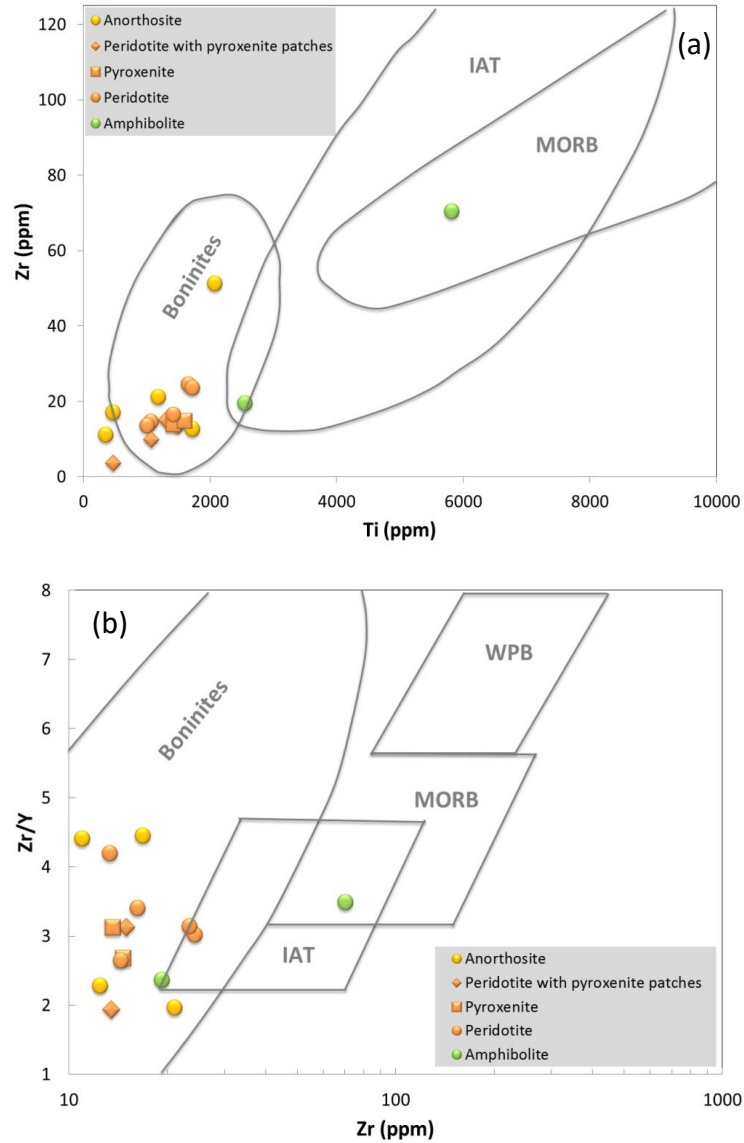


Figure 6.3. Mafic to ultramafic rocks of the Lechana layered intrusion in terms of Zr versus Ti **(a)** and Zr/Y versus Zr **(b)** discrimination diagrams. The fields for boninites, island-arc tholeiites (IAT) and mid-ocean ridge basalts (MORB) are from Pearce (2003).

6.4. Petrogenetic characteristics and tectonic setting

Parental magma composition of layered intrusions is a contentious topic. Considering the cumulate nature of mafic to ultramafic rocks in better preserved Proterozoic layered intrusions (e.g., Bushveld Complex, Stillwater Complex), often marginal rock (sills, dykes,

chilled margins) compositions are used to constrain their parental magma composition (e.g., Wager, 1960; Huppert and Sparks, 1989; Hoover, 1989; Wilson, 2012; Maier et al., 2016). With their occurrence as dismembered remnants in high-grade terranes, the scenario is different for Archean layered intrusions. Similar chondrite-normalized REE patterns of ultramafic (peridotite-pyroxenite) and mafic (anorthosite) rocks of the Lechana layered intrusion (see Fig. 5.5) indicates that they were likely derived from the same parental magma. Geochemical modelling (see Fig. 5.8) indicates that the ultramafic and mafic rocks are likely related by differentiation of the original magma. Considering the limitations of the data set at hand, especially the probable cumulate nature of some of the rocks, this study refrains from making further inference on the nature of the parental magma composition. Instead, focus is given to characterizing the likely tectonic setting in which the *boninite-like* rocks were formed, which can help to understand the petrogenetic process(es) that operated. Although Cr-spinel mineral chemical composition is an effective tool to infer the likely tectonic setting, the modified composition of Cr-spinel in the studied rocks (see Fig. 4.14) does not help the cause. Hence, whole-rock immobile element based tectonic discrimination diagrams were used to infer the likely tectonic setting of formation of rocks.

In general, mafic- to ultramafic rocks formed in settings corresponding to that similar to mid-oceanic ridge basalt (MORB), oceanic island arc basalt (IAB), continental rift basalt (CRB) and ocean island basalt (OIB) have been shown to have different trace element signatures (see Pearce and Peate, 1995; Hofmann, 1997; Kerr, 2003). Although this is obvious for modern settings, this geochemical behaviour likely also prevailed in the Archean, given that

certain groups of elements behave consistently in specific petrogenetic settings (e.g., Polat and Kerrich, 2006; Jenner et al., 2009; O'Neil et al., 2011; Manikyamba et al., 2015). Agrawal et al. (2008) proposed a four-tier immobile trace element based tectonic discrimination method. It involves utilizing the immobile trace elements La, Sm, Yb, Nb and Th. The results are computed using equations from Agrawal et al. (2008) and illustrated as a set of four log-transformed La/Th–Nb/Th–Sm/Th–Yb/Th discrimination diagrams (Fig. 6.4).

The mafic to ultramafic rocks of the Lechana layered intrusion fall in the field of IAB, indicating the possibility of formation in a subduction setting. Significantly, the typical boninite data compiled from GEOROC database falls across two fields – from MORB to IAB. This is interesting, considering that boninites commonly occur in suprasubduction (SSZ) settings, which typically involve a transition from a MORB-like setting to an active continental margin involving subduction (Crawford et al., 1989; Pearce et al., 1984; Shervais, 2001; Ishikawa et al., 2002; Dilek et al., 2008).

The tectonic setting scenario of the rocks of the Lechana layered intrusion was further evaluated using the Th/Yb versus Ta/Yb plot of Pearce (2008) (Fig. 6.5). They mostly fall above the mantle array defined by the fields for N-MORB, E-MORB and OIB. While the peridotite-pyroxenite-anorthosite samples fall in the field of subduction-related rocks, amphibolite (meta-basalt) falls separately in Fig. 6.5. The transitional (from MORB to arc) affinity of the earlier formed amphibolite is further illustrated in Fig. 6.3. Thus the mafic to ultramafic rocks of the Lechana layered intrusion likely formed in a suprasubduction setting, in which the basaltic rock (amphibolite) originally formed in a MORB-like setting and the

magma then moved (arrowed line in Fig. 6.5) on to the nearby active continental margin where it differentiated to form the remainder of the rocks (much like in a fore-arc scenario illustrated in Fig. 1.1).

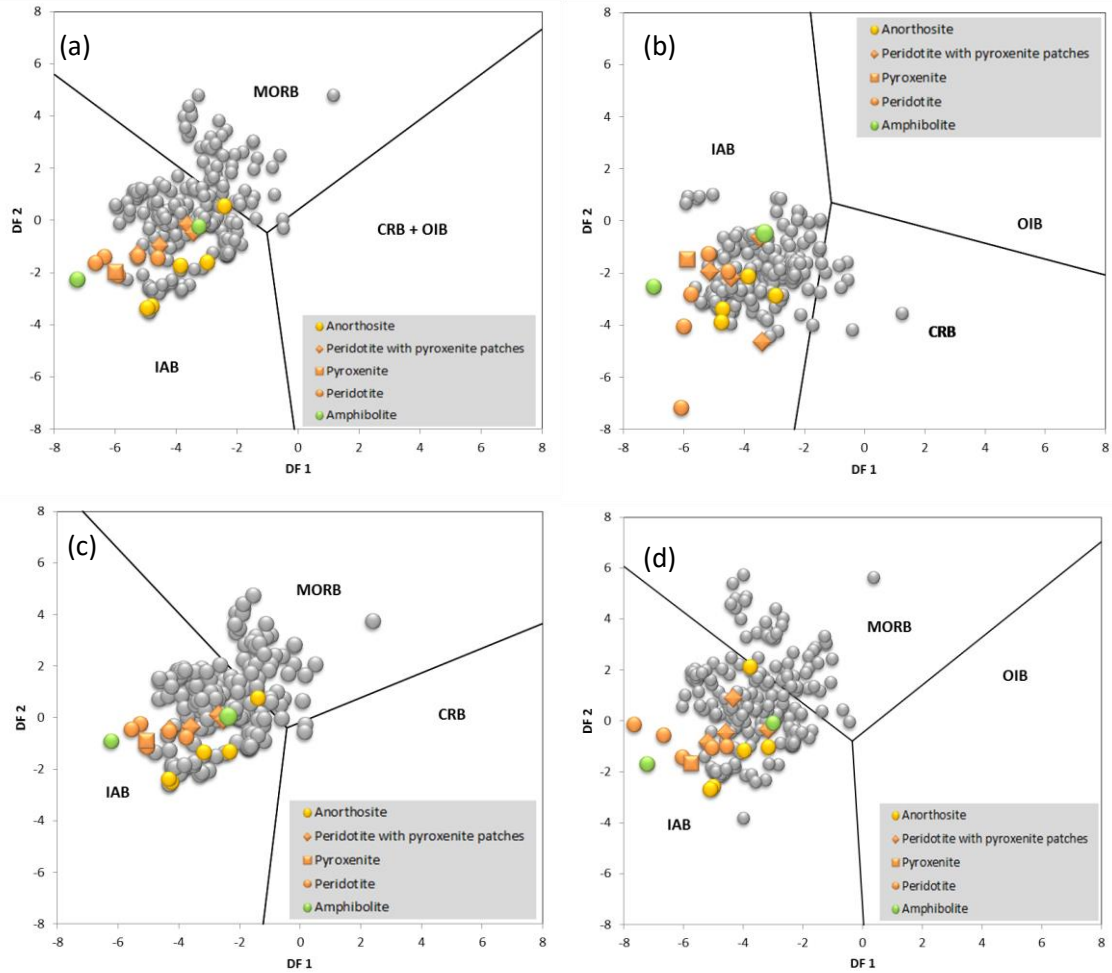


Figure 6.4. Tectonic setting characteristics of the mafic-ultramafic rocks of the Lechana layered intrusion. **(a) IAB-MORB-CRB+OIB** [$DF1 = 0.3518 \log_e (La/Th) + 0.6013 \log_e (Sm/Th) - 1.3450 \log_e (Yb/Th) + 2.1056 \log_e (Nb/Th) - 5.4763$; $DF2 = -0.3050 \log_e (La/Th) - 1.1801 \log_e (Sm/Th) + 1.6189 \log_e (Yb/Th) + 1.2260 \log_e (Nb/Th) - 0.9944$]; **(b) IAB-OIB-CRB** [$DF1 = 0.5533 \log_e (La/Th) + 0.2173 \log_e (Sm/Th) - 0.0969 \log_e (Yb/Th) + 2.0454 \log_e (Nb/Th) - 5.6305$; $DF2 = -2.4498 \log_e (La/Th) + 4.8562 \log_e (Sm/Th) - 2.1240 \log_e (Yb/Th) - 0.1567 \log_e (Nb/Th) + 0.94$]; **(c) IAB-MORB-CRB** [$DF1 = 0.3305 \log_e (La/Th) + 0.3484 \log_e (Sm/Th) - 0.9562 \log_e (Yb/Th) + 2.0777 \log_e (Nb/Th) - 4.5628$; $DF2 = -0.1928 \log_e (La/Th) - 1.1989 \log_e (Sm/Th) + 1.7531 \log_e (Yb/Th) + 0.6607 \log_e (Nb/Th) - 0.4384$]; **(d) IAB-MORB-OIB** [$DF1 = 1.7517 \log_e (Sm/Th) - 1.9508 \log_e (Yb/Th) + 1.9573 \log_e (Nb/Th) - 5.0928$; $DF2 = -2.2412 \log_e (Sm/Th) + 2.2060 \log_e (Yb/Th) + 1.2481 \log_e (Nb/Th) - 0.8243$]. Fields and discriminant scores from Agrawal et al. (2008).

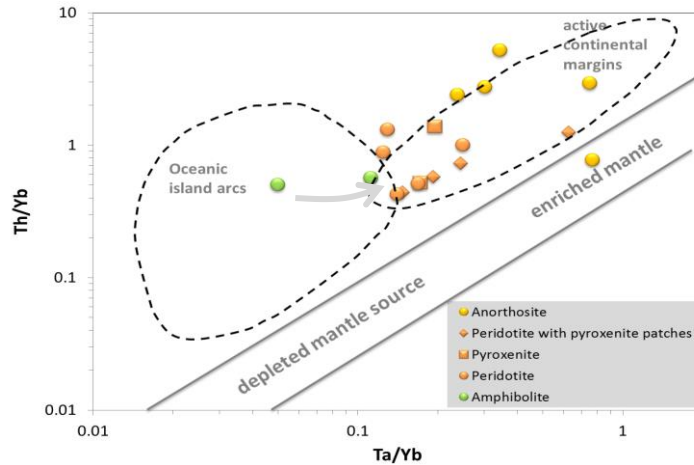


Figure 6.5. Mafic to ultramafic rocks of the Lechana layered intrusion in terms of the Th/Yb versus Ta/Yb plot. The fields are from Pearce (2008). See text for discussion on the arrowed line.

There is an additional constraint that needs to be considered in the above mentioned tectonic scenario. The original basaltic magma as well as the magma that differentiated to form the peridotite-pyroxenite-anorthosite rocks could have undergone crustal contamination. Further, the high Th/Ta (>5) and Ba/Zr (>2) values of some of the mafic to ultramafic rocks of the Lechana layered intrusion, considered as important proxies for the involvement of crustal material (e.g., Pearce, 2008), warrants the evaluation of the role of crustal contamination. When considered in terms of typical MORB and Archean crustal compositions (Fig. 6.6a), the role of crustal contamination gains support. The possibility of crustal contamination of a MORB-like magma with Archean upper crust was considered using modeled trends in the $(\text{Nb}/\text{Th})_N$ and $(\text{La}/\text{Sm})_N$ plot (Fig. 6.6b). In Fig. 6.6b, the Lechana layered intrusion rocks fall along the trend line between typical mantle values [$(\text{Nb}/\text{Th})_N > 1$; $(\text{La}/\text{Sm})_N < 1$] and crustal values with generally low $(\text{Nb}/\text{Th})_N$ and high $(\text{La}/\text{Sm})_N$. It follows that crustal contamination played a prominent role in the petrogenetic history of the

boninite-like Lechana layered intrusion rocks. One could certainly argue that the *boninite-like* characteristic was attained by crustal contamination. On the other hand, it can be considered as part of the subduction-episode involved in formation in a suprasubduction setting.

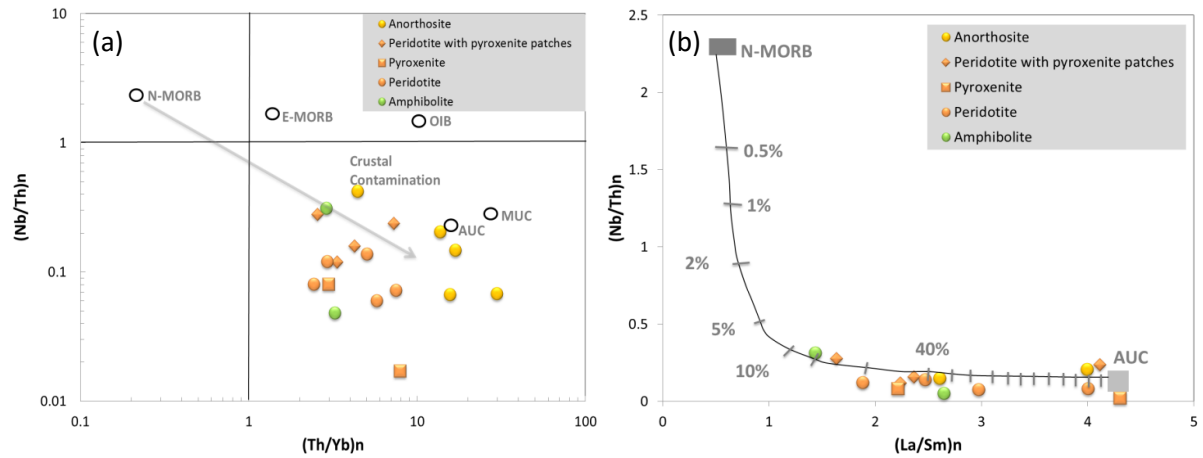


Figure 6.6. $(Nb/Th)_N$ versus $(Th/Yb)_N$ (a) and $(Nb/Th)_N$ versus $(La/Sm)_N$ (b) plots illustrating the role of crustal contamination in the petrogenetic history of Lechana layered intrusion rocks. The average compositions in (a) are from Sun and McDonough (1989) and McLennan (2001), and the trend is adapted from Wang et al. (2006). The mixing line between N-MORB (Sun and McDonough, 1989) and average upper continental crust (AUC; McLennan, 2001) in (b) indicates the degree of contamination based on the position of the sample relative to the line and is adapted from Richan et al. (2015). n – Primitive mantle normalized.

6.5. Significance of the primary magmatic amphibole reported in this study

Reports on the occurrence of primary magmatic amphiboles in mafic to ultramafic rocks of a Archean layered intrusion are rare; the only available reports are from the Mesoarchean (~2.97 Ga) Fiskensæset layered complex in southwestern Greenland (Polat et al., 2012; Huang et al., 2014). The amphibole-bearing rocks from the Fiskensæset layered complex occurs as dismembered remnants in an Archean high-grade terrane, and were subjected to amphibolite- to granulite-facies metamorphic overprints. In spite of the metamorphic re-

equilibration, the occurrence of amphibole as inclusions in olivine, pyroxenes, plagioclase and chromite in rocks from the Fiskenæsset layered complex is considered to be evidence for primary igneous phases (Polat et al., 2012; Huang et al., 2014).

The present study reports the occurrence of primary magmatic amphibole in ultramafic (peridotite-pyroxenite) and mafic (anorthosite) rocks of the Lechana layered intrusion. Unlike the Fiskenæsset layered complex, the Archean Lechana layered intrusion was not affected by any granulite-facies metamorphic overprint. However, alteration events did affect the chemistry of minerals in the rocks (e.g., isocon analyses in Figs. 4.4, 4.7 and 4.11). To better evaluate the effect of overprint event(s) on amphibole compositions from the Lechana layered ultramafic-mafic rocks, a comparative exercise was carried out. In Fig. 6.7, amphibole compositions from the anorthosite and peridotite with patchy pyroxenite domains studied here shows a similar composition to primary amphiboles reported from ultramafic rock occurrences in Archean greenstone belts (Stone et al., 2003; Fiorentini et al., 2012), the Fiskenæsset layered complex (Huang et al., 2014), and various Alaskan-type layered ultramafic to mafic intrusions/complexes, which are well known for the occurrence of magmatic amphiboles (Himmelberg and Loney, 1995, Helmy and El Mahallawi, 2003; Farahat and Helmy, 2006; Krause et al., 2007; Eyuboglu et al., 2010).

On the other hand, the close similarity of amphibole compositions from serpentinized peridotite and sericitized anorthosite studied here to those related to late-stage fluid related alteration in calc-silicate granulites and orthopyroxene-bearing tonalitic veins from the Limpopo Complex (Fig. 6.7; Kaneko et al., 2005; Rajesh et al., 2014) indicate the effect of

serpentinization and sericitization on the magmatic amphibole compositions in the respective rocks. Amphiboles designated as type A3 and B2 from the Fiskenæsset layered complex (see Huang et al. (2014) for details on the types of amphiboles) also fall along the secondary trend in Fig. 6.7.

Based on their petrographic features (e.g., see Figs. 3.5, 4.1, 4.6 and 4.9) and trends in Fig. 6.7, it is suggested that the amphiboles occurring in peridotite-pyroxenite-anorthosite of the Lechana layered intrusion are primary magmatic. But the compositions of amphiboles occurring in serpentinized and sericitized rocks (e.g., see Figs. 3.2, 3.4, 3.6 and 4.6) do show the effect of alteration overprint.

As far as the significance of finding primary magmatic amphibole in Archean layered intrusions is concerned (Huang et al., 2014; this study), it could be that the magmatic amphiboles are late-crystallizing products, as suggested for the intercumulus magmatic amphiboles reported from the Alaskan-type layered intrusions, implying that water has been added to the melt prior to emplacement (Himmelberg and Loney, 1995; Helmy and El Mahallawi, 2003; Farahat and Helmy, 2006; Krause et al., 2007; Eyuboglu et al., 2010). However unlike their intercumulus occurrence in Alaskan-type layered intrusions, the primary magmatic amphiboles reported from ultramafic to mafic rocks of the Lechana layered intrusion (this study) and the Fiskenæsset layered complex (Polat et al., 2012; Huang et al., 2014) are conspicuous in their occurrence as inclusions in olivine, pyroxenes and plagioclase (and also in chromite from the Fiskenæsset layered complex) (e.g., see Figs. 3.5, 4.1, 4.6 and 4.9 for the scenario of the Lechana layered intrusion).

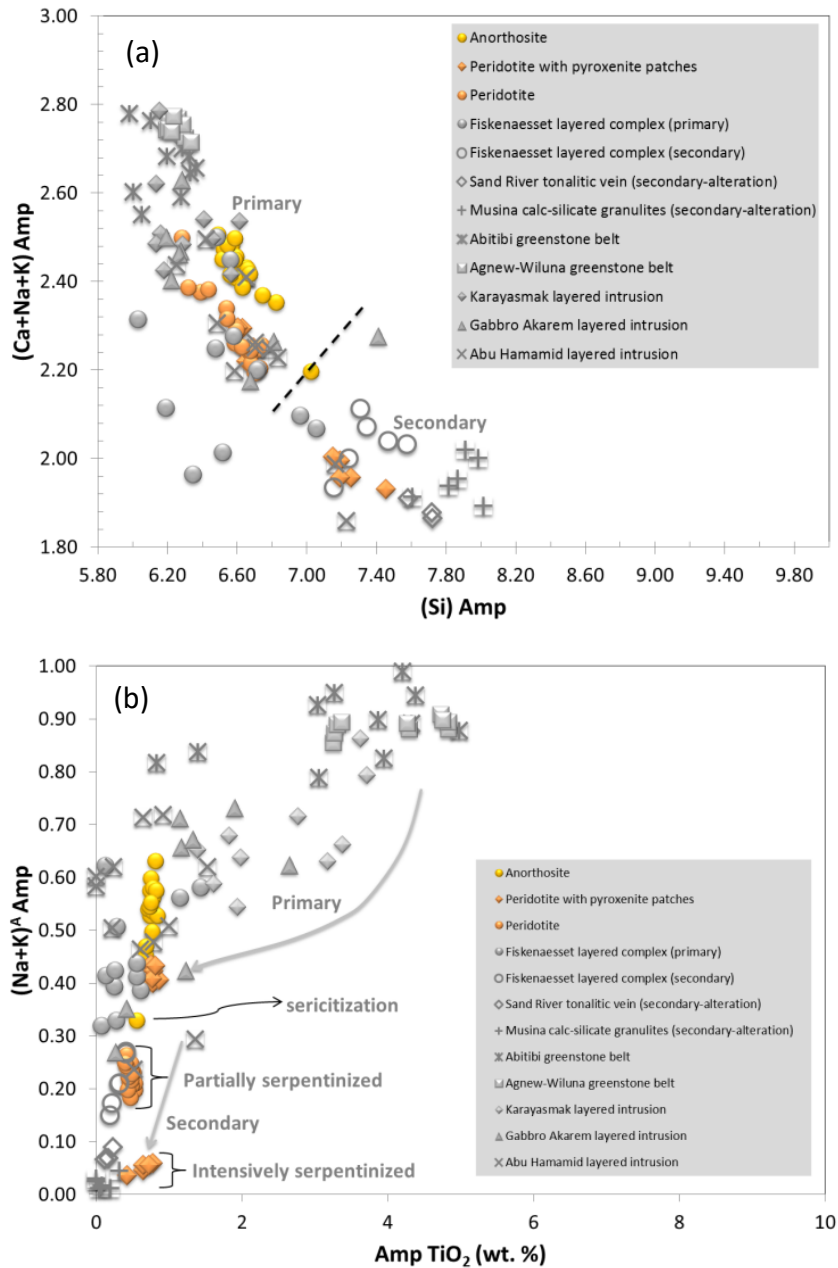


Figure 6.7. Mineral chemistry based diagrams evaluating the primary versus secondary trend of amphiboles in the Lechana ultramafic-mafic rocks. Ca+Na+K (apfu) versus Si (apfu) **(a)**; Occupancy of Na+K in A-site versus occupancy of TiO₂ content (wt.%) in tetrahedral site **(b)**, and Al **(c)**; (Na/Ca+Na) versus Al/(Si+Al) **(d)**. Primary magmatic amphiboles from the Archaean Fiskenaasset layered complex [from Huang et al. (2014)], Archaean ultramafic rocks from the Abitibi greenstone belt, Canada [from Stone et al. (2003)] and Agnew-Wiluna greenstone belt, western Australia [from Fiorentini et al. (2012)], and various Alaskan-type layered intrusions - the Karayasmak ultramafic-mafic association from NE Turkey [from Eyuboglu et al. (2010)], the Gabbro Akarem mafic-ultramafic complex in the eastern desert of Egypt [from Helmy and El Mahallawi (2003)], and the mafic-ultramafic Abu Hamamid intrusion in the south eastern desert of Egypt [from Farahat and Helmy (2006)] are shown for comparison.

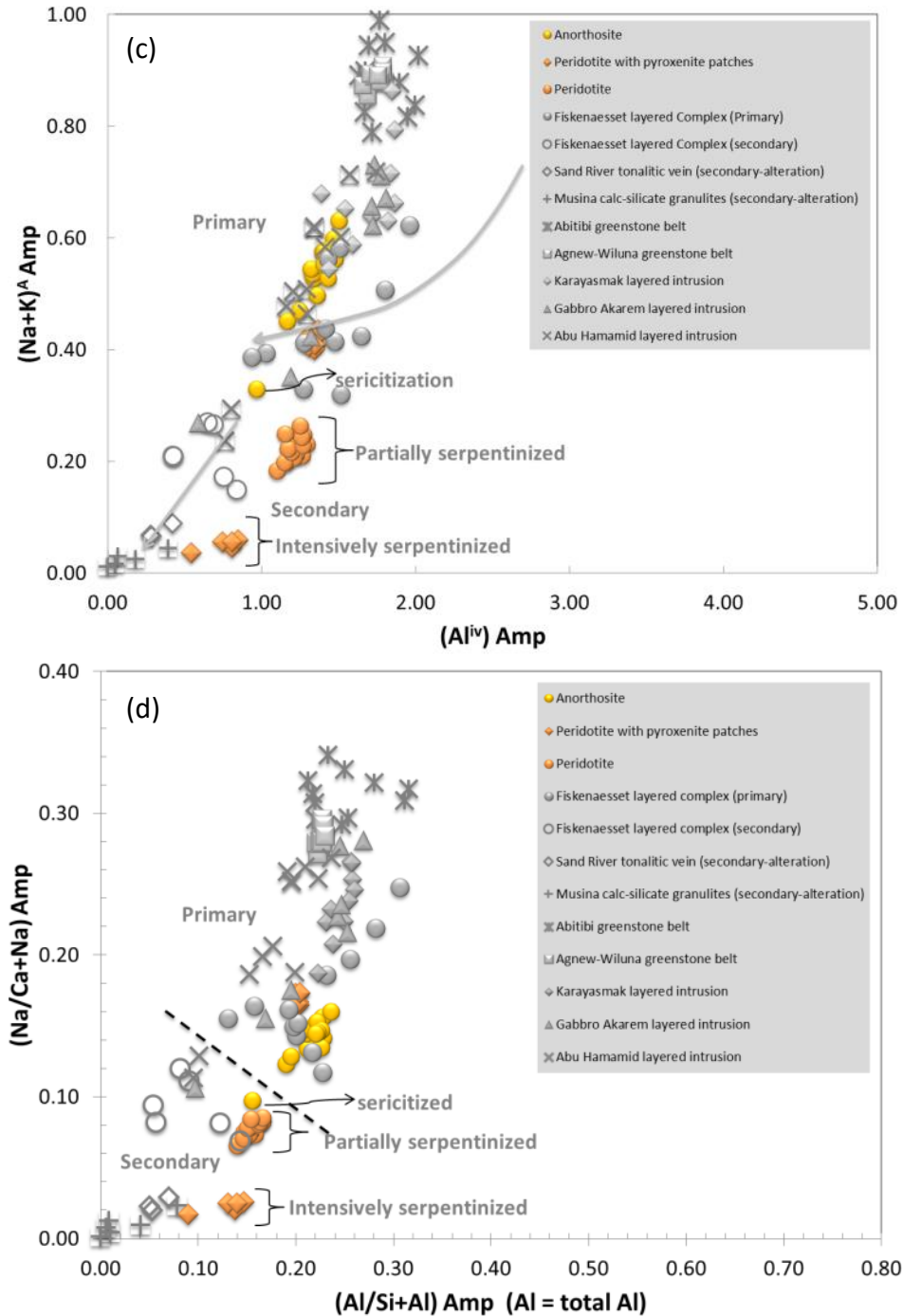


Figure 6.7. (continued) Amphibole compositions related to late-stage-fluid alteration in calc-silicate granulites [from Kaneko et al. (2005)], and secondary (hydrothermal) amphiboles from Paleoproterozoic tonalitic veins from the Limpopo Complex [from Rajesh et al. (2014)] are also shown. Types A3 and B2 amphiboles from the Fiskenaasset layered complex are separately highlighted as they fall along the secondary trend delineated in this study. The fields in (a) are from Giret et al. (1980), while the trend lines in (b) and (c) are modified from Molina et al. (2009). The dividing line (dotted line) in (d) is drawn based on the trends observed in (a) to (c).

On the basis of experimental phase equilibria studies in basic to ultrabasic systems, primary magmatic amphibole coexists in equilibrium with basic melt that contains >3.0 wt.% H₂O (Merzbacher and Eggler 1984; Johnson et al. 1991; Gaetani et al., 1993; Sisson and Grove, 1993; Parman et al., 1997; Müntener et al., 2001). The likely H₂O content of melt estimated from the Lechana layered ultramafic-mafic primary amphibole composition using the calibration of Ridolfi et al. (2010) ranges from 6.4 to 7.2 (± 0.4) wt.%. A processing of primary amphibole compositions from the Fiskensæset layered complex gave estimates that range from 5.0 (± 0.4) to 5.3 (± 0.8) wt.%. Thus, together with the report of primary magmatic amphibole from the Archean Fiskensæset layered complex, the identification of primary magmatic amphibole in ultramafic to mafic rocks of the Archean Lechana layered intrusion implies likely formation from a hydrous parental magma. The inferred hydrous conditions certainly go hand in hand with the boninite-like nature of the rocks of the Archean Lechana layered intrusion, considered to have formed in a suprasubduction setting. Significantly, all the studied rocks are characterized by negative Nb anomalies ($[\text{Nb}/\text{Nb}^* = (\text{Nb}_{\text{PM}}/\text{V}(\text{Th}_{\text{PM}} \times \text{La}_{\text{PM}})) = 0.05\text{-}0.38$), considered as a proxy for derivation from a hydrous mantle source in a suprasubduction zone setting (e.g., Hawkesworth et al., 1993; Pearce and Peate, 1995; Polat et al., 2012).

6.6. Cr-Ni-V mineralization potential of the rocks of the Lechana layered intrusion

Mafic to ultramafic intrusions occurring in Archean terranes in eastern Botswana has been known to host Cr-Ni mineralization. The prominent example is the Selebi-Phikwe belt

of mafic to ultramafic intrusions (e.g., BCL mine near Phikwe) within the Phikwe Complex high-grade (amphibolite- to granulite-facies) metamorphic terrane (see Fig. 1.5). Unlike the Phikwe Complex, Motloutse Complex, which hosts the Lechana layered intrusion was subjected only to amphibolite-facies metamorphic conditions and that too not widespread. Considering the high Cr and Ni contents of the Lechana layered intrusion rocks (e.g., Figs. 6.2a, b), an attempt is made to evaluate their mineralization potential in comparison with data available (Maier et al., 2008) from the Selebi-Phikwe belt of mineralized intrusions. It follows from Fig. 6.8 that the ultramafic rocks of the Lechana layered intrusion are possible candidates to host Cr-Ni-V mineralization. The Cr content of Lechana ultramafic rocks are higher than the available concentration data from the Selebi-Phikwe belt of mineralized intrusions (Fig. 6.8a). Ni contents are comparable to some of the mineralized Selebi-Phikwe belt intrusions (Fig. 6.8b). As reported by the present study, magnetite-rich layers (see Fig. 2.5f), which can be traced for the entire outcrop length, were found associated with peridotite-pyroxenite associations from the Lechana layered intrusion. But the V contents are lower in Fig. 6.8c. This in no way negates the possibility of Lechana layered ultramafic rocks hosting V, as it should be admitted that the present study, with focus on characterizing the primary magmatic (boninite-like) characteristics of the rocks, did not sample visible magnetite-layer-bearing ultramafic rocks. The high Cr, Ni and V contents of the studied rocks, which are considered as Archean *boninite-like* rocks, together with similar contents observed in typical boninites (Figs. 6.2a, b), could be a useful indicator for delineating the nature of mafic-ultramafic rocks associated with Cr-Ni-V mineralization.

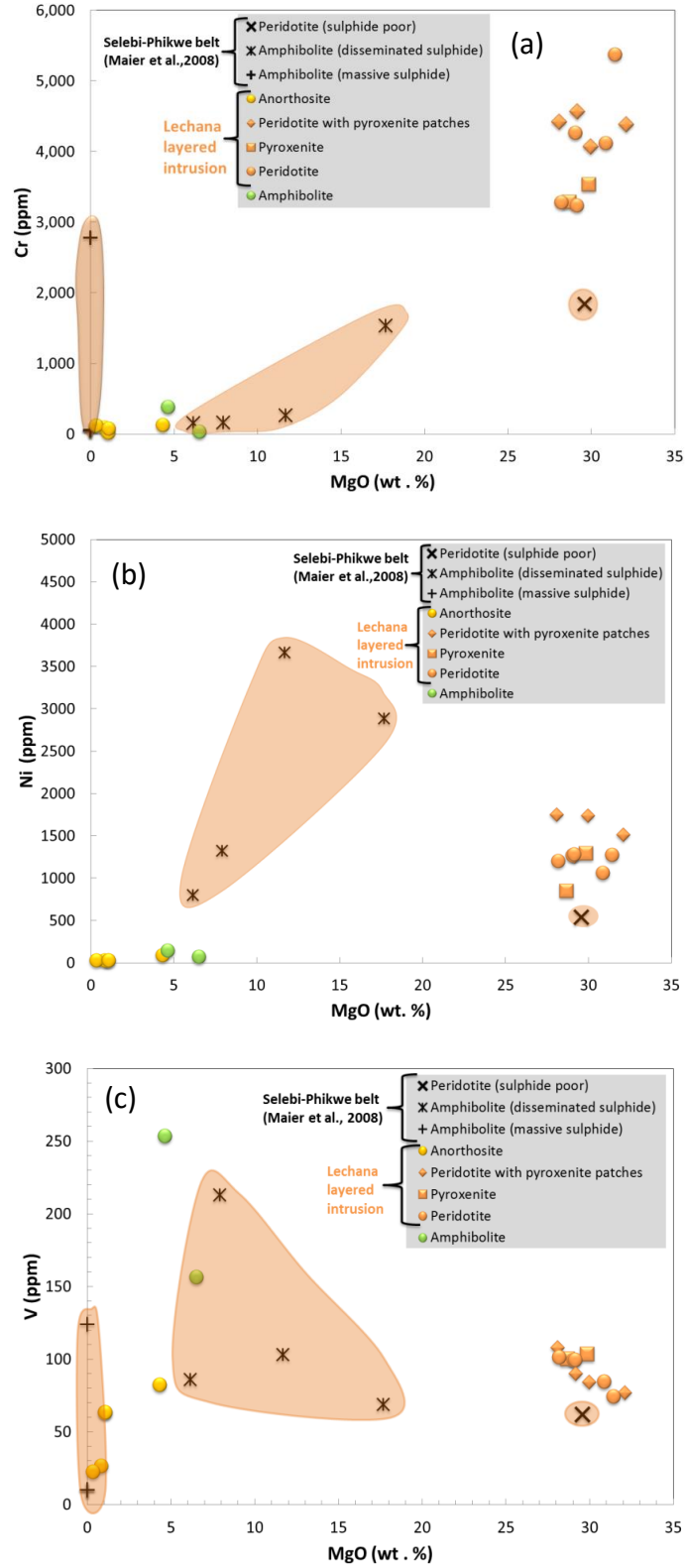


Figure 6.8. Cr (a), Ni (b) and V (c) versus MgO content of Lechana layered intrusion rocks compared with that of the mineralized Selebi-Phikwe belt of mafic to ultramafic intrusions (highlighted fields).

Chapter 7

Concluding remarks

- Layered ultramafic- to mafic- rocks occurring in the Lechana area, southern Motloutse Complex, constitute dismembered remains of an Archean layered intrusion – referred here as the Lechana layered intrusion.
- The conspicuous occurrence of amphibole as inclusions in olivine, pyroxenes and plagioclase indicates that the amphiboles occurring in the studied ultramafic and mafic rocks are likely primary magmatic. This is further supported by their mineral chemical characteristics, which are similar to primary magmatic amphiboles from literature. In contrast, amphiboles occurring in serpentinized and sericitized rocks indicate the effect of alteration. Isocon analysis indicates element gained (Cr_2O_3 , NiO and MgO) and lost (K_2O , Cl, V_2O_3 , MnO, FeO, ZnO, Na_2O , Al_2O_3 , TiO_2 and SiO_2) during alteration of amphibole.
- A set of four mineral chemical diagrams based on TiO_2 , $(\text{Na}+\text{K})_{\text{A}}$, Al(IV) , $(\text{Na}/\text{Ca}+\text{Na})$, $(\text{Al}/\text{Si}+\text{Al})$, $\text{Ca}+\text{Na}+\text{K}$ and Si of amphibole compositions to distinguish between primary and secondary amphiboles is presented. The fields and trends in the diagrams were revised based on a larger dataset. Considering the complex mineral structure of amphibole, which often makes it difficult to distinguish unambiguously if it is of magmatic, metamorphic, hydrothermal or metasomatic in origin, one should be

careful in using the trends delineated in the diagrams and is ideally used together with detailed petrographic characterization.

- The occurrence of primary magmatic amphibole as a prominent mineral in the layered ultramafic-mafic rocks implies hydrous conditions during formation.
- The good correlation between mineral chemical and whole-rock geochemical data for the Lechana ultramafic and mafic rocks argues for the general preservation of primary magmatic compositions in these rocks.
- Whole-rock geochemical composition (e.g., high SiO₂, high MgO) of the layered mafic-ultramafic rocks are similar to boninites. The unique U-shaped REE signature was observed in a peridotite sample with patchy pyroxenite domains. This finding has important implications in identifying *boninite-like* rocks in the Archean. The occurrence of primary magmatic amphibole goes hand in hand with the boninite-like nature of the rocks.
- Similar chondrite-normalized REE pattern of the mafic-ultramafic rocks indicates likely derivation from a common parental magma. Consistent trends of evolution were observed from the ultramafic to mafic rocks, arguing for differentiation of the original magma.
- Immobile element based tectonic discrimination indicate likely derivation of the rocks in a suprasubduction involving transition from a MORB-like to subduction setting.

- Trace element modelling indicate the possible role played by crustal contamination (likely during the subduction episode) to account for the *boninite-like* signature.
- In summary, mafic-ultramafic rocks occurring as part of the Lechana layered intrusion constitutes a perfect example of *boninite-like* rocks in the Archean.
- Finally, the high Cr and Ni contents of the ultramafic rocks studied here, in comparison to that of the mineralized Selebi-Phikwe belt of mafic to ultramafic intrusions in eastern Botswana, and the prominent magnetite-bearing layers associated with peridotite-pyroxenite associations, could indicate the potential of the Lechana layered intrusion rocks to host Cr-Ni-V mineralization.

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