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**CHARACTERISTICS OF SHEAR DEFORMATION ALONG THE
EASTERN AND SOUTHERN TERRANE BOUNDARIES OF THE
MOTLOUTSE COMPLEX, EASTERN BOTSWANA**

by

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Abstract

The Motloutse Complex to the southwestern margin of Zimbabwe Craton is a medium-grade terrane in northeastern Botswana. Some studies consider it as part of the Limpopo Complex high-grade terrane between the Kaapvaal and Zimbabwe cratons, while others argue it as an allochthonous terrane separate to the Limpopo Complex. A number of shear zones are postulated to delineate the extents of Motloutse Complex. Except the northern margin (the Shashe shear zone), the rest of the terrane boundaries of the Motloutse Complex are poorly understood. The Magothate-Dikalate shear zones are argued to delineate the eastern margin with the Phikwe Complex (sub-terrane of the Limpopo Complex). The western and southern terrane extents of the Motloutse Complex are buried under younger cover rocks. This study characterizes the nature, extent, and timing of shear deformation along the eastern and southern terrane boundaries of the Motloutse Complex. Representative areas from the eastern (Masikati hills), and southern (Radisele-Mogome) regions were selected. A combination of geologic (field, petrographic), geochronologic ($^{40}\text{Ar}/^{39}\text{Ar}$ amphibole-biotite), and geophysical (aeromagnetic) data were utilized.

Neoproterozoic tonalite gneiss and Mesoproterozoic mafic (amphibolite-gabbro-leucogabbro-anorthosite)-ultramafic (dunite-peridotite-pyroxenite) rocks constitute the dominant rock units in the Masikati hills area in eastern Motloutse Complex. Four concomitant overprint events variably affect the rocks, and include upright isoclinal folding, anatexis, shear deformation and metasomatic components. Shear deformation is prominent along the

Masikati hills. Kinematic indicators, including asymmetric porphyroclasts and S-C fabric, indicate dominant right lateral sense of movement, with minor left lateral movement. The extent of the shear zone (N-S trending Dikalate shear zone), including its branches, is delineated in the aeromagnetic imagery. Application of $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology on fabric-forming amphibole dates the shear deformation along the eastern terrane boundary of Motloutse Complex at 2013 ± 12 Ma.

The NW-SE trending Radisele-Mogome area, beneath the cover rocks, exposes two set of rocks – tonalite gneiss-amphibolite-ultramafic rocks (part of the Motloutse Complex) to the NE, and granodiorite-diorite gneiss-leucogranite (part of the Mahalapye Complex) to the SW. This is well exemplified in the aeromagnetic image, with change in magnetic signature between rocks in the NE and SW parts. Shear deformation and metasomatism variably overprint rocks along the contact zone. Mylonitic deformation is prominent in the SW part. Like the case of the eastern terrane boundary, asymmetric porphyroclasts and S-C fabric indicate a dominant right lateral sense of shear movement. The extent of this shear zone (northwest trending Sunnyside shear zone) and its branch is delineated in the aeromagnetic imagery. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology on biotite from a sheared diorite gneiss from the SW margin of the shear zone indicate an age of 1987 ± 8 Ma.

It is argued that both the eastern and southern terrane boundaries of the Motloutse Complex terrane were active in the Paleoproterozoic, with shear deformation slightly earlier along the Dikalate shear zone (~ 2.013 Ga), relative to the Sunnyside shear zone (~ 1.987 Ga).

Chapter 1

Introduction

1.1. Shear zone as terrane boundaries

In the common case, boundaries of Archean terranes are defined by ductile shear zones. Shear zones not only constitute regions of strain localization at different scales, but also pathways promoting fluid-rock interaction (Ramsay and Graham, 1970; Ramsay, 1980; Wernicke, 1985; Snyder and Kjarsgaard, 2013; Fossen et al., 2017; Fossen and Cavalcante, 2017; Passchier and Platt, 2017). Hence, to understand the crustal deformation along the terrane boundaries, it is important to characterize the *nature, extent and timing of shear deformation* along them. This information helps to place the shear deformation event in the context of regional tectonics.

1.2. Nature of shear deformation and regional tectonics

Archean medium-high-grade (amphibolite- to granulite-facies metamorphic) terranes are often characterized by an anatomizing network of crisscrossing shear zones (Carreras et al., 2010) separating adjacent sub-terrane. A good example is the network of shear zones separating the different terranes of the Limpopo Complex high-grade terrane in southern Africa (Fig. 1.1; McCourt and Vearncombe, 1992; Blenkinsop et al., 1995; Smit et al., 1992). In such instances, where there is a network of crisscrossing shear zones, the *nature of shear deformation*, expressed in terms of the sense of vergence, from different parts of the

terrane can be a topic of contention. For e.g., McCourt and Vearncombe (1987) and (1992) inferred a sinistral strike slip movement with a late dextral component for the Palala shear zone of the Limpopo Complex (see Fig. 1.1 for location). However, Schaller et al. (1999) and Liang et al. (2021) argue for a prominent dextral strike slip movement with a minor sinistral component for the Palala shear zone. Reports of opposite sense of movement is not uncommon for shear zones (Passchier and Williams, 1996; Dutta and Mukherjee, 2019). They could be interpreted differently – as part of multiple reactivation events, different stages of a single prolonged event or distinct events. If properly considered with the regional tectonics, possible explanations could be put forward for the contrasting inference of shear sense from the same shear zone. In any case, a study involving detailed field and petrographic characterization should help to infer the sense of movement along shear zones. Kinematic indicators (e.g., S-C fabrics, asymmetric porphyroclasts) need to be delineated, and carefully interpreted (Passchier and Simpson, 1986; Dutta and Mukherjee, 2019).

1.3. Extent of shear deformation and regional tectonics

The *extent of shear deformation* often varies along its length. Lack of continuous exposures, and effect of younger cover sequences can affect the exercise of delineation of the extent of regional-scale shear zones. Taking the example of the Palala shear zone, it is best exposed in the Koedoesrand window (Fig. 1.1), while it is poorly exposed to buried under younger cover rocks at many places along its strike (McCourt and Vearncombe, 1987, 1992; Brandl and Reimold, 1990; Cheney et al., 1995; Schaller et al., 1999; Bumby et al.,

2001). However, available aeromagnetic data clearly indicate that this lineament forms a prominent crustal-scale structure (De Beer and Stettler, 1992; Schaller et al., 1999).

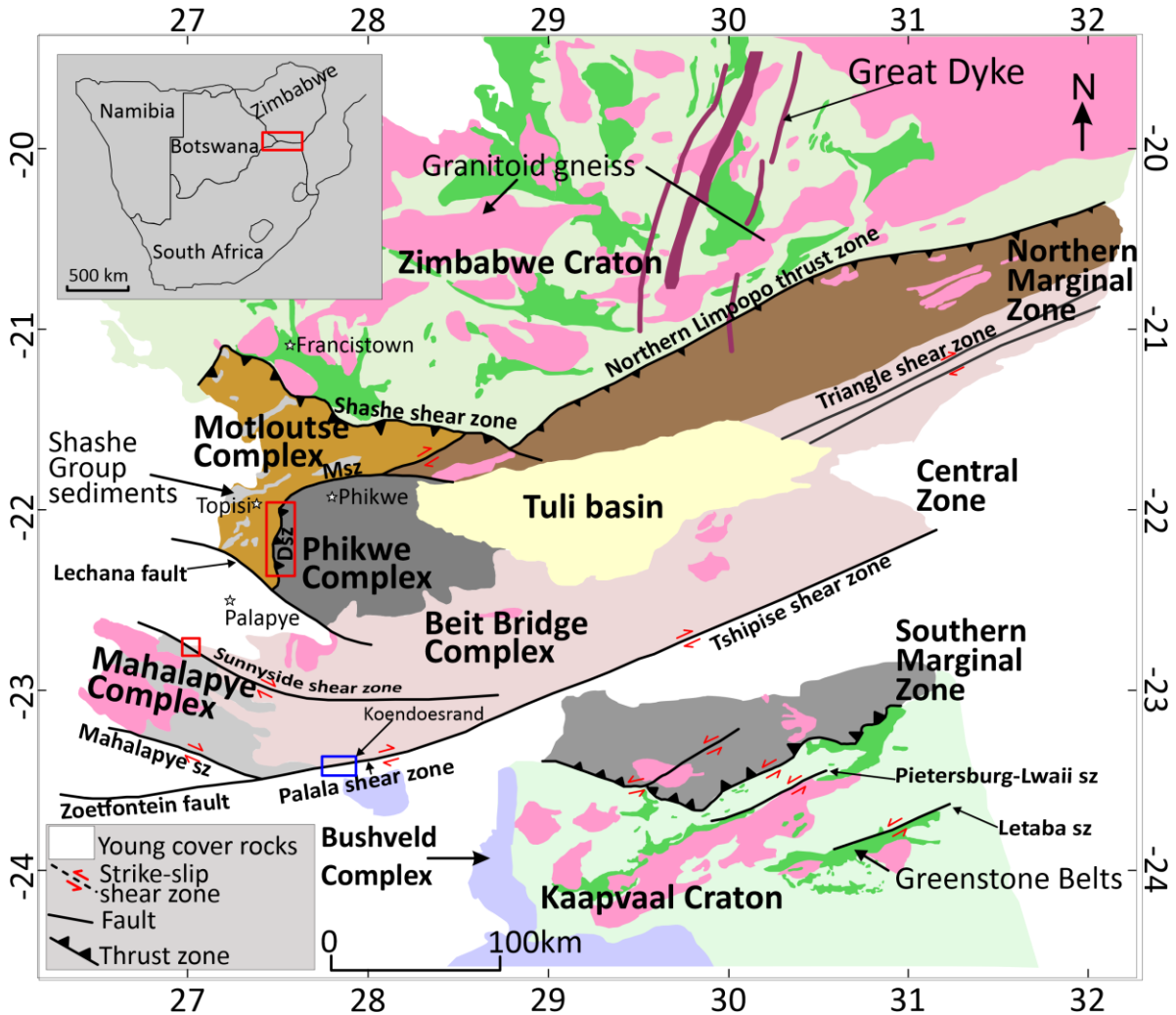


Figure 1.1. Generalized geologic map of the high-grade terrane of the Limpopo Complex between the Archean Zimbabwe and Kaapvaal cratons [modified from Aldiss (1991) and Van Reenen et al. (2011)].

The limited occurrence of outcrops exacerbates the challenge of studying the geological makeup of terranes overlain by sedimentary units, demarcating their extent, and interpreting the relation to other regional domains. Therefore, traditional geological mapping alone does not provide adequate information on the geological and tectonic setup

of terranes beneath the younger sedimentary cover, let alone their margins with other lithostratigraphic complexes. In such instances, geophysical characteristics constitute an important tool to characterize the extent of shear zones. High resolution aeromagnetic data is widely used to investigate the structural characteristics, lithologies of terranes, and their extent under sedimentary cover (e.g., Airo, 2005; Betts et al., 2007; Aitken et al., 2008; Aitken and Betts, 2009; Gibson et al., 2013; Henderson et al., 2015). Geologic structures like faults and shear zones manifest as linear anomalies (either high or low magnetic signatures) in aeromagnetic maps (Aitken and Betts, 2009). Thus, an integrated geological and geophysical approach in mapping could improve delineation of the extent of shear zones.

1.4. Timing of shear deformation and regional tectonics

In the context of regional tectonics, an understanding of the *timing of shear deformation* is important to correlate with other contemporaneous events in the region. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology on fabric-forming minerals (e.g., amphibole, mica) is a commonly used method to date the shear deformation (Page et al., 1996; McDougall and Harrison, 1999; Kelley, 2002; Reiners et al., 2005; Oriolo et al., 2018). The step-wise heating approach of $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology, resulting in a plateau or near-plateau age pattern, is a useful criterion to verify the premise of closed system (Page et al., 1996; McDougall and Harrison, 1999; Kelley, 2002; Reiners et al., 2005; Oriolo et al., 2018). Although less commonly used, Rb-Sr geochronology is another method to date the fabric forming minerals in shear zones (Steiger and Jäger, 1977; Villa et al., 2015; Oriolo et al., 2018). For e.g., Schaller et al. (1999)

presented a Rb-Sr biotite-whole-rock age of 1971 ± 26 Ma for the Palala shear zone. Belluso et al. (2000) presented an $^{40}\text{Ar}/^{39}\text{Ar}$ amphibole age of 2023 ± 5 Ma from the Palala shear zone. Cl/K and Ca/K ratios of amphibole was used to argue that there was mixing of different end members (Belluso et al., 2000). Significantly, the older age is comparable to the Pb stepwise leaching (PbSL) method (Frei and Kamber, 1995) ages on titanite from the Palala shear zone (2017 ± 6 Ma; 2020 ± 8 Ma; Holzer et al., 1999; Schaller et al., 1999). Hence, the use of $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology to date fabric forming minerals need to be combined with mineral chemical data, especially Ca/K and Cl/K ratios (Müntener et al., 1997; Villa et al., 1996, 2000), to get a better approximation of the age of shear deformation.

1.5. Terrane boundaries of the Motloutse Complex in eastern Botswana – towards the research problem

Motloutse Complex is an Archean medium-grade terrane to the southwest of the Zimbabwe Craton in eastern Botswana (Figs. 1.1, 1.2). Some studies consider it to be an allochthonous terrane which accreted to the craton margin in the Neoarchean (Aldiss, 1991; Carney et al., 1994; Key et al., 1994; McCourt et al., 2004). Others consider it to be a western extension of the adjacent Limpopo Complex high-grade terrane (Ranganai et al., 2002; Zeh et al., 2009).

The Shashe shear zone constitute the northern terrane boundary of the Motloutse Complex with the adjacent cratonic domain (Figs. 1.1, 1.2; Aldiss, 1991; Carney et al., 1994; Key et al., 1994; Paya, 1996; Paya et al., 1997; McCourt et al., 2004). The ENE-WSW-trending

Magogaphate and N-S trending Dikalate shear zones separate the Motloutse Complex to the east from the Semolale and Phikwe Complexes, two sub-terrane of the Limpopo Complex (Figs. 1.1, 1.2; Bennett, 1971; Aldiss, 1991; Key et al., 1994; Paya et al., 1997; McCourt et al., 2004). The western and southern extents of the terrane are obscured by younger cover rocks (Figs. 1.1, 1.2). To the south of the cover rocks, is the Mahalapye Complex, the youngest terrane of the Limpopo Complex (Figs. 1.1, 1.2). The NW-SE trending Sunnyside shear zone constitutes the northern margin of the Mahalapye Complex. Field reconnaissance by the author in the region to the immediate north of the Sunnyside shear zone (Fig. 1.2) indicate the occurrence of older crystalline rocks typical of the southern Motloutse Complex. This suggests the possibility of the Sunnyside shear zone defining the southern terrane boundary of the Motloutse Complex. Other than the Shashe shear zone, none of the other terrane boundaries of the Motloutse Complex have been characterized. Previous regional mapping programs by the Department of Geological Survey [now Botswana Geoscience Institute (BGI)] have proposed the Magogaphate and Dikalate shear zones as terrane boundaries (Bennett, 1971; Carney et al., 1994; Key et al., 1994; Paya et al., 1997). The southern terrane boundary is currently obscured by younger cover rocks.

1.6. Objectives and approach

The study aims to characterize the *nature, extent and timing of shear deformation* along the eastern and southern terrane boundaries of the Motloutse Complex. Field reconnaissance aided with satellite remote sensing and geophysics isolated two potential

study areas – the Masikati hills area along the eastern terrane boundary, and the Radisele-Mogome area along the southern terrane boundary, south of the cover rocks (rectangles in Fig. 1.2).

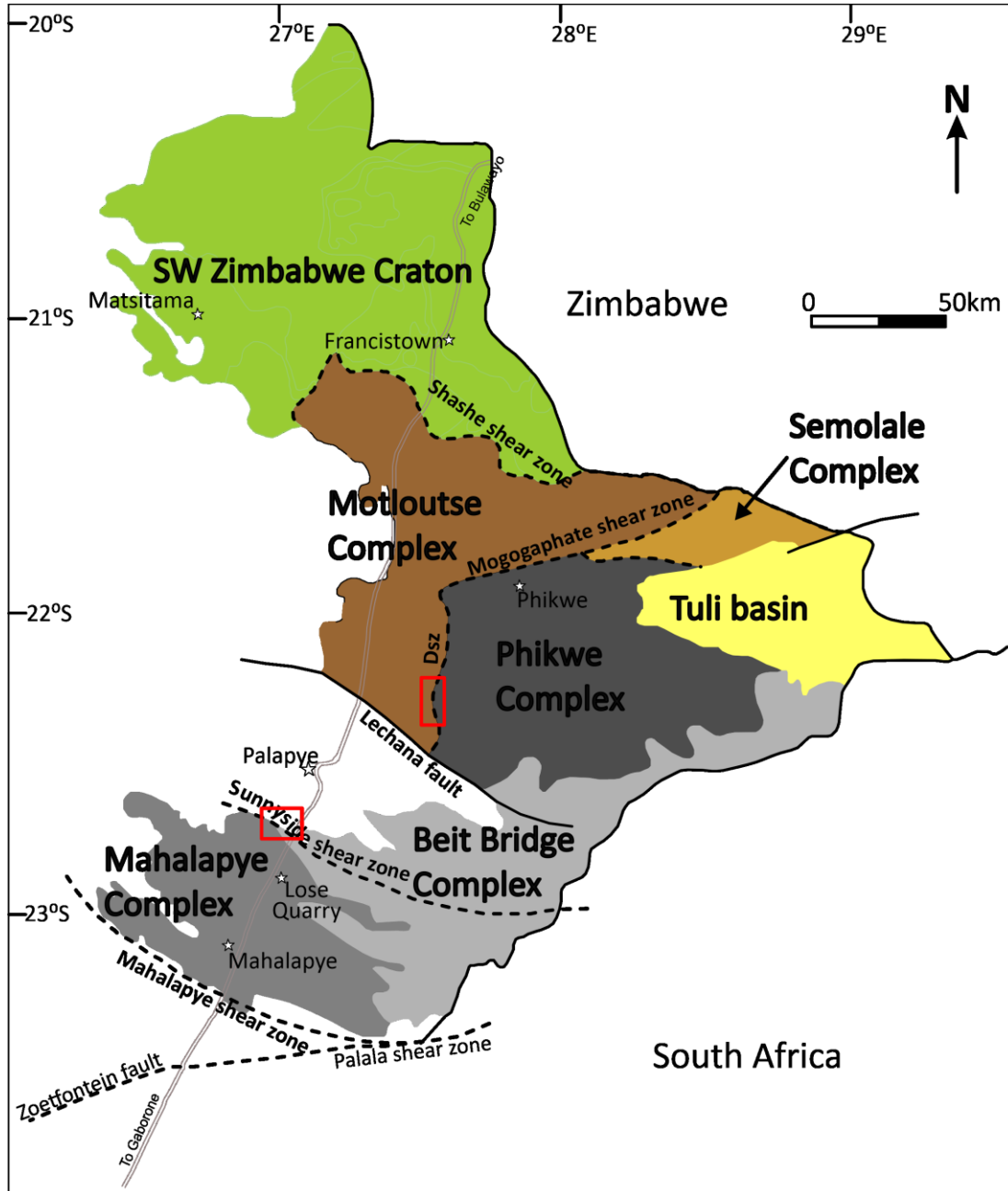


Figure 1.2. Generalized geologic map showing the known extent of the different Archean to Paleoproterozoic terranes in eastern Botswana. The present study aims to characterize the eastern and southern terrane boundaries of the Motloutse Complex. The respective study areas are shown as red rectangles.

The following three-fold objectives and approach were laid out for the study.

- Geologic characterization involving detailed field and petrographic study of sheared and non-sheared rocks to understand the *nature of shear deformation* along the study areas.
- In view of the lack of continuous exposures and the effect of cover rock sequences, geophysical study to understand the *extent of shear deformation* along the study areas. Aeromagnetic data is used for the purpose.
- $^{40}\text{Ar}/^{39}\text{Ar}$ geochronologic characterization of fabric forming minerals from sheared rocks to understand the *timing of shear deformation* along the study areas. This is supplemented by mineral chemical analyses of the fabric forming minerals so as to correlate with Ca/K and Cl/K ratios measured by $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology.

Multiple field work sessions were carried out, mostly during winter, in the two study areas since 2018. The analytical details of aeromagnetic analyses, mineral chemical analyses and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology are given in Appendix 1.

1.7. Outline of the thesis

The different chapters of the thesis are structured so that it correlates with the three-fold objective of the study. The thesis commences with an overview of the geologic setting of the Archean-Paleoproterozoic geologic units in eastern Botswana with a focus on the Motloutse

Complex in chapter 2. Detailed field relations of sheared and non-sheared rocks in the two study areas are addressed in chapter 3. Petrographic characteristics of the main rock types from the study areas is dealt in chapter 4. Chapter 5 deals with the $^{40}\text{Ar}/^{39}\text{Ar}$ geochronologic and mineral chemical data on fabric forming minerals from the study areas. Geophysical (aeromagnetic) characteristics of the eastern and southern terrane boundaries are dealt with in Chapter 6. Finally, in Chapter 7, the results from the geologic, geochronologic and geophysical studies are discussed in the context of available information from Motloutse Complex and the adjacent Limpopo Complex. The resulting concluding remarks are given in Chapter 8.

Chapter 2

Geologic setting

This chapter gives a general overview of the geology of eastern Botswana, with focus on Archean-Paleoproterozoic units. The geology of the Motloutse Complex, especially its southern part is given prominence, with a detailed description and supportive field photos.

2.1. Archean-Paleoproterozoic geologic units in eastern Botswana

The Archean-Paleoproterozoic geologic units in eastern Botswana can be grouped into three. From the NE, these are the SW Zimbabwe Craton, the different terranes of the Limpopo Complex (Semolale Complex, Phikwe Complex, Baines Drift Complex, Mahalapye Complex), and the Motloutse Complex (Fig. 2.1; Carney et al., 1994; Key et al., 1994; McCourt et al., 2004).

2.2. Francistown granitoid-greenstone complex

The granitoid-greenstone terrane around Francistown in eastern Botswana, constitute part of the southwestern Zimbabwe Craton (Fig. 2.1). It is referred to as the Francistown granitoid-greenstone complex (Key, 1976; Key et al., 1976; Aldiss, 1989, 1991; Carney et al., 1994). The prominent geologic unit in this terrane is the Neoproterozoic (~2.73 Ga) NW oriented Tati greenstone belt, made up of volcanic/volcaniclastic and sedimentary rocks (Coward and James, 1974; Key, 1976; Key et al., 1976; Aldiss, 1991; Tombale, 1992; Carney et al., 1994;

Bagai, 2008; Døssing et al., 2009; Fig. 2.1). The rocks in the Tati greenstone belt are metamorphosed at lower greenschist to lower amphibolite-facies conditions (Key, 1976; Key et al., 1976; Coward and James, 1974; Aldiss, 1991; Tombale, 1992). The volcano-sedimentary sequence is surrounded by ~2.73-2.65 Ga granitoids, and includes Na-rich grey granitoid gneisses (TTGs), Mg-rich diorites (sanukitoids), and K-rich granites (Key, 1976; Aldiss, 1989; Tombale, 1992; Kampunzu et al., 2003; Bagai et al., 2002; Zhai et al., 2006; Bagai, 2008; Zeh et al., 2009).

2.3. Limpopo Complex terranes in eastern Botswana

The high-grade Archean to Paleoproterozoic Limpopo Complex, between the Archean Zimbabwe and Kaapvaal cratons, consists of three major domains – the Northern Marginal Zone along the southwestern margin of the Zimbabwe Craton, the Central Zone in the middle, and the Southern Marginal Zone along the northeastern margin of the Kaapvaal Craton (see reviews in Blenkinsop, 2011; Kramers et al., 2011; Smit et al., 2011; Van Reenen et al., 2011). Regional scale shear zones separate the different terranes from each other and the adjacent cratonic domains. These include from north to south, the Northern Limpopo thrust zone, Triangle shear zone, Palala-Tshipise shear zone, and the Hout River shear zone (McCourt and Vearncombe, 1992; Smit et al., 1992; Fedo et al., 1995; Rollinson and Blenkinsop, 1995; Kamber et al., 1995; Mkweli et al., 1995; Holzer et al., 1999; Schaller et al., 1999; Kreissig et al., 2001). The occurrence of granulite-facies metamorphic assemblages in rocks distinguishes the Limpopo Complex, from the adjacent lower grade cratonic domains.

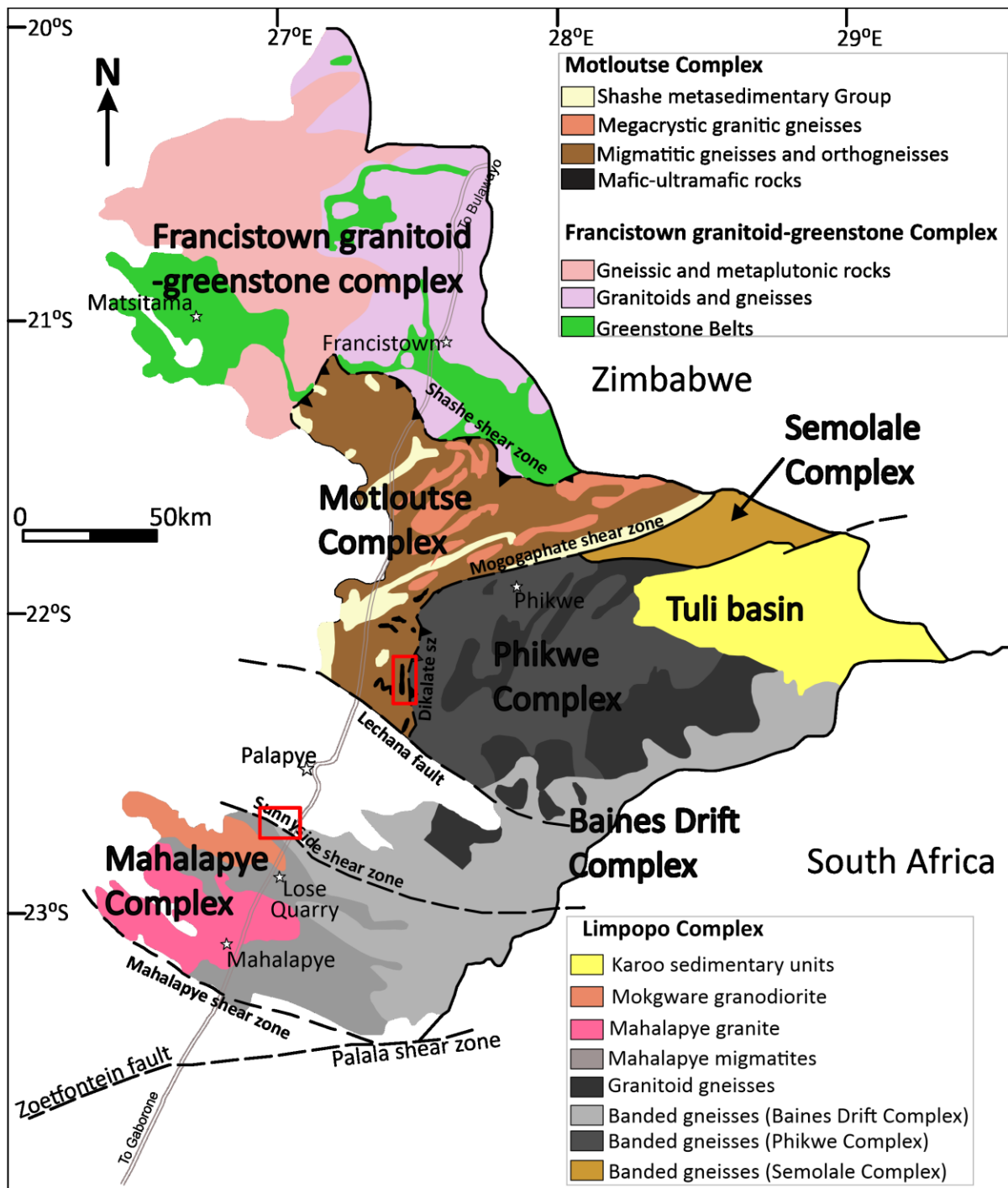


Figure 2.1. General geologic map showing the different Precambrian terranes in eastern Botswana [modified from Aldiss (1991) and Carney et al. (1994)]. The rectangles respectively indicate the extent of the respective study areas along the eastern and southern terrane boundaries of the Motloutse Complex.

2.3.1. Semolale Complex

The portion of the Northern Marginal Zone within eastern Botswana is referred to as the Semolale Complex (Fig. 2.1; Aldiss, 1991; Carney et al., 1994). Granitoid gneisses constitute the dominant rock type, and include pyroxene-bearing ones (enderbites) (Aldiss, 1989, 1991; Ridley, 1992; Berger et al., 1995; Rollinson and Blenkinsop, 1995; Blenkinsop, 2011). Available geochronologic data from the Northern Marginal Zone brackets the granitoids to 2.74–2.69 Ga (Rollinson and Whitehouse, 2011). The less dominant older supracrustal rocks include metasediments and mafic-ultramafic metavolcanics (Aldiss, 1983, 1989, 1991; Rollinson and Lowry, 1992; Carney et al., 1994; Blenkinsop, 2011). As argued for the Northern Marginal Zone, the rocks of the Semolale Complex are likely the high-grade equivalents of the low-grade cratonic rocks (Carney et al., 1994; Blenkinsop, 2011).

2.3.2. Phikwe Complex

The Central Zone of the Limpopo Complex is further subdivided into the Beit Bridge Complex, Phikwe Complex and the Mahalapye Complex (Aldiss, 1991). The high-grade terrane of Phikwe Complex is dominated by granitoid gneisses with interlayered amphibolite, metasedimentary rocks, anorthositic gneiss and ultramafic rocks (Fig. 2.1; Lear, 1971; Hor et al., 1975; Key, 1976, 1984; Aldiss, 1983, 1991; Carney et al., 1994). Relict granulite-facies mineral assemblages occur in rocks from the Phikwe Complex (Aldiss, 1983, 1989; Carney et al., 1994; Holzer et al., 1999). The granitoids are Neoarchean, with the amphibole-bearing granitoid gneisses dated to ~2.74-2.60 Ga (McCourt and Armstrong,

1998), and granites to ~2.65-2.60 Ga (Zeh et al., 2009). ~2.0 Ga overprint ages are locally reported from the Phikwe Complex (Van Breemen and Dodson, 1972; Wakefield, 1974; Zeh et al., 2009).

2.3.3. Baines Drift Complex

To the south of the Phikwe Complex, and bounded by a series of large amplitude north vergent folds is the Baines Drift Complex (Fig. 2.1; Carney et al., 1994). The Baines Drift Complex constitutes the portion of the Beit Bridge Complex within eastern Botswana. It is made up of granitoid gneisses, amphibolites, metasedimentary rocks and minor anorthositic gneiss (Mason, 1964; Key, 1984; Carney et al., 1994). The ~3.23 Ga Zanzibar granitoid gneiss in the Baines Drift Complex is considered equivalent to the ~3.31-3.27 Ga Sand River granitoid gneiss in the Beit Bridge Complex in South Africa (Barton and Key, 1983; Kröner et al., 1999; Zeh et al., 2007).

2.3.4. Mahalapye Complex

The Mahalapye Complex constitutes the westernmost terrane of the Central Zone of the Limpopo Complex (Fig. 2.1). It is a Paleoproterozoic granitoid gneiss terrane made up of ~2.06 Ga diorite gneiss, ~2.05 Ga leucogranite 1, ~2.04 Ga granodiorite, ~2.03 Ga leucogranite 2, and ~2.02 Ga alkali granite (Skinner, 1978; Key, 1979; Ermanovics, 1980; Carney et al., 1994; Chavagnac et al., 2001; McCourt and Armstrong, 1998; Holzer et al.,

1999; McCourt et al., 2004; Hisada et al., 2000, 2005; Zeh et al., 2007; Millonig et al., 2010; Rajesh, 2019; Rajesh et al., 2020b, 2022). The granodiorite is dominantly exposed to the north (the Mokgware pluton), the leucogranite in the central to southeast, and the alkali granite to the southwest (the Mahalapye pluton) (Fig. 2.1). Of the two types of leucogranites, the older leucogranite 1 occurs as leucosomes, thin veins and dykes, while the younger leucogranite 2 form massive bodies. The diorite gneiss occurs as inclusions within the different granitoids. High-grade metamorphic conditions are reported locally from the diorite gneiss, as well as amphibolite-metapelite inclusions within leucogranite (Hisada et al., 2000, 2005; Millonig et al., 2010; Rajesh et al., 2020b, 2022).

The E-W to NW-SE trending Sunnyside shear zone and the NW-SE trending Mahalapye shear zone constitute the northern and southern terrane boundaries of the Mahalapye Complex (Fig. 2.1; Ermanovics, 1977, 1980; Key, 1979; McCourt and Vearncombe, 1987, 1992; Holzer et al., 1999).

2.4. Motloutse Complex

To the south of the Francistown granitoid-greenstone Complex is the Motloutse Complex (Fig. 2.1). The SW-dipping Shashe thrust sense shear zone separates the two terranes (Fig. 2.1), and is marked by a change from NW-SE trending planar fabric in the low-grade terrane to NE-SW trending fabric in the medium-grade terrane (Aldiss, 1991; Carney et al., 1994; Key et al., 1994; Paya, 1996; Paya et al., 1997; McCourt et al., 2004). The ENE-WSW-trending Magogaphate and N-S trending Dikalate shear zones separate the Motloutse Complex to the

east from the Semolale and Phikwe Complexes (Fig. 2.1; Bennett, 1971; Aldiss, 1991; Key et al., 1994; Paya et al., 1997; McCourt et al., 2004). The western and southern extents of the terrane are obscured by younger cover rocks.

The Motloutse Complex consists of granitoid gneisses, meta-sedimentary rocks, and mafic-ultramafic rocks (Aldiss, 1991; Carney et al., 1994; Key et al., 1994). Mesoarchean mafic-ultramafic rocks of the Lechana layered complex exposed in the southeastern part of the terrane constitute the oldest known rock type (Rajesh et al., 2020a). They are associated with massive amphibolites. Together these mafic-ultramafic bodies occur as inclusions within the granitoid gneiss. The granitoid variants include tonalitic gneisses, migmatitic (granodioritic to granitic) gneisses, and porphyritic granites (Key, 1976; Smith and Phofuetsile, 1985; Aldiss, 1989, 1991; Carney et al., 1994; Key et al., 1994). Available geochronologic data bracket the granitoids between 2.71–2.63 Ga (Holzer et al., 1999; B.K. Paya unpublished data quoted in McCourt et al., 2004; Zeh et al., 2009). The Shashe Group metasediments including quartzites, quartz-mica schists, marbles, calc-silicates, with minor pelites and ironstones are prominent in the northern-central-southwestern parts of the terrane (Fig. 2.1; Key, 1976; Smith and Phofuetsile, 1985; Aldiss, 1989, 1991; Key et al., 1994). The maximum age of deposition of these sediments is around ~2.66 Ga (Mccourt et al., 2004). The metasediments were subsequently thrust northeastwards onto the craton margin (Aldiss, 1991; Carney et al., 1994; Key et al., 1994; McCourt et al., 2004). Metamorphic conditions in the Motloutse Complex vary from lower greenschist-facies in the metasedimentary rocks to amphibolite-facies in the meta-basalts (Key, 1976; Aldiss, 1989, 1991; Smith and Phofuetsile, 1985; Key et al., 1994; Holzer et al., 1999; Buick et al., 2007). A

local Paleoproterozoic overprint involving concomitant anatectic, shear deformation, and alkali metasomatism is reported from the southeastern part of the Motloutse Complex (Rajesh et al., 2020a).

2.4.1. Southern Motloutse Complex

This study focuses on the southern Motloutse Complex (Fig. 2.2). Hence, it is important to clarify the known chronologic relations. The dominant Neoarchean granitoids include earlier tonalite gneiss and younger porphyritic granite gneiss (Fig. 2.2). Zeh et al. (2009) reported a U-Pb zircon age of 2645 ± 22 Ma for tonalite gneiss from the Maope area. They also reported a xenocrystic zircon of ~ 2856 Ma from the tonalite gneiss. Based on the intrusive field relation between the tonalite gneiss and layered mafic rocks, the provenance of the Mesoarchean zircon is inferred to be the later (Rajesh et al., 2020a). Layered mafic-ultramafic rocks in the southern Motloutse Complex are dated to between 2817 ± 9 Ma (leucogabbro) and 3020 ± 22 Ma (peridotite) (U-Pb zircon; Rajesh et al., 2020a). The inherited ~ 3.13 Ga zircon in the leucogabbro, and its intrusive relation with the closely associated amphibolite is used to argue that the meta-basalts are slightly older than the layered intrusion (Rajesh et al., 2020a).

Large upright isoclinal folds constitute the dominant regional structure in the southern Motloutse Complex (Fig. 2.2.; Key et al., 1994). Although poorly exposed, these folds can be clearly seen in the aeromagnetic maps (see Chapter 6). Anatectic overprint follows, and is dated by the U-Pb zircon overgrowth age of 2056 ± 12 Ma from the tonalite gneiss (Zeh et

al., 2009). The younger overgrowth age of 2013 ± 18 Ma from the ultramafic rocks is interpreted as the age of shear deformation (Rajesh et al., 2020a). Thus, it seems that the different overprint events are contemporaneous, and importantly, Paleoproterozoic.

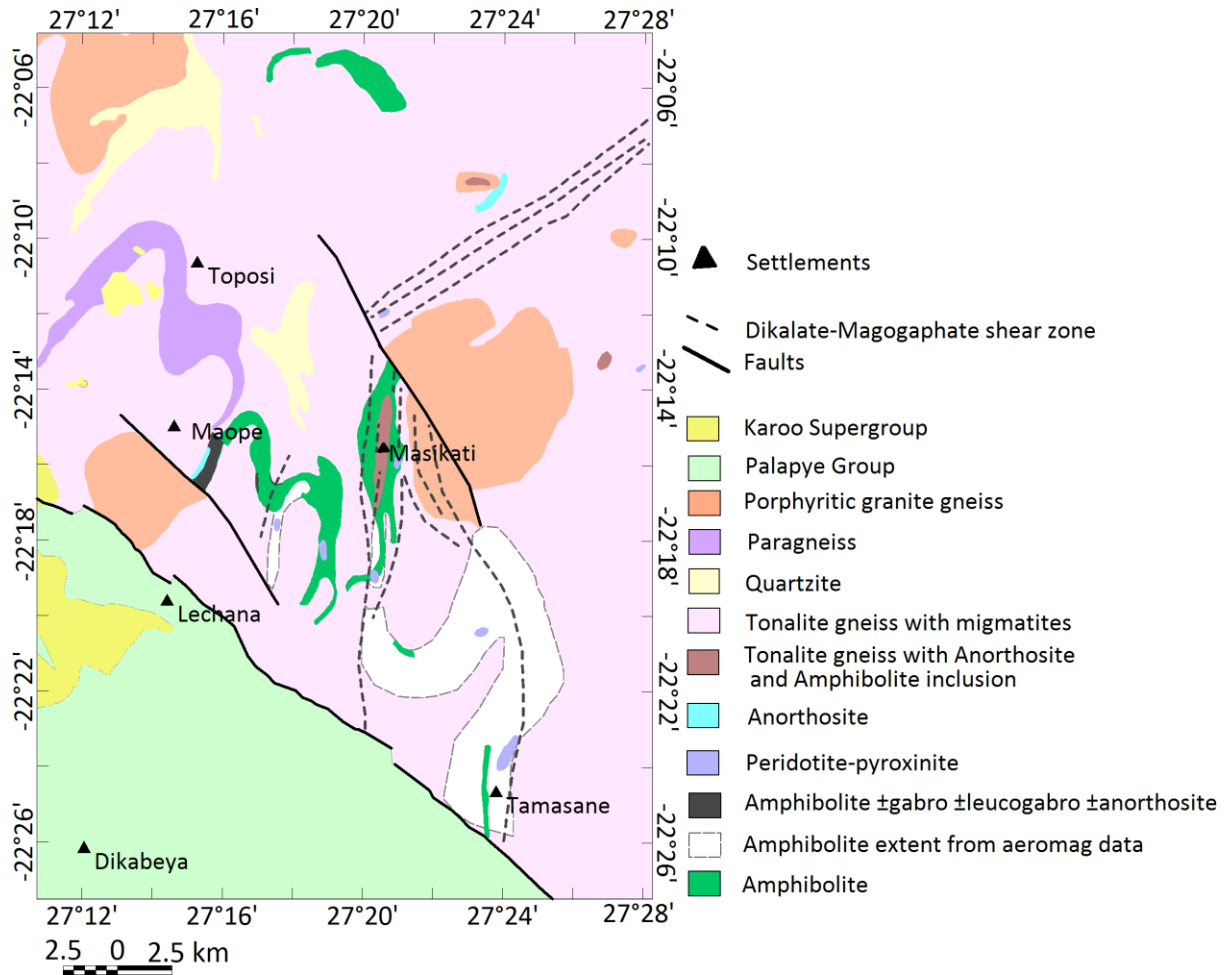


Figure 2.2. General geologic map of southern Motloutse Complex, north of the Lechana fault [modified from Key et al. (1994), with inputs from Rajesh et al. (2020a) and this study].

The currently known southern limit of the Motloutse Complex is obscured by prominent cover rocks of the late Paleoproterozoic Palapye Group, and poorly exposed Upper Carboniferous to Lower Jurassic rocks of the Karoo Supergroup (Fig. 2.2; Ermanovics and Skinner, 1980; Ermanovics, 1980; Smith, 1984; Key et al., 1994; Mapeo et al., 2004).

Chapter 3

Field relations

Satellite remote sensing and aeromagnetic maps (see chapter 6 for details) were used to isolate potential field areas. After the preliminary field reconnaissance, two study areas, the Masikati and the Radisele-Mogome areas, were selected for detailed mapping. This chapter deals with the field relations of rock types from the two study areas. Those from the eastern terrane boundary are presented first, followed by the southern terrane boundary.

3.1. Masikati hills – eastern terrane boundary

The Masikati hills and surrounding area, shown in Figure 3.1, constitute the study area along the eastern terrane boundary of the Motloutse Complex. In general, rock types are well exposed along the hills and ridges (Fig. 3.1). Exposures in the surrounding low-lying areas are isolated. The geologic map prepared as part of the present study is shown in Figure 3.2. The rock types include tonalite gneiss, amphibolite, gabbro, anorthosite, peridotite-pyroxenite, and dolerite dyke. Tonalite gneiss constitute the dominant rock type, and occupies the low- and high-lands. Amphibolite is the next dominant rock type, and primarily occur in the hills. Minor gabbro occurs associated with amphibolite. Anorthosite and peridotite-pyroxenite, respectively occur as minor rock associations in the western and eastern portions of the Masikati hills. The NW-SE trending dolerite dykes cut across all the other rock types.

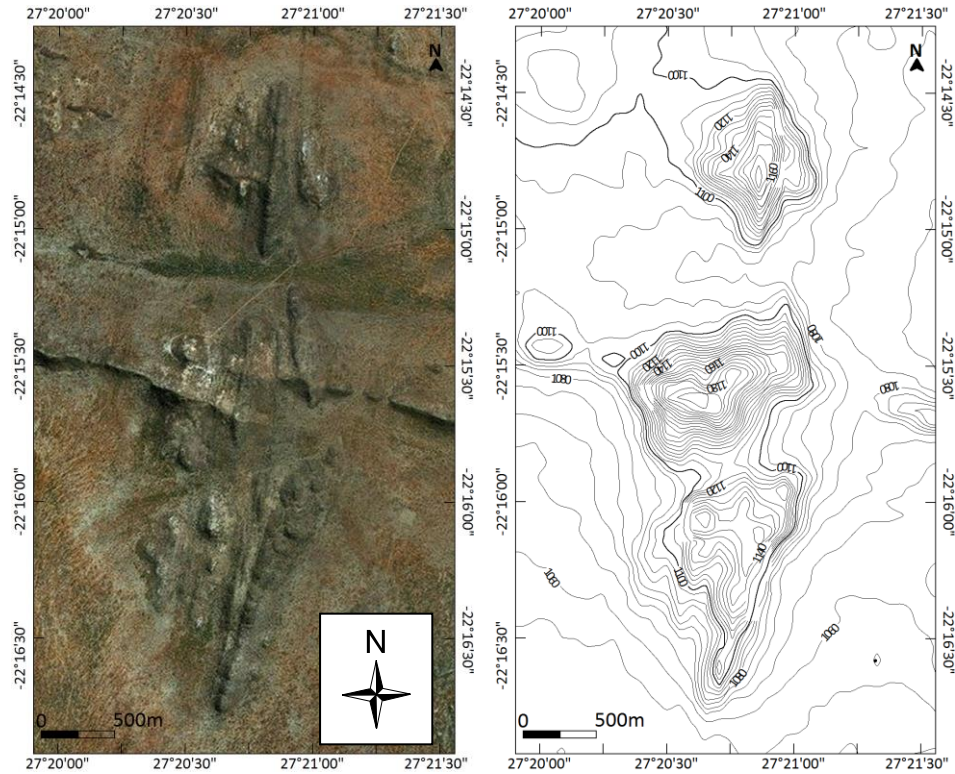


Figure 3.1. Satellite image **(a)** and contour map **(b)** of the Masikati hills area, along the eastern terrane boundary of the Motloutse Complex.

3.1.1. Tonalite gneiss

The greyish tonalite gneiss constitute the dominant rock type, and is best exposed along the western set of hills (Figs. 3.2, 3.3a, b). It can be banded (Figs. 3.3a, b). The dominant planar fabric trends NE and dips SE (Fig. 3.2). The different deformation/overprint events variably affect the tonalite gneiss (Figs. 3.3, 3.4). The earliest one is a prominent, locally well preserved, isoclinal folding event with subvertical axial plane parallel to the dominant foliation (Figs. 3.3d, g, h). The anatectic overprint follows, and is characterized by irregular mostly concordant leucocratic veins, and the local presence of garnet (Figs. 3.3b, c, e, f). The next overprint event is the pervasive shear deformation (Fig. 3.3). Both the intrafolial folds

and anatectic veins are offset by the shear deformation, the earlier resulting in drag folds (Figs. 3.3d, e, f). Metasomatic alteration accompanies shear deformation, often following pathways defined by earlier deformation/overprint events (Figs. 3.3, 3.4). The progression of the metasomatic overprint is highlighted by the pinkish to reddish discoloration of the gneissic rock (Figs. 3.3d, g, h).

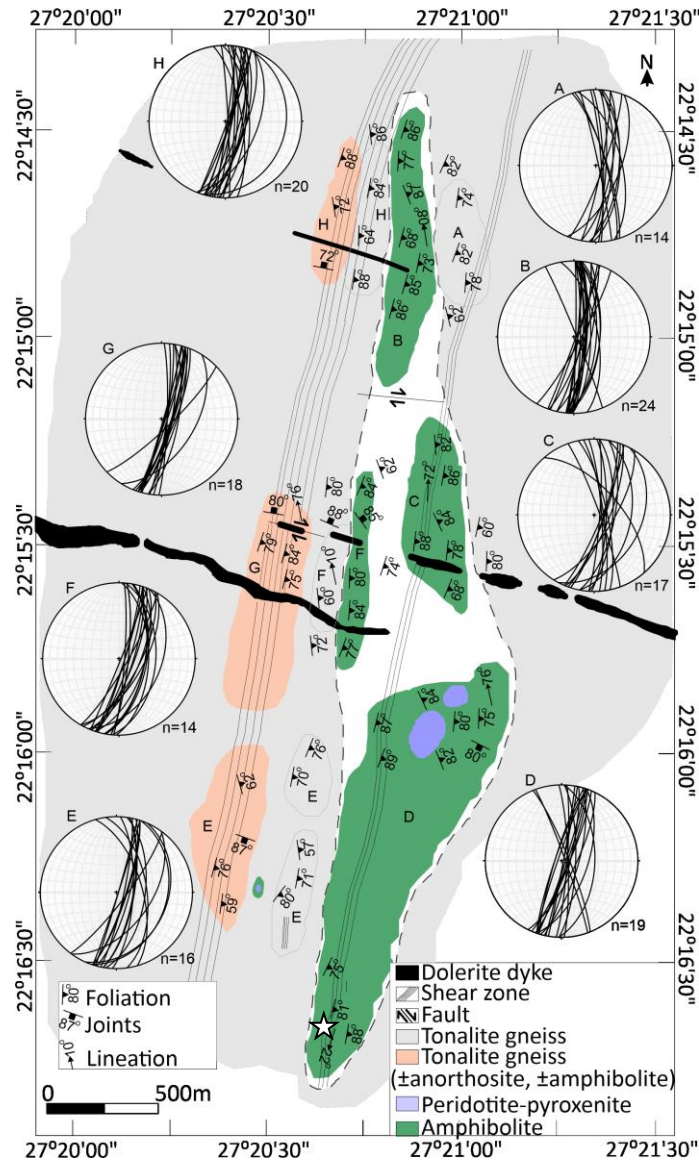


Figure 3.2. Geologic map of the Masikati hills area prepared as part of the present study. The location of amphibolite sample collected for ⁴⁰Ar/³⁹Ar geochronology is indicated by star.



Figure 3.3. Representative field photos of tonalite gneiss from the Masikati hills area. On fresh surface it is greyish, and pinkish on weathered surface. Intrafolial folds are prominent, and locally well preserved. Anatectic overprint is manifested as irregular outlined mostly concordant leucocratic veins, and local presence of garnet. Pervasive shear deformation affects the rock. Progression of metasomatism is indicated by pinkish to reddish discoloration of the rock. Local faulting can be seen.



Figure 3.4. Representative field photos illustrating the effect of shear deformation (indicated by S-C fabrics and asymmetric porphyroblasts) on tonalite gneiss from the Masikati hills area.

Shear deformation is characterized by S-C fabrics and asymmetric porphyroclasts (Fig. 3.4). Discrete mylonitic zones occur, and are characterized by rotated porphyroclasts. The inferred extent of shear deformation in the tonalite gneiss is shown in Fig. 3.2. A sub-horizontal north-east trending mineral elongation lineation is prominent. The different kinematic indicators point to a dominant right-lateral sense of movement (Figs. 3.4a to e), with a minor opposite sense (Figs. 3.4f to h).

3.1.2. Amphibolite

Amphibolite is well exposed along the eastern set of hills (Fig. 3.2). Two variants of amphibolite occur – massive amphibole-rich and layered plagioclase-amphibole-rich (Figs. 3.5a, b). The dominant planar fabric trends NE and dips SE (Fig. 3.2). Xenoliths of amphibolite of variable size are seen within the tonalite gneiss (Figs. 3.5c, d). Eye-shaped inclusions elongate parallel to the gneissic fabric are common (Fig. 3.5d). Anatectic overprint is prominent in the amphibolite, and is manifested by irregular leucocratic veins with or without garnet, and garnet porphyroblasts with or without associated melt-bearing portions (Figs. 3.5e to h). Pinch and swell, and boudin structures associated with anatectic overprint are common (Figs. 3.5e to h). Minor gabbro occurs associated with the amphibolite, and is characterized by its prominent association with anatectic leucocratic veins with or without garnet. Like in the tonalite gneiss, an earlier isoclinal folding event with sub vertical axial plane parallel to the dominant foliation is seen in the amphibolite (Figs. 3.6a, b).



Figure 3.5. Representative field photos of amphibolite from the Masikati hills area. Two variants occur – massive (amphibole-rich) and layered (amphibole-plagioclase rich). Amphibolite xenoliths in tonalite gneiss are common. Anatectic overprint is prominent, and is manifested by irregular leucocratic veins, presence of garnet, pinch and swell, and boudin structures. Shear deformation overprints earlier structures. Local faulting can be seen.



Figure 3.6. Representative field photos illustrating the earlier intrafolial folds, and the pervasive shear deformation of amphibolite from the Masikati hills area.

They are often highlighted by the pinkish metasomatic alteration, which follows the intrafolial folds (Figs. 3.6a, b). The metasomatic overprint accompanies shear deformation. Shear deformation is pervasive, and is primarily characterized by asymmetric porphyroclasts (Figs. 3.5e to h, 3.6c to g). Discrete mylonitic zones with rotated porphyroclasts occur. The inferred extent of shear deformation in the amphibolite is shown in Fig. 3.2. A sub-vertical north-east trending mineral elongation lineation is prominent (Fig. 3.6h). The kinematic indicators point to a dominant right-lateral sense of movement, with minor opposite sense.

3.1.3. Anorthosite and peridotite-pyroxenite

Anorthosite and peridotite-pyroxenite are minor rock associations in the Masikati hills. Anorthosite closely associated with amphibolite commonly occur interlayered with tonalite gneiss in the westernmost set of hills (Figs. 3.2, 3.7a to e). Eye-shaped elongate amphibolite inclusions are common in the tonalite gneiss (Fig. 3.7c). Locally, amphibolite occurs as enclaves within the anorthosite (see top portion of Fig. 3.7b). Anorthosite typically occur as boudins with rounded or irregular outline (Figs. 3.7a to e). Pinch and swell structures commonly accompany anorthosite boudins. Fresh surface of anorthosite is whitish, and coarser-grained than tonalite gneiss and amphibolite. Association of anorthosite with linear units of amphibolite, concordant to the gneissic fabric, is conspicuous (Figs. 3.7a to e). Two types of anorthosite occur – amphibole-bearing and plagioclase-rich (Figs. 3.7b, c). Garnet associated with anatectic overprint occur locally. Shear deformation is pervasive, and is characterized by asymmetric porphyroclasts and S-C fabrics (Figs. 3.7b to g).

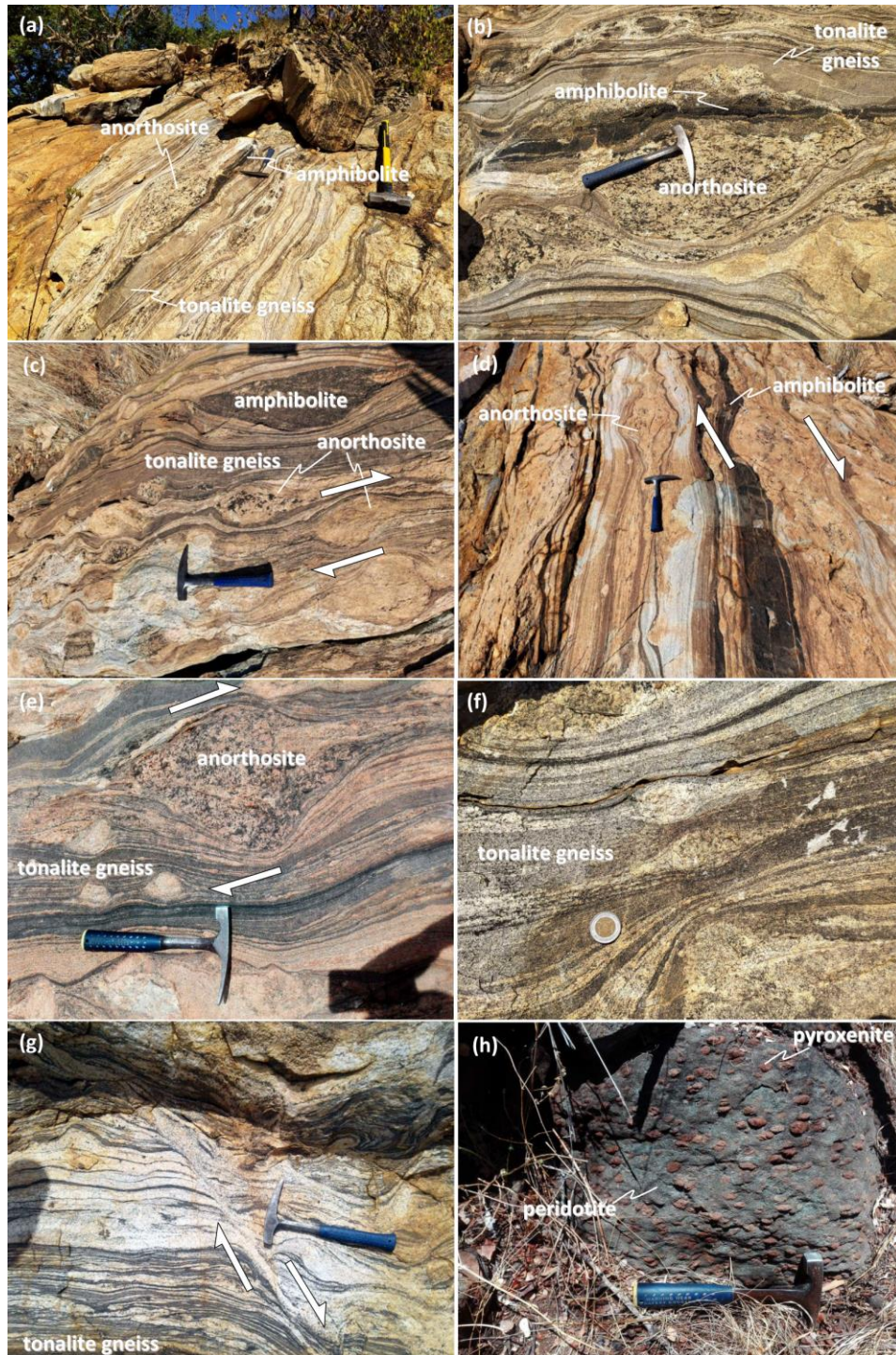


Figure 3.7. Representative field photos of anorthosite and peridotite-pyroxenite from the Masikati hills area. Anorthosite closely associated with amphibolite is interlayered with the tonalite gneiss. Anorthosite boudins are common. Two types of anorthosite occur – amphibole-bearing and plagioclase-rich. Effect of pervasive shear deformation is seen in all outcrops with anorthosite, amphibolite and tonalite gneiss. Peridotite with pyroxenite nodules constitute the dominant ultramafic rock association in the Masikati hills.

Necking and warping of the gneissic fabric around the asymmetric anorthosite bodies is common (Figs. 3.7e, f). Elongated amphibole is characteristic of anorthosite in these marginal portions (Figs. 3.7e, f). A dominant right-lateral sense of shear movement is inferred. A significant proportion of the extent of shear deformation inferred from the western set of hills shown in Fig. 3.2 are from anorthosite dominant regions. Pinkish metasomatic veins in tonalite gneiss are seen to continue to anorthosite locally.

Light grey to dark grey peridotite (serpentinized) with brownish pyroxenite nodules constitute the ultramafic rock association in the Masikati hills (Figs. 3.2, 3.7h). The peridotite-pyroxenite association is best exposed towards the easternmost hill (Fig. 3.2). Alternate layers of peridotite-pyroxenite, peridotite, and pyroxenite occur, and are closely associated with the amphibolite. The olivine dominant rocks are serpentinized. No visible overprint events were found with the ultramafic rocks. Also, no association of mafic (anorthosite, gabbro) and ultramafic (peridotite, pyroxenite, peridotite-pyroxenite) intrusive rocks were found in the Masikati hills.

3.1.4. Mafic dykes

NW-SE trending mafic dykes constitute the last geologic event in the Masikati hills area (Fig. 3.2). They occur as prominent ridges, as well as semi-continuous linear mafic intrusions cutting across the different rock types (Figs. 3.8a to d). Chilled margins can be locally seen. The dykes can be locally faulted.

3.1.5. Relative chronology of rock types/events in the Masikati hills area

Amphibolite is inferred as the oldest rock unit in the Masikati hills area, and is supported by its occurrence as xenoliths within the anorthosite and tonalite gneiss. The massive occurrence, covering large areas, is typical of a meta-basalt. Both the peridotite-pyroxenite, and the gabbro/anorthosite are closely associated with the amphibolite. As the ultramafic and mafic intrusive rocks do not occur together, the inference on which formed earlier is less obvious from the field relations. Available geochronologic data indicate that the ultramafic rocks are older than the mafic rocks (Rajesh et al., 2020a). Tonalite gneiss intruded all the three rock types – amphibolite, peridotite-pyroxenite, anorthosite±gabbro.

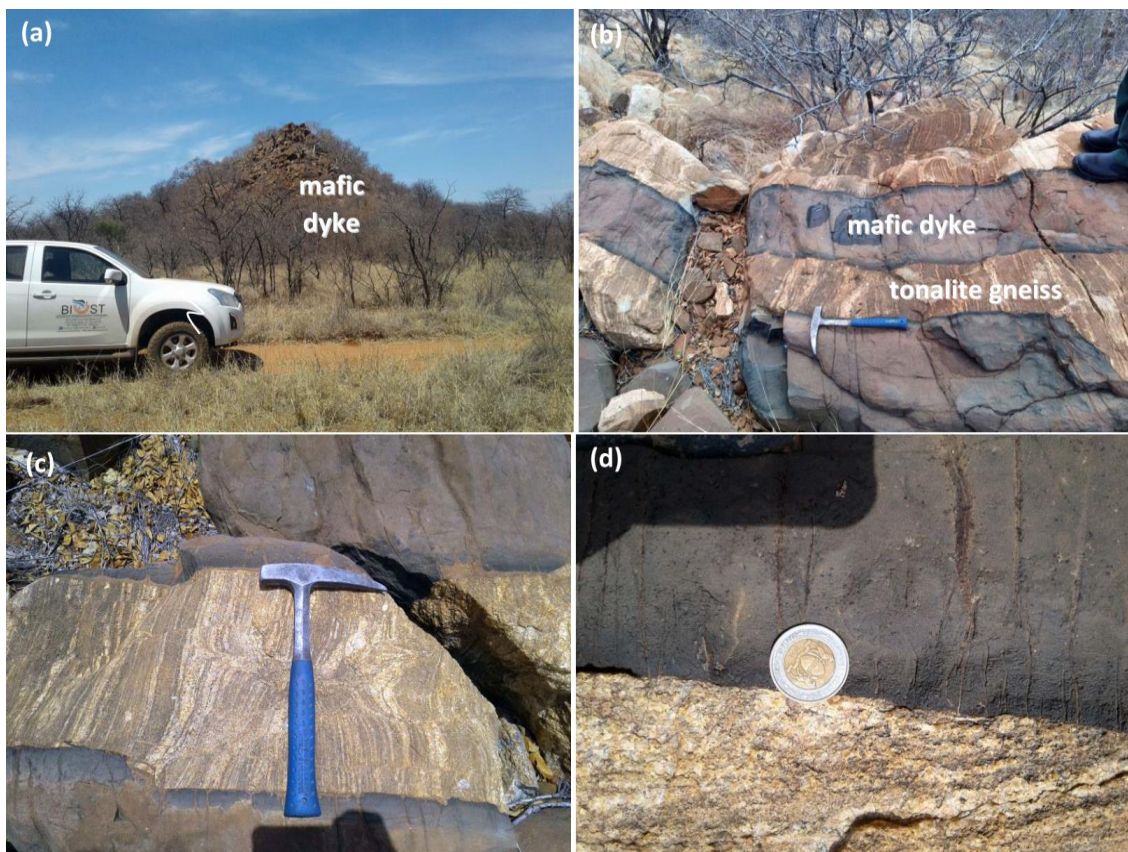


Figure 3.8. Representative field photos of NW-SE trending mafic dykes from the Masikati hills area.

In terms of deformation/overprint events, the intrafolial folding, preserved in the tonalite gneiss and amphibolite is inferred as the earliest event. This compressive event was accompanied by the anatectic overprint, resulting in the formation of garnet. The pervasive shear deformation occurred next, and was accompanied by metasomatic alteration of rocks. The inferred extent of the shear zone is shown in Fig. 3.2, with an increase of intensity towards the west. Kinematic indicators point to a right-lateral sense of movement along the shear zone. Lastly, the younger NW-SE trending mafic dykes cut across the different rock types. Based on the orientation, the dykes are likely of Karoo (?) age.

3.2. Radisele-Mogome area – southern terrane boundary

The Radisele-Mogome area, shown in Figure 3.9, constitute the study area along the southern terrane boundary of the Motloutse Complex. In general, rock types are well exposed along the hills and ridges (Fig. 3.9). Exposures in the surrounding low-lying areas are isolated. The geologic map prepared as part of the present study is shown in Figure 3.10. The crystalline basement rock types in the Radisele-Mogome area can be grouped into two. The first group of rocks occur in the NE part, and consists of tonalite gneiss, amphibolite and ultramafics (Fig. 3.10). The second group of rocks occur in the SW part, and consists of granodiorite, diorite gneiss and leucogranite (Fig. 3.10). An alkali granite, restricted mostly around the Mogome area, is common to both group of rocks (Fig. 3.10). In addition, the Palapye Group cover rocks and two sets of mafic dykes occur in the study area (Fig. 3.10).

3.2.1. Rocks in the NE part

3.2.1.1. Tonalite gneiss

Greyish tonalite gneiss constitute the dominant rock type in the NE part (Figs. 3.10, 3.11a to c). It can be banded. The dominant planar fabric in the rock trend NW-SE, and dip to the NE. Intrafolial isoclinal folds are common (Figs. 3.11b, d). No visible evidence for anatectic overprint occurs. Dykes and veins of alkali granite intrude the tonalite gneiss (Figs. 3.11a, e).

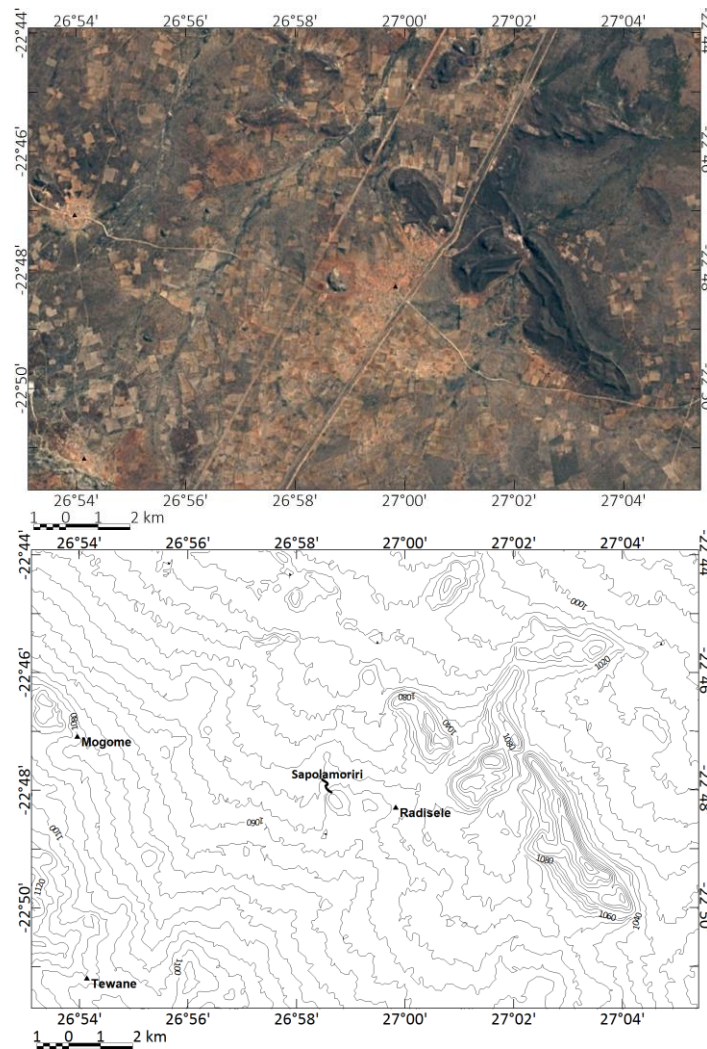


Figure 3.9. Satellite image (a) and contour map (b) of the Radisele-Mogome area, along the southern terrane boundary of the Motloutse Complex.

Shear deformation overprints the earlier structures, resulting in closely spaced layers, drag folds, and asymmetric porphyroclasts (Figs. 3.11e to j). Discrete zones of mylonitic deformation occur (Fig. 3.11h). The inferred extent of shear deformation in tonalite gneiss is shown in Fig. 3.10. A sub-horizontal mineral elongation lineation is locally seen. The kinematic indicators point to a prominent right-lateral sense of movement with minor opposite-sense. Metasomatism accompanies shear deformation, and is highlighted by the pinkish to reddish discoloration of the gneissic rock (Figs. 3.11d, f, k).

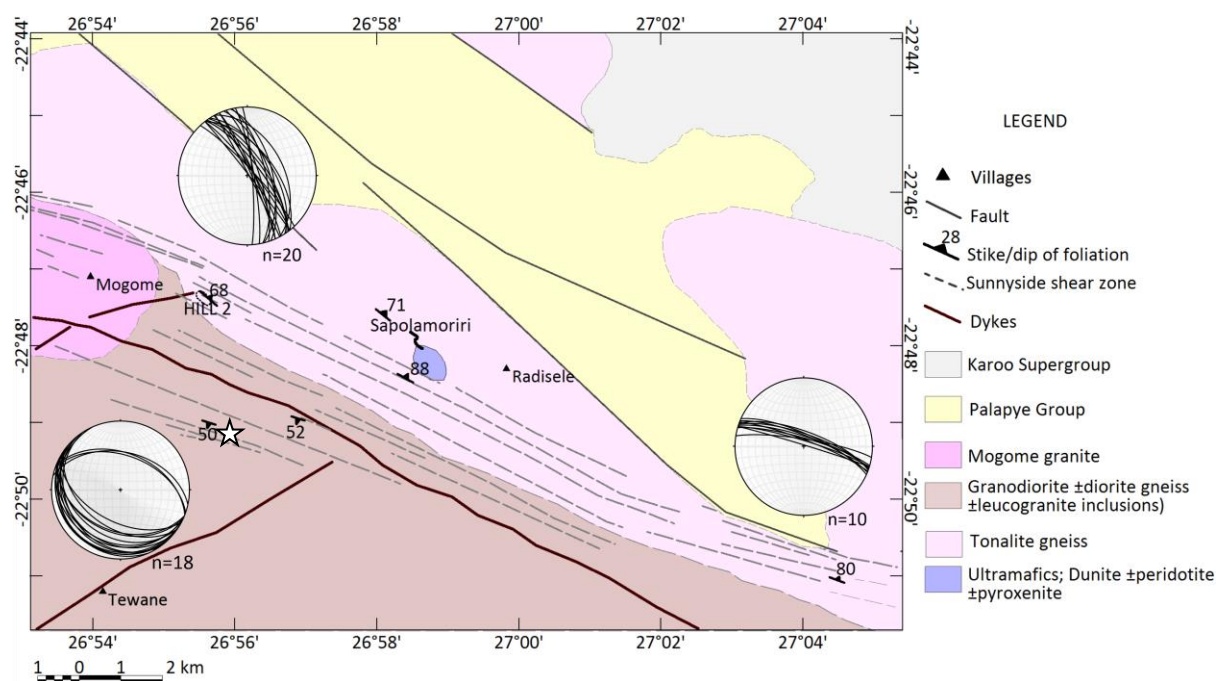


Figure 3.10. Geologic map of the Radisele-Mogome area prepared as part of the present study. The location of diorite gneiss sample collected for $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology is indicated by star.

3.2.1.2. Amphibolite and ultramafic rocks

Amphibolite and ultramafic rocks constitute the two other prominent rock types in the NE part. Rare inclusions of amphibolite occur within the ultramafic rocks.



Figure 3.11. Representative field photos of tonalite gneiss from the Radisele-Mogome area. Greyish tonalite gneiss is the dominant rock in the NE part. Intrafolial isoclinal folds are common. Dykes and veins of alkali granite cuts across the tonalite gneiss. Amphibolite xenoliths occur locally within the tonalite gneiss. Shear deformation affects all the earlier structures. Mylonitic deformation is locally seen. Metasomatism accompanies shear deformation and results in pinkish to reddish discoloration of the gneissic rock.

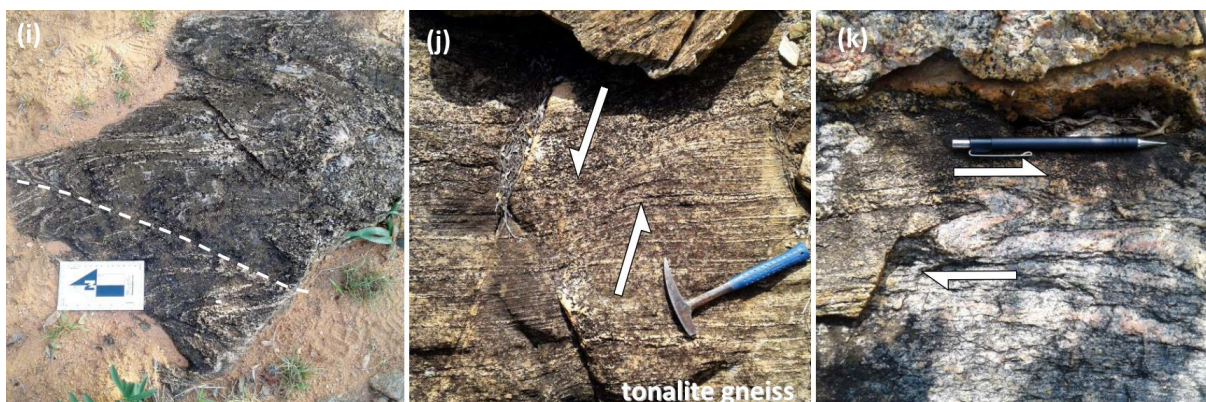


Figure 3.11. continued Shear deformation overprints the earlier structures in the tonalite gneiss. Metasomatic alteration follows the earlier pathways in the gneissic rock.

Amphibolite inclusions of variable size occur within the tonalite gneiss (Figs. 3.11e, 3.12a, b). Some inclusions are not affected by overprint events. For e.g., the amphibolite inclusion in Fig. 3.12a is undeformed, while the surrounding tonalite gneiss is sheared and metasomatized. In other instances, the amphibolite inclusions are affected by both shear deformation and associated metasomatism (Figs. 3.12b, c). No visible evidence of anatectic overprint, including irregular leucocratic veins and/or garnet, is seen in the amphibolites.

A prominent amphibolite layer occurs at the interface of tonalite gneiss and ultramafic rocks (Fig. 3.12d). Ultramafic rocks are best exposed at the Sapolamorori hills (Fig. 3.10). Alternate layers of peridotite-pyroxenite, peridotite, serpentinite (formerly dunite), and pyroxenite constitute the ultramafic rocks (Figs. 3.12e to g). Peridotite-pyroxenite association (peridotite with pyroxenite nodules) is conspicuous (Figs. 3.12f, g). Bulk of the Sapolamorori hills is occupied by schist-like serpentinitized dunite (Fig. 3.12h). The southern marginal portions of the Sapolamorori hills rocks are affected by shear deformation. No effect of anatectic overprint and metasomatism is seen in the ultramafic rocks.



Figure 3.12. Representative field photos of amphibolite and layered ultramafic rocks from the NE part of the Radisele-Mogome area. Amphibolite xenoliths of variable size occur within the tonalite gneiss. They are variably deformed, with some inclusions undeformed. Amphibolite is closely associated with ultramafic rocks. Alternate layers of peridotite-pyroxenite, peridotite, dunite and pyroxenite constitute the ultramafic rocks. Serpentinized dunite occurs dominantly as a schist-like rock.

3.2.2. Rocks in the SW part

3.2.2.1. Diorite gneiss, granodiorite and leucogranite

Granodiorite constitutes the dominant rock type in the SW part of the Radisele-Mogome area. Undeformed granodiorite is best exposed in and around Tewane (Figs. 3.10, 3.13a). Diorite gneiss is the next dominant rock type and occurs as xenoliths within the granodiorite and leucogranite (Figs. 3.13b, c). Two variants of diorite gneiss occur – porphyritic and non-porphyritic (Figs. 3.13b to d). The dominant planar fabric trends NW-SE to WNW-ESE. Anatectic overprint is locally seen in diorite gneiss, with garnet associated with irregular leucosomic veins. Garnet without any associated melt-bearing material is locally seen in granodiorite with diorite gneiss inclusions. In comparison, to the diorite gneiss and granodiorite, minor garnet is uniformly distributed in the leucogranite. As one move towards the northern margin of the SW part (dotted line in Fig. 3.10), the three rock types get variably overprinted by pervasive shear deformation. Diorite gneiss best exposes the effects of shear deformation (Figs. 3.13e to h, 3.14). With increase of shear deformation, the phenocrysts of the porphyritic rock get transformed to asymmetric and rotated porphyroclasts, with the matrix becoming mylonitic (Figs. 3.13e to h). Like in the NE part, dykes and veins of alkali granite cuts across all the rock types in the SW part (Fig. 3.13b). Protomylonitic to mylonitic deformation with asymmetric rotated porphyroclasts are prominent in rock types from the SW part of the Radisele-Mogome area (Fig. 3.14). Often one can trace the progress of deformation from the protomylonitic to mylonitic stages (Fig. 3.14).



Figure 3.13. Representative field photos of granodiorite, diorite gneiss and leucogranite from the SW part of the Radisele-Mogome area. Granodiorite is the dominant rock type. Away from the contact with the NE part, the granodiorite is undeformed. Diorite gneiss occur as inclusions within the granodiorite and leucogranite. Diorite gneiss occurs as porphyritic and non-porphyritic variants. The effect of pervasive shear deformation is best seen in the diorite gneiss, with phenocrysts becoming asymmetric and rotated porphyroclasts, with a mylonitic matrix.



Figure 3.14. Representative field photos illustrating the protomylonitic to mylonitic deformation seen in diorite gneiss, granodiorite and leucogranite from the SW part of the Radisele-Mogome area (within the dashed line in Fig. 3.10).

No visible evidence for metasomatic overprint, including pinkish to reddish discoloration is seen in rocks from the SW part. A sub-horizontal mineral elongation lineation is prominent. The kinematic indicators point to a dominant right-lateral sense of movement with minor opposite sense for the SW part of the Radisele-Mogome area. The inferred extent of shear deformation in the SW part is shown in Fig. 3.10.

3.2.3. Mogome alkali granite

An alkali granite body occurs around Mogome, to the western extremity of the area covered in Fig. 3.10. The pinkish alkali granite body contains xenoliths of varying size of rock types from both the NE and SW parts (Fig. 3.15). The large size of some of these inclusions, covering continuous outcrops, attest to the host rock as a prominent magmatic unit – referred hereafter as the Mogome granite. The dominant xenoliths are diorite gneiss occurring both in the NE and SW parts (Figs. 3.15a to c). Both porphyritic and non-porphyritic diorite gneiss inclusions occur (Figs. 3.15a to d). The next dominant inclusions are those of the tonalite gneiss (Figs. 3.15e to g). Most of these inclusions preserve the intrafolial isoclinal folds commonly associated with the tonalite gneiss (Figs. 3.15e to g). Amphibolite is the least dominant xenolith within the alkali granite (Fig. 3.15h). Closer inspection (especially at hand-specimen scale) indicate that the alkali granite is affected by shear deformation. The inferred extent of shear deformation in the Mogome granite is shown in Fig. 3.10. Alkali metasomatism accompanies the structures in tonalite gneiss inclusions, and can locally be traced into the host alkali granite.



Figure 3.15. Representative field photos of Mogome alkali granite from the Radisele-Mogome area. The alkali granite contains inclusions of rock types from both NE (tonalite gneiss, amphibolite) and SW (diorite gneiss) parts.

As mentioned earlier, dykes and veins of the alkali granite cross cuts the rock types in both the NE and SW parts (see Figs. 3.11a, e, 3.13b).

3.2.4. Palapye Group cover rocks and mafic dykes

Clastic sedimentary rocks of the Palapye Group cover a dominant portion of the NE part of the Radisele-Mogome area (Fig. 3.10). In addition, two sets of poorly exposed mafic dykes occur in the Radisele-Mogome area (Fig. 3.10). The extent of the NW-SE and NE-SW dykes are extrapolated from the geophysical maps of the study area (see Chapter 6 for details). In one of the outcrops, the NW-SE trending dyke was seen cutting across granodiorite-diorite gneiss in the SW part.

3.2.5. Relative chronology of rock types/events in the Radisele-Mogome area

In view of the two distinct groups of rocks, the relative chronology of rock types/events is separately inferred for the NE and SW parts of the Radisele-Mogome area.

Amphibolite is inferred as the oldest rock unit in the NE part of the Radisele-Mogome area, and is supported by its occurrence as inclusions within the ultramafic rocks and tonalite gneiss. Based on its occurrence as an extensive unit, amphibolite is likely a meta-basalt. The layered ultramafic rocks formed next. Both the amphibolite and ultramafic rocks are intruded by the tonalite gneiss. Intrafolial isoclinal folds constitute the earliest recognizable

structure. Shear deformation overprints the earlier structures, and is accompanied by metasomatic alteration. The inferred extent of shear zone in the NE part of the Radisele-Mogome area is shown in Figure 3.10.

Diorite gneiss is inferred as the oldest rock unit in the SW part of the Radisele-Mogome area, and is supported by its occurrence as xenoliths within the granodiorite and leucogranite. Granodiorite formed next. Veins of leucogranite cutting across the granodiorite indicate that it is later. Anatectic overprint is locally seen in the diorite gneiss. Pervasive shear deformation is overwhelming in rock types of the SW part, leading to protomylonitic to mylonitic textures. The inferred extent of shear zone in the SW part of the Radisele-Mogome area is shown in Fig. 3.10. In comparison to the NE part, there is an increase in the intensity of shear deformation towards the SW part. No visible evidence for metasomatism is seen in diorite gneiss, granodiorite, and leucogranite.

As indicated by the xenoliths within it, the Mogome alkali granite is younger than rock types from both the NE and SW parts. Effects of shearing indicates that the Mogome alkali granite is an important time marker. Thus, the shear deformation has to be younger than the age of the Mogome alkali granite. Kinematic indicators point to a right-lateral sense of movement along the shear zone.

The Palapye Group cover sequence is older than the mafic dykes. The two sets of mafic dykes (NW-SE and NE-SW) represent the youngest rock types in the Radisele-Mogome area. Based on the orientations, they could of Karoo (?) age.

Chapter 4

Petrography

The chapter presents petrographic characteristics of the main rock types from the two study areas – Masikati hills and Radisele-Mogome areas. The purpose is to *clarify* the inferences from field relations, especially the effect of anatectic overprint, shear deformation, and metasomatic alteration. As similar rock types occur in both the eastern and southern terrane boundaries, their description is grouped together. The rock types are arranged chronologically, as inferred from field relations.

4.1. Amphibolite

Amphibolite is essentially either amphibole-rich with minor plagioclase, or amphibole-plagioclase rich (Figs. 4.1, 4.2a, b). Granoblastic texture with 120° triple junction is prominent (Fig. 4.1a, 4.2a, b). Amphibole occurs as inclusions in plagioclase and vice versa. Variable content of quartz is present in the amphibolites. Sulphides constitute the dominant accessory phase, and is mostly interstitial. Minor oxides are also present.

Locally, samples collected from amphibolite inclusions within tonalite gneiss preserve little to no evidence for deformation (Figs. 4.2a, b), confirming the field observations (see Fig. 3.12a).

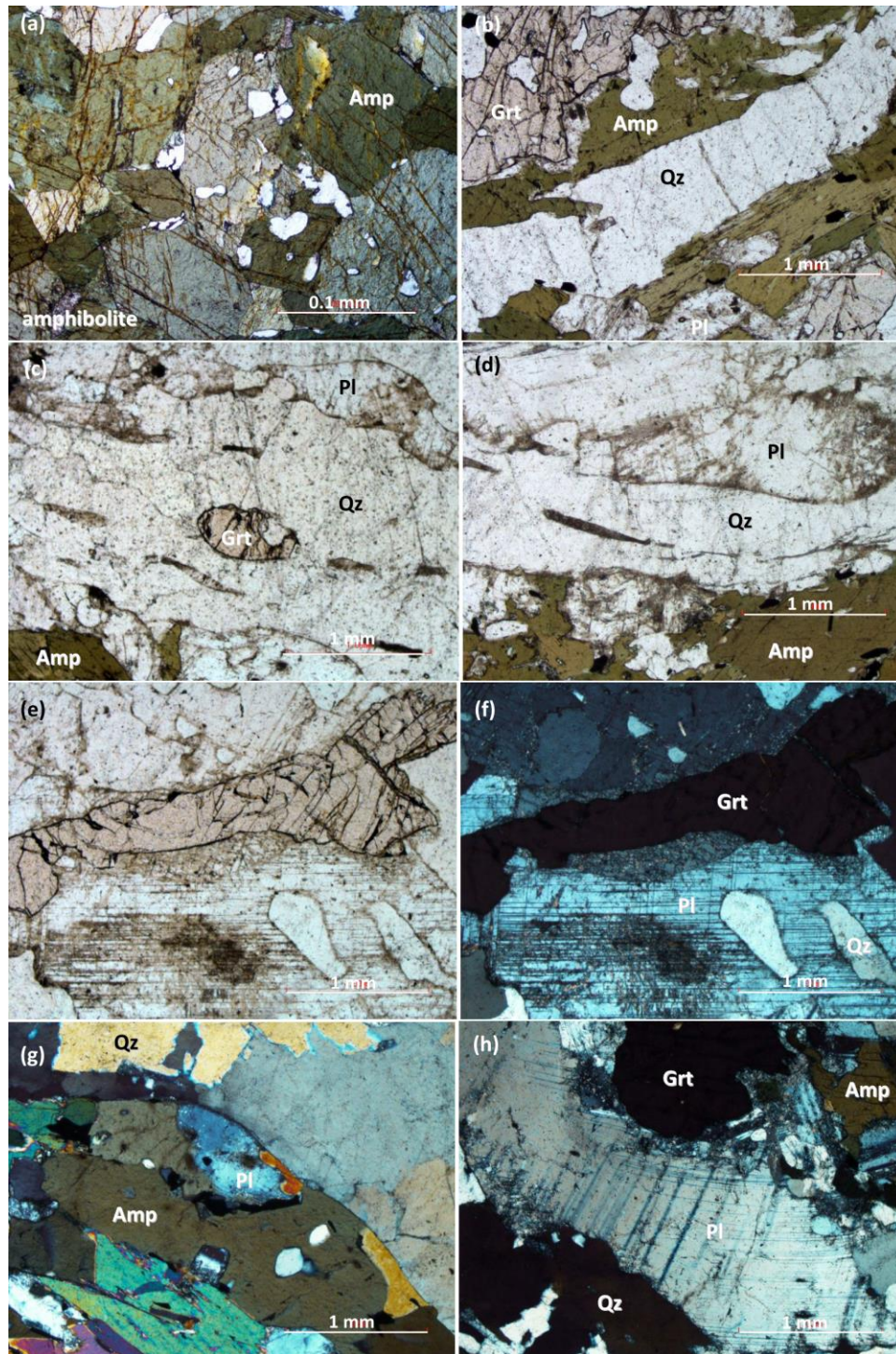


Figure 4.1. Representative photomicrographs illustrating the petrographic characteristics of amphibolite from the Masikati hills and the Radisele-Mogome areas. Amphibolite is either amphibole(Amp)-rich or amphibole-plagioclase(Pl)-rich. Garnet (Grt) is a product of anatectic overprint. Irregular lobate rounded grain margins are related to anatectic overprint. Effect of shear deformation include elongated plagioclase, quartz (Qz), amphibole and garnet, and recrystallization of quartz. Alteration features include sericitization and chloritization. (a) to (e) – PPL; (f) to (h) – XPL.

Anatectic overprint is characterized by the presence of garnet (after amphibole), and irregular lobate grain margins of associated minerals (Figs. 4.1b to f, h). Evidence of shear deformation is prominent in the amphibolite. These include elongated plagioclase, amphibole, quartz and garnet, recrystallized quartz with or without sutured grain margins, and local plagioclase grains with bent twin planes (Figs. 4.1b to h). Alteration is variable, with the least effected being the amphibole-rich samples (Fig. 4.1a). Extensive alteration features are observed in plagioclase-rich amphibolites, and include sericitization of feldspar, and chloritization of amphibole (Fig. 4.1).

4.2. Ultramafic rocks

Serpentinite (formerly dunite) preserves few relics of olivine (Figs. 4.2c, d). In comparison, peridotite is less serpentinized with olivine, orthopyroxene and amphibole (Figs. 4.2e, f). Amphibole occurs interstitial to orthopyroxene and as rare inclusions within it. Pyroxenite is least effected by serpentinization. It is dominated by orthopyroxene, with minor amphibole and olivine, and is essentially an orthopyroxenite (Figs. 4.2g, h). In peridotite-pyroxenite, serpentinization-related veins from the peridotite invade into the adjacent pyroxenite domains (Figs. 4.2g, h). Magnetite constitute the dominant accessory phase, and is widely distributed in the olivine-rich domains (Figs. 4.2g, h). The schist-like ultramafic rocks, unique to the Sapolamorori hills in the Radisele-Mogome area (see Figs. 3.10, 3.12h), are petrographically serpentinized dunites. No schistose fabric was observed under the petrographic microscope.

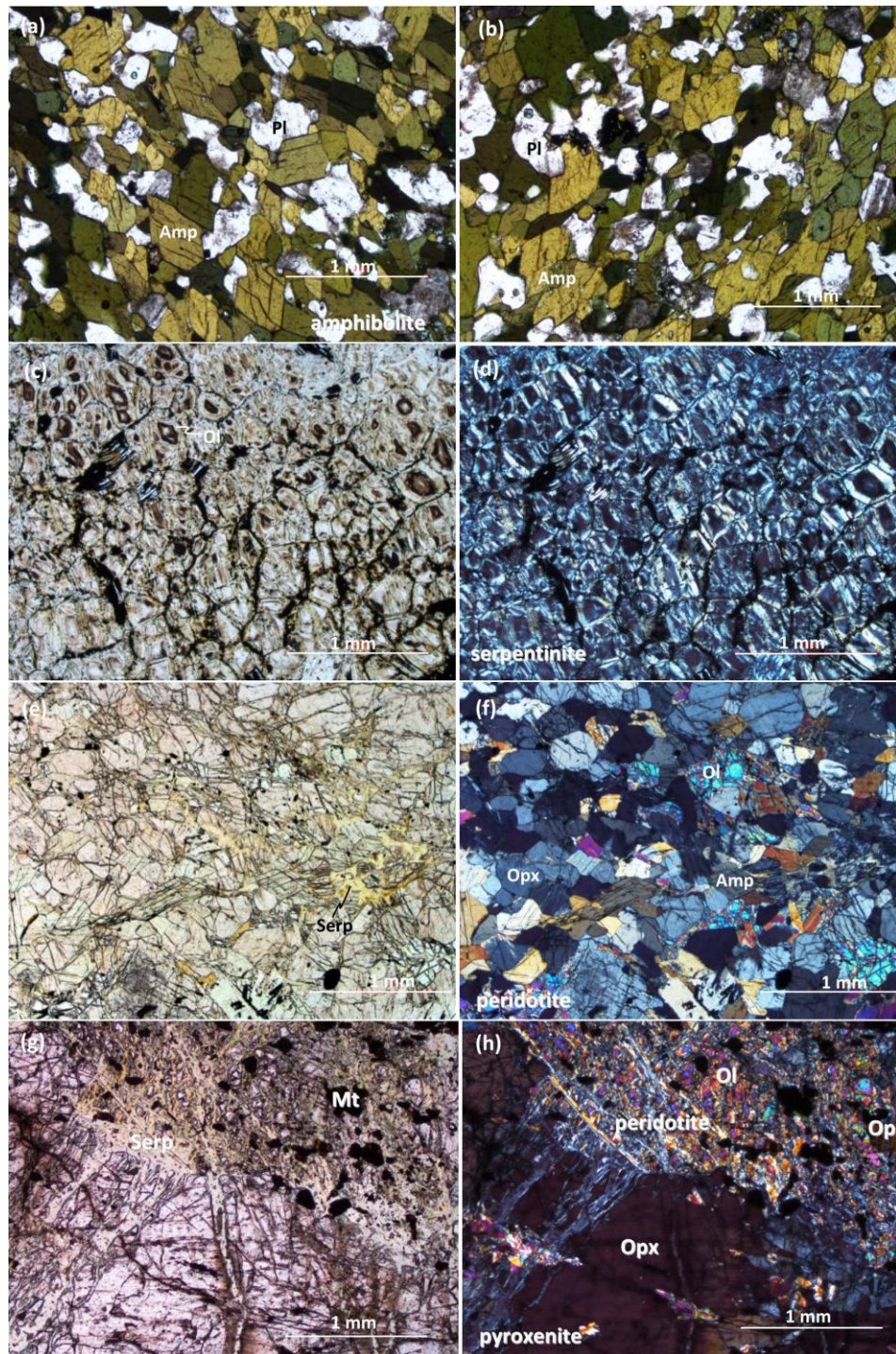


Figure 4.2. Representative photomicrographs illustrating the petrographic characteristics of amphibolite (a, b) and ultramafic rocks from the Masikati hills and the Radisele-Mogome areas. Locally, amphibolite inclusions preserve no evidence of deformation. Ultramafic rocks include serpentinite (formerly dunite), peridotite, pyroxenite and peridotite-pyroxenite (peridotite with pyroxenite nodules). Olivine-bearing rocks are serpentinized to varying degrees. Ol – olivine; Opx – orthopyroxene; Serp – serpentine. (a), (b), (c), (e), (f) – PPL; (d), (f), (h) – XPL.

No evidence of anatectic overprint, shear deformation, and metasomatic alteration is seen in any of the studied ultramafic rock samples.

4.3. Anorthosite

Anorthosite only occurs in the Masikati hills. It can be either plagioclase-dominant with minor amphibole or plagioclase-amphibole-rich (Fig. 4.3). Typical magmatic interlocking texture is preserved (Figs. 4.3a to d). The rock is typically coarser grained than the amphibolite or tonalite gneiss. Interstitial amphibole is the dominant mafic mineral (Fig. 4.3). Locally, pyroxene occur together with amphibole (Figs. 4.3c, d). Amphibole inclusions can occur in plagioclase and vice versa (Figs. 4.3e, f). Minor sulphides and oxides occur. Irregular lobate grain margins are likely related to the anatectic overprint (Figs. 4.3b, g). No garnet was found in the studied samples. Effect of alteration is overwhelming in the anorthosite, and is characterized by sericitization of feldspar and chloritization of amphibole (Figs. 4.3b, e to h). Plagioclase with bent twin planes occur locally.

4.4. Tonalite gneiss

Tonalite gneiss is dominantly made up of plagioclase, quartz, and biotite (Figs. 4.4, 4.5). Sulphides and oxides are the common accessory phases. Evidence for shear deformation is overwhelming in the tonalite gneiss. Plagioclase varies from rounded to asymmetric eye-shaped to elongated grains (Figs. 4.4, 4.5).

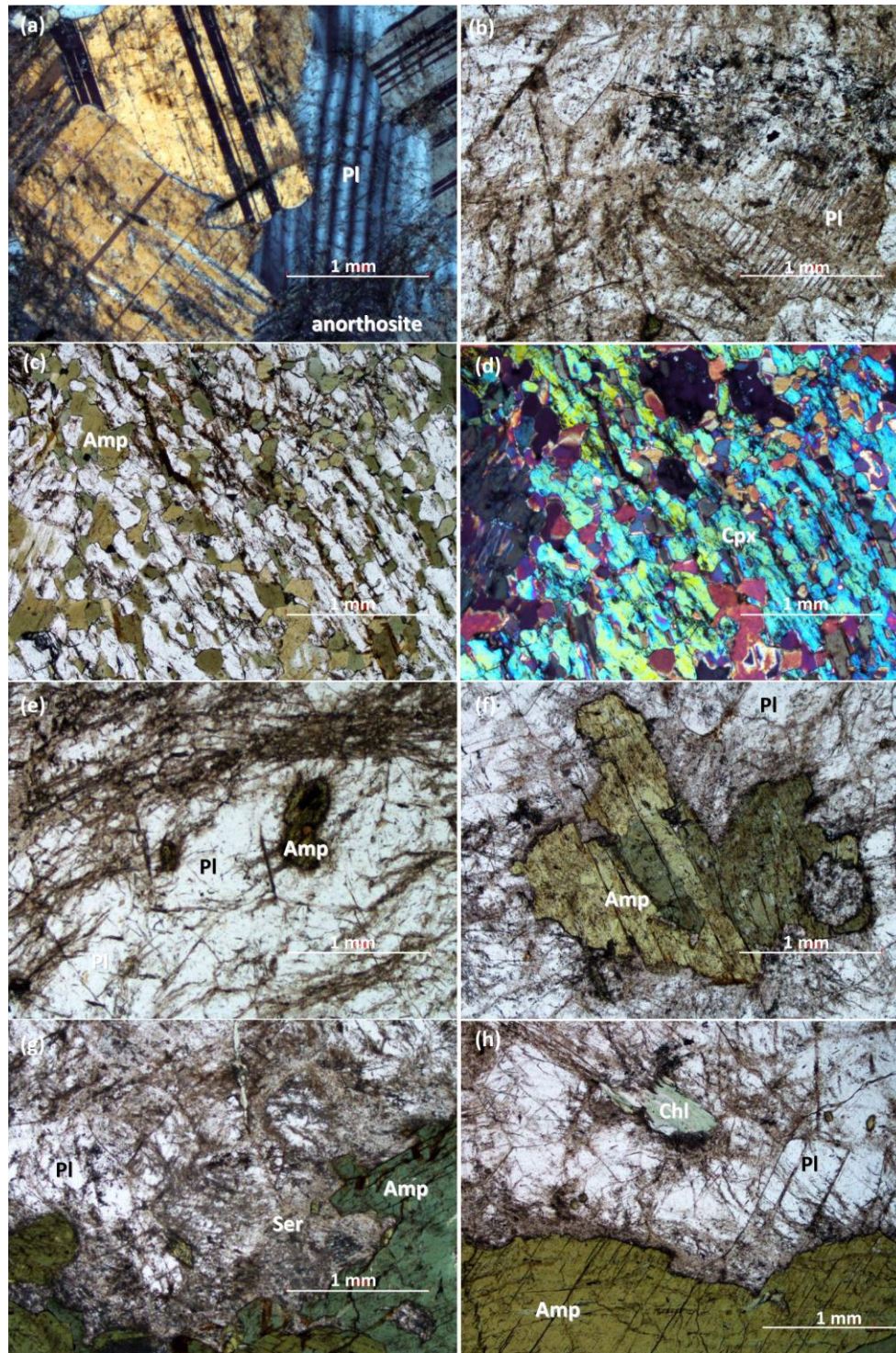


Figure 4.3. Representative photomicrographs illustrating the petrographic characteristics of anorthosite from the Masikati hills. Anorthosite is either plagioclase dominant or amphibole-rich. Locally, pyroxene occurs together with amphibole. Irregular lobate rounded grain margins are likely related to anatectic overprint. Effect of alteration is overwhelming, and manifested as sericitization and chloritization. Ser- sericite; Chl- chlorite. (b), (c), (e) to (h) – PPL; (a), (d) – XPL.

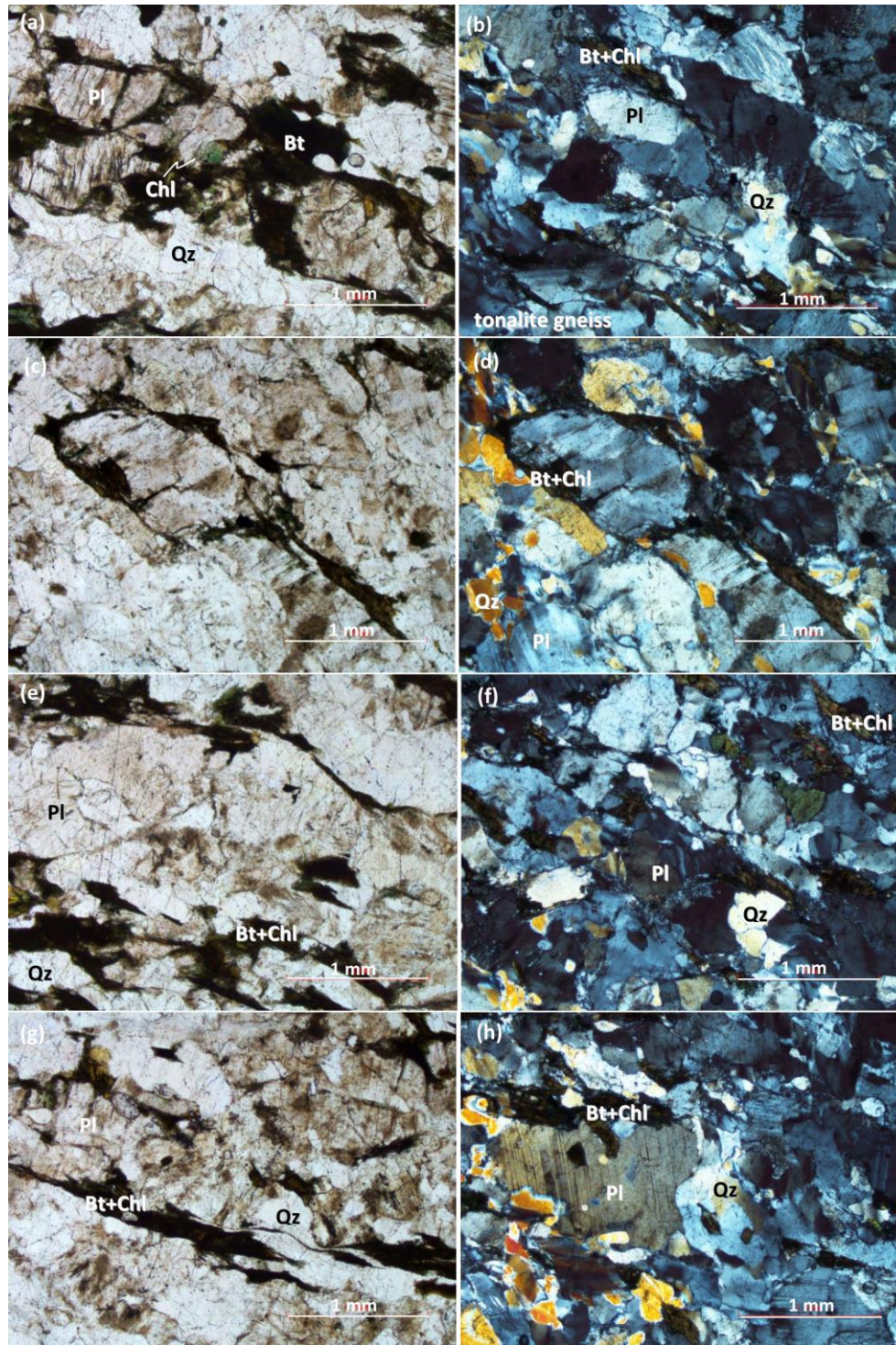


Figure 4.4. Representative photomicrographs illustrating the petrographic characteristics of tonalite gneiss from the Masikati hills area. It is dominantly made up of plagioclase, quartz and biotite (Bt). Effect of shear deformation is overwhelming, and include elongated plagioclase, quartz, and biotite, and recrystallization of quartz. Alteration features include sericitization of feldspar and chloritization of biotite. (a), (c), (e), (g) – PPL; (b), (f), (h) – XPL.

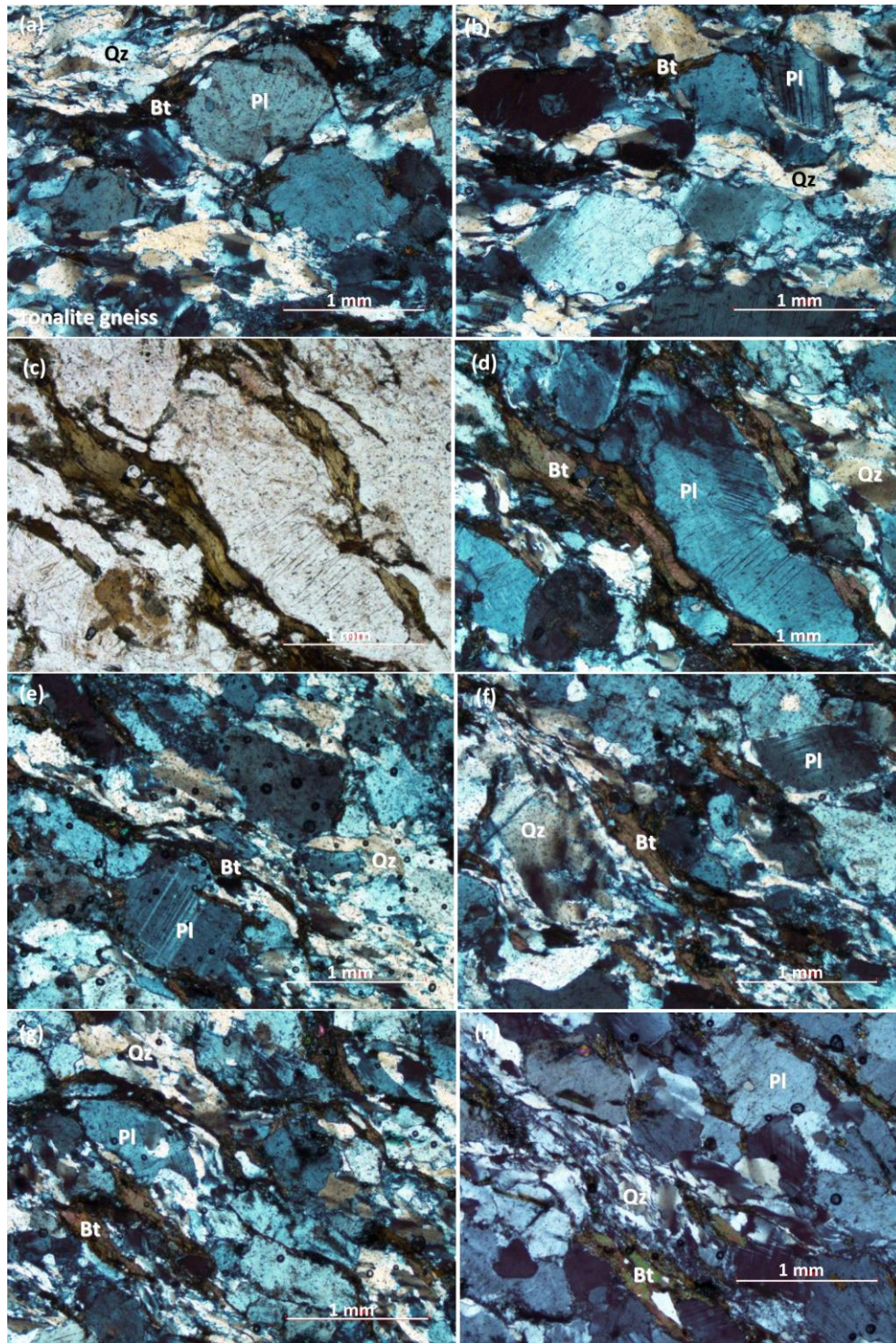


Figure 4.5. Representative photomicrographs illustrating the petrographic characteristics of tonalite gneiss from the NE part of the Radisele-Mogome area. It is dominantly made up of plagioclase, quartz and biotite. Effect of shear deformation is overwhelming, and include elongated plagioclase, quartz, and biotite, and recrystallization of quartz. Alteration features include sericitization of feldspar and chloritization of biotite. (c) – PPL; (a), (b), (d) to (h) – XPL.

Locally, plagioclase grains with bend twin planes occur. Interstitial biotite is elongated parallel to the ductile fabric. Recrystallized quartz grains with or without sutured grain margins, follow plagioclase and biotite (Figs. 4.4, 4.5). Alteration features are also prominent, and accompany the shear deformation. These include sericitization of feldspar, and chloritization and epidotization of biotite (Figs. 4.4, 4.5).

4.5. Diorite gneiss, granodiorite and leucogranite

Diorite gneiss, granodiorite and leucogranite occur only in the Radisele-Mogome area. Diorite gneiss is dominantly made up of plagioclase, quartz and biotite (Fig. 4.6a). Diorite gneiss samples studied from locations away from shear zone (dashed line in Fig. 3.10) are undeformed (Fig. 4.6a). Anatectic overprint is locally preserved, as indicated by the presence of garnet, and irregular lobate grain margins of associated minerals (Fig. 4.6b). Myrmekite is locally seen. Effect of shear deformation is overwhelming in diorite gneiss samples from within the shear zone, and is characterized by elongate plagioclase, quartz, and biotite, recrystallized quartz with or without sutured grain margins, and plagioclase with bent twin planes (Figs. 4.6c to f). The porphyritic variant is characterized by asymmetric rotated plagioclase phenocrysts. Metasomatic alteration accompanies shear deformation, and is characterized by widespread sericitization of feldspar and chloritization and epidotization of biotite (Figs. 4.6c to h). The association of epidote in the metasomatized rock is conspicuous (Figs. 4.6g, h).

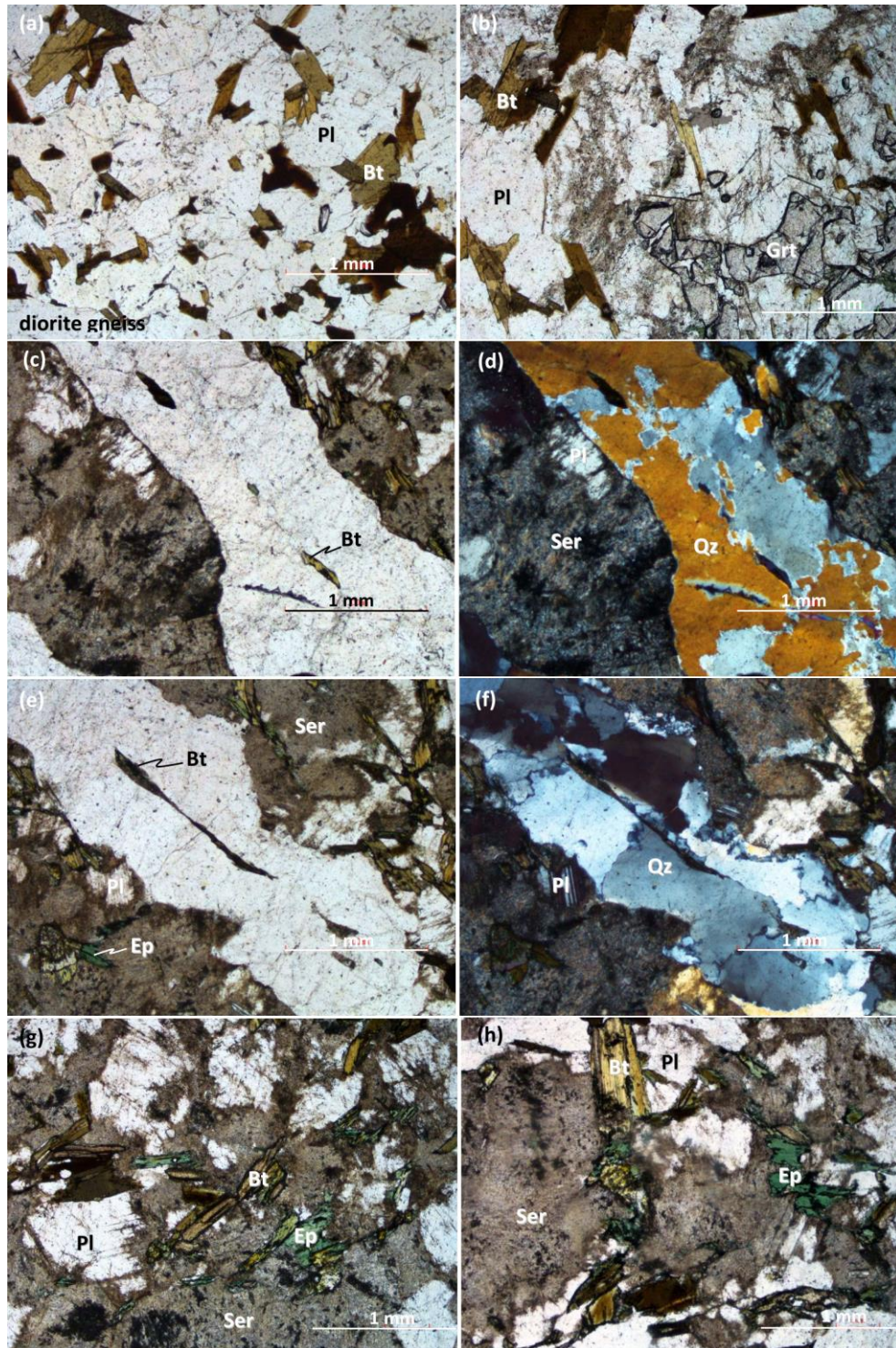


Figure 4.6. Representative photomicrographs illustrating the petrographic characteristics of diorite gneiss from the Radisele-Mogome area. It is dominantly made up of plagioclase, quartz and biotite. Effect of shear deformation is overwhelming, and include elongated plagioclase, quartz, and biotite, and recrystallization of quartz. Alteration features include widespread sericitization of feldspar and chloritization and epidotization of biotite. Epd - epidote; all images taken under PPL.

Granodiorite is dominantly made up of K-feldspar, plagioclase, quartz and biotite (Figs. 4.7a to d). Sutured grain margins and undulose extinction of quartz, and elongate biotite is seen in granodiorite samples from outside the extents of shear zone (Figs. 4.7a to d). Biotite is often altered to chlorite, and sericitic alteration of feldspar is common. Within the shear zone, the effect of shear deformation is overwhelming, and characterized by elongate feldspar, quartz and biotite, and recrystallized quartz with sutured grain margins.

Leucogranite is the least dominant rock type in the SW part of the Radisele-Mogome area. The sheared leucogranite outcrops were heavily weathered. Hence, the studied samples were from fresh least deformed rocks. The leucogranite preserves a typical granitic texture with K-feldspar, quartz, plagioclase, biotite and garnet (Figs. 4.7e to h). Microcline is common (Figs. 4.7e, f). Straight line grain margins dominate (Figs. 4.7e, f). Irregular lobate grain margins are seen locally (Fig. 4.7g). Although minor, garnet is uniformly dispersed in the leucogranite (Fig. 4.7h). Sericite and chlorite are common alteration minerals.

4.6. Mogome granite

The alkali granite is dominated by K-feldspar and quartz, with minor interstitial biotite (Fig. 4.8a). Perthite is common (Figs. 4.8a, b). Myrmekite is locally seen (Fig. 4.8c). The effect of shear deformation is indicated by recrystallized quartz with sutured grain margins, and elongate quartz, feldspar and biotite (Figs. 4.8d to h). Alteration accompany shear deformation, and include sericitization of feldspar and chloritization of biotite (Fig. 4.8h).

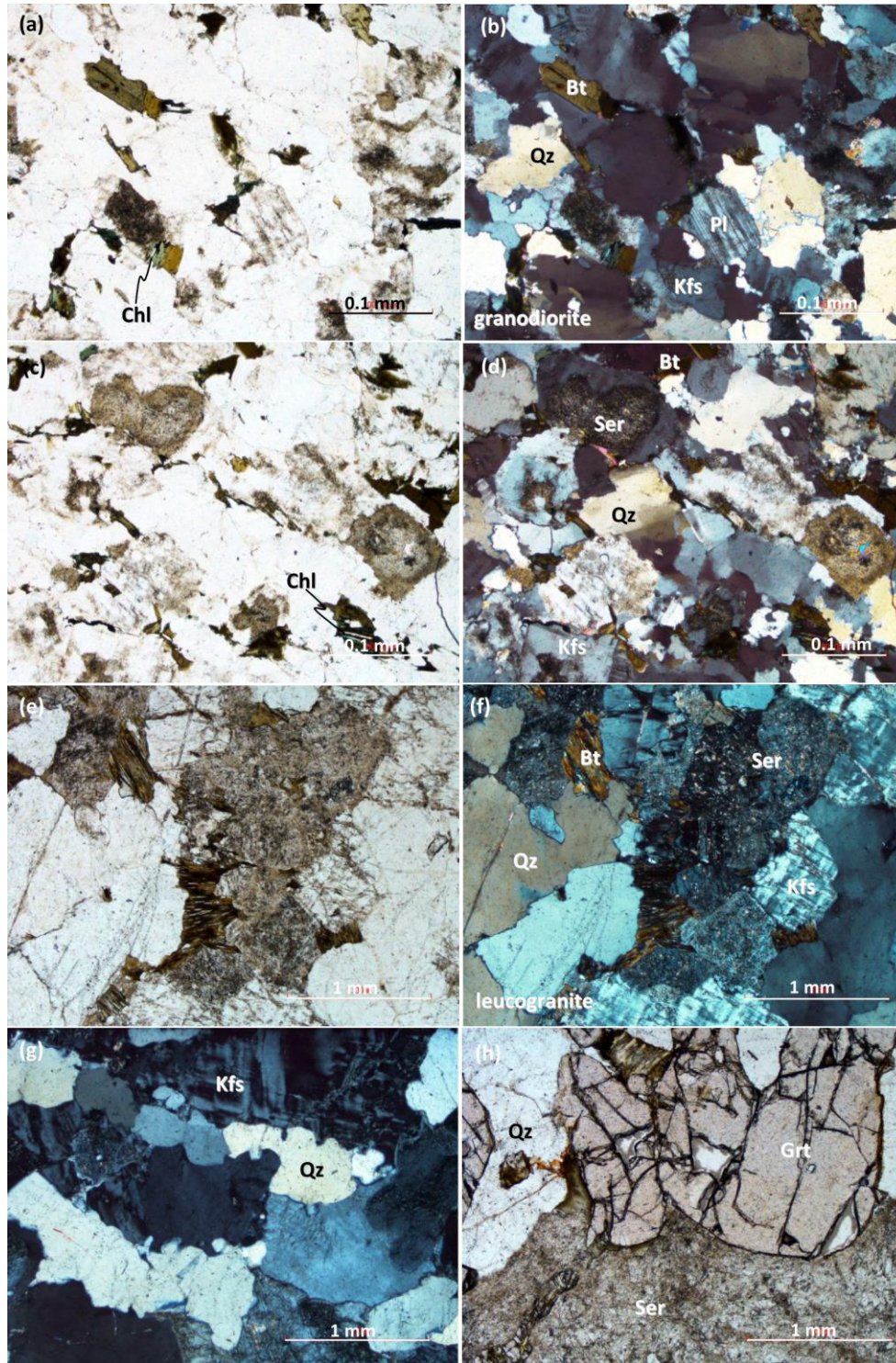


Figure 4.7. Representative photomicrographs illustrating the petrographic characteristics of granodiorite (a to d) and leucogranite (e to h) from the Radisele-Mogome area. Granodiorite is dominantly made up of K-feldspar, plagioclase, quartz and biotite. Leucogranite is dominantly made up of K-feldspar, quartz, plagioclase, biotite and garnet. Sericite and chlorite are common alteration minerals in both rocks. (a), (c), (e), (h) – PPL; (b), (d), (f), (g) – XPL.

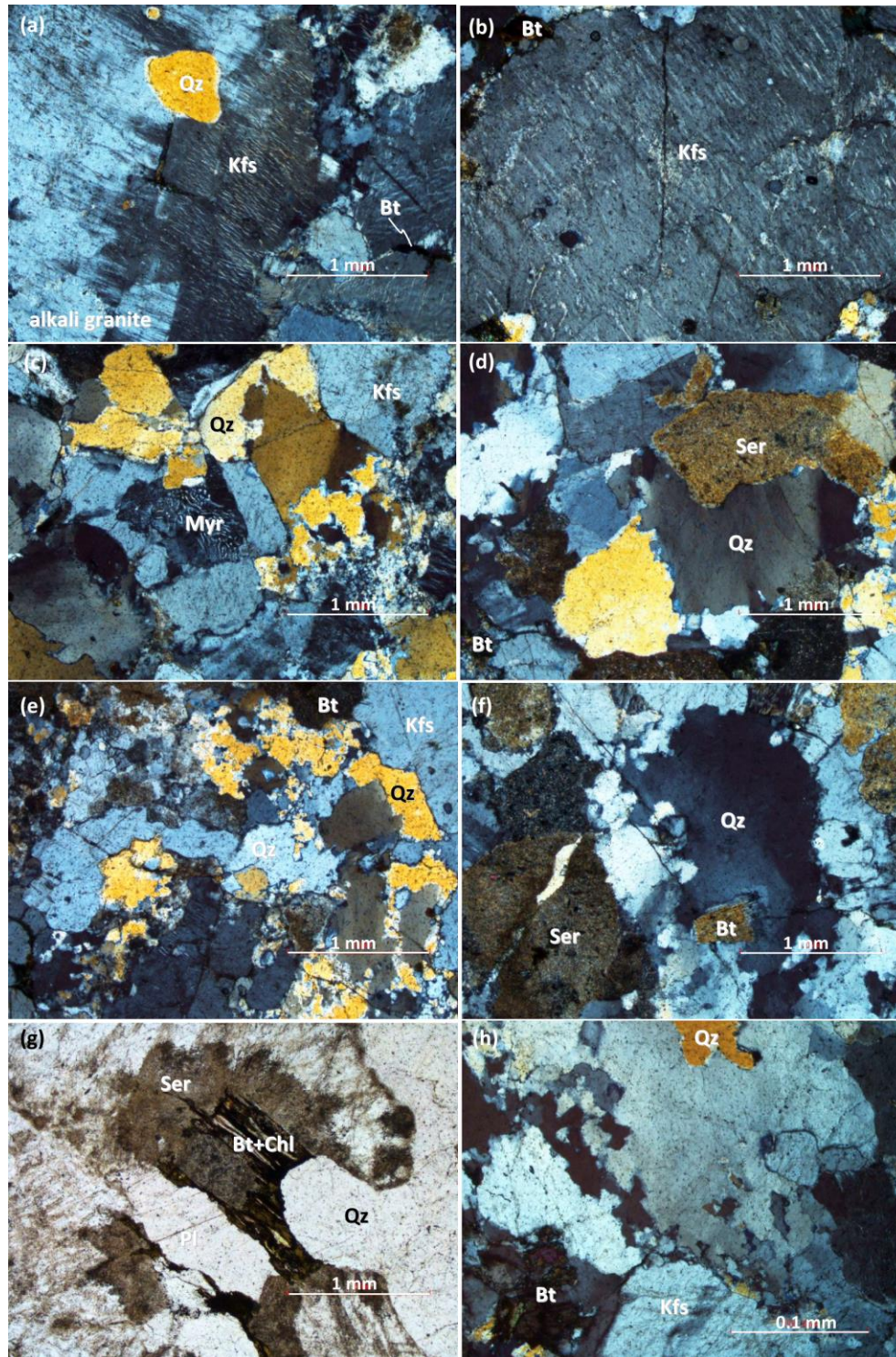


Figure 4.8. Representative photomicrographs illustrating the petrographic characteristics of the Mogome alkali granite from the Radisele-Mogome area. Effect of shear deformation include recrystallized quartz with sutured grain margins, and elongate quartz, feldspar and biotite. Alteration accompany shear deformation, and form sericite and chlorite. Kfs – K-feldspar; Myr – myrmekite. (g) – PPL; (a) to (f), (h) – XPL.

Chapter 5

⁴⁰Ar/³⁹Ar geochronology

This chapter presents ⁴⁰Ar/³⁹Ar geochronologic data obtained respectively on fabric forming minerals from the eastern and southern terrane boundaries of the Motloutse Complex. The aim is to understand the timing of shear deformation along the respective terrane boundaries. Representative mineral chemical data on the dated minerals is also included to understand the correlation with Cl/K and Ca/K ratios measured from ⁴⁰Ar/³⁹Ar geochronology. Analytical details for the ⁴⁰Ar/³⁹Ar geochronology and electron microprobe analysis are given in Appendix 1.

5.1. Masikati hills – eastern terrane boundary

Amphibole in a sheared amphibolite from the Masikati hills (see Fig. 3.2 for location) was subjected to ⁴⁰Ar/³⁹Ar geochronology from the eastern terrane boundary of the Motloutse Complex. The Ar analytical data, including Ca/K and Cl/K ratios, are listed in Table 5.1. ⁴⁰Ar/³⁹Ar step heating of an amphibole grain from the sheared amphibolite (sample MA2) yielded a near-plateau (94% of ³⁹Ar) with an integrated age of 2013 ± 12 Ma (Fig. 5.1). The corresponding Ca/K and Cl/K ratios are 10.17 and 0.04 (Table 5.1). There is good correspondence of Cl/K ratios from amphibole mineral chemical data and ⁴⁰Ar/³⁹Ar geochronology (Fig. 5.2; Tables 5.1, 5.2). The high Ca/K ratio is likely due to the presence of

plagioclase inclusions in the amphibole. Minor low-temperature heating steps include older ages (Table 5.1).

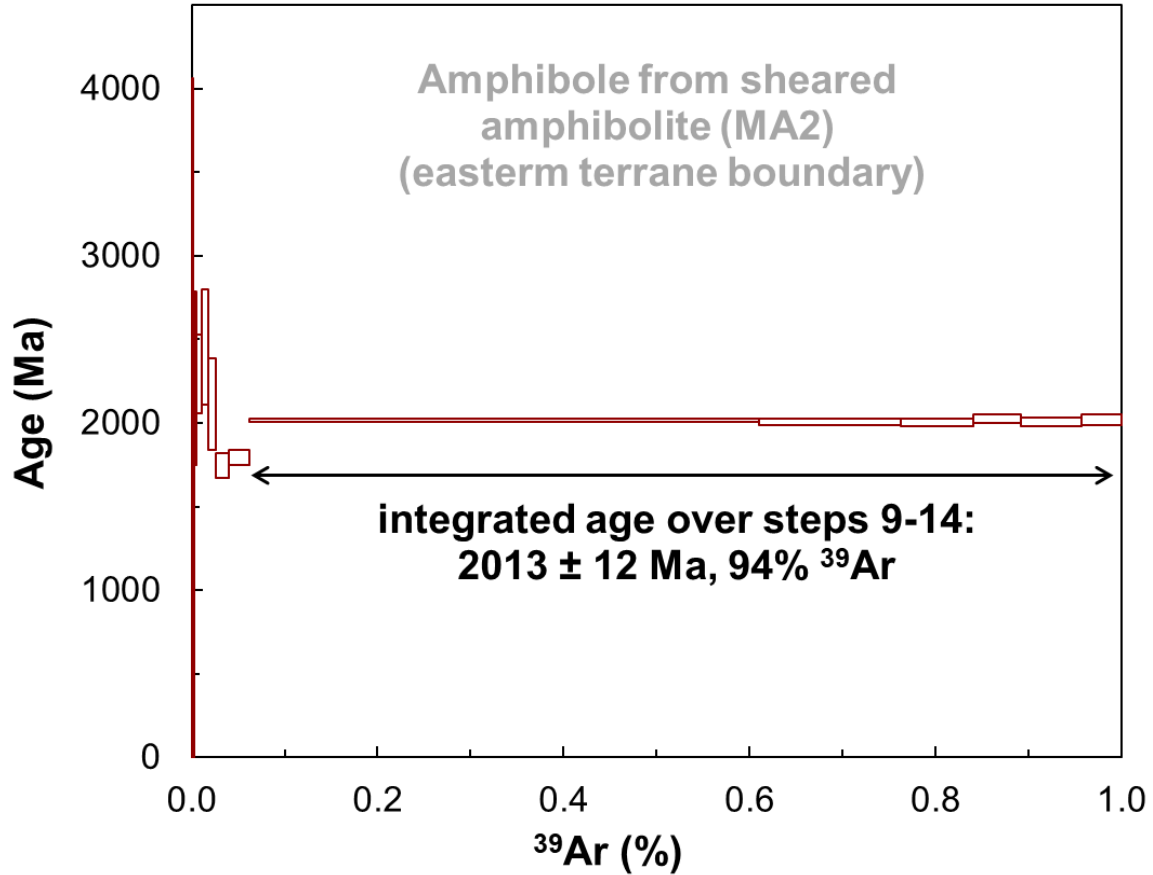


Figure 5.1. $^{40}\text{Ar}/^{39}\text{Ar}$ spectra of amphibole in a sheared amphibolite from the Masikati hills, along the eastern terrane boundary of the Motloutse Complex.

5.2. Radisele-Mogome area – southern terrane boundary

Biotite in a sheared diorite gneiss from the Radisele-Mogome area (see Fig. 3.10 for location) was subjected to $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology from the southern terrane boundary of the Motloutse Complex. The Ar analytical data, including Ca/K and Cl/K ratios, are listed in Table 5.3. $^{40}\text{Ar}/^{39}\text{Ar}$ step heating of a biotite grain from the sheared diorite gneiss (sample

M4) gave a marginally acceptable plateau (89% of ^{39}Ar) with an integrated age of 1987 ± 8 Ma (Fig. 5.3). The corresponding Ca/K and Cl/K ratios are 0.01 and 0.03 (Table 5.3). There is good correspondence of Cl/K ratios from amphibole mineral chemical data and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology (Fig. 5.2; Tables 5.2, 5.3).

Table 5.1. $^{40}\text{Ar}/^{39}\text{Ar}$ age data, including Ca/K and Cl/K ratios, of amphibole in a sheared amphibolite from the Masikati hills, along the eastern terrane boundary of the Motloutse Complex.

Sample: MA2_Amp_1								Relative irradiation coordinate z: 46.9 mm			
J value: 0.004054 +/- 0.000011								Heating time: 5 min			
Step, #	Laser, A	cc stp ^{40}Ar	^{40}Ar (nA)	$\pm 2\text{SE Abs}$	^{39}Ar (nA)	$\pm 2\text{SE Abs}$	^{38}Ar (nA)	$\pm 2\text{SE Abs}$	^{37}Ar (nA)	$\pm 2\text{SE Abs}$	
1	10.30	2.26E-10	0.05881	6.68E-05	0.000020	5.02E-06	0.000216	8.49E-06	0.00002	3.34E-06	
2	10.60	1.97E-10	0.05112	6.16E-05	0.000044	3.73E-06	0.000217	4.10E-06	0.00001	4.60E-06	
3	10.90	2.76E-10	0.07170	6.07E-05	0.000073	4.25E-06	0.000195	6.14E-06	0.00012	5.53E-06	
4	11.20	7.26E-10	0.18866	1.94E-04	0.000173	4.08E-06	0.000449	6.69E-06	0.00052	5.83E-06	
5	11.50	9.38E-10	0.24370	3.12E-04	0.000197	5.87E-06	0.000544	1.51E-05	0.00117	6.96E-06	
6	11.80	8.01E-10	0.20800	5.56E-04	0.000250	7.41E-06	0.000478	1.17E-05	0.00107	8.09E-06	
7	12.10	8.71E-10	0.22612	1.02E-04	0.000401	3.98E-06	0.000388	4.78E-06	0.00119	5.11E-06	
8	12.40	1.16E-09	0.30050	3.50E-04	0.000666	5.42E-06	0.000318	5.12E-06	0.00098	6.83E-06	
9	12.70	3.11E-08	8.08361	4.69E-03	0.016049	1.71E-05	0.005344	1.62E-05	0.00894	1.31E-05	
10	13.00	8.57E-09	2.22567	1.19E-03	0.004462	1.19E-05	0.001641	8.39E-06	0.00280	1.38E-05	
11	13.30	4.35E-09	1.12929	4.77E-04	0.002263	7.58E-06	0.000842	5.12E-06	0.00137	8.52E-06	
12	13.60	2.93E-09	0.75996	2.24E-04	0.001502	6.37E-06	0.000588	4.15E-06	0.00129	5.11E-06	
13	13.90	3.63E-09	0.94348	1.12E-03	0.001898	8.07E-06	0.000723	4.35E-06	0.00120	4.88E-06	
14	14.20	2.46E-09	0.63805	2.47E-04	0.001266	7.34E-06	0.000486	6.58E-06	0.00082	5.49E-06	

Days after irradiation: 112											
^{36}Ar (nA)	$\pm 2\text{SE Abs}$	$^{40}\text{Ar}/^{36}\text{Ar}$	$\pm 2\text{SE Abs}$	% ^{39}Ar	Age Ma	$\pm 95\%$	Included	Ca/K	$\pm 2\text{SE}$	Cl/K	$\pm 2\text{SE}$
0.000231	4.45E-06	266	10	0.1	0.0	4059.7	no	16.61	12.23	1.0432	0.63495
0.000186	3.95E-06	288	12	0.2	-360.4	2946.9	no	5.67	4.51	0.5052	0.10674
0.000097	3.65E-06	776	56	0.2	2265.9	519.8	no	27.98	5.13	0.2977	0.04816
0.000292	4.06E-06	678	17	0.6	2292.9	234.4	no	52.11	3.36	0.2842	0.01978
0.000389	7.83E-06	659	25	0.7	2454.7	342.6	no	104.53	7.82	0.3043	0.03046
0.000272	1.03E-05	808	64	0.9	2110.5	274.1	no	74.79	5.64	0.2146	0.02033
0.000247	3.33E-06	967	26	1.4	1745.3	75.3	no	51.37	1.39	0.1058	0.00438
0.000096	4.61E-06	3367	340	2.3	1794.5	47.5	no	25.10	0.68	0.0554	0.00257
0.000244	4.67E-06	37886	1628	54.8	2016.0	12.5	yes	9.46	0.07	0.0403	0.00069
0.000059	5.94E-06	44415	12058	15.2	2006.2	17.2	yes	10.67	0.16	0.0446	0.00092
0.000040	3.65E-06	32492	7316	7.7	2003.8	20.3	yes	10.30	0.19	0.0450	0.00102
0.000017	2.88E-06	56397	47561	5.1	2027.5	25.7	yes	14.64	0.22	0.0476	0.00120
0.000021	3.29E-06	54657	32395	6.5	2003.9	25.4	yes	10.75	0.17	0.0463	0.00109
0.000012	3.15E-06	65290	999868	4.3	2021.5	31.3	yes	11.08	0.25	0.0466	0.00181

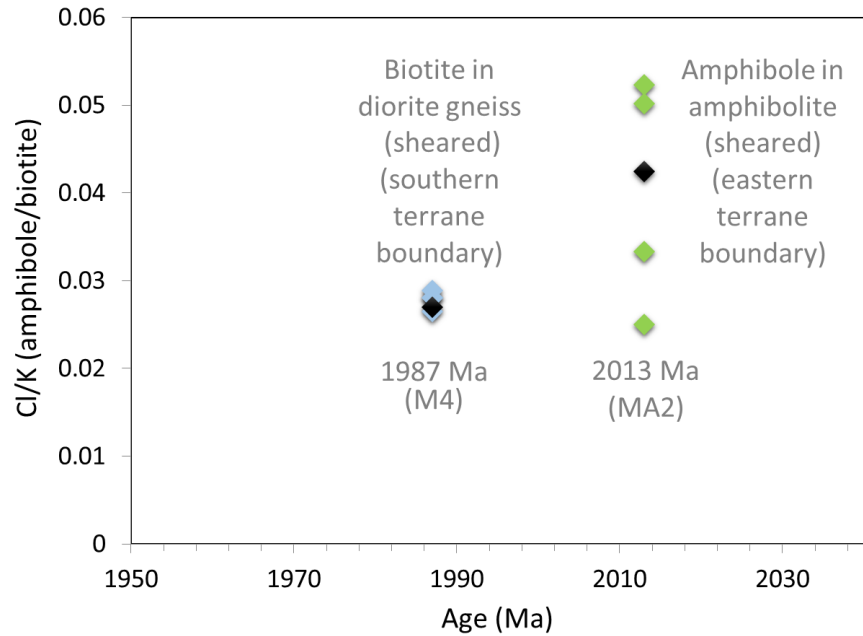


Figure 5.2. Comparison of Cl/K ratios of amphibole and biotite from mineral chemistry (blue and green filled) and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology (dark filled).

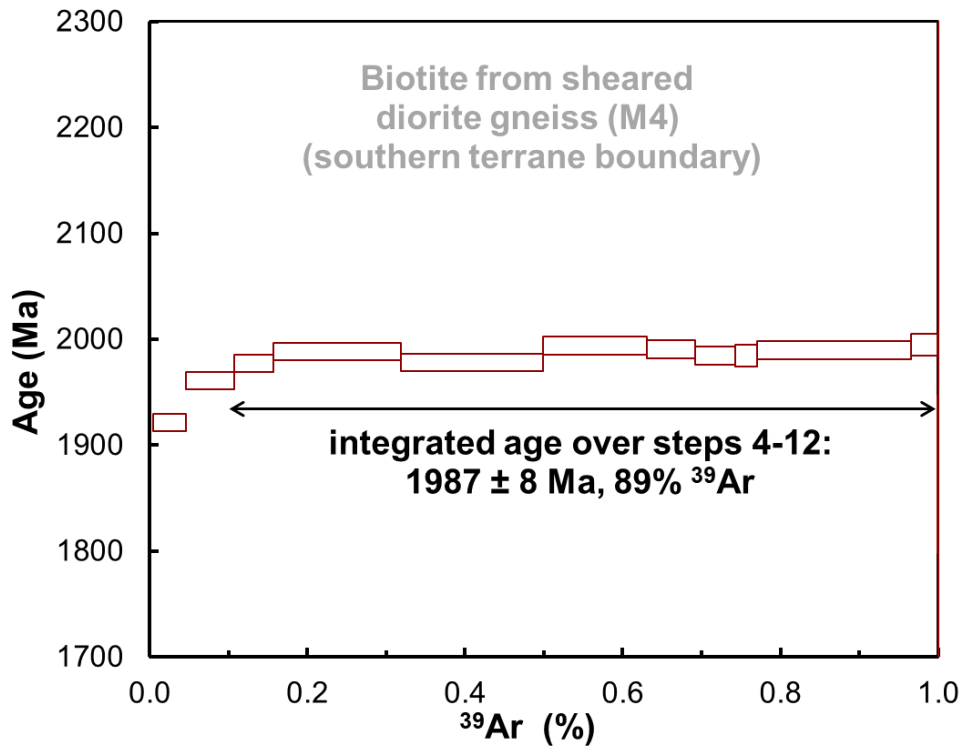


Figure 5.3. $^{40}\text{Ar}/^{39}\text{Ar}$ spectra of biotite in a sheared diorite gneiss from the Radisele-Mogome area, along the southern terrane boundary of the Motloutse Complex.

Table 5.2. Representative mineral chemical of amphibole from the sheared amphibolite (sample MA2), and biotite from the sheared diorite gneiss (samples M4).

Sample No	M4	M4	M4	M4		MA2	MA2	MA2	MA2
Mineral	Biotite*	Biotite*	Biotite*	Biotite*		Amphibole*	Amphibole*	Amphibole*	Amphibole*
SiO ₂	35.66	35.75	35.93	35.62	SiO ₂	39.60	39.17	39.04	40.09
TiO ₂	4.31	4.27	4.10	4.07	TiO ₂	2.72	2.81	2.69	2.60
Al ₂ O ₃	14.56	14.39	14.37	14.47	Al ₂ O ₃	13.12	13.23	13.34	11.77
FeO	22.07	21.60	22.02	21.82	FeO	19.62	20.85	20.78	20.34
MnO	0.19	0.15	0.18	0.12	MnO	0.45	0.43	0.43	0.48
MgO	9.02	9.23	9.42	9.27	MgO	6.83	6.08	6.08	6.29
CaO	0.01	0.09	0.00	0.03	CaO	11.68	11.54	11.54	11.65
Na ₂ O	0.25	0.23	0.19	0.19	Na ₂ O	1.66	1.66	1.77	1.78
K ₂ O	9.00	8.97	8.70	8.97	K ₂ O	1.98	2.00	1.92	1.72
F	0.40	0.49	0.52	0.48	F	0.00	0.01	0.07	0.00
Cl	0.18	0.19	0.19	0.19	Cl	0.04	0.08	0.05	0.07
–O=F+Cl	0.21	0.25	0.26	0.25	–O=F+Cl	0.01	0.02	0.04	0.02
Total _{initial}	95.50	95.16	95.45	95.06	Total _{initial}	97.91	98.14	98.04	97.12
Fe ₂ O _{3calc}	5.38	5.46	6.49	5.65	Fe ₂ O _{3calc}	3.96	3.93	3.99	3.71
FeO _{calc}	17.23	16.69	16.18	16.74	FeO _{calc}	16.06	17.31	17.19	17.00
H ₂ O _{calc}	2.56	2.53	2.59	2.60	H ₂ O _{calc}	1.53	1.48	1.49	1.61
Total _{lcalc}	98.60	98.24	98.69	98.23	Total _{lcalc}	99.84	100.01	99.92	99.11
T. Si	2.792	2.800	2.791	2.789	T.Si	6.129	6.100	6.083	6.255
T. Al	1.054	1.040	1.030	1.046	T. Al	1.857	1.883	1.904	1.732
T. Fe ³⁺	0.154	0.159	0.179	0.165	T. Ti	0.017	0.022	0.017	0.019
sum Tet	4.000	4.000	4.000	4.000	T. sum	8.003	8.005	8.004	8.005
M. Al	0.289	0.288	0.285	0.289	C. Al	0.536	0.545	0.546	0.433
M. Mg	1.072	1.099	1.102	1.102	C. Ti	0.299	0.308	0.299	0.286
M. Fe ²⁺	1.128	1.093	1.051	1.096	C. Fe ³⁺	0.461	0.461	0.468	0.436
M. Fe ³⁺	0.163	0.162	0.200	0.168	C. Mn ²⁺	0.055	0.054	0.054	0.060
M. Ti	0.253	0.252	0.241	0.241	C. Mg	1.576	1.411	1.412	1.463
M. Mn	0.013	0.010	0.012	0.008	C. Fe ²⁺	2.036	2.184	2.176	2.223
sum oct	2.918	2.907	2.893	2.905	C. sum	4.990	4.999	5.001	4.944
Oct Vacancy	0.082	0.093	0.107	0.095	B. Mn ²⁺	0.004	0.003	0.003	0.003
A. K	0.900	0.898	0.867	0.898	B. Fe ²⁺	0.043	0.071	0.064	0.000
A. Na	0.038	0.035	0.029	0.029	B. Mg	0.000	0.000	0.000	0.000
A. Ca	0.001	0.008	0.000	0.003	B. Ca	1.915	1.901	1.902	1.925
sum inter	0.939	0.941	0.895	0.929	B. Na	0.095	0.082	0.091	0.149
Inter Vacancy	0.061	0.059	0.105	0.071	B. sum	2.058	2.056	2.058	2.078
W. F	0.108	0.130	0.128	0.126	A. Ca	0.022	0.025	0.025	0.022
W. Cl	0.024	0.025	0.025	0.025	A. Na	0.403	0.420	0.444	0.390
W. OH	1.340	1.324	1.344	1.360	A. K	0.384	0.390	0.375	0.338
W. O ²⁻	0.528	0.521	0.503	0.489	A. sum	0.808	0.835	0.844	0.750
Fe ³⁺ /Fe _{tot}	0.219	0.227	0.265	0.233	W. OH	1.581	1.538	1.545	1.680
					W. F	0.000	0.020	0.047	0.000
X _{Mg}	0.43	0.44	0.44	0.44	W. Cl	0.010	0.020	0.012	0.017
Al _{total}	1.34	1.33	1.32	1.34	W. O ²⁻	0.410	0.421	0.395	0.303
X _{Mg} = Mg/(Mg+Fe);					Fe ³⁺ /Fe _{tot}	0.181	0.170	0.173	0.164
*biotite formula recalculation following Li et al. (2020)									
					X _{Mg}	0.38	0.34	0.34	0.35
					Al _{total}	2.39	2.43	2.45	2.16
					X _{Mg} = Mg/(Mg+Fe);				
					*amphibole formula recalculation following Li et al. (2020)				

Table 5.3. $^{40}\text{Ar}/^{39}\text{Ar}$ age data, including Ca/K and Cl/K ratios, of biotite in a sheared diorite gneiss from the Radisele-Mogome area, along the southern terrane boundary of the Motloutse Complex.

Sample: M4_Bt_2		Relative irradiation coordinate z: 6.8 mm									
J value: 0.008306 +/- 0.000021		Heating time: 5 min									
Step, #	Laser, A	cc stp ^{40}Ar	^{40}Ar (nA)	$\pm 2\text{SE Abs}$	^{39}Ar (nA)	$\pm 2\text{SE Abs}$	^{38}Ar (nA)	$\pm 2\text{SE Abs}$	^{37}Ar (nA)	$\pm 2\text{SE Abs}$	
1	9.80	1.79E-09	0.46541	4.38E-04	0.003204	7.66E-06	0.000642	3.88E-06	0.000027	2.32E-06	
2	9.98	2.39E-08	6.19709	7.91E-04	0.027213	2.15E-05	0.005639	1.12E-05	0.000043	2.94E-06	
3	10.16	3.71E-08	9.63483	1.06E-03	0.041055	3.09E-05	0.008629	1.81E-05	0.000009	1.33E-06	
4	10.34	3.02E-08	7.85028	1.56E-03	0.032999	2.23E-05	0.007128	1.58E-05	0.000011	2.51E-06	
5	10.52	5.66E-08	14.69277	3.61E-03	0.061270	2.96E-05	0.013057	2.06E-05	0.000005	2.47E-06	
6	10.70	6.25E-08	16.23390	3.71E-03	0.068240	3.19E-05	0.014421	2.37E-05	-	-	
7	10.88	4.70E-08	12.20048	2.39E-03	0.050638	4.22E-05	0.010709	1.75E-05	-	-	
8	11.06	2.21E-08	5.73010	1.93E-03	0.023874	1.97E-05	0.005101	1.29E-05	-	-	
9	11.24	3.04E-08	7.90891	9.26E-04	0.033070	2.51E-05	0.006964	1.35E-05	0.000036	2.01E-06	
10	11.42	1.73E-08	4.48611	8.61E-04	0.018724	2.52E-05	0.004050	1.10E-05	0.000051	3.48E-06	
11	11.60	7.11E-08	18.47236	6.90E-03	0.076977	3.06E-05	0.016920	2.03E-05	0.000058	2.14E-06	
12	11.80	1.22E-08	3.17904	9.96E-04	0.013197	1.76E-05	0.002832	7.62E-06	0.000011	2.74E-06	
13	12.00	9.67E-11	0.02512	5.41E-05	0.000156	2.52E-06	0.000044	2.25E-06	0.000085	2.13E-06	

Days after irradiation: 124											
^{36}Ar (nA)	$\pm 2\text{SE Abs}$	$^{40}\text{Ar}/^{36}\text{Ar}$	$\pm 2\text{SE Abs}$	% ^{39}Ar	Age Ma	$\pm 95\%$	Included	Ca/K	$\pm 2\text{SE}$	Cl/K	$\pm 2\text{SE}$
0.000085	2.23E-06	5761	285	0.5	1394.9	12.7	no	0.19	0.04	0.0246	0.0020
0.000150	2.49E-06	43249	1352	4.1	1921.4	8.4	no	0.04	0.01	0.0259	0.0020
0.000104	3.18E-06	96979	5615	6.2	1960.8	8.1	no	0.00	0.00	0.0264	0.0021
0.000098	3.36E-06	83563	5175	5.0	1977.2	8.3	yes	0.01	0.00	0.0271	0.0021
0.000079	3.58E-06	195419	17291	16.1	1988.6	8.1	yes	0.00	0.00	0.0268	0.0021
0.000070	3.86E-06	242793	28427	18.1	1978.0	8.3	yes	-	-	0.0265	0.0021
0.000065	4.00E-06	196854	24812	13.2	1993.9	8.6	yes	-	-	0.0266	0.0021
0.000039	3.99E-06	152923	37967	6.2	1990.6	8.3	yes	-	-	0.0268	0.0021
0.000085	2.57E-06	97962	5859	5.0	1984.5	8.3	yes	0.02	0.00	0.0264	0.0021
0.000075	3.32E-06	62576	5659	2.8	1984.8	10.1	yes	0.06	0.01	0.0271	0.0021
0.000081	2.93E-06	238780	17280	19.5	1989.7	8.3	yes	0.02	0.00	0.0276	0.0022
0.000027	3.33E-06	122508	37903	3.4	1994.5	10.3	yes	0.02	0.01	0.0269	0.0021
-	-	-	-	0.0	1872.4	74.0	no	12.44	1.11	0.0373	0.0057

Chapter 6

Geophysics

This chapter presents geophysical (aeromagnetic) characteristics associated with the terrane boundaries of the Motloutse complex. Those for the eastern boundary is present first, followed by the southern boundary. The respective geologic maps for the study areas are repeated here to aid with the correlation of aeromagnetic signatures.

6.1. Aeromagnetic data set and analysis

This study used existing high resolution aeromagnetic data obtained from the Botswana Geosciences Institute. Various digital enhancement algorithms (Fourier transformations) were applied to the aeromagnetic grid to improve signatures, so as to interpret structures and geological characteristics of the study areas. These include reduction to magnetic pole (RTP), first vertical derivative (1VD), tilt angle derivative (TDR), Butterworth low-pass filter, and analytic signal (AS). Details of the data set, image processing, and individual digital enhancement algorithms are included in Appendix 1.

6.2. Aeromagnetic characteristics of the eastern terrane boundary

To map the eastern terrane boundary, this study focuses on southern Motloutse Complex, north of the Lechana fault (Fig. 6.1). In general, the outcrops are restricted mostly

to hills and ridges (Fig. 6.1a). In the lowlands, outcrops are isolated and scanty. The region of interest is between Maope-Masikati-Lechana-Tamasane areas.

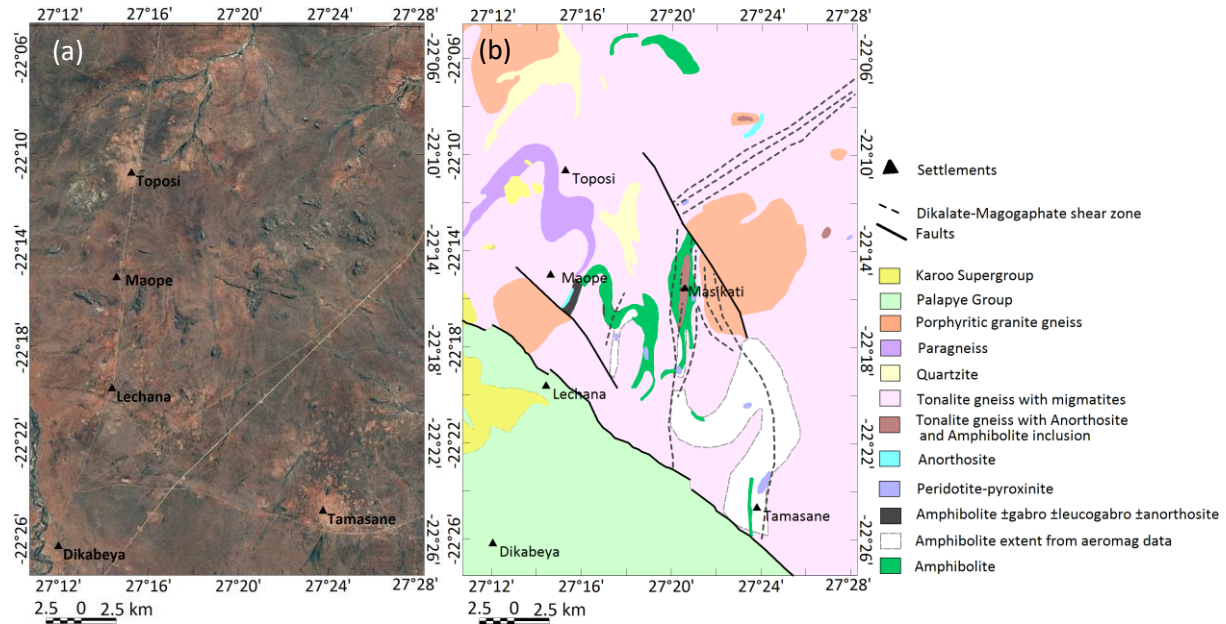


Figure 6.1. Google map (a) and general geologic map (b) of the region covered in southern Motloutse Complex. The geologic map is modified from Key et al. (1994), with inputs from Rajesh et al. (2020a) and this study. The region of interest is between Maope-Masikati-Lechana-Tamasane areas.

In the reduced to magnetic pole (RTP) map, the central region covering Maope-Masikati-Lechana-Tamasane areas is characterized by medium- to high-magnetic anomalies (Fig. 6.2). The region to the north (north of Toposi) is characterized by low- to medium-magnetic anomalies, and correspond to sediments and granitoids (Figs. 6.1b, 6.2). The lower magnetic region to the south (south of Lechana-Tamasane) is occupied by cover rocks (Figs. 6.1b, 6.2). The prominent WNW-ESE trending linear high magnetic anomalies correspond to mafic dykes, including the one that cross cuts the Masikati hills (Figs. 6.1b, 6.2). The high magnetic anomalies with definite (often part of elongate to folded structures) outlines in the region covering Maope-Masikati-Lechana-Tamasane areas correspond to mafic to ultramafic rocks

(Figs. 6.1b, 6.2). Granitoid units can be either medium- or high-magnetic, with the porphyritic granite body occupying the Dikalate hills constituting a good example of the later (Figs. 6.1b, 6.2). A steep magnetic gradient observed as a termination of the high magnetic anomaly to the north of the Dikalate hills signifies the existence of a NE trending structure (Fig. 6.2). This corresponds to the NE-SW trending Magogaphate shear zone (Figs. 6.1b, 6.2). The southwestern extent of the Dikalate Hills is also truncated by a near N-S-trending structure, and correspond to the Dikalate shear zone (Figs. 6.1, 6.2). Masikati hills falls along the Dikalate shear zone (Figs. 6.1, 6.2).

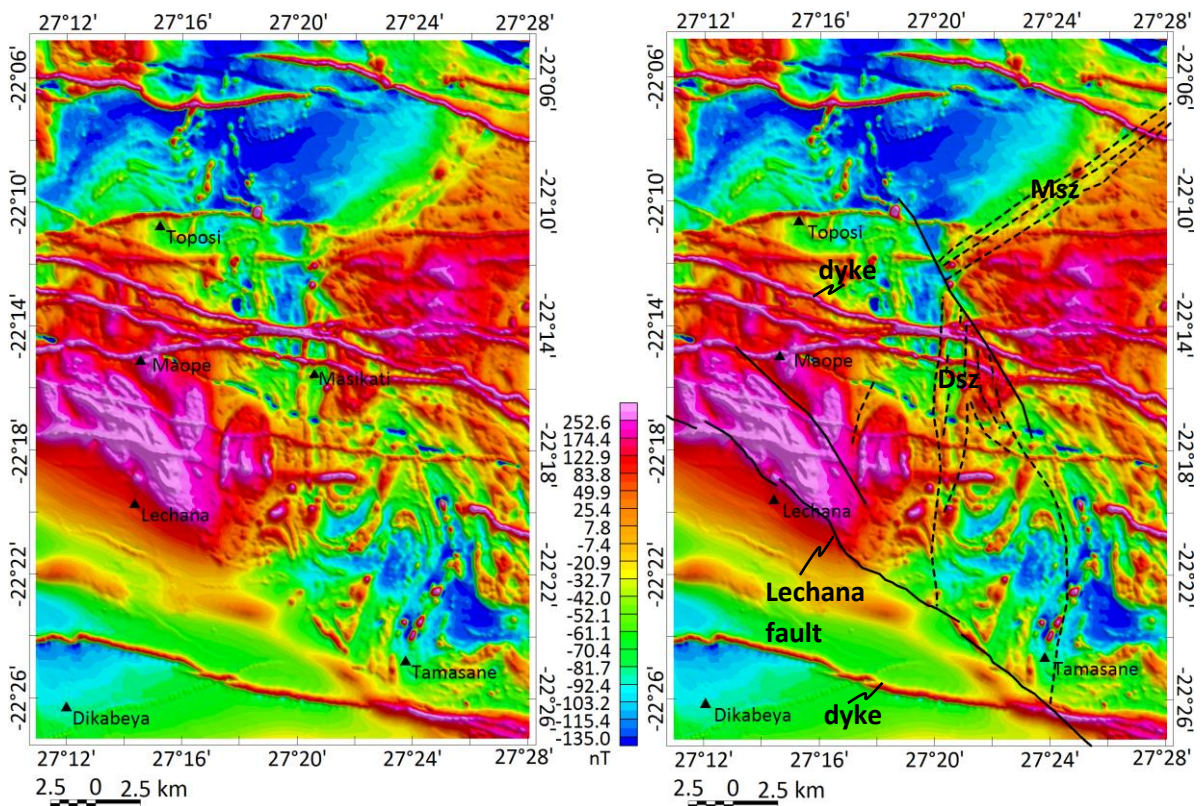


Figure 6.2. RTP map of the region covered in the southern Motloutse Complex. The image to the right is a interpretation of geologic features that can be delineated in the RTP map. These include the NW-SE trending Lechana fault, NE-SW trending Magogaphate shear zone (MsZ), N-S trending Dikalate shear zone (DsZ), and WNW-ESE trending mafic dykes.

Both the NE- trending Magoaphate and the N-S trending Dikalate shear zones can be clearly delineated in the first vertical derivative (1VD) and the tilt angle derivative (TDR) maps (Figs. 6.3, 6.4). Regional upright NE-trending isoclinal fold structures seen in the central region of the RTP map are also clearly delineated in the 1VD and TDR maps (Figs. 6.3, 6.4). It should be pointed out that most parts of the fold structures are buried, with isolated hills and ridges along the limbs of the fold structures constituting the best exposures (Fig. 6.1a). The Dikalate shear zone crosscuts the fold structures (Figs. 6.3, 6.4). The WNW-ESE trending dykes crosscut the earlier structures (Figs. 6.3, 6.4).

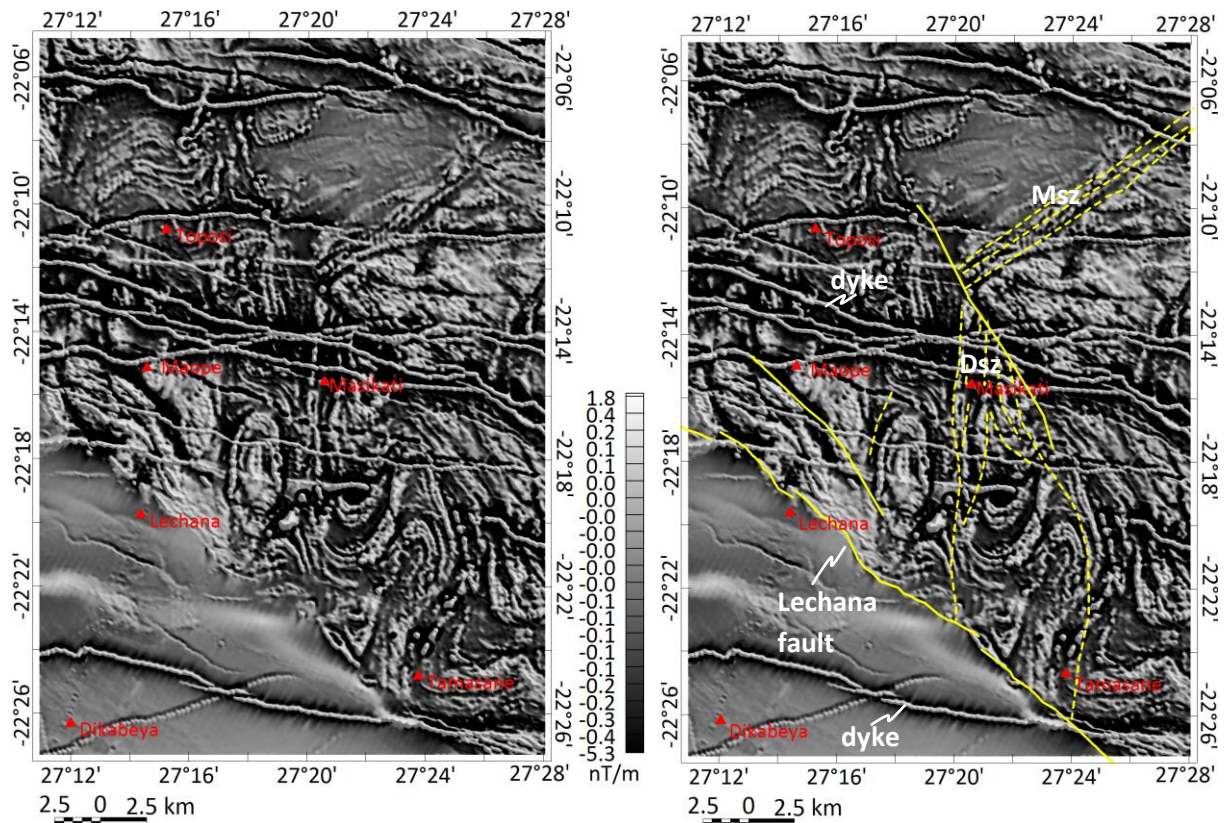


Figure 6.3. The greyscale first vertical derivative (1VD) map of the RTP grid of the region covered in the southern Motloutse Complex. The image to the right is a interpretation of various geologic features that can be delineated in the 1VD map. The delineated geologic features are same as in Fig. 6.2. In addition, the regional upright isoclinal folds can be clearly seen.

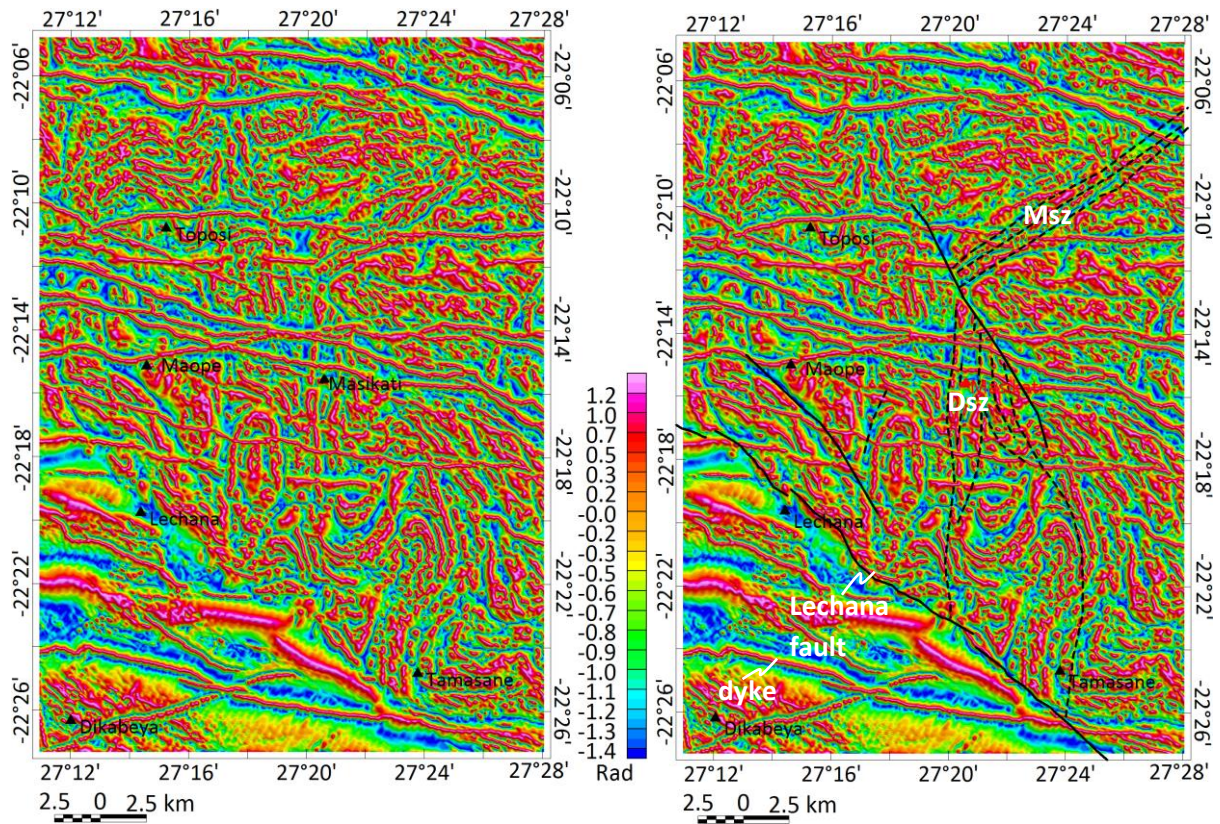


Figure 6.4. The tilt angle derivative (TDR) map of the RTP grid of the region covered in the southern Motloutse Complex. The image to the right is a interpretation of various geologic features that can be delineated in the TDR map, and are same as in Figs. 6.2 and 6.3.

The linear break to the south separating the crystalline rocks of the southern Motloutse Complex from the sedimentary rocks of the Palapye Group, correspond to the NW-SE trending Lechana fault (Fig. 6.2). The Lechana fault is better delineated in the greyscale 1VD map, where the Palapye Group sediments are characterized by a smooth signature (Fig. 6.3). The different linear regional structures delineated in the magnetic maps (Figs. 6.2, 6.3, 6.4) are seen to broadly affect the high anomalies of deep-seated causative bodies in the regional magnetic anomaly map (Fig. 6.5). The possible interference of the linear regional magnetic structures is minimal in the analytical signal map, which is a more accurate

representation of the outline of various magnetic geologic units, including mafic and ultramafic rocks, in the region (Fig. 6.6). The isolated circular units with high magnetic anomalies correspond of the different outcropping mafic to ultramafic rocks in the area (Figs. 6.1, 6.6). These include exposures at the Masikati, Maope, Lechana, Mokobjwe, Senthane and Tamasane hills. The WNW-ESE trending mafic dykes and the NW-SE Lechana fault can also be clearly delineated in the analytical signal map (Fig. 6.6). To the south of the Lechana fault are the low magnetic anomaly cover rocks of the Palapye Group (Fig. 6.6). The crystalline basement rocks are again exposed beneath the cover rocks around the Radisele-Mogome areas, which is addressed in the next section dealing with the southern terrane boundary of the Motloutse Complex.

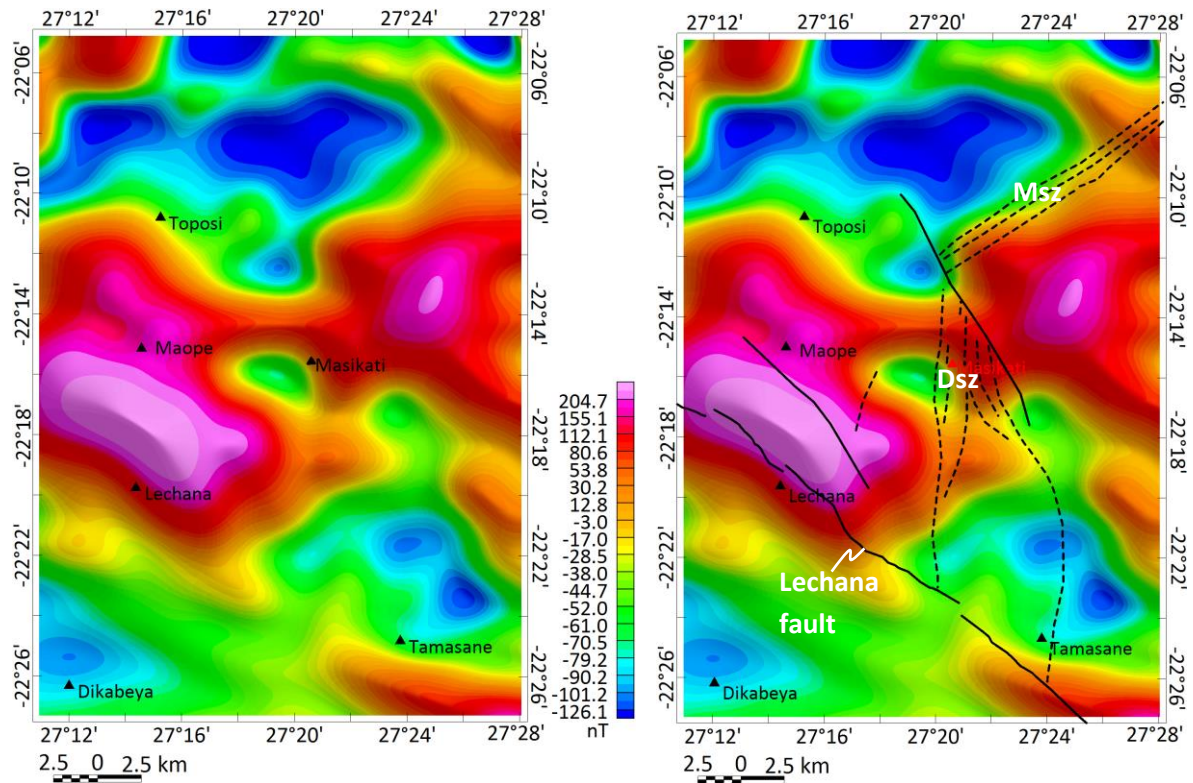


Figure 6.5. The regional anomaly map of the region covered in the southern Motloutse Complex. The various geologic features shown in the image to the right is derived from Figs. 6.2, 6.3 and 6.4.

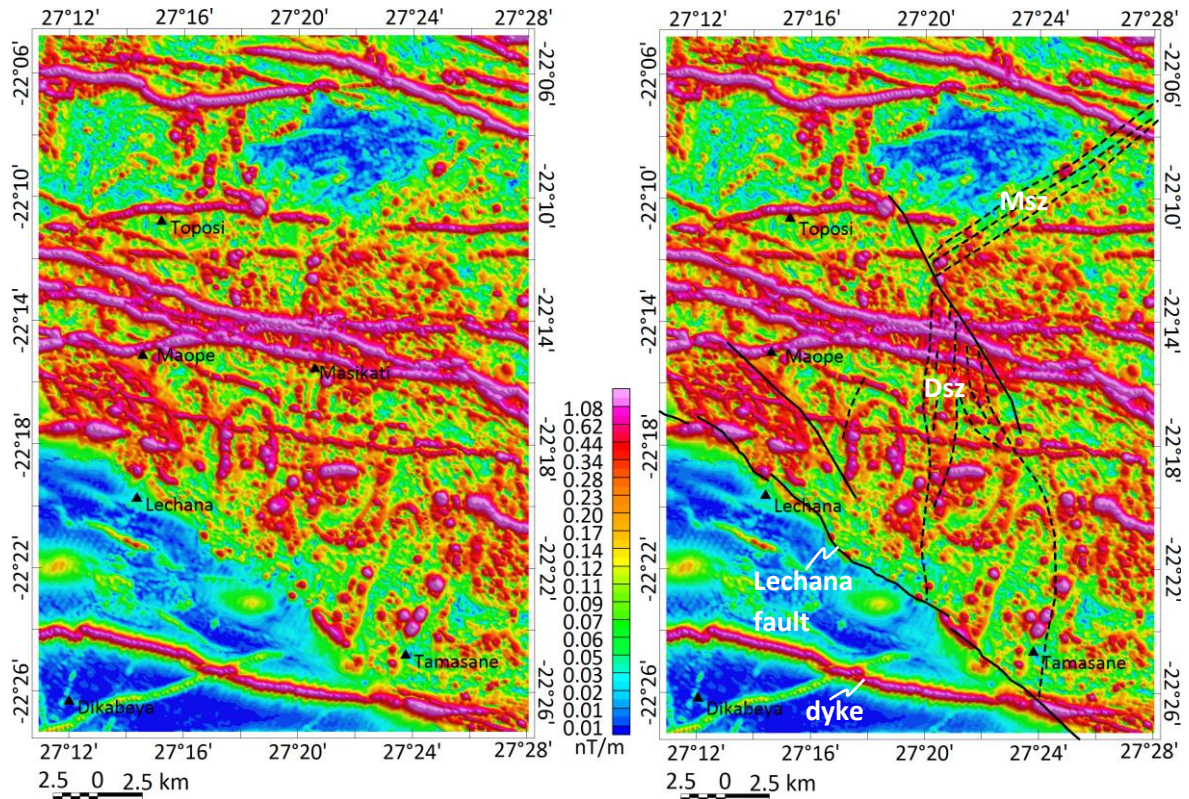


Figure 6.6. The analytic signal map of the region covered in the southern Motloutse Complex. The isolated circular outline units with high magnetic intensity closely correspond to the outcropping and inferred magnetic rock units (mafic to ultramafic rocks) in the region. The various geologic features shown in the image to the right is similar to that in Figs. 6.2, 6.3 and 6.4.

6.3. Aeromagnetic characteristics of the southern terrane boundary

The region between the Lechana fault and the southern terrane boundary of the Motloutse Complex is relatively flat, and occupied by cover rocks of the Palapye Group and the Karoo Supergroup. Palapye Group rocks form highlands in between, while the Karoo rocks are mostly not exposed. Aeromagnetic image analyses focus in the region beneath the cover rocks, between the Radisele-Mogome area (Fig. 6.7a). The RTP map of the study area is characterized by medium to high magnetic anomalies in the northeastern part and low magnetic anomalies in the southwestern part (Fig. 6.8). A clear demarcation between the

two contrasting magnetic anomalies is observed (Fig. 6.8), and could indicate the existence of a linear regional structure.

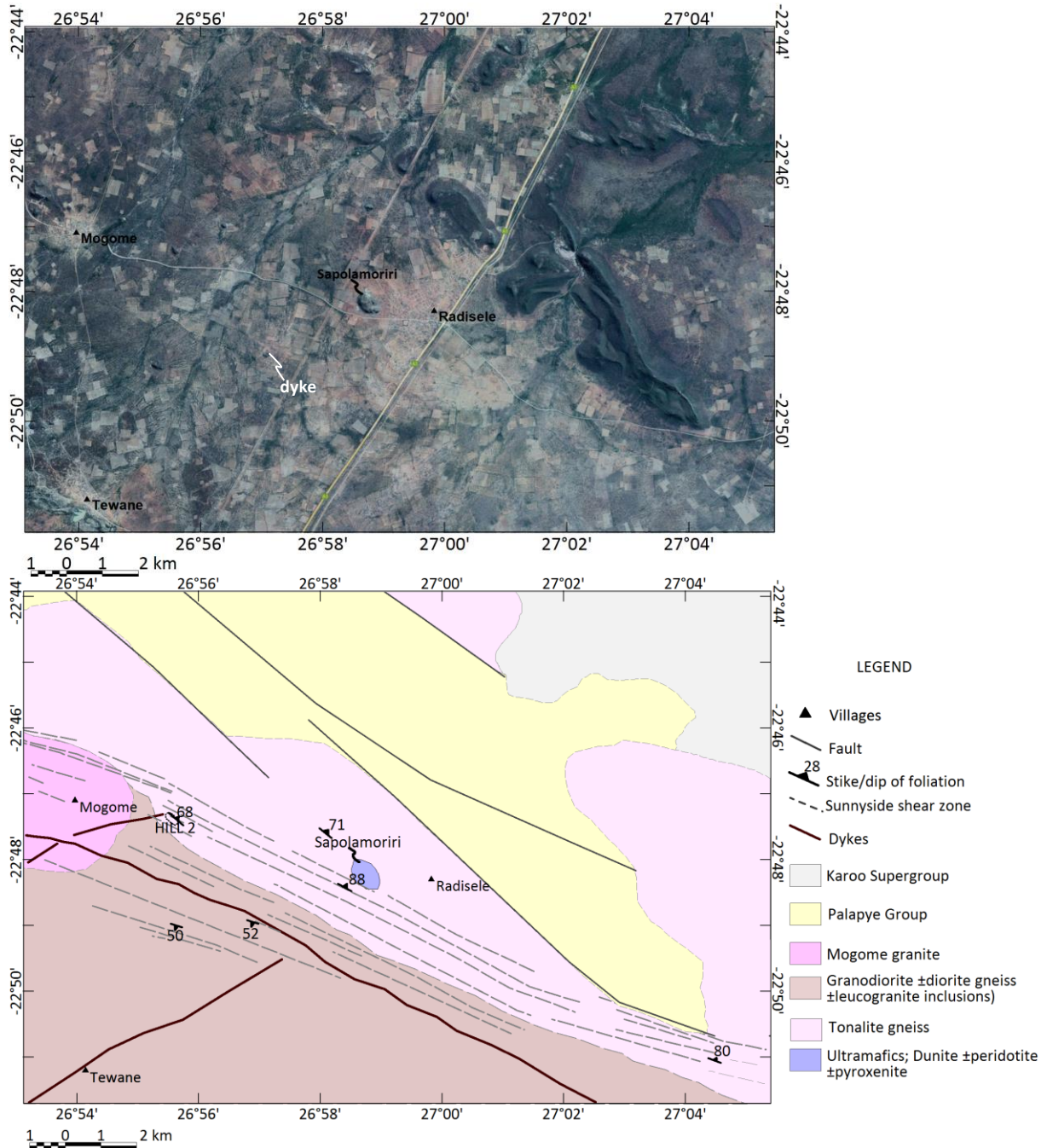


Figure 6.7. Google map (a) and geologic map (b) of the region covering Radisele-Mogome-Tewane areas, towards the southern terrane boundary of the Motloutse Complex.

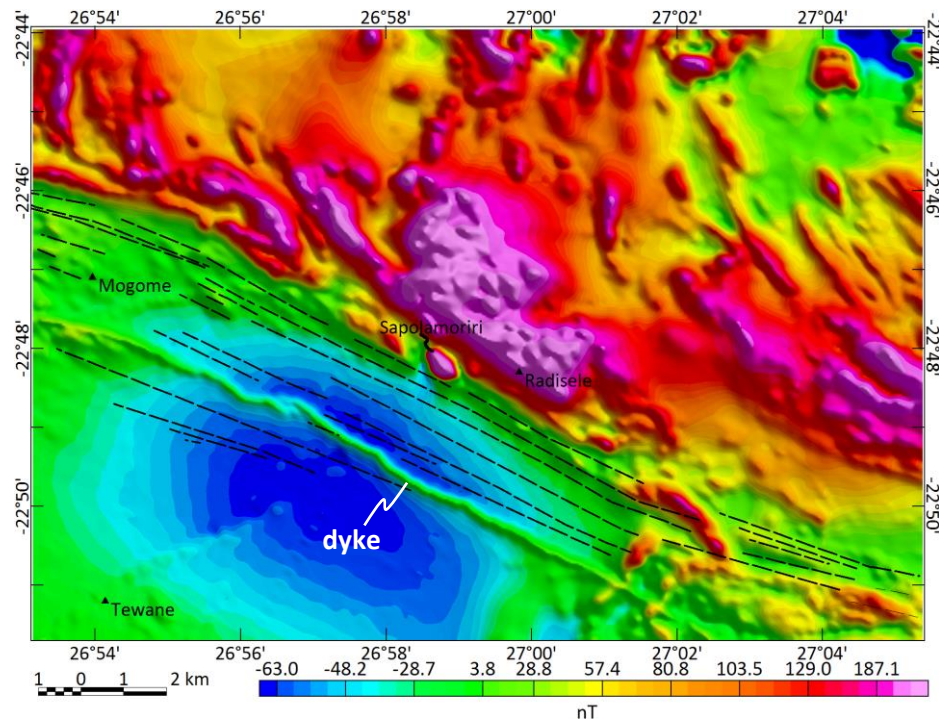


Figure 6.8. The RTP map of the region covering Radisele-Mogome-Tewane areas, towards the southern terrane boundary of the Motloutse Complex. The inferred extent of Sunnyside shear zone is indicated.

The linear structure is clearly delineated in the first vertical derivative and the tilt angle derivative maps (Figs. 6.9, 6.10), and correspond to the NW-SE trending Sunnyside shear zone (Fig. 6.7b). The NW-SE trending linear feature in the SW part of the study area with medium magnetic anomaly in the RTP map (Fig. 6.8), and a strong anomaly in the vertical derivative (Fig. 6.9) and the tilt angle derivative (Fig. 6.10) maps is a mafic dyke (Fig. 6.7b). The dyke is mostly buried and exposed only near a hill (see Fig. 6.7a for location). In addition, a set of NE-SW trending linear features occurring in the SW part is delineated in the vertical derivative and the tilt angle derivative maps (Figs. 6.9, 6.10). They also have medium magnetic anomalies (Fig. 6.8), and correspond to another group of buried mafic dykes (Fig. 6.7b). The NW-SE trending dykes cut across the NE-SW trending ones (Figs. 6.9, 6.10).

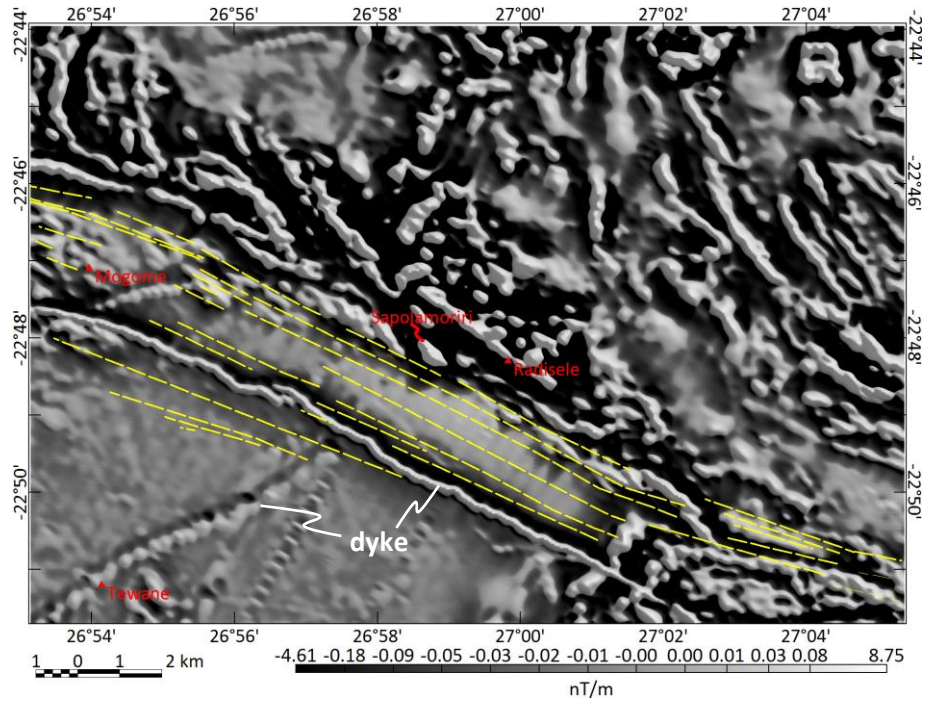


Figure 6.9. The first vertical derivative map in greyscale of the region covering Radisele-Mogome-Tewane areas, towards the southern terrane boundary of the Motloutse Complex. The inferred extent of Sunnyside shear zone is indicated. Two sets of mafic dykes can be seen.

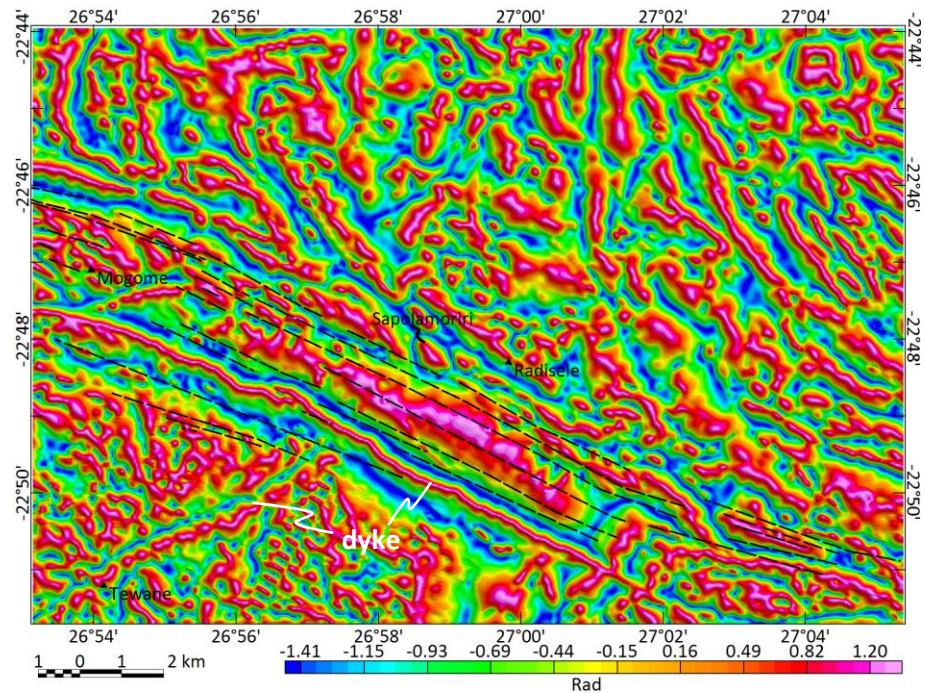


Figure 6.10. The tilt angle derivative map of the region covering Radisele-Mogome-Tewane areas, towards the southern terrane boundary of the Motloutse Complex. The inferred extent of Sunnyside shear zone is indicated. Two sets of mafic dykes can be seen.

The regional anomaly map further highlights the break in magnetic signatures between the northeastern and southwestern parts of the study area (Fig. 6.11), delineating the southern terrane boundary of the Motloutse Complex. The delineation of rock types is best seen in the analytical signal map (Fig. 6.12). Circular outlined bodies with high magnetic anomalies in the northeastern part correspond mostly to mafic and ultramafic rocks (Fig. 6.12). Ultramafic rocks are best exposed at the Sapolamorori hills (Figs. 6.7, 6.12). The medium anomaly region to the south of the high magnetic region correspond to the tonalite gneiss (Figs. 6.7b, 6.12). The lower anomaly region to the north of the high magnetic region is dominated by cover rocks of the Palapye Group (Figs. 6.7b, 6.12). Although exposures are poor, the occurrence of basement tonalite gneiss, and mafic and ultramafic rocks are encountered from bore holes to the northeast of the Palapye Group cover rocks (Fig. 6.7b).

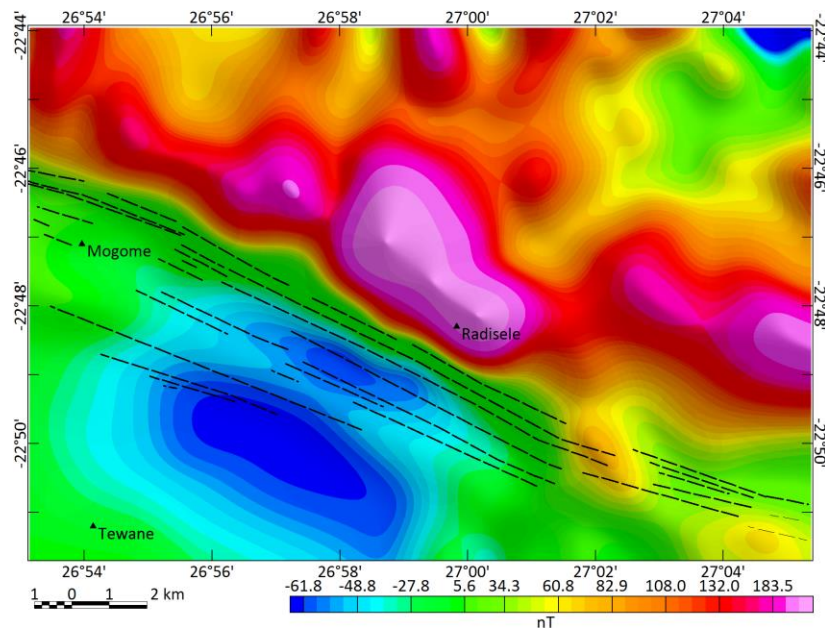


Figure 6.11. The regional anomaly map from the 2.4 km wavelength cut off Butterworth low-pass filtered aeromagnetic data of the region covering Radisele-Mogome-Tewane areas, towards the southern terrane boundary of the Motloutse Complex. The inferred extent of Sunnyside shear zone is indicated.

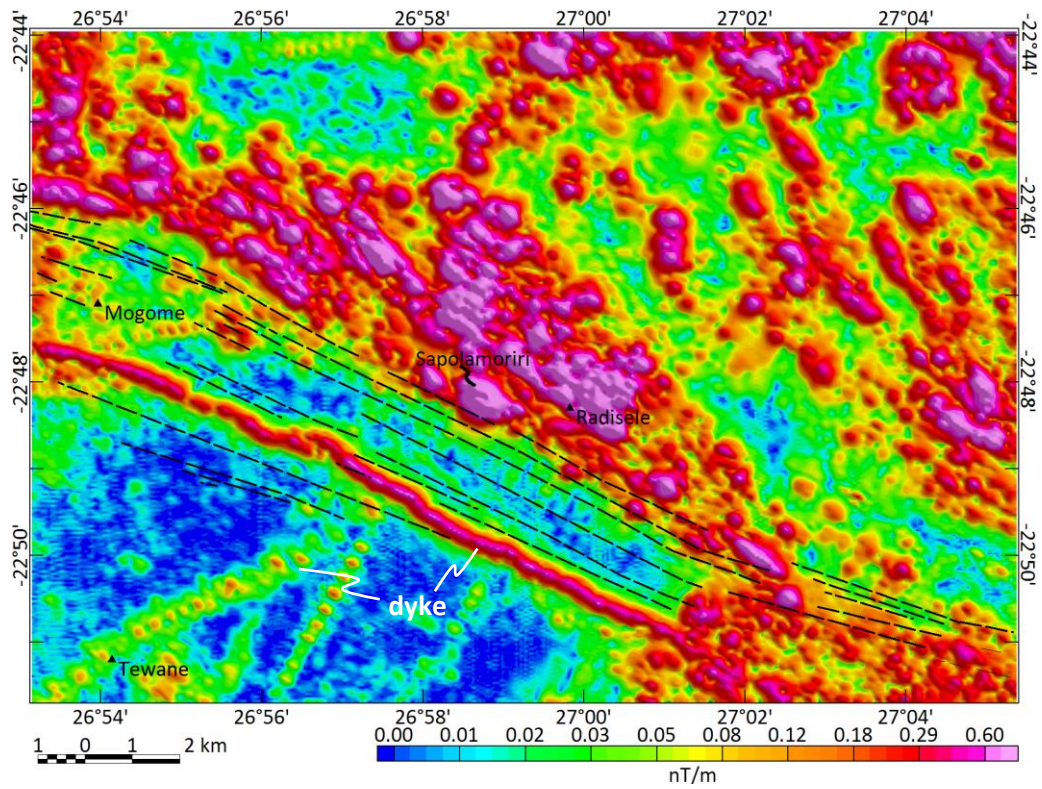


Figure 6.12. The analytical signal map of the region covering Radisele-Mogome-Tewane areas, towards the southern terrane boundary of the Motloutse Complex. The inferred extent of Sunnyside shear zone is indicated. Two sets of mafic dykes can be seen. The round outline units with high magnetic intensity to the NE part are dominantly mafic to ultramafic rocks. The ultramafic rocks are best exposed at the Sapolamoriri hills.

Chapter 7

Discussion

This chapter summarizes the results from the geologic, geochronologic and geophysical studies carried out on the study areas. This is done in comparison to available information, including geochronological data, from the southern Motloutse Complex and adjacent Mahalapye Complex. The ensuing discussion incorporates information from the Limpopo Complex, to extrapolate the significance of the results in a regional framework. Only the Archean and Paleoproterozoic events are addressed.

7.1. Sequence of events in the Masikati hills – eastern terrane boundary

The amphibolite constitutes the earliest rock type in the Masikati hills, and was intruded by peridotite-pyroxenite, gabbro and anorthosite. The close association of the ultramafic and mafic intrusive rocks with metabasalt is conspicuous, and typical of Archean terranes (e.g., Polat et al. 2012; Hoffmann et al. 2012; Berger et al. 2013; Mohan et al. 2013; Bagas et al. 2016). The ultramafic and mafic intrusive rocks form part of the Lechana layered intrusion. Based on the available geochronologic data (Rajesh et al., 2020a), these mafic-ultramafic rocks constitute the oldest (Mesoarchean) units in southern Motloutse Complex. The protolith of the ~2.65 Ga (Zeh et al., 2009) tonalite gneiss intruded, and likely dismembered the Mesoarchean mafic-ultramafic rock associations.

Four contemporaneous events variably affect the different Archean rock types. The earliest one is a compressive event, highlighted by the upright NE-trending isoclinal fold structures. This was accompanied by the anatectic overprint, which formed garnet. Available geochronologic data (2056 ± 12 Ma; Zeh et al., 2009) indicate a Paleoproterozoic age for the anatectic overprint. The effect of pervasive shear deformation and accompanying metasomatism is overwhelming in the Masikati hills. Intensity of shear deformation increases westwards. A prominent right-lateral strike-slip movement is inferred for the shear deformation.

The combination of aeromagnetic maps and field mapping indicate that there is a main shear zone, and associated branches (Fig. 7.1). The main shear zone extends along a near-linear N-S trending array in southeastern Motloutse Complex (Fig. 7.1). It has minor branches to the west and east of the Masikati hills. The western branch of the shear zone is best exposed in the Lechana hills (see dotted line to the east of Dsz; Fig. 7.1). The eastern branch is poorly exposed, and extends all the way up to Tamasane. This is the inferred extent of the Dikalate shear zone in this study (Fig. 7.1).

The $^{40}\text{Ar}/^{39}\text{Ar}$ amphibole age of 2013 ± 12 Ma obtained in this study is similar to that obtained from ultramafic rocks affected by shear deformation from the adjacent Lechana hills (from the western branch of the Dikalate shear zone; 2013 ± 18 Ma; Rajesh et al., 2020a). This confirms the age of shear deformation along the eastern terrane boundary (Dikalate shear zone) of the Motloutse Complex to ~ 2.013 Ga.

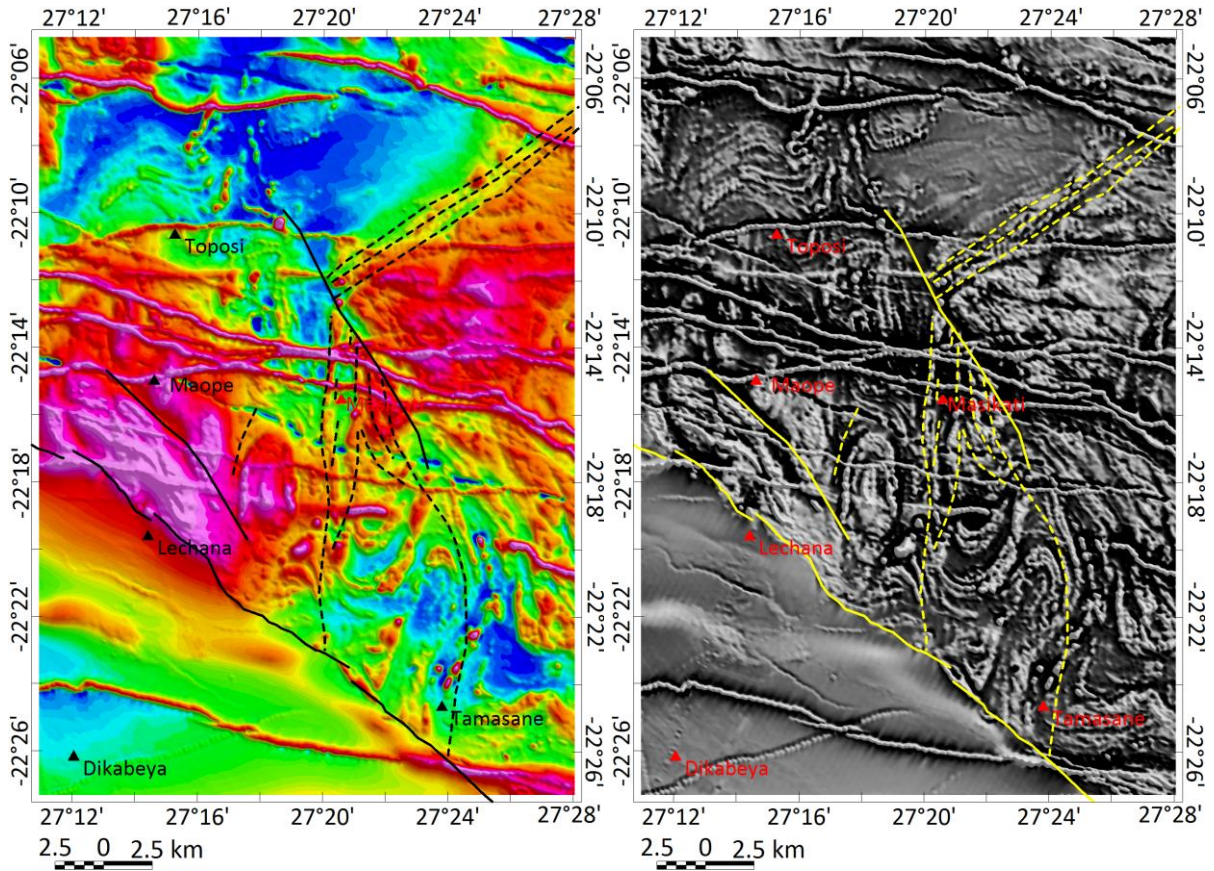


Figure 7.1. RTP map (a), and greyscale 1VD map (b) showing the inferred extent of the Dikalate shear zone and its branches in southern Motloutse Complex. The present study focusses on the Masikati hills.

7.2. Sequence of events in the Radisele-Mogome area – southern terrane boundary

Two groups of basement crystalline rocks occur in the Radisele-Mogome area. Those occurring in the NE part include the amphibolite, ultramafic rocks and tonalite gneiss. The field relations between the three rock types are similar to that observed in the Masikati hills (this study), and elsewhere in the southern Motloutse Complex (Rajesh et al., 2020a). Amphibolite and the layered ultramafic rocks constitute the Mesoarchean units, while the protolith of the Neoarchean tonalite gneiss intruded the mafic-ultramafic rocks. Thus, it can

be inferred that the Motloutse Complex continues beneath the cover (Palapye Group and Karoo Supergroup) rocks, all the way up to the northern margin of the Mahalapye Complex. This inference is supported by the Neoproterozoic and Mesoproterozoic detrital zircon ages reported from the ~1.6 Ga Palapye Group sediments (2841 ± 7 Ma, 2703 ± 8 Ma, 2658 ± 12 Ma; Mapeo et al., 2004).

The rocks occurring in the SW part of the Radisele-Mogome area include diorite gneiss, granodiorite and leucogranite. No such rock types form part of the Motloutse Complex. But these are prominent rock types in the Mahalapye Complex. The field relations are similar to those reported for the ~2.06 Ga diorite gneiss, ~2.04 Ga granodiorite, and the ~2.03 Ga leucogranite of the Mahalapye Complex (Chavagnac et al., 2001; McCourt et al., 2004; Hisada et al., 2000, 2005; Millonig et al., 2010; Rajesh et al., 2020b, 2022). Thus, it can be inferred that the Radisele-Mogome area represent the contact between the southern Motloutse Complex and northern Mahalapye Complex.

The Mogome alkali granite occurring along the contact, has xenoliths of rocks from both complexes, making it an important time marker. Zeh et al. (2007) presented a U-Pb zircon age of 2019 ± 8 Ma for the Mogome granite. Significantly, the two groups of zircon xenocrysts in the granite – 2520-2645 Ma and 2929 ± 14 Ma (Zeh et al., 2007), are comparable to the Neoproterozoic and Mesoproterozoic ages (Zeh et al., 2009; Rajesh et al., 2020a) reported from the southern Motloutse Complex.

Like for the eastern terrane boundary of the Motloutse Complex, four contemporaneous events variably affect the rock types along the Radisele-Mogome area. Evidence for a

compressive event is seen only in rocks from the NE part (part of the Motloutse Complex). Anatectic overprint is locally seen in rocks from the SW part, and correlates with a similar event reported from other parts of the Mahalapye Complex (Chavagnac et al., 2001; Millonig et al., 2010; Rajesh et al., 2020b). Pervasive shear deformation affects rocks from both the NE and SW parts of the Radisele-Mogome area, with an increase of intensity towards the SW. Mylonitic deformation is prominent in the SW. A right-lateral strike-slip movement is inferred for the shear deformation. Metasomatic alteration accompanies shear deformation, and seem to be prominent in the NE part as indicated by the pinkish to reddish discoloration of the rocks.

The shear deformation has to be younger than ~ 2.019 Ga, as it affects the Mogome granite. It is argued that the $^{40}\text{Ar}/^{39}\text{Ar}$ biotite age of 1987 ± 8 Ma dates the shear deformation event along the southern terrane boundary (Sunnyside shear zone) of the Motloutse Complex. In view of the poor exposure, including the effect of cover rocks, an attempt was made using aeromagnetic maps to delineate the eastward continuation of the Sunnyside shear zone in eastern Botswana (Fig. 7.2). The inferred extent of the Sunnyside shear zone (dashed line in Fig. 7.2) correlates with a prominent break in magnetic signatures. Possible branching of the main shear zone to the east of Chadibe and east of Ramokgonami is possible, and indicated by a break in magnetic signatures (Fig. 7.2). This supports the contention of McCourt and Vearncombe (1992) on the NW-SE trending branch of the Sunnyside shear zone.

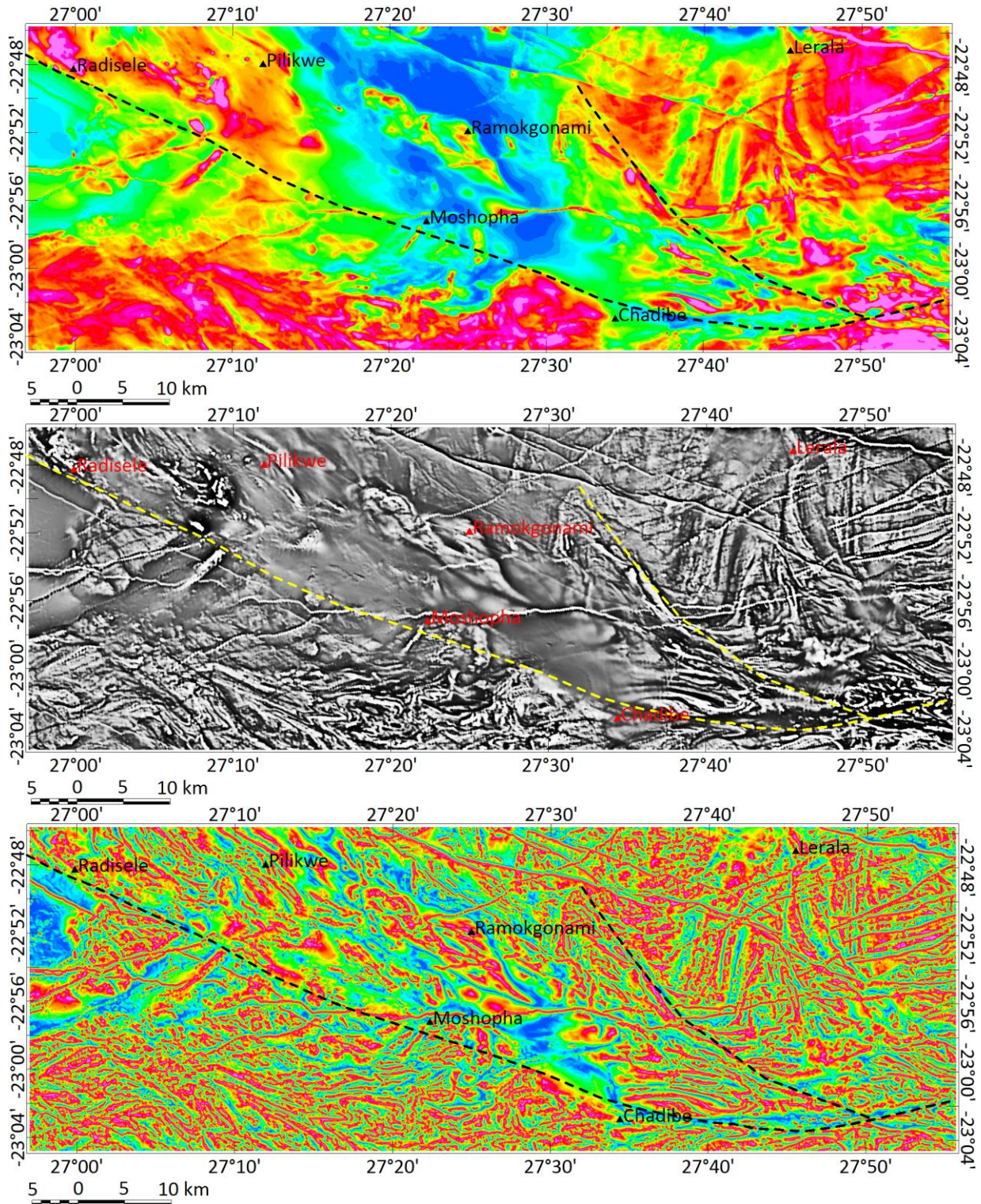


Figure 7.2. RTP (a), greyscale 1V (b) and TDR (c) maps showing the inferred extent of the Sunnyside shear zone in eastern Botswana. The possible NW-SE trending branch of the Sunnyside shear zone (to the east of Chadibe and Ramakgonami) is also shown. The present study focuses on the Radisele-Mogome area. Exposures to the east and southeast are poor.

7.3. Correlation with other regional-scale shear zones of the Limpopo Complex

Different studies argued for a prominent Proterozoic transpressive movement involving strike-slip shearing along the terrane boundaries of the Limpopo Complex (Barton et al., 1994; Kamber et al., 1995; Jaeckel et al., 1997; Holzer et al., 1998, 1999). As the Motloutse Complex occurs to the west of the Limpopo Complex and southwest of the Zimbabwe Craton (Fig. 7.3), a correlation of the nature, extent and timing of shear deformation along the various terrane boundaries is important.

The North Limpopo Thrust zone is a several kilometers wide protomylonitic to mylonitic zone with a dominant right-lateral sense of movement, defining the thrust contact between the Northern Marginal Zone of the Limpopo Complex and the southeastern Zimbabwe Craton (Fig. 7.3; Fedo et al., 1995; Mkweli et al., 1995; Rollinson and Blenkinsop, 1995). Mkweli et al. (1995) presented a 2.63 Ga minimum age of thrust deformation along the North Limpopo Thrust Zone. Tsunogae and Belyanin (2020) reported $^{40}\text{Ar}/^{39}\text{Ar}$ amphibole ages of 2020 ± 8 Ma to 1968 ± 10 Ma from amphibolites of the Buhwa greenstone belt, a marginal unit to the North Limpopo Thrust Zone (Fig. 7.3). These ages likely indicate the reactivation of the North Limpopo Thrust Zone in the Paleoproterozoic (Tsunogae and Belyanin, 2020).

The Paleoproterozoic event is prominent towards from the Triangle shear zone, a ~30–50 km wide intense mylonitic zone, which separates the Northern Marginal Zone from the Central Zone of the Limpopo Complex (Fig. 7.3; Kamber et al., 1995; Rollinson and Blenkinsop, 1995). Kinematic indicators point to a right lateral sense of movement along the

Triangle shear zone (Kamber et al., 1995; Rollinson and Blenkinsop, 1995). $^{40}\text{Ar}/^{39}\text{Ar}$ amphibole ages on gneissic rocks from the shear zone range from 2040 ± 15 Ma to 1984 ± 12 Ma, while those on the amphibolites range from 2001 ± 11 Ma to 1955 ± 8 Ma (Fig. 7.3; Kamber et al., 1995a, b).

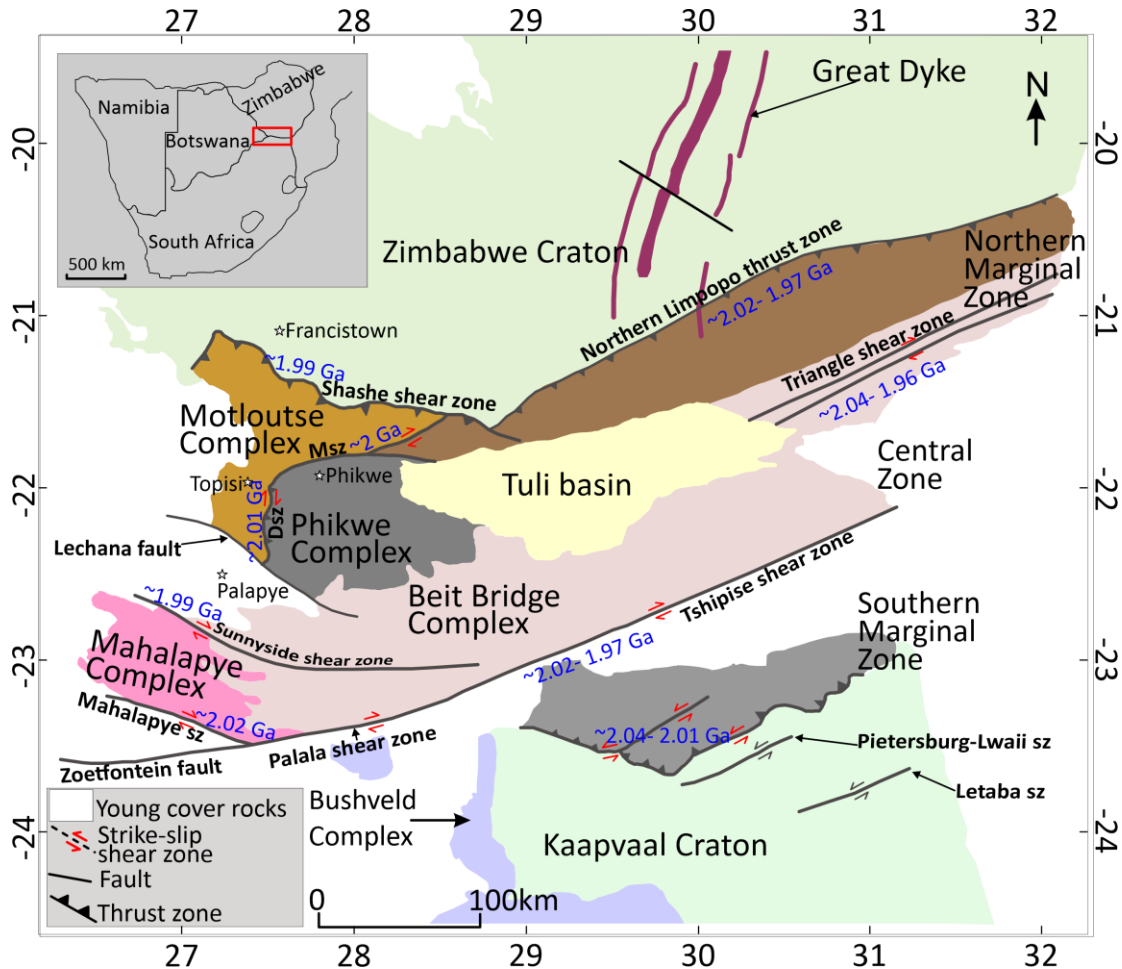


Figure 7.3. Generalized geologic map showing the different terrane boundaries of the high-grade terrane of the Limpopo Complex and adjacent Motloutse between the Archean Zimbabwe and Kaapvaal cratons [modified from Aldiss (1999), Van Reenen et al. (2011)]. The Paleoproterozoic ages discussed in the text are indicated. See text for references of the geochronologic data.

Like the case of the North Limpopo Thrust Zone, the Southern Marginal Zone of the Limpopo Complex is thrust on to the northeastern Kaapvaal Craton along the Hout River

shear zone in the Neoproterozoic (~2.76 Ga – 2.62 Ga; Fig. 7.3; Roering et al., 1992; Smit et al., 1992; Passeraub et al., 1999; Kreissig et al., 2001; Kramers et al., 2014). Belyanin et al. (2014) reported $^{40}\text{Ar}/^{39}\text{Ar}$ amphibole-mica ages of 2043 ± 8 Ma to 2013 ± 8 Ma, to indicate strike-slip shearing and metasomatic alteration from the contact zone. Kinematic indicators from the Nthabala shear zone, which crosscuts the Hout River shear zone, argue for a prominent left-lateral sense of movement (Fig. 7.3). Thus, the southern terrane boundary of the Limpopo Complex was reactivated in the Paleoproterozoic.

Paleoproterozoic ages (2020 ± 8 Ma to 1971 ± 26 Ma) have been reported for the composite structure comprising the >20 km wide Tshipise shear zone and the Palala shear zone, that separates the Central Zone from the Southern Marginal Zone of the Limpopo Complex (Fig. 7.3; Horrocks, 1983; McCourt and Vearncombe, 1987, 1992; Holzer et al., 1998, 1999; Brandl and Reimold, 1990; Schaller et al., 1999; Belluso et al., 2000). Although both right-lateral and left-lateral sense of movement are inferred for the Palala shear zone, the later is argued to be Neoproterozoic in age (McCourt and Vearncombe, 1992; Broekhuizen et al., 1995). On the other hand, right-lateral sense of movement in the Palala shear zone is Paleoproterozoic in age (Holzer et al., 1999; Schaller et al., 1999; Belluso et al., 2000; Liang et al., 2021). This could indicate a scenario of Paleoproterozoic re-activation for the Palala shear zone. A prominent Paleoproterozoic right-lateral strike-slip movement has been inferred for the Tshipise shear zone (Horrocks, 1983; Holzer et al., 1998).

In contrast to the ones discussed so far, the shear zones that bound the westernmost terranes (Phikwe Complex, Mahalapye Complex) of the Central Zone of the Limpopo

Complex and the adjacent Motloutse Complex are slightly oblique in trends (Fig. 7.3). The Shashe shear zone accommodates the crustal shortening between the Motloutse Complex and the SW Zimbabwe Craton (Aldiss, 1991; Carney et al. 1994; Key et al. 1994; Paya, 1996; McCourt et al. 2004). The thrusting along the Shashe shear zone is argued to be Neoproterozoic (~2661 Ma – 2647 Ma; McCourt et al., 2004). Betsi et al. (2020) reported $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite age of 1987 ± 24 Ma from the Tati greenstone belt (Fig. 7.3; SW margin of the Zimbabwe Craton), close to the Shashe shear zone. The scenario is comparable to that of the SE margin of the Zimbabwe Craton (Tsunogae and Belyanin, 2020), and likely indicate the reactivation of the Shashe shear zone in the Paleoproterozoic. This suggestion needs to be verified by future studies from the northern margin of the Motloutse Complex.

Prominent right-lateral strike-slip movement is reported from the Magogaphate and Dikalate shear zones, which separate the Phikwe Complex from the Motloutse Complex (Paya, 1996; this study). ~2 Ga ages are reported from both the shear zones. Those from the Magogaphate shear zone include ~2 Ga Rb-Sr biotite ages and 2001 ± 6 Ma PbSL titanite age (Van Breemen and Dodson, 1972; Holzer et al., 1999). This study (2013 ± 12 Ma) and Rajesh et al. (2020a) (2013 ± 18 Ma) report comparable ages for the Dikalate shear zone. In comparison, this study reports an age of 1987 ± 8 Ma for the right-lateral strike-slip movement along the Sunnyside shear zone, that separates the Motloutse Complex from the Mahalapye Complex (Fig. 7.3).

The southern boundary of the Mahalapye Complex is marked by the up to 10 km wide Mahalapye shear zone (Fig. 7.3; McCourt and Vearncombe, 1987; Holzer et al., 1999).

Kinematic indicators point to a right lateral displacement, with the shear intensity increasing towards the SE (Holzer et al., 1999). No geochronologic information is available from the Mahalapye shear zone. Field relations indicate the affect of shear deformation on the Mahalapye granite (Rabewu, 2016). Hence, the timing of shear deformation has to be younger than the age of the granite (2023 ± 11 Ma; 2023 ± 7 Ma; McCourt and Armstrong, 1998). Different studies argued for the Mahalapye shear zone to be an extension or branch of the Palala shear zone (McCourt and Vearncombe, 1992; Holzer et al., 1999; Schaller et al., 1999; Chavagnac et al., 2001). The scenario could be comparable to the branching of the Sunnyside shear zone shown in Figure 7.2.

In summary, it becomes obvious that the different terrane boundaries of the Limpopo Complex and adjacent Motloutse Complex were either active and/or reactivated during the Paleoproterozoic (Fig. 7.3). Significantly, there seems to be two groups of ages – an older group between $\sim 2.04 - 2.02$ Ga, and a second group of < 2.02 Ga. Additional ages from the different terrane boundaries, and adjacent regions, should refine the two contemporaneous groups. The ages reported in the present study, respectively from the eastern and southern terrane boundaries of the Motloutse Complex, belong to the younger group of ages, with a prominence of shear deformation. This argues for a major transcurrent movement in the central Kalahari cratonic regions (between the Zimbabwe and Kaapvaal cratons) in the Paleoproterozoic. The younger time frame likely continued to accommodate the large-scale post-1.9 Ga lateral displacement between the Zimbabwe and Kaapvaal cratons, as argued by Hanson et al. (2011).

Chapter 8

Concluding remarks

- Amphibolite, peridotite-pyroxenite, gabbro, anorthosite and tonalite gneiss constitute the prominent rock types at the Masikati hills, along the eastern terrane boundary of the Motloutse Complex. The mafic-ultramafic intrusive rocks form part of the Lechana layered intrusion. The protoliths of the tonalite gneiss likely intruded, and dismembered the earlier mafic-ultramafic rocks.
- Upright isoclinal folds argue for an earlier compressive event, followed by anatectic overprint, which formed garnet. Pervasive shear deformation affects the earlier structures. Kinematic indicators (S-C fabrics, asymmetric porphyroclasts, mineral elongation lineation) point to a right-lateral sense of movement. Metasomatic (pinkish to reddish) discoloration persistently accompanies the shear deformation.
- Shear deformation along the Masikati hills form part of the N-S trending Dikalate shear zone. The aeromagnetic maps helps to define the N-S extent as well as the branches of the Dikalate shear zone. $^{40}\text{Ar}/^{39}\text{Ar}$ amphibole age of 2013 ± 12 Ma date the shear deformation along the Dikalate shear zone.
- Rock types in the Radisele-Mogome area can be grouped into two. Amphibolite, ultramafic rocks and tonalite gneiss constitute the rock types in the NE part, and are prominent rock types in the southern Motloutse Complex. It is argued that the Motloutse Complex continues beneath the cover rocks all the way up to the northern

margin of the Mahalapye Complex. This redefines the known extent of the Motloutse Complex.

- Diorite gneiss, granodiorite and leucogranite constitutes the rock types in the SW part of the Radisele-Mogome area, and are prominent rock types in the Mahalapye Complex. Mogome alkali granite with xenoliths of rock types from both the Motlotuse and Mahalapye complexes, is an important time marker. As observed for the eastern terrane boundary, pervasive shear deformation affects earlier structures along the southern terrane boundary. This shear deformation form part of the NW-SE trending Sunnyside shear zone. Aeromagnetic maps help to define the extent as well as the branches of the Sunnyside shear zone. $^{40}\text{Ar}/^{39}\text{Ar}$ biotite age of 1987 ± 8 Ma date the shear deformation along the Sunnyside shear zone.
- In summary, it is argued that the eastern and southern terrane boundaries of the Motloutse Complex were active in the Paleoproterozoic, with the shear deformation slightly earlier along the Dikalate shear zone (~ 2.013 Ga), relative to the Sunnyside shear zone (~ 1.987 Ga).
- Finally, as an extension of the results of the present study, it is argued that the different terrane boundaries of the Limpopo Complex and adjacent Motloutse Complex were either active and/or reactivated as part of a prominent Paleoproterozoic regional scale transcurrent movement.

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Appendix 1

Analytical details

1. Aeromagnetic image data set

This study used existing high resolution aeromagnetic data obtained from the Botswana Geosciences Institute (BGI). The magnetic field was computed to the International Geomagnetic Reference Field (IGRF). The aeromagnetic data was provided as a 50 m cell size total magnetic intensity (TMI) grid.

The aeromagnetic data is a compilation of surveys conducted by the Department of Geological Survey (DGS; now BGI) and various private exploration companies from the early 1960s (e.g., Reeves, 1978; Hutchins and Reeves, 1980; Reeves and Hutchins, 1982). Lately (2010 to 2011), the data was ameliorated by leveling and merging the archived aeromagnetic data with new data from aeromagnetic tie line surveys covering the whole of Botswana [detailed in the Final Logistics Report to DGS for Botswana, Tender No. PR10/2/3/10 (I)].

Some recent applications of the aeromagnetic dataset include geothermal investigation of Kasane hot springs (Ramotoroko et al., 2021), characterization of the extent of different geological units and terranes (Ramotoroko et al., 2016; Chisenga et al. 2020), and mapping structures associated with seismic activities (Kolawole et al., 2017).

1.1. Processing of aeromagnetic data

For aeromagnetic data processing, the acquired TMI grid was imported into the Geosoft Oasis Montaj 2021.2.1, a program designed for analyses, visualization, processing and interpretation of integrated geoscience data. The grid was windowed into two smaller grids, covering the two study areas – one around the eastern terrane boundary and other around the southern terrane boundary of the Motloutse Complex. Each grid was reprojected to the Universal Transverse Mercator (UTM) coordinate grid system prior to application of data enhancing algorithms for easier use in Geosoft program and interpretation. Different data enhancing algorithms were used in this study. These included reduction to magnetic pole, first vertical derivative, tilt angle derivative, Butterworth low pass filter, and analytic signal, with the aim to interpret structures and geological characteristics of the study areas.

1.1.1. Reduction to magnetic pole (RTP)

Magnetic patterns positioned somewhere besides the magnetic poles are highly skewed due to the polarization character of the geomagnetic field (Arkani-Hamed., 1988; Cooper and Cowan, 2005). To eliminate complications in the interpretation of magnetic data, the reduction to the magnetic pole (RTP) transformation is done to correct the location of anomalies in relation to the position of their causative body (Blakely, 1995; Cooper and Cowan, 2005). Anomalies are subsequently positioned directly above their causative bodies, and better represent the location and shape of the anomaly source. The RTP assumes that

magnetism of all lithologies in an area is parallel to the geomagnetic field, and is therefore only a result of induction (Blakely, 1995). In this study, the TMI anomaly grids were reduced to the magnetic pole using an inclination value of -61.75 and declination of -13.15 from the calculated International Geomagnetic Reference Field model of Botswana. The RTP grids in this study were further enhanced to improve the high amplitude anomalies and reduce the effect of unwanted parts of the signal. This enables to investigate the magnetic response of textures and geometries that assist in interpreting lithology distribution, overprinting relations, and geological structures.

1.1.2. First vertical derivative (1VD)

In general, the derivative algorithms are employed to improve the vertical and horizontal gradients of potential datasets in geophysical studies. The vertical derivative algorithm basically calculates the gradient in total magnetic intensity in the downward direction (Miller and Singh, 1994). It accentuates anomalies induced by sudden variations of petrophysical properties of causative bodies that are in the shallow subsurface while diminishing anomalies caused by bodies at greater depths. This enhancement technique is useful in identification of structures and geological contacts. Vertical derivative grids in this study are displayed as greyscale maps to highlight structural details of the study area.

1.1.3. Tilt angle derivative (TDR)

The tilt angle derivative (TDR) enhancement technique was pioneered by Miller and Singh (1994) for detection of edges of the anomaly sources. The tilt-angle derivative is primarily a relative measure of the vertical derivative to the total horizontal derivative, enabling calculation of the amount of the general gradient of total magnetic intensity in different directions (Salem et al., 2008). The tilt-angle derivative has become one of the commonly used effective edge-detection algorithm owing to its ability to improve all the anomaly boundaries in aeromagnetic data set irrespective of their trend. Tilt angle derivative algorithm is applied on the RTP grids in this study to enhance anomalies related to geological structures in the study areas.

1.1.4. Butterworth low-pass filter

To investigate the extent of geological structures in the subsurface, the RTP grids are separated into the residual and regional anomaly grids using the high-pass and the low-pass filters of Butterworth algorithm. The high-pass filter suppresses long wavelengths associated with deep magnetic anomaly sources while the low-pass filter accentuates long wavelengths at the expense of short wavelengths. The Butterworth algorithm permits the adjustment of the degree of the filter at the wavelength cutoff, thus eliminating data distortion known as the Gibbs phenomenon. In this study regional anomaly grids were produced by applying Butterworth low-pass filter to the RTP grids of the study areas. A wavelength cutoff of 5 km

and a filter order of 6 were applied to the Butterworth low-pass filter to the RTP grid of the area along the eastern terrane margin of Motloutse Complex. To produce a regional map for the proposed southern margin of Motloutse Complex a 2.4 km wavelength cutoff and filter order set to 8 to produce a smooth filter response.

1.1.5. Analytic signal (AS)

The square root of the sum of the squares of the derivatives in three axes (thus total horizontal and vertical derivatives) yields the analytic signal. The analytic signal is important for defining the boundary of causative bodies in gridded magnetic data, especially in areas of low magnetic latitude or when magnetic remanence makes evaluation and explanation of magnetic data difficult (Roest et al., 1992; Blakey, 1995). Because it is applied to data that has been reduced to pole, the method is often more useful at low magnetic latitudes. Due to the non-dependant nature of the direction of magnetization of the causative bodies, the analytic signal technique can be directly applied to data that has not been reduced to pole and yet still produce the desired result. This is attributed to the fact that the peak value of the analytical signal is directly over the boundary of magnetic bodies and structures (Blakely, 1995).

2. Electron microprobe analyses

Electron microprobe analyses of amphibole and biotite in representative thin sections of amphibolite and diorite gneiss samples selected for $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology, were carried out using a CAMECA SX100, equipped with four WDS spectrometers, housed at the Spectrum analytical facility, University of Johannesburg (UJ), South Africa. Analytical conditions are 15 kV accelerating voltage, 15–20 nA (feldspar: 15 nA; garnet, biotite: 20 nA) beam current, counting times of 10–20 s for most elements, except 50 s for F and 30 s for Cl, and 1 to 5 μm beam spot size. A combination of well characterized natural and synthetic standards, including jadeite for Na, forsterite for Mg, diopside for Si, and almandine for Al (TAP crystal); sodium chloride for Cl, orthoclase for K, wollastonite for Ca, and rutile for Ti (PET crystal); chromite for Cr, rhodonite for Mn, hematite for Fe, nickel oxide for Ni, and sphalerite for Zn (LLIF crystal); fluorite for F (PC1 crystal), were used for calibration. Corrections were made using the ZAF method.

3. ^{40}Ar - ^{39}Ar geochronology

Extracted amphibole and biotite fractions (particle size up to ~ 1 mm) from rock types from the Masikate hills and Radisele-Mogome area were used for $^{40}\text{Ar}/^{39}\text{Ar}$ dating. Details of the analytical procedure are given by Makhubela et al. (2017). Each extracted aliquotes were irradiated in the SAFARI1 nuclear reactor at NTP radioisotopes at Pelindaba, Pretoria, South Africa, for 20 hours in position B2W with the reactor running at 20 MW (dates of irradiation

are listed in Table 3). Flux monitors used were McClure Mountain amphibole (523.1 ± 1 Ma, Renne et al., 1998), Hb3GR amphibole (1080.4 ± 1.1 Ma, Renne et al., 2010), and Fish Canyon sanidine (28.201 ± 0.046 Ma, Kuiper et al., 2008). The isotope analysis was done in the Noble Gas Laboratory at the University of Johannesburg (UJ), South Africa. A stepwise heating protocol was followed, using a defocused beam from a SPECTRON® continuous Nd-YAG 1064 nm laser and the MAP 215-50 noble gas mass spectrometer. The heating time for each lasing step was set to 5 minutes. Heating steps for each sample yielded temperatures between 600°C and 1300°C at which point samples were fully molten. After gas purification by getters, the argon isotopes (40, 39, 38, 37 and 36 - in that order) were measured in seven cycles using a Johnston electron multiplier detector operated in analogue mode. The regression analysis for the measured data, corrections on ^{39}Ar and ^{40}Ar (using ^{37}Ar and ^{39}Ar , respectively) and calculation of the age were done using software developed in-house, which includes full error propagation by Monte Carlo simulations. J-values, identical within error for the three monitors, were interpolated between top and bottom of the 42 mm sample stack. Apart from corrections, ^{37}Ar yielded the Ca abundance relative to K, and ^{38}Ar the relative Cl content, both calibrated via the values for the McClure Mountains amphibole. This stage further allowed comparison between Ca/K and Cl/K ratios obtained from argon isotopes with mineral chemical data. The age data were plotted as spectra of individual heating steps, each representing an apparent age plotted against the percentage of the total ^{39}Ar released (McDougall and Harrison, 1999). For near-plateaus, integrated ages and their 95% confidence limits were obtained by pooling the analytical results from all included steps.