



Faculty of Sciences
Department of Earth and Environmental Sciences

**MINERALOGICAL AND GEOCHEMICAL CHARACTERISATION OF THE
KGWEBE VOLCANIC FORMATION IN THE GHANZI-CHOBE BELT PORTION
OF THE KALAHARI COPPER BELT: INSIGHTS INTO COPPER AND SILVER
SOURCE (S).**

by

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BSc (Geology) (BIUST)

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the Award of the Degree of Master of Science in Geological Sciences of BIUST

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March, 2022

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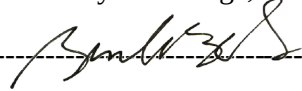
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ABSTRACT

A combination of petrography and geochemistry (XRF, ICP-OES and ICP-MS) was utilized in order to investigate the magma source(s), magma evolution and petrogenesis implications of the Kgwebe Volcanic Formation (KVF) rock units in the Ghanzi-Chobe Belt portion of the Kalahari Copper Belt (NW Botswana). Based on their texture, the KVF rock units were discriminated into amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks, porphyritic subvolcanic bodies, quartz-feldspar porphyries and clastic sedimentary rocks (intercalated with amygdaloidal rocks). The amygdaloidal rocks commonly crosscut by calcite veins, are characterized by amygdales-filled vesicles set in hyalopilitic groundmass. The porphyritic mafic flows are essentially made up of plagioclase laths set in a sericitised groundmass. The pyroclastic rocks are made up of both phenocrysts and lithic fragments set in a fine-grained microlithic groundmass. Porphyritic subvolcanic bodies are characterized by high content in subrounded epidote (after plagioclase) set in a microcrystalline groundmass. The quartz-feldspar porphyries are characterized by quartz and feldspar phenocrysts in variable proportions set in a fine-grained groundmass of variable colour. Magmatic rocks of the KVF represent two geochemically contrasting series that are not co genetic and derived from different geotectonic settings. The amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and porphyritic subvolcanic bodies are subalkaline basalt in composition, whereas the quartz-feldspar porphyries span from the rhyolite/dacite (mostly) to the andesite/andesite basalt (accessorily) field compositions. Likewise, while quartz-feldspar porphyries are consistently high-K calc-alkaline bodies, their spatially associated amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and porphyritic subvolcanic bodies counterparts are calc-alkaline. Similarly, quartz-feldspar porphyries are within plate bodies, whereas the more mafic KVF units are arc-related. Furthermore, the ferroan quartz-feldspar porphyries generated from the crust and the magnesian amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and

porphyritic subvolcanic bodies are mantle-derived, with however, significant crustal contamination fingerprints. Textural evidences (resorbed, embayed and rounded phenocrysts) as well as the inferred high-water content (as supported by the abundance of plagioclase phenocrysts) also suggest a rapid magma ascent and magma mixing occurred during the KVF eruption, which was both effusive and explosive. Concomitant volcanism and sedimentary processes likely occurred as supported by the intercalation of clastic sedimentary rocks within volcanics of the KVF. Furthermore, The KVF rock units' Cu and Ag quantities were calculated to be 1183 million tonnes and 42 million tonnes, respectively. Because the total metal budget of the KCM deposits exceeds 500 million tonnes, the KVF is likely to have accounted for some extent to the total metal budget at the KCM property. But apart from the KVF, additional sources of Cu and Ag such as Ngwako Pan and D'Kar formations are to be considered.

Keywords: Magma sources, Kgwebe Volcanics, Porphyritic, Calc-alkaline, Cu and Ag.

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List of Abbreviations

Av. - Average

Bt - Biotite

CC - Chalcocite zone

KCB - Kalahari Copper Belt

KCM - Khoemacau Copper Mining

Kfs - K-feldspar

KVF - Kgwebe Volcanic Formation

LOI - Loss On Ignition

Mcl - Microcline

Mt - Magnetite

ND - New Discovery

NEF- North East Fold

NL- North Limb

Orth - Orthoclase

Plg - Plagioclase

Qtz - Quartz

Rt - Rutile

SLD - South Limb Definition

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CHAPTER 1

GENERAL INTRODUCTION

1.1. Background

The Khoemacau Mining (KCM) Cu-Ag deposits are located in a sparsely populated region of the Northwest District of Botswana, 80 km southwest of Maun Village. They are hosted within the SW-NE trending Kalahari Copper Belt (KCB) (**Kampunzu et al., 2000**), located in the Neoproterozoic Damara Orogeny comprising several strata-bound copper and silver deposits hosted by metasedimentary rocks (**Schwartz et al., 1995**). The Kalahari Copper Belt (Fig. 1.1) is a 1000 km long and 250 km wide (**Lehmann et al., 2015**) belt that runs southwest and northeast along the strike in Botswana (**Kampunzu et al., 2000**). The KCM Cu-Ag deposits cover an area of ~ 4040 km² and contain numerous mineralized zones including from south to north: the Chalcocite Zone (CC), New Discovery (ND), North Limb (NL), South Limb Definition (SLD), North East Fold (NEF), Mango, Zone 5, Zone 5 North, Boseto, Zeta NE, and Zone 6 (**Hall, 2017**) (Fig. 1.2).

In Botswana, the above-mentioned deposits are within the Ghanzi-Chobe Belt, a Mesoproterozoic-to-Neoproterozoic elongated volcano-sedimentary basin (**Modie, 1996**). More than 5 km of Ghanzi Group sedimentary rocks filled the northeast-trending northwest Botswana rift basin. During the Pan-African Damara Orogeny (600 to 480 Ma), the basin was inverted into a fold and thrust belt (**Modie, 1966**). In Botswana, this belt is known as the Ghanzi-Chobe Zone, and in Namibia, it is known as the Southern Foreland Zone of the Damara Orogen (**Miller, 2008; Lehmann et al., 2015**). The width and lateral extent of the belt in

Namibia and Botswana were redefined as two continuous magnetic domains based on regional geophysics, confirming for the first time the correlation of stratigraphy across international borders (**Lehmann et al., 2015**).

The Kalahari Copper Belt (KCB) contains several sedimentary-hosted copper-silver deposits and prospects that have many similarities to those in the world class mining districts of the European Kupferschiefer and Central African Copper Belt (**Hall, 2017**). A number of stratabound Cu-Ag deposits and mining operations in southern Africa are hosted by the Kalahari Copper Belt. These include; the Klein Aub Mine in Namibia, Boseto Cu-Ag Mine (which the first deposits within KCB to go into commercial production since the closure of Namibia's Klein Aub Mine in 1986 (**Hall, 2013**), Zone 5 Mine and Sandfire Resources Motheo Copper Mine (which is outside the KCM property). Stratabound sediments-hosted copper deposits comprise of an ore horizon that is restricted to a narrow range of layers within a sedimentary sequence. They are structurally-controlled deposits which contain sulphide-bearing veins and veinlets that do not necessarily follow sedimentary bedding (**Cattrall, 2012**). The sedimentary rock-hosted copper-silver deposits of the Kalahari Copper Belt in the country's northwest district are covered by the Late Carboniferous-Middle Jurassic Karoo Supergroup and Cenozoic Kalahari sand and calcrete (**Hall et al., 2018**). This has therefore affected the mineral exploration in the belt because the focus has only been on the northeastern sector of the Ghanzi Ridge where the Kalahari sands are typically less than ~65 m thick (**Hall et al., 2018**). The Kalahari cover has resulted in a limited supply of geological data on the Ghanzi-Chobe Belt and subsequently a poor constraint on its past geological history. Therefore, the delineation of the sub-surface geology of the Ghanzi-Chobe Belt is largely based on regional air-borne geophysical investigations, supplemented by data from known exposed areas and also from mineral exploration.

In the last 4 decades, various exploration companies had discovered a significant sedimentary-hosted stratabound copper deposits/mineral occurrences in the Ghanzi-Chobe Belt portion of the Kalahari Copper Belt. During the recent years, driven by the increase in the price of copper, exploration activities in the area intensified, resulting in the successful identification of significant copper-silver resources (**Botswana Resource Sector Report, 2013**).

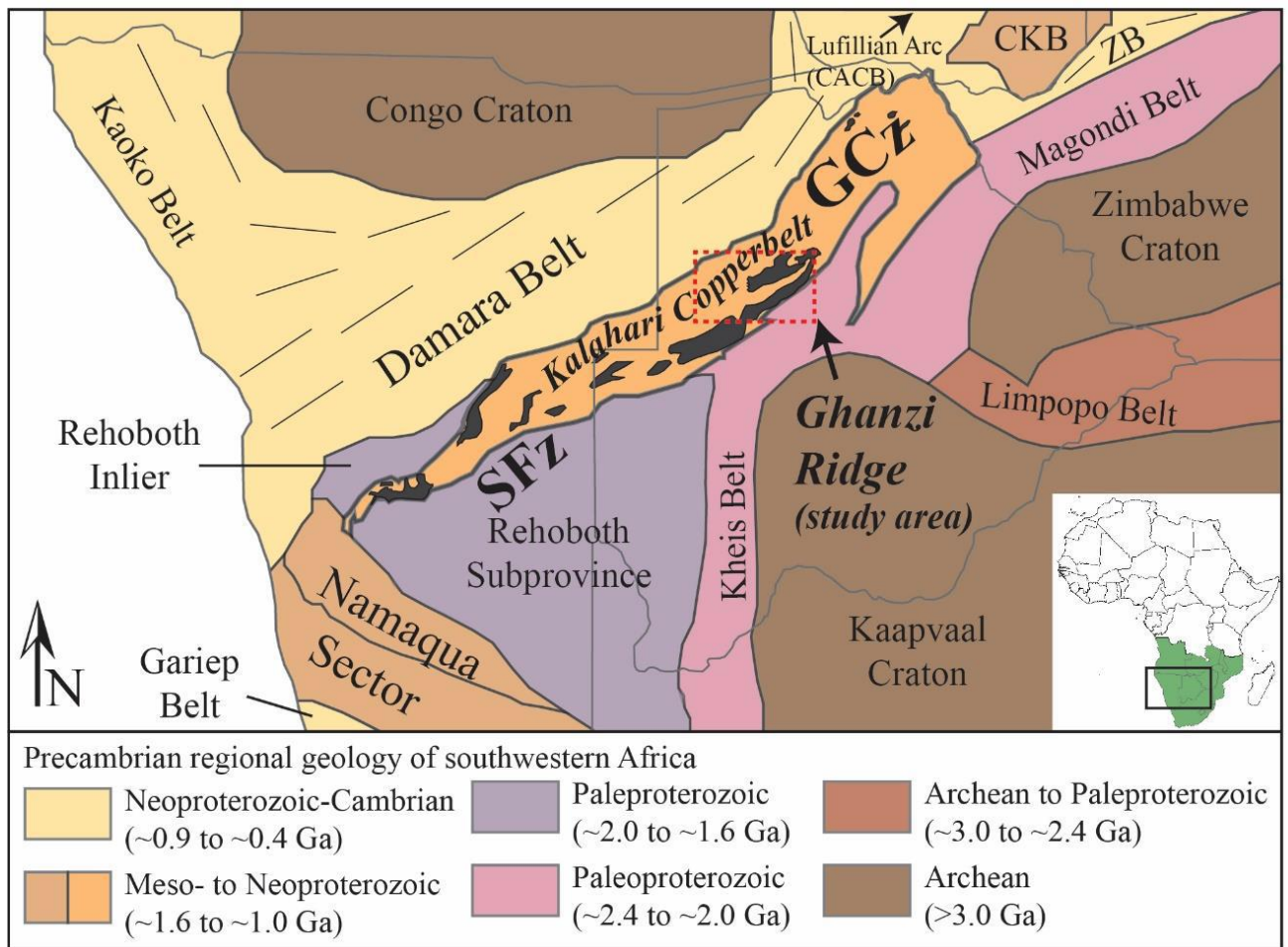


Fig. 1.1: Tectonic framework of southern Africa showing the location of KCM Cu-Ag deposits located in the Ghanzi Ridge portion of the Kalahari Copper Belt (modified after **Maiden and Borg, 2011**).

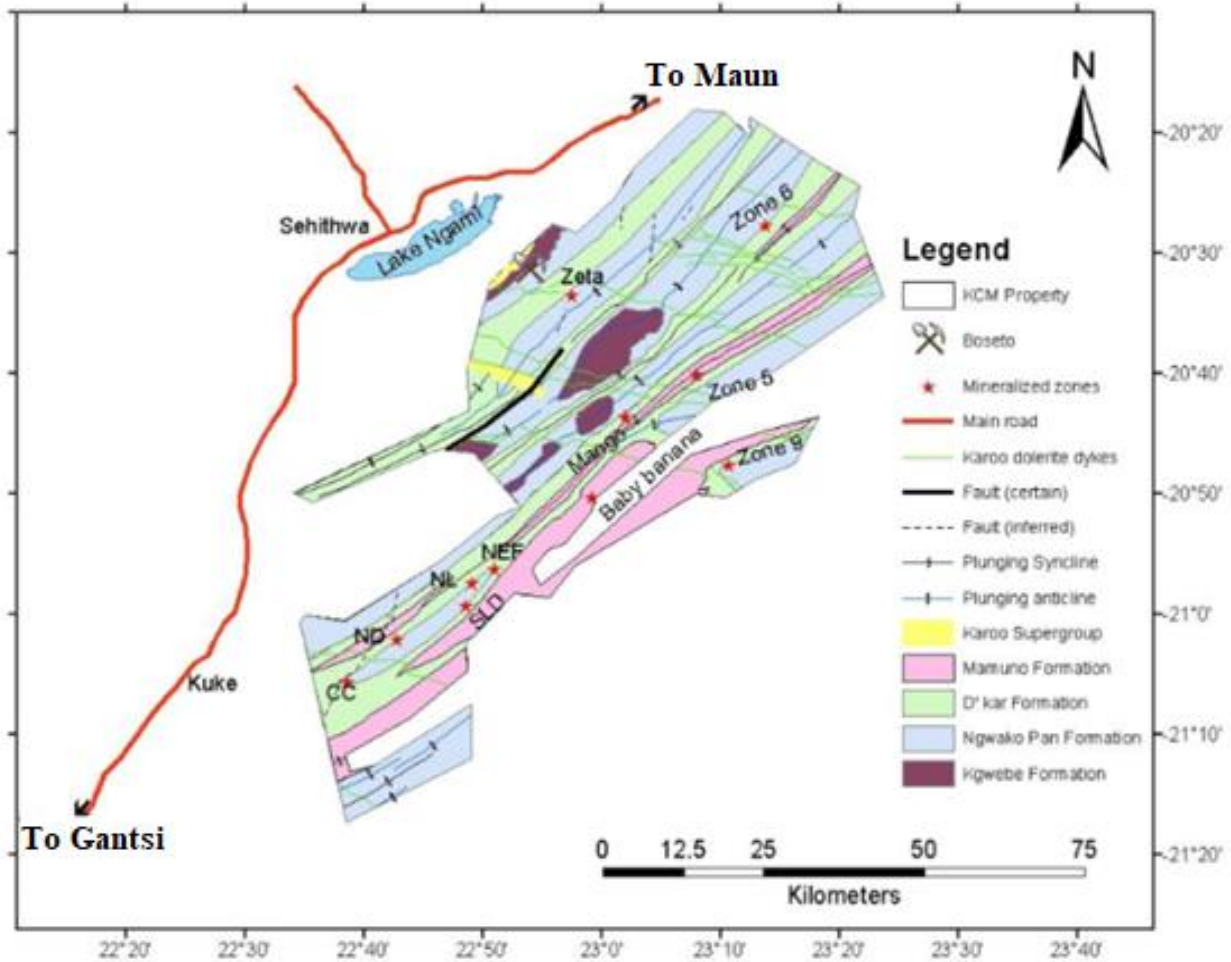


Fig. 1.2: A map showing an outline of different mineralized sites of the Khoemacau Cu-Ag deposits; CC Chalcocite Zone, ND New Discovery, NL North Limb, NEF North East Fold, SLD South Limb Definition (modified after **Hall, 2017**).

In terms of exploration history, Johannesburg Consolidated Investments (JCI) conducted geological mapping in the Khoemacau Cu-Ag Mining area in the early 1960's (**Van Der Heever et al., 2010**). Agloovaal South West Africa worked around Cu soil anomalies between 1967 and 1970 at what is now called the Zeta deposit currently under KCM (**Hall, 2007**; **Lehmann et al., 2015**). Between 1970 - 1980, successive drilling, soil geochemistry, ground geophysics, trenching and drilling by US (Steel) discovered the Zeta deposit with ore reserves estimated at 20 Mt, with 1.74 percent Cu grade and Ag at 39 ppm and discovered the

mineralized zone at the Plutus Prospect (**Schwartz et al., 1995**). Another deposit, the Banana deposit was successfully discovered by Anglo American Botswana in the year 1989-1994 through airborne and ground geophysical surveys, Landsat and photo-geological interpretation, soil geochemistry and drilling. Also held by the KCM, the Banana deposit is a massive deposit with potential ore reserves of 102.9 Mt Cu at 1.46 percent and 16.6 g/t Ag (**Catterall, 2012; Master et al., 2015; Magonono, 2020**). A joint venture between Delta Gold, Kalahari Gold and Copper (Pty) Ltd and Gencor/Billiton conducted some exploration work and deposit modelling on the copper belt between 1996 – 2000 (**Van Der Heever et al., 2010**). The Kalahari Copper Belt was gaining momentum and many exploration companies were coming forward to conduct as much exploration work as possible.

In 2005, Discovery Metal (Botswana) Limited acquired the Boseto license area and began a drilling program that defined a mineral resource (measured, indicated, and inferred) of 131.0 Mt at 1.3% Cu and 16.2 g/t Ag with a cut-off grade of 0.6% Cu and ore reserves of 29.1 Mt at 1.4% Cu and 19.8 g/t Ag (**Discovery Metal Limited Report, 2012**). Discovery Metal Limited acquired an exploration and mining license in 2005 – 2011, where their exploration activities led to opening of the Boseto Mine. Open-pit mining at the Zeta deposit commenced in 2012. However, the mining activities lasted from 2011- 2014. MOD Resources and Cupric Canyon Capital (formerly known as Hana Mining Limited) conducted drilling, geophysical and geochemical survey between 2007 and 2011-present. The Zone 5 deposit was discovered and is currently a mine. Zone 5 resource stands at just over 100 Mt of ore in measured, indicated and inferred categories grading 1.95 percent copper and 20g/t silver. (**KCM report, 2016**).

1.2 Problem statement

Mining companies were particularly interested in the KCB since it is a target location with the most similarities to the Central African Copper Belt (e.g., **Fleisher et al., 1976; Annels, 1984; Cahen et al., 1984; Unrug, 1988**). The age, geotectonic setting, and depositional environment of these two copper belts are comparable. In the Botswana's portion of the KCB, numerous works (e.g., **Huch et al., 1992; Schwartz et al., 1995; Modie, 1996; Kampunzu et al., 1998; Modie, 2000; Pretorius and Park, 2011**) that touched upon the KVF were carried out. However, a complete petrographic and geochemical description and categorization of the different KVF rock units is missing. Likewise, the petrogenesis of the KVF is poorly understood and the process(es) that combined and led to its formation are yet to be constrained, thus justifying the necessity of the current investigation.

Moreover, according to **Hall et al. (2018)**, there are two probable rock sources for the base metals of the Kalahari Copper Belt. The first and most likely are the red bed sandstones of the Ngwako Pan Formation (NPF) (**Schwartz et al., 1995**), the second possible source is the basaltic rocks of the underlying KVF and associated mafic to ultramafic intrusive rocks of the Umkondo Large Province that occur south of the Kalahari Copper Belt. Moreover, previous work (**Schwartz et al., 1995**), in the study area claimed that the KVF are likely sources of Cu and Ag in the Khoemacau deposit. However, **Kelepile et al. (2020)** based on Pb isotope investigations precluded the possibility of Cu and Ag to have been sourced from the KVF. This therefore, triggered the interest to carry out further research on the KVF rocks in order to deeply assess whether or not the KVF are likely to be the source of elements of interest, namely Cu and Ag within the KCM Project.

1.3 Aim and objectives of the study

The aim of the study is to investigate the possibilities of the KVF being the source of Cu and Ag mineralisation in the Khoemacau Mining Project. This will be attained by:

- assessing the contents of Cu-Ag of the KVF rocks;
- investigating the mineralogy of the KVF;
- assessing whether the KVF could have accounted for the total Cu-Ag budget in the Khoemacau Mining Project.

1.4 Methodology

In order to attain the objectives outlined above, two methods were used which include: Field work at Khoemacau Copper Mining (KCM) and Laboratory work at the Botswana International University of Science and Technology (BIUST) and SGS Laboratories, Johannesburg South Africa.

1.4.1 Field Work

A detailed and intensive field study was carried out and representative samples of the KVF were collected from all the four corners of the KCM area, from both outcrops and drill cores availed by the KCM (Table 1.1). Eleven representative samples were collected from availed drill core of borehole HA_1112_D at Zone 5. In addition, four quartz-feldspar porphyry samples were collected from Mabeleapudi Quarry, three quartz-feldspar porphyries and three porphyritic subvolcanic body samples from Kgwebe Hills, three quartz-feldspar porphyry samples from Mango Dome making the KVF representative samples to be twenty-five in total.

Although clastic sedimentary rocks are not volcanic, they are however part of the KVF (see geological section) and they were found intercalated with the volcanic rocks, and as a result they cannot be ignored.

Table 1.1

Lithologies and sampling locations of the investigated KVF rock samples.

Sample I.D	Lithologies	Location
EE_01	Amygdaloidal rock	Zone 5, borehole ID:HA_1112
EE_02	Amygdaloidal rock	Zone 5, borehole ID:HA_1112
EE_04	Amygdaloidal rock	Zone 5, borehole ID:HA_1112
EE_05	Amygdaloidal rock	Zone 5, borehole ID:HA_1112
EE_07	Porphyritic mafic flow	Zone 5, borehole ID:HA_1112
EE_08	Porphyritic mafic flow	Zone 5, borehole ID:HA_1112
EE_06	Pyroclastic rock	Zone 5, borehole ID:HA_1112
EE_09	Pyroclastic rock	Zone 5, borehole ID:HA_1112
EE_10	Pyroclastic rock	Zone 5, borehole ID:HA_1112
EE_12	Quartz-feldspar porphyry	Kgwebe Hills
EE_14	Quartz-feldspar porphyry	Kgwebe Hills
EE_15	Quartz-feldspar porphyry	Kgwebe Hills
EE_16	Quartz-feldspar porphyry	Mabeleapudi Hills
EE_17	Quartz-feldspar porphyry	Mabeleapudi Quarry
EE_18	Quartz-feldspar porphyry	Mabeleapudi Quarry
EE_19	Quartz-feldspar porphyry	Mabeleapudi Quarry
EE_20	Quartz-feldspar porphyry	Mabeleapudi Quarry
EE_21	Quartz-feldspar porphyry	Mango Dome
EE_22	Quartz-feldspar porphyry	Mango Dome
EE_23	Quartz-feldspar porphyry	Mango Dome
EE_13	Porphyritic subvolcanic body	Kgwebe Hills
EE_27	Porphyritic subvolcanic body	Kgwebe Hills
EE_28	Porphyritic subvolcanic body	Kgwebe Hills
EE_03	Clastic sedimentary rock	Zone 5, borehole ID:HA_1112
EE_11	Clastic sedimentary rock	Zone 5, borehole ID:HA_1112

1.4.2 Laboratory Work

Laboratory works involved sample washing, sample crushing, sample pulverization, optical microscopy, X-ray fluorescence (XRF), Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-OES).

Least-altered/weathered twenty-five representative samples of the KVF were washed in distilled water and air-dried. The samples were then divided into two, one portion of the sample was for lithogeochemistry, while the other portion of the sample was put aside for polished thin sections confection. The samples for lithogeochemistry were broken down into small pieces using a hammer in preparation for crushing. A jaw crusher was used to crush the samples into smaller fragments (1 – 2 cm). The materials were then pulverized to a grain size $< 125 \mu\text{m}$ using a ball mill pulverisette of model Fritch consisting of a horizontal rotating cylinder that contained cascading steel balls. To avoid cross-contamination between the samples, the apparatus used for crushing and pulverizing were washed and cleaned with distilled water and rinsed with ethanol after each sample preparation. Crushing and pulverisation were performed at the Department of Earth and Environmental Sciences and at the Department of Mining and Geological Engineering of the Botswana International University of Science and Technology (BIUST).

Twenty-five polished thin sections were prepared from 25 rock samples for microscopical petrographic analyses in order to further constrain sample's mineral composition and assess mineral textural relationships. A glass slide was prepared and labelled accordingly. To avoid rust after grinding, grinding wheel was cleaned promptly. The glass slide was then frosted in order to flatten it out and roughen the surface so the epoxy can bind well. A slab was cut along the line marked on a rock sample and it was then cleaned and reduced in size to slightly smaller

than a thin section. The chip was glued to the glass slide and most of the chip was cut, leaving a thin slice attached. The slide was finally grinded to the correct thickness (0.03 mm) thus making a polished thin section. Polished thin sections were prepared at the Department of Earth and Environmental Sciences, mineral dressing laboratory of the Botswana International University of Science and Technology (BIUST) and Standard petrographic polished thin sections were studied using both transmitted and reflected light microscopes.

For geochemical studies, the selected twenty-five least-altered KVF samples were analysed by Wavelength Dispersive X-Ray Fluorescence (WDXRF) and Inductively Coupled Plasma-Mass Spectrometry/Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-MS/OES) at SGS, Johannesburg, South Africa. WDXRF implemented for the whole rock determination of twelve major element oxides, was carried out by borate fusion method using a Panalytical AXIOS-WDXRF mass spectrometer. The samples were mixed with lithium tetra borate flux and fused to form a homogenous glass bead on the WDXRF spectrometer. These suite of twelve major rock-forming oxides includes; SiO_2 , Al_2O_3 , Fe_2O_3 , MgO , V_2O_5 , CaO , Na_2O , K_2O , P_2O_5 , MnO , TiO_2 and Cr_2O_3 reported in %. The loss on ignition (LOI) at 1000 °C was determined separately by gravimetry, approximately 1g of the sample was roasted for 1 hour in a furnace. Two mass spectrometers were used to assess the abundances of selected trace elements. Whereas ICP-MS Nexion 300D spectrometer was used to measure the contents of 41 elements including Ag, Be, Ce, Hf, La, Nd, Pr, Sc, Th, U, Yb, Bi, Co, Dy, Ga, Ho, Mo, Ni, Rb, Se, Ta, As, Er, Gd, In, Lu, Sm, Tb, Ti, W, Cd, Cs, Eu, Ge, Nb, Pb, Sb, Sn, Te, Tm and Y, ICP-OES, Agilent 5110 spectrometer was utilised to measure the abundances of Cu, Fe, Mn, Sr, Al, Li, Ti, V, Zn, Ca, Cr, Na, P, S, Zr, Ba, K and Mg. The analytical technique involved weighing samples, transferring the powder to a Teflon dish, adding nitric acid (HNO_3), hydrochloric acid (HCl), hydrofluoric acid (HF) and perchloric acid (HClO_4) and heating the

solution until dry. The residue was dissolved in HNO₃ and HCl, transferred to a test tube and the sample was then analysed by ICP-OES and ICP-MS.

For Quality control, there was a minimum of one reagent blank and certified/in-house reference material and one duplicate for each and every 25 samples with a precision rate of 0.01 and 1.0 for major and trace elements, respectively. The in-house reference materials (standards) used for trace and major elements are OREAS 906 and AMIS0534, respectively.

1.5 Outcomes

The research will contribute enormously to a better understanding the petrogenesis of the KVF and elaborate to some extent on the source of Cu-Ag mineralisation at the Khoemacau Mining (KCM) Project. Especially, it will provide insights into mineralogical and geochemical characterisation of the KVF and this will help in designing exploration models likely to lead to further Cu-Ag discoveries in the entire Ghanzi Chobe Belt portion of the Kalahari Copper Belt.

1.6 Thesis organisation

This thesis is divided into six chapters. **Chapter 1** is an introductory chapter that presents the study's background, problem statement, aim and objectives, analytical techniques, and study outcomes.

Chapter 2 introduces the geological setting, focusing on the regional and local geological settings of the study area.

Chapter 3 deals with the rocks of interest which are the Kgwebe Volcanic rocks. It includes detailed petrographic sample descriptions at the both the macroscopic and microscopic scales

Chapter 4 deals with the geochemical characteristics of the KVF rock units (amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks, porphyritic subvolcanic bodies, quartz-feldspar porphyries and clastic sedimentary rocks). There are four sections in this geochemistry component. The first section characterises KVF rock units based on their major elements content, whereas the second and third sections characterise the KVF rock units based on the trace element and rare earth element concentrations, respectively. The last section of this chapter discusses the Cu-Ag content of the KVF rock units as well as the total Cu-Ag budget within the KCM project.

Chapter 5 presents the discussion of the results. It covers the magma source (s) of the KVF rock units, their magma evolution, as well as the magma emplacement mechanisms that occurred during the formation of the KVF. It also discusses the source (s) of Cu-Ag in the KCM property, based on the Cu-Ag content of the KVF.

Chapter 6 presents the general conclusions and recommendations.

CHAPTER 2

GEOLOGICAL SETTINGS

This chapter discusses the geological settings of northwestern Botswana, including regional and study area geology.

2.1 Regional geology

The KCM deposits are contained within the Ghanzi-Chobe Belt, which is a component of the Kalahari Copper Belt (KCB) (**Modie, 2000, (Fig. 2.1.)**). The deposits are located in the Kalahari Desert, which is a semi-arid sandy savannah. The area hosting the KCM deposits has low relief, with the exception of the Ghanzi Ridge, which is a linear chain of small hills (**Hall, 2013**). The KCB is located on the Kalahari Craton's northwestern and northern margins, and it is bounded to the north by the Late Proterozoic Damara Orogenic Belt (**Borg, 1988**). The deposits are located in northwestern Botswana, which is characterized by several Precambrian orogenic belts, including the Paleoproterozoic Eburnian Magondi Belt and the Mesoproterozoic to Early Palaeozoic Pan African Ghanzi-Chobe Belt (**Kampunzu et al., 2000**).

The KCB (**Fig. 2.1**) was formed by a collision between the Congo Craton and the Kalahari Craton (including the Kaapvaal Craton and the Zimbabwe Craton), during Gondwana's amalgamation between 600 and 450 Ma (**Stanistreet et al., 1991**). It is a 1,000-kilometer-long series of geophysically linked, inverted Meso-to Neoproterozoic volcano-sedimentary basins on the northwestern margin of the Kalahari Craton in Southern Africa (**Borg, 1988; Modie, 2000; Maiden and Borg, 2011; Lehmann et al., 2015**). The belt runs from central Namibia through Botswana and into northern Zambia (**Pretorius and Park, 2011**). The metallogenic

province of the Precambrian Kalahari Copper Belt is primarily concealed by unconsolidated sand of the Kalahari Group cover (Hall, 2017; Haddon, 2005). Furthermore, Hall (2007) and Haddon (2005) stated that deposits within the belt range in size from 10 Mt to 100 Mt and have grades ranging from 1.0 to 4% copper and 10 to 40 grams per ton silver. U-Pb Zircon ages from felsic volcanic and intrusive rocks across the rift basins show widespread bimodal magmatic activity between 1112 and 1080 Ma (Schwartz et al., 1996; Singletary et al., 2003; Becker et al., 2005; Miller, 2012).

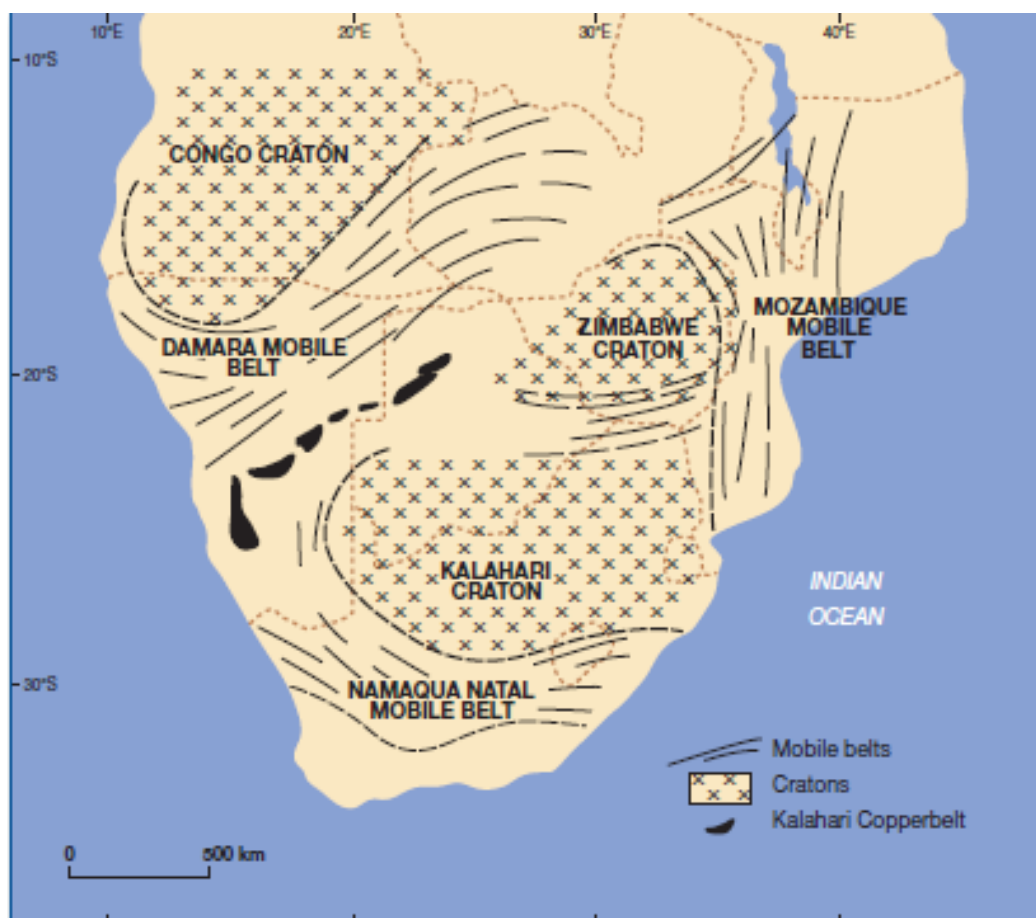


Fig. 2.1: A map showing the location and tectonic setting of the Kalahari Copper Belt (KCB) (modified after Maiden & Borg, 2011)

The Ghanzi-Chobe Belt is the portion of the Kalahari Copper Belt in Botswana that hosts the KCM deposits. The 500-kilometer-long and 100-kilometer-wide Ghanzi-Chobe Belt runs from the Namibia-Botswana border in the south to the Shinamba Hills in the north, near the Botswana-Zambia border (**Borg and Maiden, 1989; Modie, 2000; Maiden and Borg, 2011**). The Karoo Supergroup (303-180 Ma) and the younger Cainozoic sedimentary rocks of the Kalahari Group cover most of Botswana's tectonic framework and regional basement rocks (**Lehmann et al., 2015**). As a result, the geological interpretation beneath the Kalahari Group cover is based primarily on prior drill hole data, stratigraphy, and tectonic structure correlation with known similar sequences in Namibia (**Modie, 1996**). The Ghanzi-Chobe Belt is defined as a series of deformed metavolcanics and metasediments known as the Sinclair Group (**Watters, 1977**) in Namibia, the Ghanzi-Chobe supergroup (**Modie et al., 1988**) in Botswana, and the Katanga Supergroup (**Kampunzu et al., 1998**) in Zambia.

Furthermore, the aforementioned sedimentary rocks were deposited in an intracontinental rift, which was followed by a proto-oceanic rift system, which eventually evolved into a syn-to post-orogenic sequence (**Kampunzu et al., 1991; Miller et al., 2009; Master, 2010**).

The Okwa Basement Complex and the Xangwa area are the oldest rocks in northern Botswana, representing the Paleoproterozoic basement (2055 Ma, **Borg, 1988; Ramokate et al., 2000**). Okwa Basement Complex rocks are composed of granitoids and porphyritic rhyolitic felsite that evolved from Okwa granitic magma. The Okwa area's exposed rocks are mostly porphyritic rhyolitic felsite, augen gneiss, granite, and microgranite (**Aldiss, 1988; Ramokate et al., 1996**). The Okwa gneiss has a strong foliation defined by biotite and feldspar with a NE-SW trend, as well as a variable amount of mafic xenoliths of igneous origin (**Ramokate et al., 1996**). The Okwa Valley's basement rocks yielded a U-Pb zircon crystallisation age of 2055 ± 1.3 Ma (**Mapeo et al., 2006; Ramokate et al., 1996**). The exposures in the Qangwa area are

mostly augen gneiss and granite with faint foliation to non-foliation that is NE-SW trending with subvertical dips (**Wright, 1958**).

The Mesoproterozoic basement in the northwestern part of Botswana is represented by the KVF, comprising of metarhyolite and metabasalt (**Modie, 1996**). The Kgwebe Volcanic rocks trends from SW to NE within the Kibaran Belt (**Ramokate et al., 2000**). The bimodal suite of rocks comprising the KVF marks the late stage of extensional rifting of the Kibaran Orogeny (**Fig. 2.2**) (**Ramokate et al., 2000**). U-Pb zircon dating of a sample of the Kgwebe Metarhyolite from Mabeleapudi Hills in the Ghanzi-Ridge constrained the crystallization of the Kgwebe Volcanic rocks at 1106 +/- 2 Ma (**Shwartz et al., 1996; Modie, 2000; Kampunzu et al., 2000**).

Three lithostratigraphic units namely; the Ghanzi Group, Roibok Complex, Kaonaka, Xaudum and Tsodilo Hills Group form part of the Neoproterozoic Ghanzi-Chobe Supergroup (**Kampunzu et al., 2000; Key and Ayers, 2000**) (**Fig. 2.2**). The Ghanzi Group (**Fig. 2.2**) is basically a sedimentary succession that overlies the KVF with an unconformable contact (**Kampunzu et al., 1998**). Roibok Complex is composed of schist and gneissic, which are not exposed (**Kampunzu et al., 2000**). The rocks are only encountered in boreholes (**Singleton et al., 2003**). In the Kaonaka Group, the dolomitic marble is exposed in the Kihabe and the Kaonaka Hills (**Wright, 1958**). The Xaudum Group (**Fig. 2.2**) exposes metasedimentary rocks of varied sequence and there is quite a variety of rocks exposed ranging from shale, sandstone, dolomite just to mention a few. Moreover, the Tsodilo Hills Group is characterized by an association of ferruginous and micaceous metamorphosed rocks, which have been altered to kyanite metamorphic grade (**Wendorff, 2005**). Lastly, the Karoo Supergroup comprises a succession of sedimentary and volcanic rocks that unconformably overlie Archean and Proterozoic beds and overlain unconformably by the Kalahari beds (**Carney et al., 1994**).

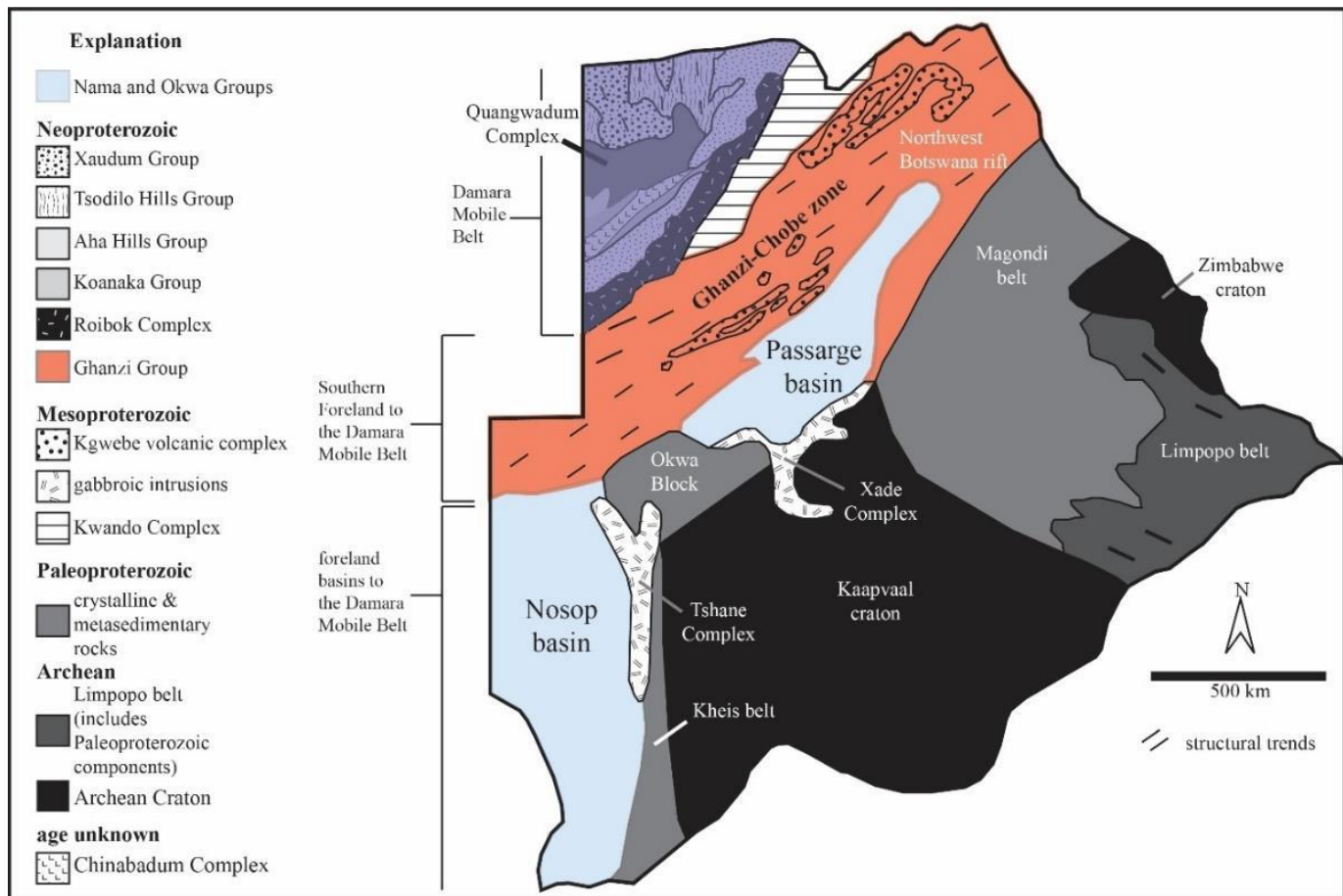


Fig. 2.2: Regional basement terranes of Botswana, largely inferred from geophysics, highlighting the different tectonic zones and basins (Damara Mobile Belt, Southern Foreland Fold Belt, and Foreland Basins) associated with the Pan-African Damara Orogeny (modified after **Hall, 2017**).

2.2 Local geology

The geology of the Ghanzi-Chobe Belt is defined by the KVF, which forms the belt's base. The KVF is overlain by a sedimentary succession known as the Ghanzi Group.

2.2.1 Kgwebe Volcanic Formation (KVF)

The rocks of interest in this study are the basal KVF (**Fig. 2.3 and Table 2.1**), which has a composite thickness of 2500 m and is composed of a bimodal volcanic suite with minor

intercalated epiclastic and tuffaceous sedimentary units (**Modie, 2000**). According to **Modie (2000)**, volcanics consist of porphyritic rhyolite-dacite, pyroclastic flow deposits, minor peperite, and subaerial basaltic lavas. Furthermore, according to **Shwartz et al. (1995)** it is composed of within-plate low Ti-P continental tholeiites and within-plate high-K rhyolites derived from the melting of Mesoproterozoic calc-alkaline basement rocks (**Kampunzu et al., 1998**). The composite thickness of the metabasalt layers interbedded with the KVF metarhyolites and metasediments in the Ghanzi-ridge decreases from 1.5 km in the northeast (Kgwebe Hills) to less than 200m in the southwest (Mabeleapudi Hills). The KVF represents the first phase which initiated by extensional tectonics in small lake environments (**Modie, 1996**). According to **Kampunzu et al. (1998)**, the chemical composition and field relations suggest that these volcanic rocks were emplaced during a collision-related extensional collapse event. Their exposures have been found in the core of a regional anticline in the Mabeleapudi and Kgwebe Hills and trend north-east of the Kuke Village (**Pretorius and Park, 2011**). The KVF is the oldest exposed structural and stratigraphic unit within the KCM Project. **Schwartz et al. (1996)** obtained a zircon U-Pb age of 1106 ± 2 Ma from the basal rhyolite at Mabeleapudi Hills. Therefore, the age of the Kgwebe Porphyry is the only reliable depositional age for any lithological unit within the Ghanzi-Chobe Belt thus representing the maximum age of the Ghanzi Group sedimentary deposits (**Schwartz et al., 1996**).

2.2.2 Ghanzi Group

The deformed Ghanzi Group (**Fig. 2.3 & Table 2.1**) rocks occur in the southwestern half of the Ghanzi-Chobe Belt. The metasedimentary rocks were folded with underlying meta-volcanic rocks, some of which form isolated chains of basement inliers in the Lake Ngami area (**Fig. 2.3**) of the Ghanzi Ridge (**Modie, 1996**). These rocks have undergone lower greenschist facies metamorphism and tightly folded, with the regional SW-NE trend of fold axes (**Modie,**

1996). The depositional age of the Ghanzi Group is between 1047 ± 24 Ma (youngest detrital zircons; **Kampunzu et al., 2000**) and 550 Ma (**Walraven and Borg, 1992**) corresponds to the peak of metamorphism.

The base of the Ghanzi Group is formed by the Kuke Formation (**Table 2.1**) with a thickness of a 500 m and rests unconformably above the KVF (**Modie, 2000**). It comprises of sandstones and conglomerates (**Ramokate et al., 2000**), and the later contain fragments of basalt filled with chert, derived from bimodal Volcanic suite of the KVF (**Modie, 2000**). The Ghanzi Group is characterized by cross-bedding, graded bedding, reaction surfaces and pebbly layers (**Modie, 2000**). The Kuke Formation is overlain by the Ngwako Pan Formation (**Table 2.1**) with a stratigraphic thickness of approximately 200 m and represents a succession deposited in an oxic environment (**Modie, 2000**). The Ngwako Pan Formation exposes poorly sorted, matrix-grey sandstones with purplish-red mudstones intercalations at the base, while at its uppermost part it shows moderate-to well-sorted reddish arkosic sandstone (**Kampunzu et al., 2000**). **Catterall (2012)** interpreted the sorting of Ngwako Pan clastic sediments as a continental fluvial facies, which deposited coarse grits fining into medium-grained sandstones as an alluvial fan sediments discharge. The Ngwako Pan Formation is characterized by graded bedding bipolar cross-bedding and pebble-rich layers (**Kampunzu et al., 2000**).

Conformably overlaying the Ngwako Pan Formation along the Ghanzi Ridge is a 1500 m thick marine siliciclastic and carbonate package of D'Kar Formation (**Table 2.1**). The D'Kar Formation exhibits a progressive marine transgression shown by the parallel laminated greyish-green mudstones and siltstones, which interchanges with finely grained interbedded sandstone (**Modie, 1996; Catterall, 2012**). The Siliciclastic rocks characterized by a repeated fining upward succession of pale siltstones interbedded with dark shale beds, which suggests a rhythmic seasonal sedimentation due to storm activities (**Modie, 1996**). According to **Hall**

(2007) and Catterall (2012), the paleocurrent measurements on the D’Kar Formation shows sediments deposited from a northeast direction, with marine reworking event from the west.

The Mamuno Formation (Table 2.1) with a thickness of 1500 m occupies the upper succession of the Ghanzi Group and exhibits a gradational contact with the underlying D’Kar Formation (Ramokate et al., 2000). The Mamuno Formation is characterized by a thick package of purple oxidized siliciclastic facies slightly metamorphosed and alternating limestone layers at the top (Modie, 1996). The Sedimentary structures are dominated by the cross-bedding and wave ripples (Magonono, 2020), the red-bed facies association with alluvial-fluvial system marks the transition between continental systems and marine environment (Modie, 2000).

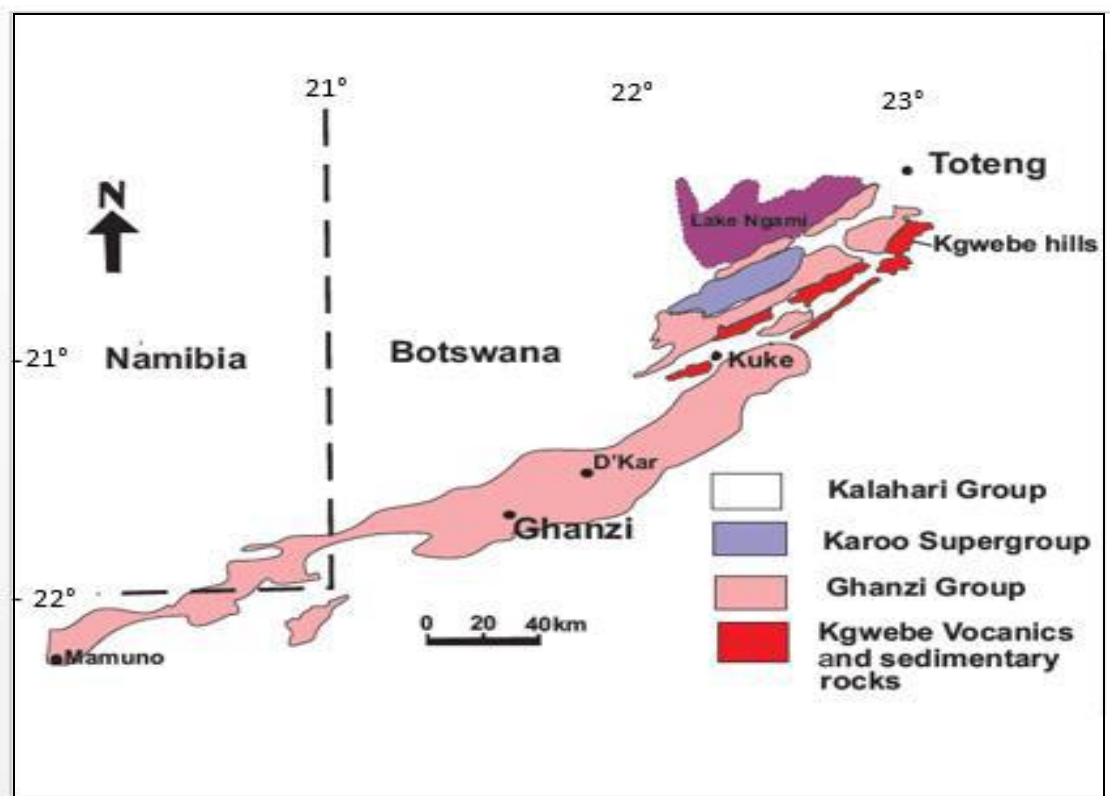


Fig. 2.3: Outline of the Ghanzi-Chobe belt depicting different lithological units housed within the belt, KVF included (modified after Kampunzu et al., 1998).

Table 2.1

Stratigraphy of the Ghanzi-Chobe Supergroup (modified after **Modie et al., 1998**).

Age	Group	Formation (Thickness)	Lithology	Depositional setting
Neoproterozoic	Ghanzi	Mamuno (~1500 m)	Arkose, siltstone, shale, mudstone and limestone	Alluvial system changing to shallow marine and progradational shoreline
		D'Kar (~1500m) <u>Cu-Ag mineralisation</u>	Shale, mudstone, siltstone, arkose, marlstone and limestone	
		Ngwako Pan (~2000 m)	Arkose, sub-arkose, siltstone and shale	
		Kuke (~500 m)	Sandstone and conglomerate	
Mesoproterozoic	Kgwebe Volcanic (~2000 m)		Metarhyolite, tuff. metabasalt, agglomerate, minor intercalated metasedimentary rocks	Bi-modal volcanism

CHAPTER 3

PETROGRAPHY OF THE KGWEBE VOLCANIC FORMATION

Representative units belonging to the KVF were sampled from four corners of the Khoemacau Copper Mining area. The rock samples were discriminated based on their texture and included amygdaloidal rocks, pyroclastic rocks, porphyritic mafic flow, porphyritic subvolcanic bodies, the quartz-feldspar porphyries and clastic sedimentary rocks. Although clastic sedimentary rocks are not volcanic, they were however intercalated with the volcanic rocks and as a result they cannot be ignored. Below are detailed hand specimen and optical microscopy descriptions of each rock unit;

3.1 Amygdaloidal rocks

Amygdaloidal rock samples of the KVF were collected from availed drill cores of Zone 5 borehole (HA_1112_D) at depths of 40.00 - 40.14 m (sample EE_01), 40.14 - 40.25 m (sample EE_02), 47.95 - 47.97 m (sample EE_04) and 88.20 - 91.58m (sample EE_05). The rock samples commonly exhibit amygdales-filled vesicles (5 - 50 vol. %) and an overprint of calcite veins (5 vol. %) on a fine-grained grey-to dark-grey groundmass (Fig. 3.1). They are variably altered and generally display a micro hyalopilitic groundmass.

The amygdaloidal rocks of the KVF also contain phenocrysts (50 vol. %) set in a fine-grained hyalopilitic groundmass (10 vol. %) (Fig. 3.2 a, b, e, f). The aphanitic groundmass (< 1 mm) is built up of a combination of microcrystalline plagioclase, pyroxene, minor olivine, minor glass and opaque minerals, particularly magnetite. The phenocrysts are essentially made up of abundant needle-shaped plagioclase laths and constitute 95 vol. % to the entire phenocrysts' population (Fig. 3.2a). Plagioclase lath is tabular, randomly arranged and generally shows a

subhedral-to euhedral shape (Fig. 3.2a). Its size ranges between 0.5 – 4 mm and rarely up to 6 mm in length. Locally, plagioclase laths convey a brownish colour, probably due to iron staining and it is slightly epidote-altered (Fig. 3.2c). Moreover, the plagioclase is mostly enclosed in segregations of devitrified glass giving an intersertal texture (Fig. 3.2b). The amygdales are commonly filled with quartz and calcite (Fig. 3.2e). They are rounded and in places show an irregular meandering-like shape surrounded by a light green rim (Fig. 3.2d). Amygdales vary in size from 2 – 5 mm and rarely up to 5 cm (Fig. 3.2d, e). Twin lamellae parallel to the rhombic cleavages or the crystal outline is observed on a calcite vein (Fig. 3.2g). The twin lamella is usually induced by deformation in a rock. Magnetite is roughly rectangular in shape and occurs locally on the groundmass or as phenocrysts scattered within the amygdaloidal rocks (Fig. 3.2a). A rare xenolith (5 – 10 mm) probably from the surrounding country rock is observed (Fig. 3.2i). The xenolith displays a rich whitish-green colour and is constituted by both acicular and granular green minerals and clear whitish carbonate minerals (Fig. 3.2 j).

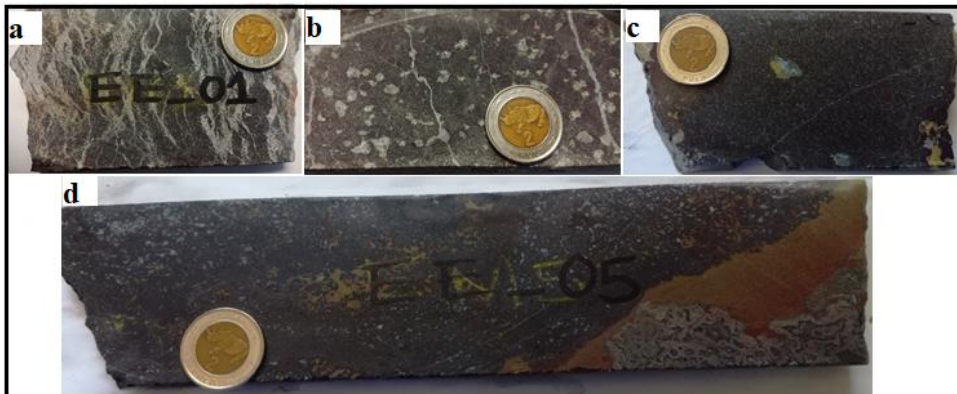


Fig. 3.1: Photographs showing amygdaloidal rocks of the KVF. (a) An aphanitic amygdaloidal rock sample showing a light grey matrix overprinted by calcite veins (sample EE_01, drill core HA_1112_D; 40.00 - 40.14 m). (b) A fine-grained amygdaloidal rock characterised by amygdale-filled vesicles and minor calcite veins set on a fine-grained light grey groundmass (sample EE_02, drill core HA_1112D;

40.14 - 40.25). (c) A least-altered amygdaloidal rock exhibiting a dark grey fine-grained groundmass and amygdales-filled cavities on a small percentage (sample EE_04, drill core HA_1112_D; 47.95 - 47.97). (d) An amygdaloidal rock with a fine-grained grey matrix, which at some instances appear rusty-red (due to ferruginisation), and also displaying feldspar phenocrysts (sample EE_05, drill core HA_1112_D; 88.20 - 91.58).

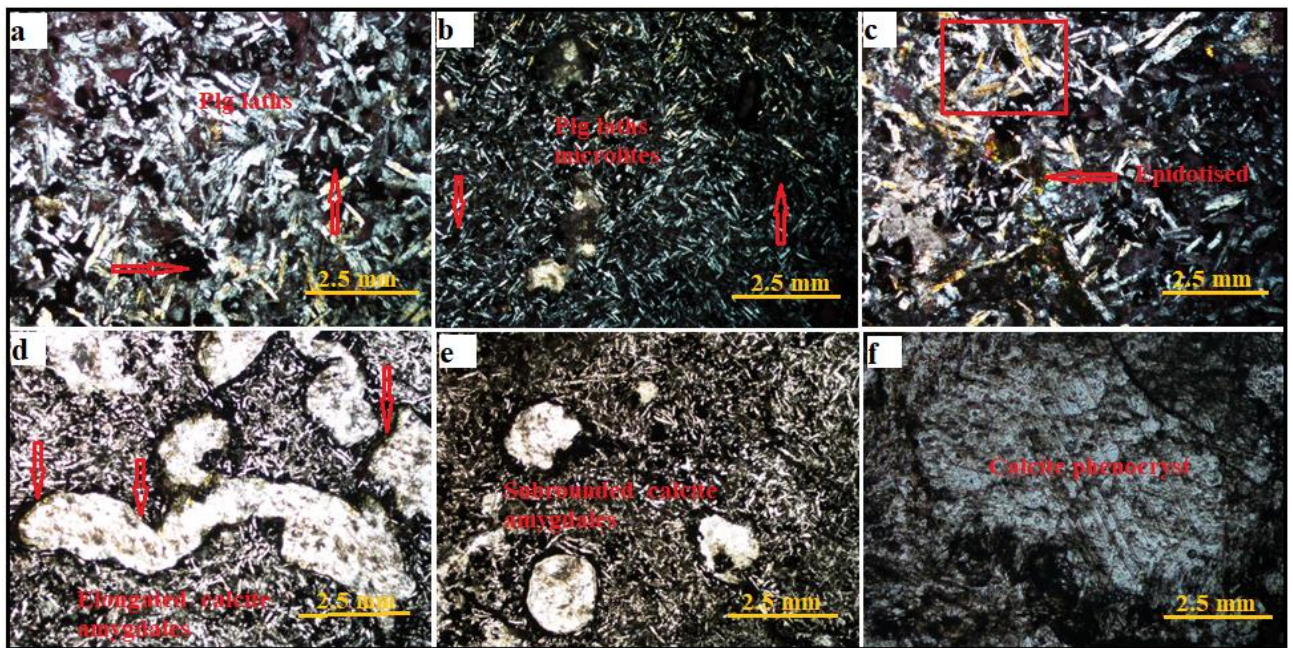


Fig. 3.2: Photomicrographs (transmitted light) depicting in detail the different features as observed in amygdaloidal rocks of the KVF. (a) Laths-shaped plagioclase (plg) phenocrysts and magnetite (arrows) set in a fine-grained groundmass (sample EE_01, drill core HA_1112_D; 40.00 - 40.14 m). (b) An aphanitic groundmass of numerous lath-shaped plagioclase (plg) microlith, pyroxene, magnetite and minor glass (arrows) (sample EE_05, drill core HA_1112_D; 88.20 - 91.58). (c) Plagioclase laths conveying a brownish colour probably due to iron staining (rectangle) and slightly epidotised. (d) Irregular-shaped calcite and quartz amygdales with a meandering-like shape surrounded by a light green rim (arrow) (sample EE_05, drill core HA_1112_D; 88.20 - 91.58). (e) Rounded calcite and quartz amygdales (sample EE_05, drill core HA_1112_D; 88.20 - 91.58). (f) Calcite phenocryst set on a fine-grained groundmass (sample EE_02, drill core HA_1112D; 40.14 - 40.25).

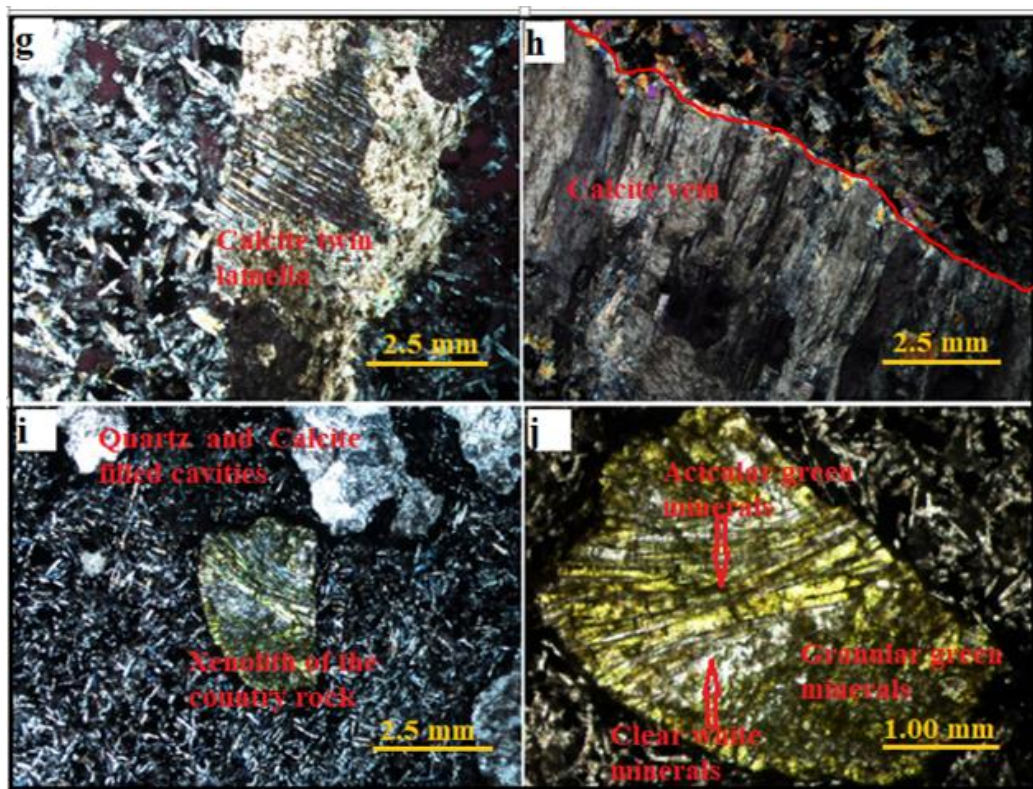


Fig. 3.2 Continued: (g) Calcite vein showing twin lamella (sample EE_02, drill core HA_1112D; 40.14 - 40.25). (h) Calcite vein. (i, j) A xenolith from the surrounding country rock characterised by clear whitish calcite and both acicular and granular green minerals (sample EE_05, drill core HA_1112_D; 88.20 - 91.58).

3.2 Porphyritic mafic flows

Porphyritic mafic flow samples forming part of the KVF were collected from an availed Zone 5 borehole (HA_1112_D) at depths of 71.90 - 71.97 m (sample EE_07) and 74.27 - 74.35 m (sample EE_08). The porphyritic mafic flows generally show 55 vol. % phenocrysts set in a relatively grey (Fig. 3.3a) and light-reddish (Fig. 3.3b) aphanitic groundmass (45 vol. %). The phenocrysts are needle-shaped (Fig. 3.3b) and relatively small in size (< 1 mm). Heavy epidotisation is evident and occurs as an overprint and splash within the porphyritic mafic flows

(Fig. 3.3b). The phenocrysts are essentially made up of abundant needle-shaped plagioclase laths and minor quartz (Fig. 3.4a, b). Plagioclase phenocrysts represent 95 vol. % of the total phenocrysts' population. Dominating plagioclase phenocryst is represented by slightly resorbed prismatic, tabular and lath-shaped crystals ranging in size from 1 to 3 mm (Fig. 3.4a) and rarely showing polysynthetic twinning. Porphyritic mafic flows have more or less been subjected to hydrothermal alteration, clearly evidenced by the replacement of plagioclase by sericite and epidote (Fig. 3.4b, c, d, e). The hydrothermal alteration replacement was a static event and did not affect the original crystal shape. Hence, the primary intergranular rock texture is retained. The plagioclase crystals have experienced sericitization with distinct preferred orientation (Fig. 3.4c). Subrounded minor quartz phenocryst is characterised by undulose extinction and constitutes relatively smaller percentage (< 5 vol. %) of the whole rock population (Fig. 3.4b). Porphyritic mafic flows are also commonly crosscut by calcite veins (0.5 – 1 mm) (Fig. 3.4f).

The aphanitic (< 1 mm) groundmass is composed of slightly sericitised plagioclase, opaque minerals and minor glass. Magnetite represents the opaque minerals and occurs locally as subrounded-to subangular randomly oriented grains in the groundmass.

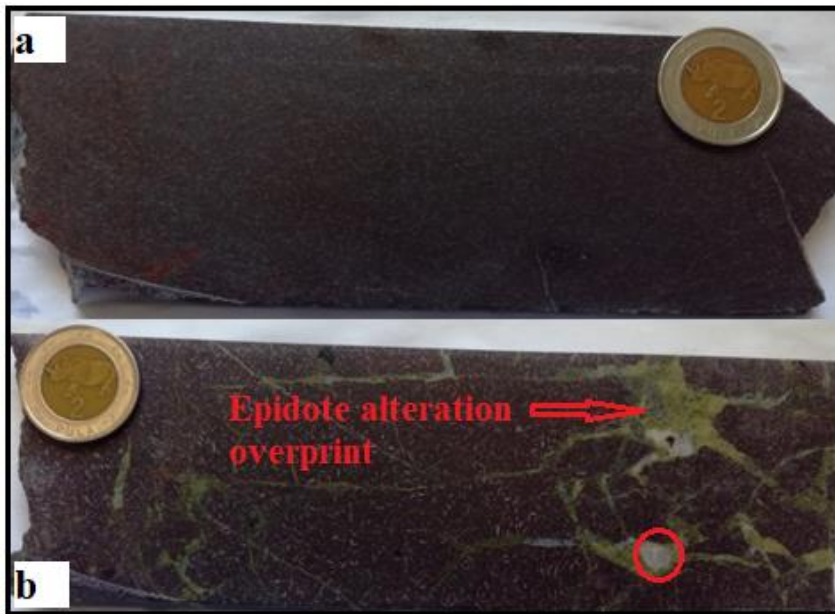


Fig. 3.3: Photographs of the porphyritic mafic flows of the KVF. (a) Phenocrysts set in a fine-grained and grey coloured groundmass (sample EE_07, drill core HA_1112_D; 71.90 - 71.97 m). (b) A porphyritic mafic flow sample exhibiting needle-like crystals, epidotisation and clear white minerals (circle) set in a fine-grained groundmass (sample EE_08, drill core HA_1112_D; 74.27 - 74.35 m).

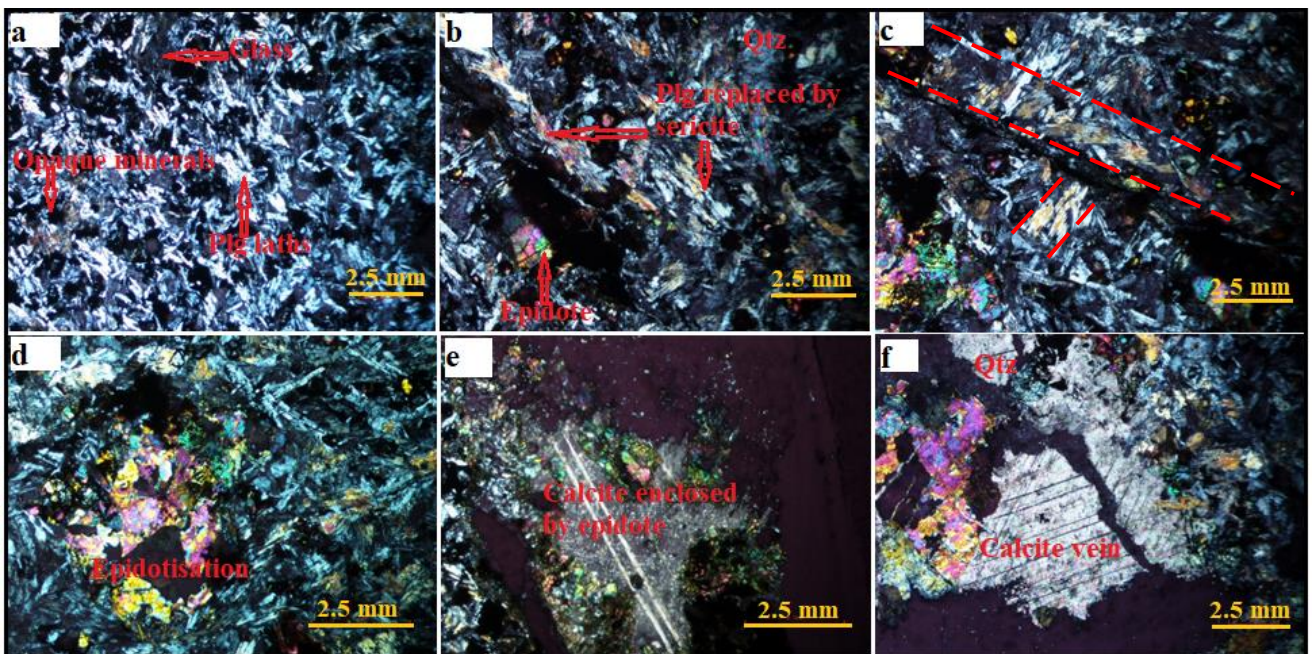


Fig. 3.4: Photomicrographs (transmitted light) of the porphyritic mafic flow forming part of the KVF (all pictures in crossed polarised light). (a) Randomly-oriented needle-shaped plagioclase laths and

opaque minerals set in a fine-grained groundmass (sample EE_07, drill core HA_1112_D; 71.90 – 71.97 m). (b) Plagioclase (Plg) laths altered to sericite and (c) Porphyritic mafic flow has experienced sericitisation with distinct preferred orientation (red-dashed lines) (sample EE_07, drill core HA_1112_D; 71.90 – 71.97 m). (d) A strong epidotisation depicted, the plagioclase (Plg) is observed to have completely been replaced by epidote agglomerates (sample EE_08, drill core HA_1112_D; 74.27 - 74.35 m). (e) A calcite crystal engulfed by epidote, evidence of replacement (sample EE_08, drill core HA_1112_D; 74.27 - 74.35 m). (f) Calcite vein exhibiting a perfect rhombohedral cleavage (sample EE_08, drill core HA_1112_D; 74.27 - 74.35 m).

3.3 Pyroclastic rocks

Pyroclastic rocks of the KVF were collected from Zone 5 drill core borehole (HA_1112_D), from a depth of 47.97 – 50.97 m (sample EE_06), 77.97 - 81.47 m (sample EE_09) and 91.58 - 91.65 m (sample EE_10). The KVF pyroclastic rocks are generally characterised by up to 55 vol. % phenocrysts and lithic fragments (15 vol. %) set in a fine-grained microlithic groundmass (30 vol. %) (Fig. 3.5a, b, c). In sample EE_09, the lithic fragments are commonly subrounded-to angular and occur in two forms; small sized (1 – 5 mm) dark grey lithic fragments and large sized (10 – 20 mm) whitish-grey lithic fragments set in a medium-grey aphanitic groundmass (Fig. 3.5a). However, in sample EE_06 and EE_10 the dark grey lithic fragments are quite homogenous in terms of their colour index and size (1 - 5 mm) (Fig. 3.5b, c). Lithics therein are essentially subrounded and are set within a light-grey (EE_10) and reddish-grey (EE_06) aphanitic groundmass (Fig. 3.5b, c). The different lithic fragments form a sharp contact with the host rock (Fig. 3.5d, e). The pyroclastic rock is crosscut by calcite veins (Fig. 3.5a).

The fine-grained groundmass is built up mainly of microliths of plagioclase and opaque oxides occurring between microliths, thus leading to an intergranular texture (Fig. 3.6a). The randomly

arranged plagioclase laths rarely depicts polysynthetic twinning. Minor sericite replacing plagioclase is observed (Fig.3.6a, b). The phenocrysts are made up of plagioclase and calcite (Fig.3.6b, c). Plagioclase phenocryst constitutes 45 vol. % of the total phenocryst's population and is mostly subhedral (Fig. 3.6c). Calcite phenocryst represents 55 vol. % of the total phenocryst's population. It shows a euhedral shape and is characterised by multiple twinning (Fig.3.6b).

The pyroclastic rocks (EE_09) are also composed of different lithic fragments (Fig. 3.6d). The first type of lithic fragment observed is characterised by varying phenocrysts (30%) set in a recrystallised quartz groundmass (60 vol. %) with a few scattered opaque minerals 10 vol. % (Fig. 3.6e, f). Phenocrysts in lithics are essentially made up of epidote and calcite (Fig.3.6d, e, f). Epidote phenocryst (15 vol. %) is commonly subrounded-to rounded and occurs locally as inclusions in calcite crystals (Fig. 3.6e, f). Calcite (15 vol. %) exists as either euhedral free grains (phenocrysts) or veins cross cutting the rocks (Fig. 3.6h). Another type of lithic fragment observed is 90 vol. % made up of calcite (90 vol. %) and minor opaque minerals (5 vol. %) cemented together by minor (5 vol. %) recrystallised quartz (Fig. 3.6g). The calcite-rich lithic fragment also depicts a sharp contact with the host rock.

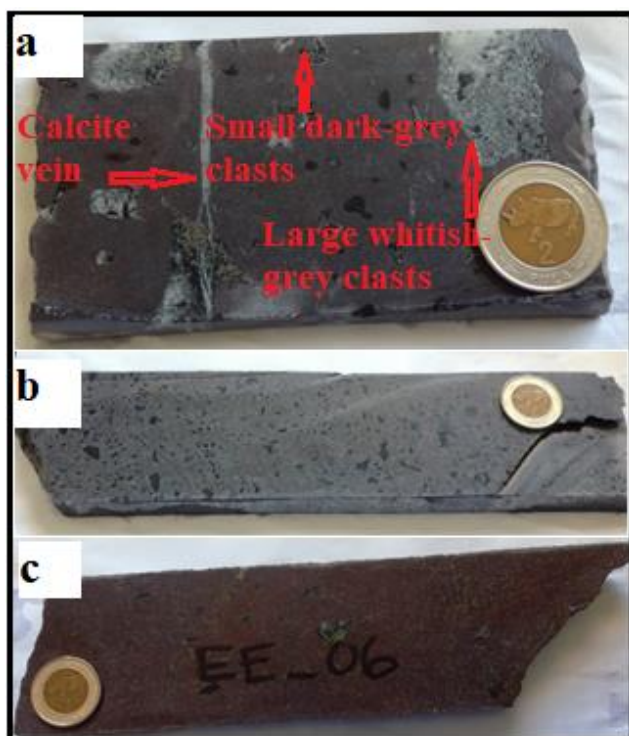


Fig. 3.5: Photographs displaying pyroclastic rocks of the KVF. (a) A pyroclastic rock with whitish-grey and dark-grey clasts within a fine-grained grey groundmass, characterised by calcite veins (sample EE_09, drill core HA_1112_D; 77.97 - 81.47 m). (b) A pyroclastic rock with homogenous small sized clasts set in a light grey aphanitic groundmass (sample EE_10, drill core HA_1112_D; 91.58 - 91.65 m). (c) A pyroclastic rock sample with a rusty red matrix with both phenocrysts and lithic fragments set in it (sample EE_06, drill core HA_1112_D; 47.97-50.97 m).

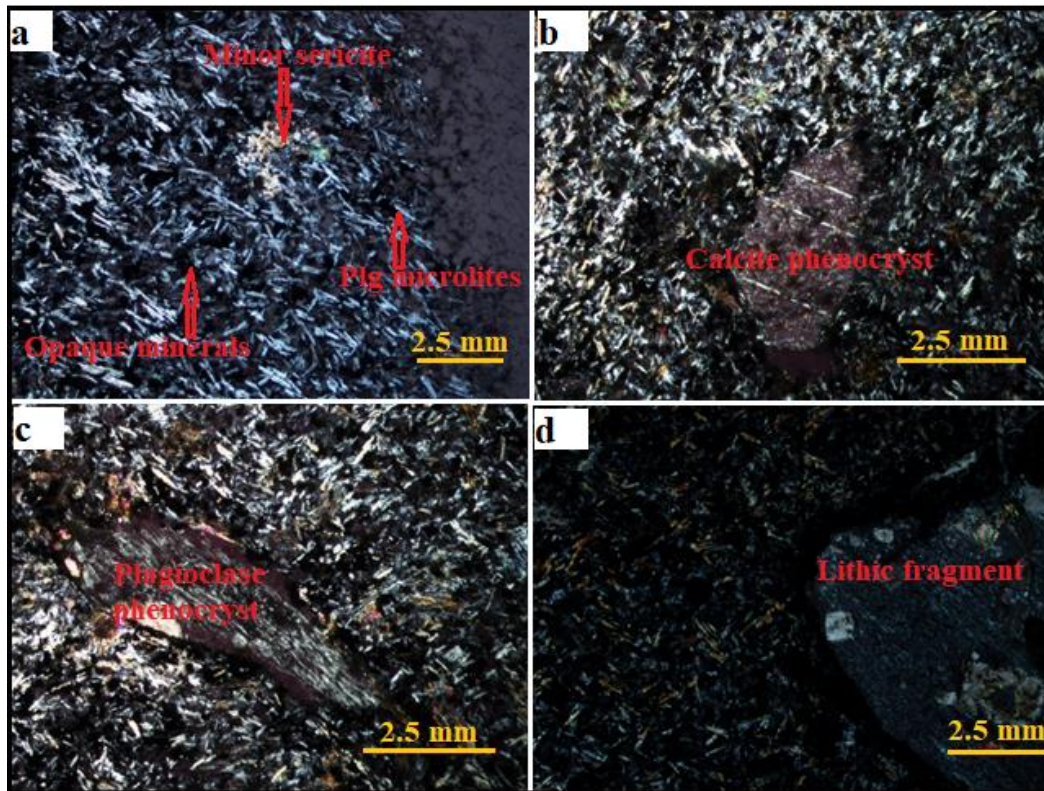


Fig. 3.6: Photomicrographs (transmitted light) of the KVF pyroclastic rocks (a) Microlithic groundmass, in some instances sericitised (sample EE_06, drill core HA_1112_D; 47.97 – 50.97 m). (b) Calcite phenocryst set in a fine-grained microlithic groundmass (sample EE_09, drill core HA_1112_D; 77.97 – 81.47 m). (c) Plagioclase phenocryst set in a fine-grained microlithic groundmass (sample EE_09, drill core HA_1112_D; 77.97 – 81.47 m). (d) A lithic fragment set in a microlithic groundmass (sample EE_09, drill core HA_1112_D; 77.97 – 81.47 m).

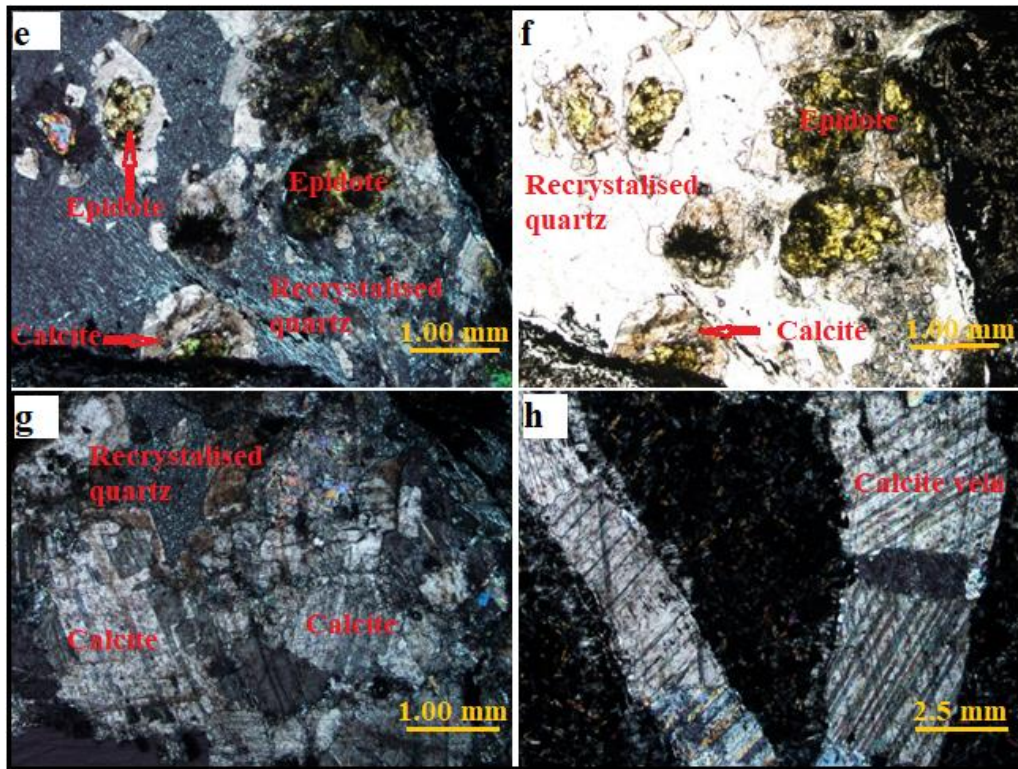


Fig. 3.6. Continued: (e, f) Lithic fragments characterised by calcite and epidote phenocrysts set in a fine-grained recrystallised quartz (sample EE_09, drill core HA_1112_D; 77.97 – 81.47 m). (g) Calcite-rich lithic fragment cemented together by recrystallised quartz (sample EE_10, drill core HA_1112_D; 91.58 -91.65 m). (h) Calcite veins cross-cutting the pyroclastic rocks (sample EE_10, drill core HA_1112_D, 91.58 – 91.65 m).

3.4 Porphyritic subvolcanic bodies

Porphyritic subvolcanic bodies (sample EE_13, EE_27 & EE_28) were collected from Kgwebe Hills, which form part of the KVF. Those mafic bodies are generally fine- to medium-grained and dark green-to light green in colour (Fig .3.7a, b). The phaneritic porphyritic subvolcanic bodies are highly rich in subrounded epidote mineral grains (Fig. 3.7b). Porphyritic subvolcanic

bodies display up to 35 vol. % phenocrysts set in an aphanitic groundmass, which constitutes 65 vol. % to the entire rock composition.

Phenocrysts of plagioclase, epidote and biotite commonly vary in size from 1 - 9 mm and rarely up to 6 cm (Fig. 3.8a, b, l). Plagioclase phenocryst represents about 65 vol. % of the entire phenocrysts' population, while epidote aggregates and biotite phenocryst represent up to 15 and 10 vol. % of the entire phenocryst population, respectively (Fig. 3.8a, b, c, l). Plagioclase is lath-shaped, subhedral-to eumorphic and occurs as well-formed prismatic crystals (Fig. 3.8a, b). It is well-twinned on albite law and Carlsbad-albite twins are rare. The lath-shaped plagioclase crystal is rarely fresh, variably and unevenly saussurite, epidote and calcite-altered (Fig. 3.8, g). Highly skeletal plagioclase is observed on a crystalline groundmass (Fig. 3.8h). Epidote phenocryst occurs commonly as coarse aggregates ranging from 5 – 15 mm and rarely up to 3 cm (Fig. 3.8a, b, c) and accessorially rutile occurs along its fracture planes (Fig. 3.8d). An alteration assemblage of epidote, actinolite and calcite was observed (Fig. 3.8i, j). In addition to the phenocrysts described above, actinolite constitutes 6 vol. % of the whole phenocryst population, while calcite constitutes 4 vol. %. Actinolite occurs as a subhedral tabular and acicular blue-green mineral (Fig. 3.8j). Calcite is clear white in colour and observed showing multiple twinning (Fig. 3.8j).

The porphyritic subvolcanic bodies have extensively been altered due to hydrothermal activity. Interstitial material, consisting mainly of chlorite is common within the rock samples (Fig. 3.8k). Interstitial chlorite is widespread and appears to have replaced primary ferromagnesian material. Assemblage of actinolite, epidote and chlorite, is an indication that the rock has undergone propylitic alteration. Biotite phenocryst is observed in most cases highly strained and the deformation affects mostly cleavage planes (Fig. 3.8l). Biotite commonly occurs with opaque minerals and mostly altered to chlorite in places and the alteration usually starts at the

margin of biotite. (Fig. 3.8l). Primary oxide grains occupy the interstices between plagioclase lath-shaped crystals (Fig. 3.8k).

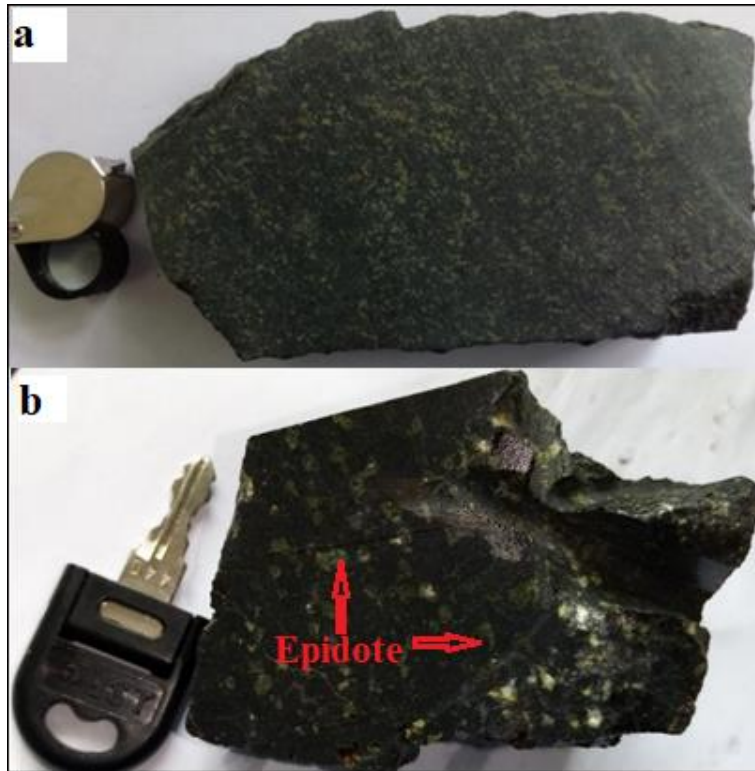


Fig. 3.7: Photographs of the porphyritic subvolcanic bodies of the KVF. (a) A fine-grained, light green porphyritic subvolcanic body (sample EE_13, Kgwebe Hills). (b) A medium-grained, dark green porphyritic subvolcanic c body highly rich in visible epidote mineral grains (sample EE_28, Kgwebe Hills).

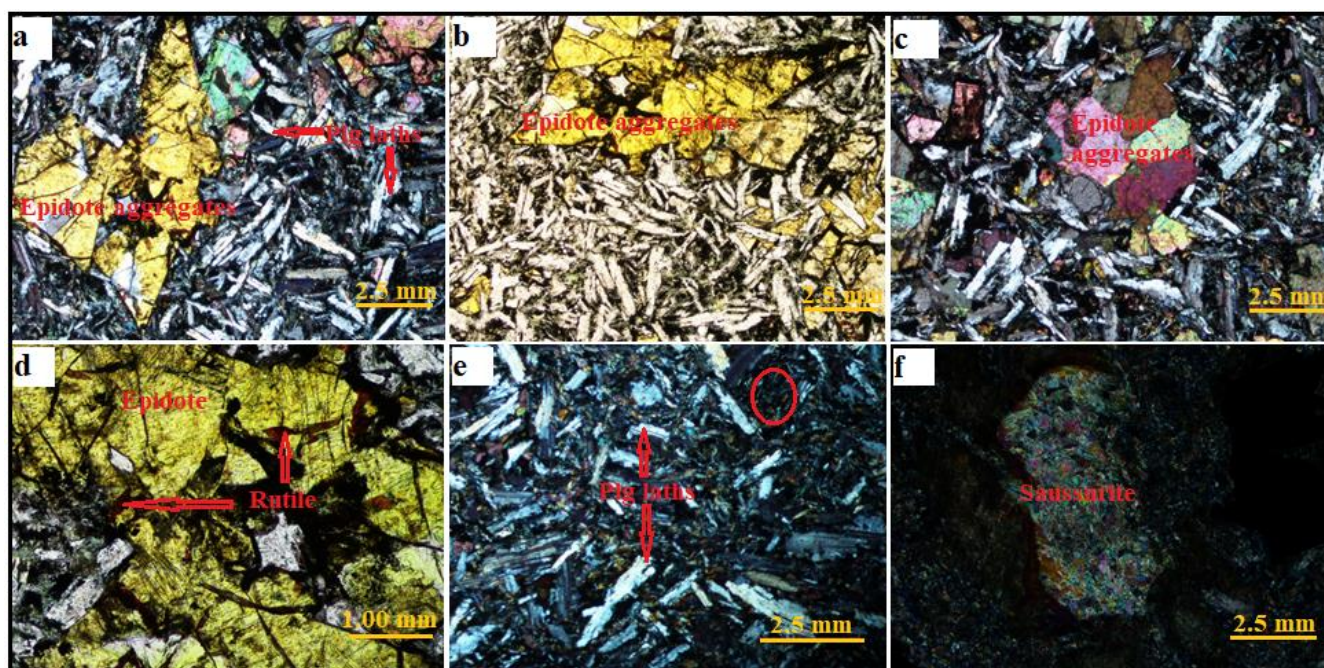


Fig. 3.8: Photomicrographs (transmitted light) of the porphyritic subvolcanic bodies. (a, b) Photomicrographs in cross polars and plane polarized light respectively showing lath-shaped plagioclase and epidote aggregates set on a fine-grained groundmass (sample EE_28, Kgwebe Hills). (c) Epidote aggregates showing high birefringence colors (sample EE_28, Kgwebe Hills). (d) A zoomed photomicrograph of an epidote with accessory rutile occurring along its fracture planes (sample EE_28, Kgwebe Hills). (e) Subhedral to eumorphic plagioclase occurring as prismatic crystals with white and grey interference colors on a fine-grained slightly epidotised groundmass (circle) (sample EE_13, Kgwebe Hills). (f) Saussuritised plagioclase laths resulting into a mineral aggregate of epidote, sericite and calcite (sample EE_27, Kgwebe Hills).

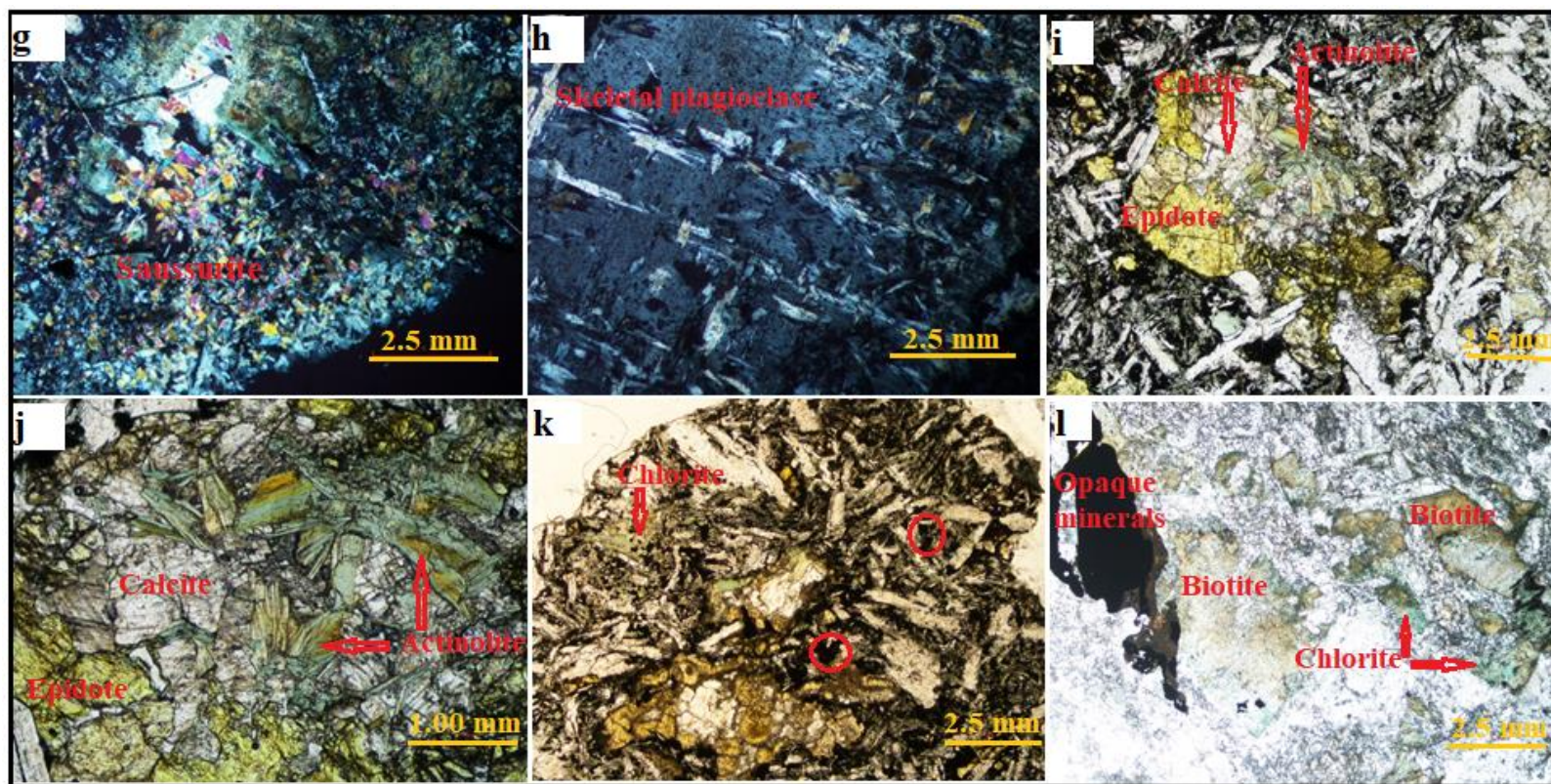


Fig. 3.8 Continued: (g) Saussuritised plagioclase laths resulting into a mineral aggregate of epidote, sericite and calcite (sample EE_27, Kgwebe Hills). (h) Highly skeletal plagioclase laths on a fine-grained groundmass (sample EE_27, Kgwebe Hills). (i, j) Plane polarized photomicrographs showing alteration assemblage of epidote, actinolite and calcite (sample EE_28, Kgwebe Hills). (k) Photomicrographs of plane polarized light displaying interstitial material, consisting mainly of chlorite occupying spaces between plagioclase lath-shaped crystals and opaque minerals (circles) (sample EE_28, Kgwebe Hills). (l) Biotite occurring with opaque minerals and replaced at the rim by chlorite (sample EE_27, Kgwebe Hills).

3.5 Quartz-feldspar porphyries

The quartz-feldspar porphyries forming part of the KVF were collected from four localities; Kgwebe Hills (samples EE_12, EE_14, and EE_15), Mabeleapudi Hills (sample EE_16), Mabeleapudi Quarry (samples EE_17, EE_18, EE_19, and EE_20) and Mango Dome (samples EE_21, EE_22, EE_23) (see Table 1.1 for the sample locations). The quartz-feldspar porphyries are generally characterised by subrounded-to rounded isolated phenocrysts (45 vol. %) of various sizes, set in either a grey, dark grey, blackish-grey or medium purple fine-grained groundmass (55 vol. %) (Fig. 3.9a, b, c, d). The quartz-feldspar porphyries are either altered or unaltered and exhibit a porphyritic texture. The quartz-feldspar porphyries were discriminated into three groups according to the nature and abundance of phenocrysts and the texture. These include: quartz-orthoclase porphyries; quartz-orthoclase-plagioclase-microcline porphyries, and; flow-banded quartz-feldspar porphyries.

Massive quartz-orthoclase porphyries are characterised by quartz, orthoclase phenocrysts and opaque minerals set in a fine-grained groundmass (Fig. 3.10a, b). The groundmass shows an equigranular texture defined by near equal microcrystalline quartz and orthoclase, with few dispersed opaque mineral crystals (Fig. 3.10a, b). Quartz phenocrysts represent about 45 vol. % of the entire phenocryst population, while orthoclase constitutes 40 vol. % to the entire phenocryst population and the remaining 15vol. % is contributed by the opaque mineral magnetite (Fig. 3.10a, b). Phenocrysts of quartz and orthoclase commonly vary in size from 1 – 4 mm and rarely up to 2 cm. Quartz phenocryst is abundant as euhedral crystals with linear dimensions up to 3 mm (Fig. 3.10a). However, some quartz crystals are anhedral and small in size (1 mm) (Fig. 3.10c). In places, quartz phenocrysts correspond to “quartz eyes” which are partly resorbed (**cf. Bineli Betsi and Lentz 2010**) (Fig. 3.10c). Resorbed crystals commonly have rounded corners or are embayed with an amoeboid appearance. “Quartz eyes” are unstrained (Fig. 3.10c). Feldspar phenocrysts are represented by orthoclase, which is mostly

euohedral-to subhedral and displays a brownish speckling or clouding colour (Fig. 3.10b). The orthoclase phenocryst varies in size from 2 – 4 mm and rarely up to 3 cm. Magnetite is scattered within the quartz-feldspar porphyries and is variable in terms of its size (0.5 mm – 1 mm) (Fig. 3.10a, b) and is subhedral-to anhedral (Fig. 3.10b).

Quartz-orthoclase-plagioclase-microcline porphyries are characterised by quartz, orthoclase, plagioclase, microcline and opaque minerals set in a microcrystalline sericitised groundmass (Fig. 3.10e). The microcrystalline groundmass (< 1 mm) built up of minute crystalline grains of feldspar is widely altered to saussurite mainly, with in places, epidote and sericite. The phenocrysts are represented by quartz, orthoclase, plagioclase, opaque minerals and microcline, constitute about 45 vol. %, 30 vol. %, 8 vol. %, 5 vol. % and 2 vol. % respectively of the total phenocryst's population. Quartz phenocryst varies in size from 1 – 3 mm and it is commonly euohedral with undulose extinction, thus indicating the rock has been strained. Orthoclase phenocryst is cloudy, anhedral-to subhedral with sizes varying from 2 – 7 mm and rarely up to 2 cm. Microcline crystals (3 – 5 mm) showing weak tartan twinning are rarely observed (Fig. 3.10g). Anhedral plagioclase phenocryst is also rare and it displays polysynthetic twinning on rotation, strong resorbed margins and slight epidotisation at the margins (Fig. 3.10d). Magnetite is scattered within the quartz-orthoclase-plagioclase-microcline porphyries and is variable in terms of its size (0.5 mm – 1 mm). It exhibits subhedral-to anhedral crystal shapes and it is locally observed as isolated crystals. Accessory minerals present are subrounded epidote (Fig. 3.10d), rutile and tabular biotite (Fig. 3.10h). Quartz does not only occur as phenocrysts but also as an infill in fractures (Fig. 3.10f). Fractures are commonly filled by euohedral equant quartz crystals with undulatory extinction with no suturing. In some instances, quartz shows very fine grains with both sutured and gradational

boundaries (Fig. 3.10i, j). Quartz is also observed displaying an elongated fabric-like texture, suggesting that the quartz has been strained and recrystallised (Fig. 3.10j).

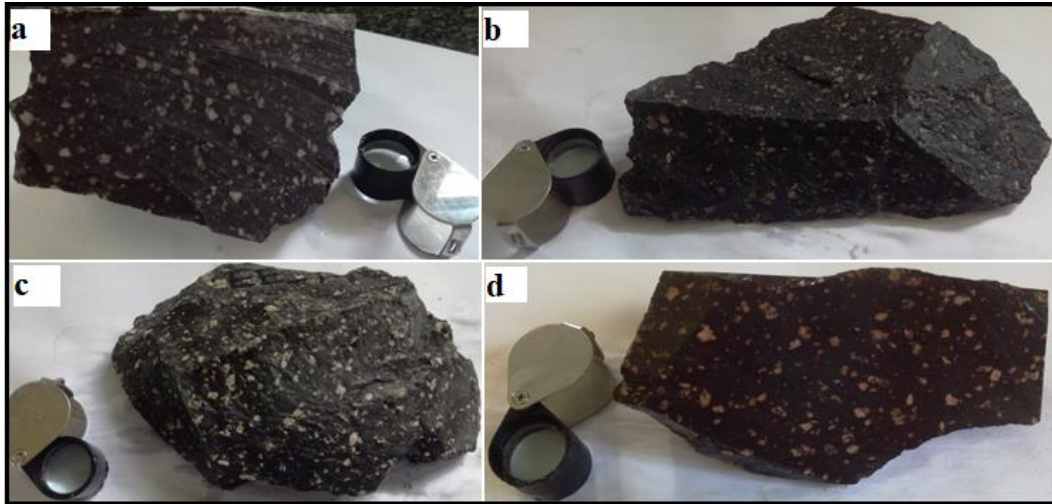


Fig. 3.9: Photographs of different Quartz-feldspar porphyries of the KVF varying in colour of the groundmass. The Quartz-feldspar porphyries displays subrounded to rounded isolated phenocrysts of various sizes set in either (a) grey (sample EE_17, Mabeleapudi Quarry), (b) dark grey (sample EE_16, Mabeleapudi Hills), (c) blackish-grey (sample EE_19, Mabeleapudi Quarry) or (d) medium purple (sample EE_14, Kgwebe Hills) fine-grained groundmass.

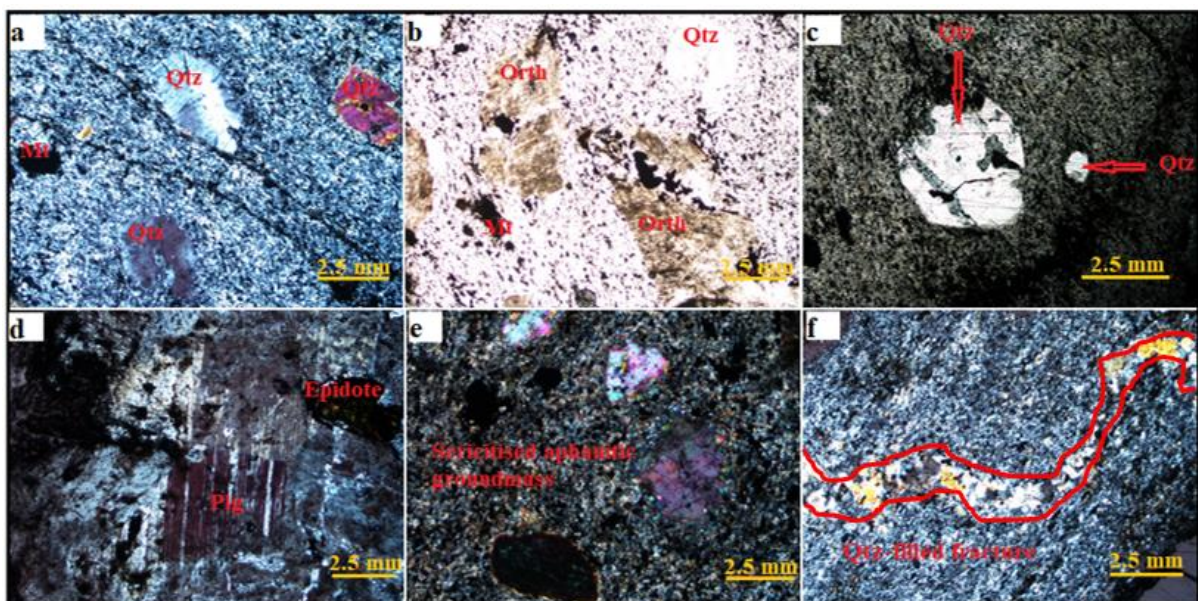


Fig. 3.10: Photomicrographs (transmitted light) of Quartz-feldspar porphyries of the KVF. (a) Euhedral quartz (Qtz) phenocrysts displaying undulose extinction and magnetite (Mt) set on a fine-grained groundmass of near equal quartz, plagioclase and orthoclase (quartz-orthoclase porphyry, sample EE_12). (b) Euhedral to subhedral orthoclase (orth) phenocrysts displaying a brownish speckling or clouding colour in plane polarised light and scattered magnetite (Mt) (quartz-orthoclase porphyry, sample EE_12) (c) Varying sizes of quartz phenocrysts on a fine-grained matrix (Quartz-orthoclase porphyry, sample EE_14). (d) A cross polarised light photomicrograph of plagioclase (plg) phenocryst showing a polysynthetic twinning and slightly epidotised at the margins (Quartz-orthoclase-plagioclase-microcline porphyry, sample EE_16) (e) A porphyritic texture defined by quartz, orthoclase, plagioclase and opaque minerals set in a microcrystalline sericitised groundmass (Quartz-orthoclase-plagioclase-microcline porphyry, sample EE_17). (f) Fracture filled by euhedral equant quartz crystals showing undulatory extinction with no suturing (quartz-orthoclase-plagioclase-microcline porphyry, sample EE_19)

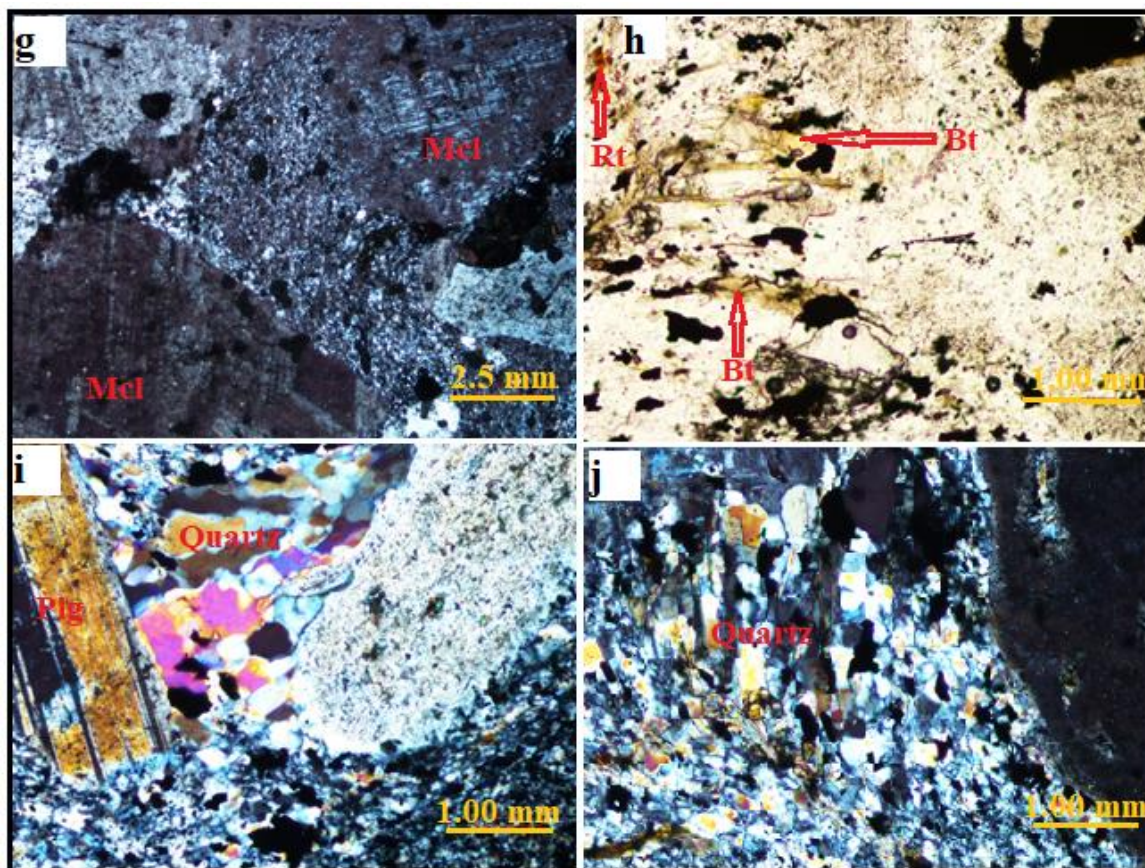


Fig. 3.10 Continued: (g) Microcline (Mcl) crystals showing weak tartan twinning (Quartz-orthoclase-plagioclase-microcline porphyry, sample EE_19). (h) Accessory minerals biotite (Bt) and rutile (Rt) (quartz-orthoclase-plagioclase-microcline porphyry, sample EE_20) (i, j) Recrystallised quartz with sutured and gradational margins and a plagioclase grain (quartz-orthoclase-plagioclase-microcline porphyry, sample EE_20).

Flow-banded quartz-feldspar porphyries are characterised by isolated phenocrysts and phaneritic felsic bands set in a microcrystalline flow-banded groundmass (Fig. 3.11a, b). The groundmass represents 45 vol. % to the entire rock and is built up of microcrystalline quartz, plagioclase, orthoclase and opaque minerals with flow-banding locally preserved (Fig. 3.12a, b). The phenocrysts constitute 30 vol. % to the rock and include quartz, orthoclase, myrmekite, plagioclase and opaque minerals. These phenocrysts constitute 45 vol. %, 35 vol. %, 10 vol. %, 5 vol. % and 5 vol. %, respectively of the total phenocrysts population. Quartz phenocryst

generally shows a size range between (1 – 2 mm) and it is commonly anhedral, broken and embayed (Fig. 3.12c). However, in some instances the quartz phenocryst is well-formed and euhedral in shape (Fig 3.12g). Quartz phenocryst occurs as either individual mineral grains within the rock or as inclusions in k-feldspar (Fig. 3.12d). Undulose extinction is common in the quartz grains. K-feldspar is the most abundant feldspar phenocryst and includes euhedral orthoclase (3- 5mm) depicting a cloudy texture (Fig. 3.12d). Myrmekitic texture is observed and occurs as vermicular or wormy intergrowth of quartz and plagioclase (Fig. 3.12e). Plagioclase mineral crystal is rare (5 vol. %) and where it is observed, it is a bit fresher and polysynthetic twinning is depicted (Fig. 3.12h). The coarse-grained felsic bands were observed representing 15 vol. % to the entire rock population (Fig. 3.12f, g, h). They are elongated and almost parallel to one another, although the mineral bands are long and narrow, they are made up of mineral crystals that are roughly equidimensional (Fig. 3.12f, g). The felsic bands are entirely built by subhedral quartz grains showing both sutured and sharp boundaries, plagioclase and myrmekite (Fig. 3.12h).

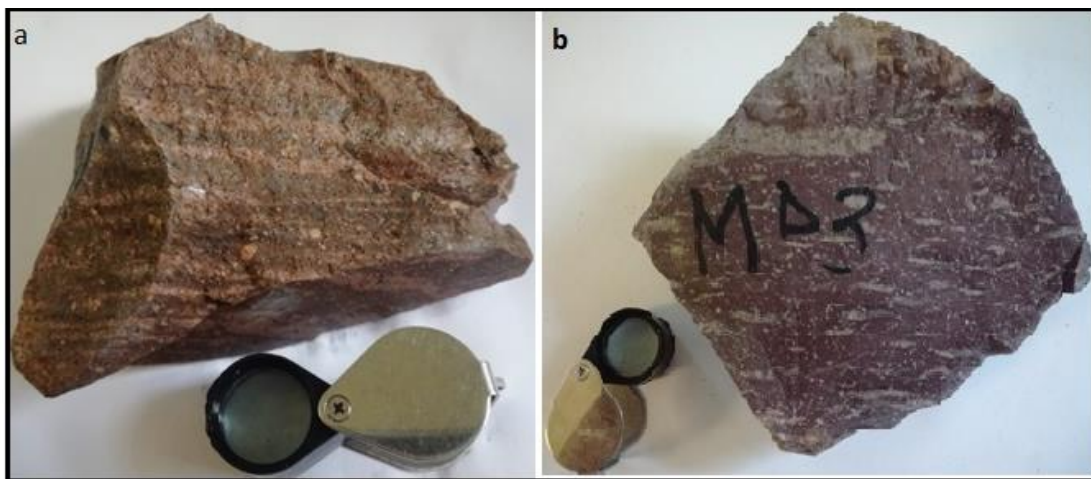


Fig. 3.11: Photographs of flow-banded quartz-feldspar porphyries of the KVF (a) A light pink phaneritic quartz-feldspar porphyry with flow-banding depicted (sample EE_21, Mango Dome). (b) An intensely purple coloured quartz-feldspar porphyry (sample EE_23, Mango Dome).

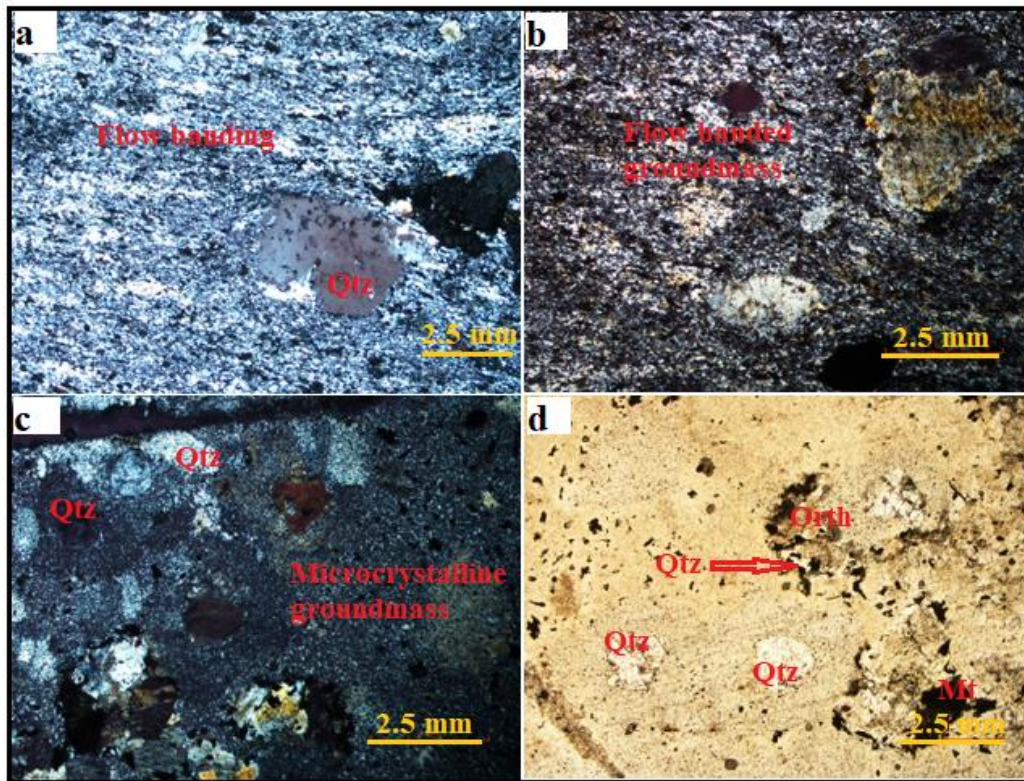


Fig. 3.12: Photomicrographs (transmitted light) of flow-banded quartz-feldspar porphyries. (a, b) Flow-banded groundmass locally preserved (sample EE_21, Mango Dome). (c, d) Flow-banded quartz-feldspar porphyries with quartz (Qtz), orthoclase (Orth) phenocrysts and scattered magnetite (Mt) set in a microcrystalline groundmass (EE_21). In (d) quartz is observed occurring as an inclusion in orthoclase (arrow).

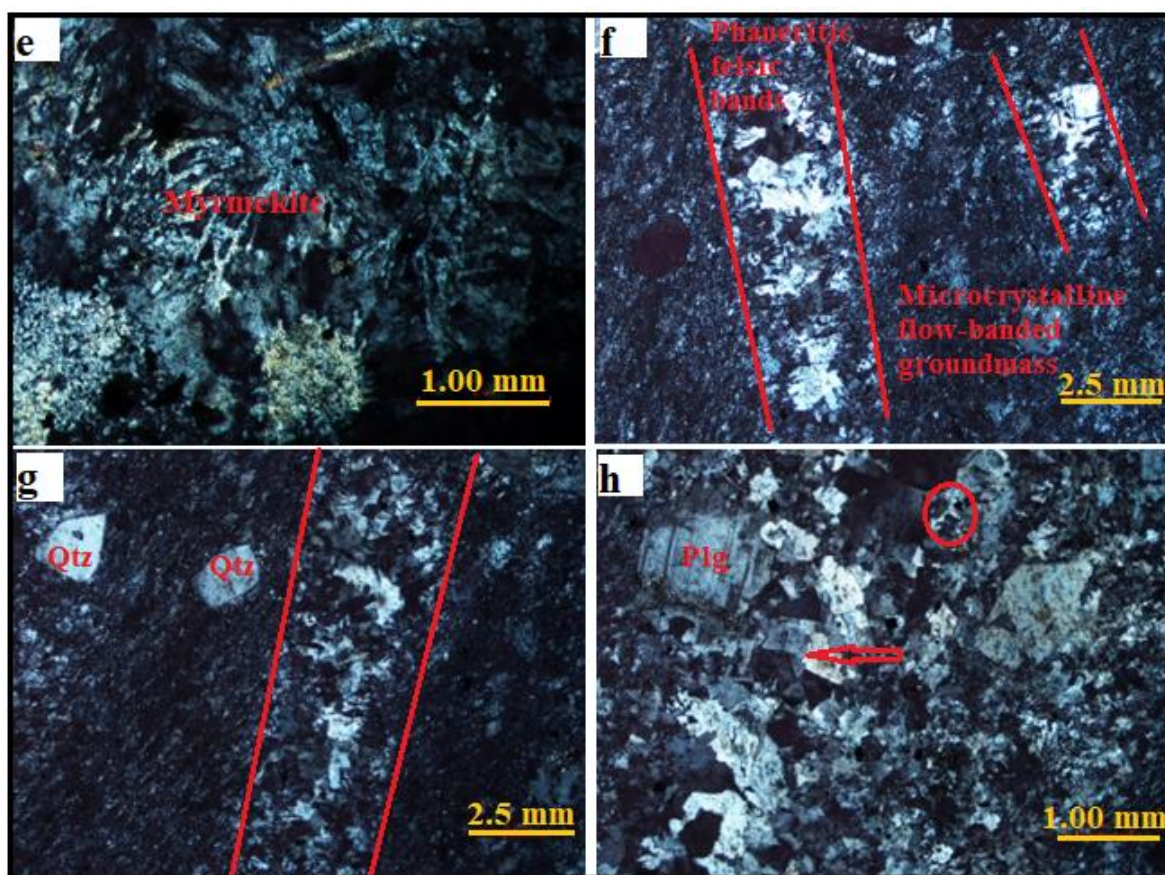


Fig. 3.12 continued: (e) Photomicrograph showing myrmekite texture occurring as vermicular or wormy intergrowth of quartz and plagioclase (sample EE_23, Mango Dome). (f) Elongated and almost parallel phaneritic felsic bands (red lines) set in a microcrystalline flow-banded groundmass (sample EE_23, Mango Dome). (g) Both quartz (Qtz) phenocrysts and coarse-grained felsic bands (red lines) set in a microcrystalline flow-banded groundmass (sample EE_23, Mango Dome). (h) A zoomed image of the felsic bands made up of minerals roughly equidimensional, quartz shows both sutured (circle) and sharp boundaries (arrow) and a plagioclase (plg) mineral grain (sample EE_23, Mango Dome).

3.6 Clastic sedimentary rocks

Clastic sedimentary rocks of various colour and texture (samples EE_03 and EE_11) were collected from Zone 5 availed drill cores of borehole HA_1112_D, from depths of 41.65 - 41.81m and 79.19 - 80.23m. A medium grained planar laminated and brownish sand-sized

clastic sedimentary rock (EE_03) was observed (Fig. 3.13a). It is intercalated within the amygdaloidal rocks of the KVF. A sharp contact is depicted by the two rock types (Fig. 3.13a). Another fine-grained clastic sedimentary rock (sample EE_11) showing a fairly uniform light green colour was observed (Fig. 3.13b). It is locally crosscut by minor calcite veins (Fig. 3.13b).

Petrographic study of the clastic sedimentary rocks reveals that they consist of fine-to coarse sand- sized grains, thus poorly-to-moderately sorted. Poor sorting is an evidence that the rocks are texturally immature. The clastic sedimentary rocks are characterised by sand-sized grains (0.07 – 2 mm) of more than one mineral (Fig. 3.14a, b). The varying amounts of framework grains are identified to be quartz (Qtz) constituting 70 vol. % of the whole rock population, feldspars especially plagioclase (Plg) 10 vol. %, k-feldspar 5 vol. % and biotite (Bt) 5 vol. %, all adhered together by commonly opaque minerals, particularly magnetite (2 vol. %) and calcite (8 vol. %) cement (Fig. 3.14a, b, d). The mineral grains are commonly subrounded-to subangular. Quartz is invariably clear unaltered and exhibits undulose extinction (Fig. 3.14c). Quartz grains consists of crystals with both sharp and sutured boundaries (Fig. 3.14d). The feldspathic framework grains are commonly the second most abundant mineral and are represented by the plagioclase feldspar and k-feldspar. The plagioclase minerals show simple and polysynthetic twinning (Fig. 3.14c). K-feldspar grains are anhedral and display a cloudy texture (Fig. 3.14f). Calcite veins cross-cutting the clastic sedimentary rocks (Fig. 3.14f, g, h) are locally observed. Common accessory minerals include biotite and it was observed as an inclusion in a quartz crystal (Fig. 3.14e).

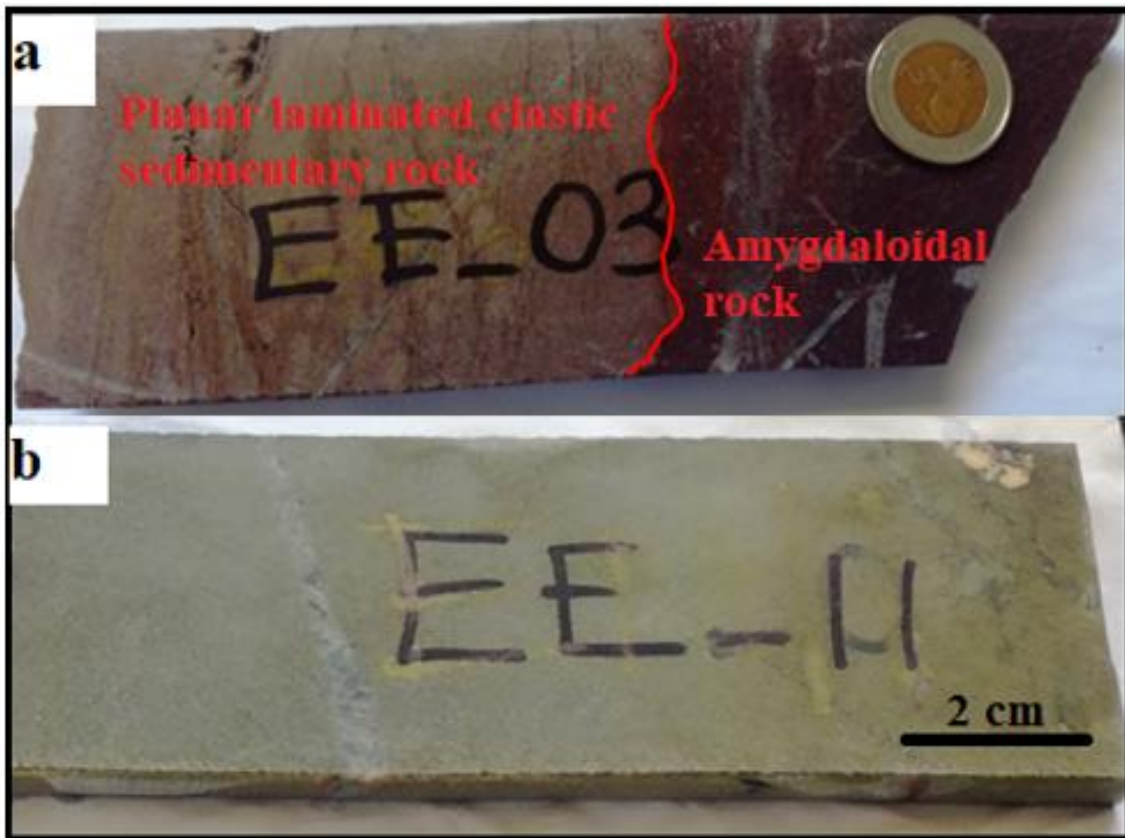


Fig. 3.13: Photographs of clastic sedimentary rocks depicting variations in colour, texture and structures. (a) A medium-grained planar laminated brownish sand-sized clastic sedimentary rock in a sharp contact with an amygdaloidal rock (sample EE_03, drill core HA_1112_D; 41.65 - 41.81 m). (b) A fine-grained clastic sedimentary rock showing a fairly uniform light green colour cut across by calcite veins (EE_11, drill core HA_1112_D; 79.19 - 80.23 m).

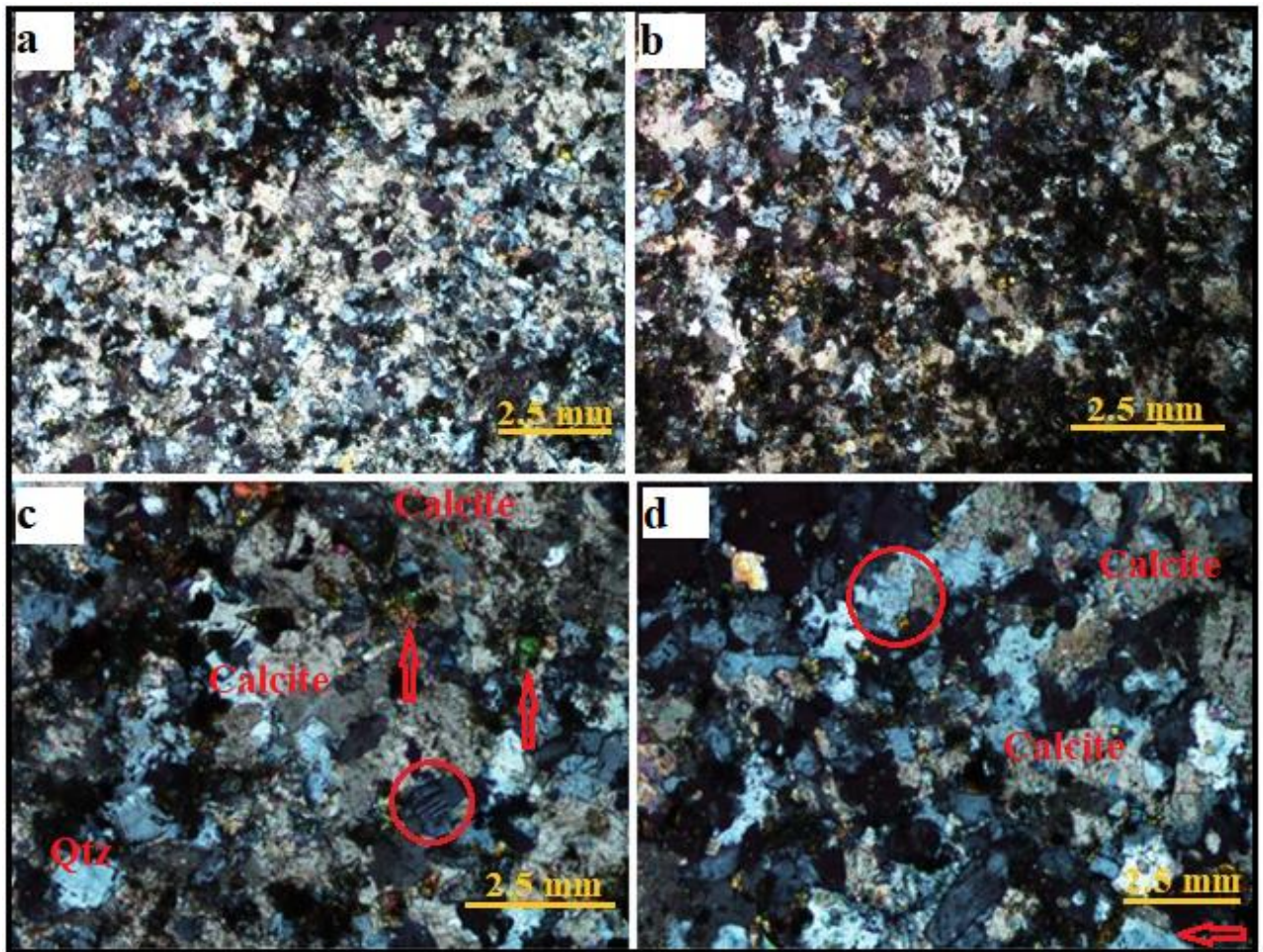


Fig. 3.14: Photomicrographs (transmitted light) of clastic sedimentary intercalated within the KVF. (a, b) Poorly-to moderately sorted clastic rock (sample EE_03, drill core HA_1112_D; 41.65 - 41.81 m and EE_11, drill core HA_1112_D; 79.19 - 80.23m). (c) Varying amount of framework grains: quartz (Qtz), plagioclase (circle) and slightly epidotised plagioclase (arrows) adhered together by calcite cement. (d) Sutured (circle) and straight boundaries (arrow) in quartz framework grain.

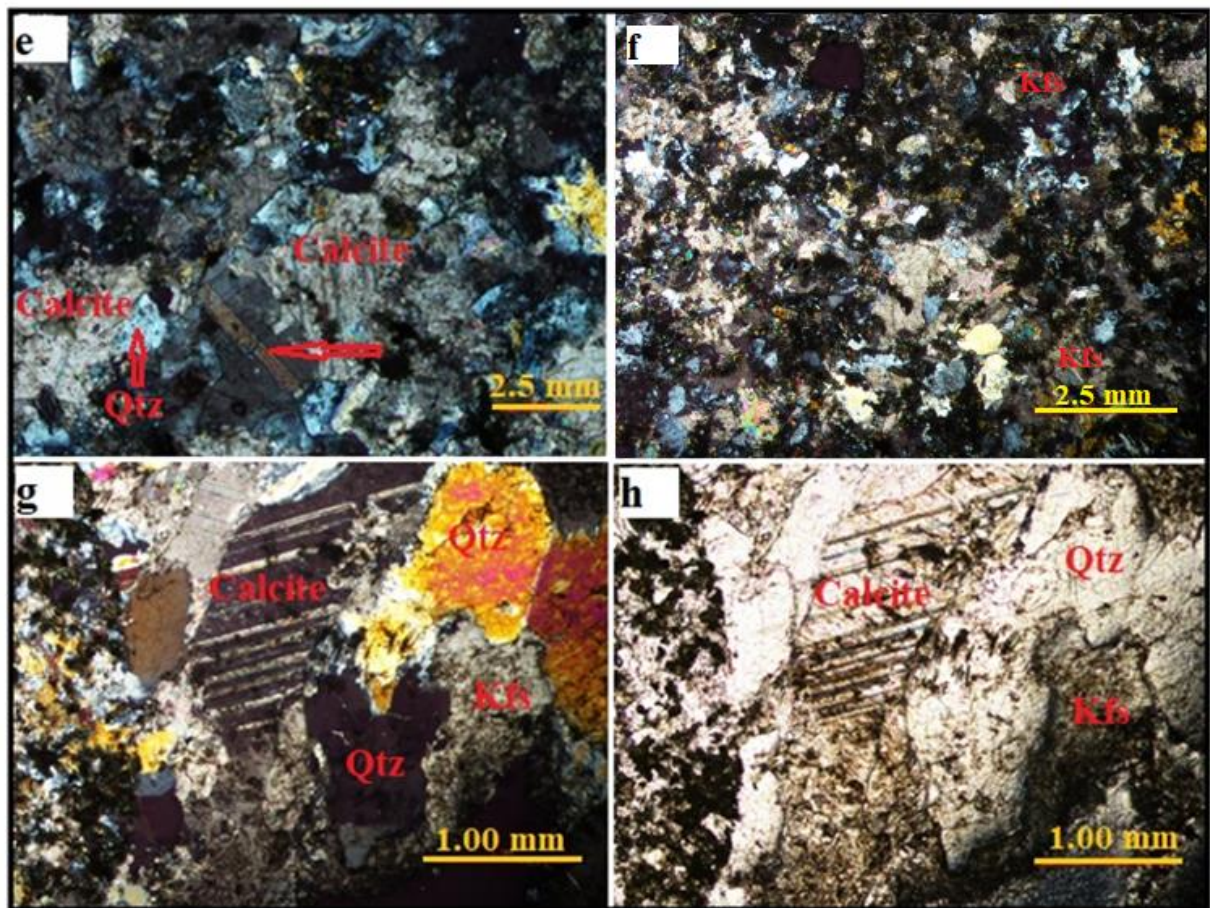


Fig. 3.14 Continued: (e) A biotite (Bt) mineral as an inclusion inside a quartz grain (red arrow). (f) K-feldspar mineral depicting a cloudy texture within a clastic sedimentary rock. (g, h) Cross polarised and plane polarised light of zoomed images of a carbonate vein, filled dominantly by calcite, quartz (Qtz) and k-feldspar (Kfs).

CHAPTER 4

GEOCHEMICAL COMPOSITIONS OF THE KGWEBE VOLCANIC FORMATION.

The main purpose of this chapter is to highlight the geochemical features of the different units of the KVF and elaborate on the Cu-Ag content of the KVF rock units. As every sample has a loss on ignition (LOI) effect and in order to eliminate the effect of LOI, the major and minor-element analysis results have been normalized to 100 wt. % for the results to be anhydrous. Moreover, the chapter also answer to the objective stating whether or not the Cu and Ag in the KVF rock units could have accounted for the total Cu and Ag budget at the KCM Property.

4.1 Mobility

As indicated in Chapter 3, KVF rock units are deformed and variably altered/weathered. Rocks subjected to post-formation processes such as hydrothermal alteration, metamorphism and weathering are likely to undergo elements mobility, because their mobility is controlled by mineralogical changes taking place during alteration and the fluid phase nature (**Floyd and Winchester, 1978**). The magnitude of alteration was estimated from LOI (see **Table 4.1**), where the quartz-feldspar porphyries recorded 0.37 wt. % LOI on average, whereas the porphyritic subvolcanic have an average LOI of 1.97 wt. %. Porphyritic mafic flows and pyroclastic rocks recorded LOI of 4.19 wt. % and 6.13 wt. %, respectively. Of all the KVF rock units, the amygdaloidal rocks and the clastic sedimentary rocks recorded the highest LOI values, averaging 9.93 wt. % and 12.78 wt. %, respectively. **Rollinson (1993)** suggested that before undertaking any petrogenetic investigation of rocks, it is vital to show or demonstrate

that concentrations of assessed elements are undisturbed by post formation processes. Hydrothermal alteration for example changes the behaviour of an element such that its ionic potential changes (**Pearce, 1996**) and elements forming ions of low ionic potential ($< 0.03 \text{ pm}$) are usually removed in solution as hydrated oxyions (**Hastie, 2007**), whereas those with intermediate ionic potential ($0.03\text{-}0.10 \text{ pm}^{-1}$) tend to remain in the solid product and are thus immobile.

Table 4.1

LOI values of the investigated KVF rock samples.

SAMPLE ID	LITHOLOGIES	LOI (wt.%)	Av. (wt.%)
EE_01	Amygdaloidal rock	15.56	9.93
EE_02	Amygdaloidal rock	10.76	
EE_04	Amygdaloidal rock	6.87	
EE_05	Amygdaloidal rock	6.54	
EE_07	Porphyritic mafic flow	4.73	4.19
EE_08	Porphyritic mafic flow	3.64	
EE_06	Pyroclastic rock	3.79	6.13
EE_09	Pyroclastic rock	7.98	
EE_10	Pyroclastic rock	6.62	
EE_12	Quartz-feldspar porphyry	0.56	0.37
EE_14	Quartz-feldspar porphyry	0.34	
EE_15	Quartz-feldspar porphyry	0.45	
EE_16	Quartz-feldspar porphyry	0.2	
EE_17	Quartz-feldspar porphyry	0.61	
EE_18	Quartz-feldspar porphyry	0.29	
EE_19	Quartz-feldspar porphyry	0.19	
EE_20	Quartz-feldspar porphyry	0.33	
EE_21	Quartz-feldspar porphyry	0.28	
EE_22	Quartz-feldspar porphyry	0.51	
EE_23	Quartz-feldspar porphyry	0.33	
EE_27	Porphyritic subvolcanic body	2.02	1.93
EE_28	Porphyritic subvolcanic body	2.3	
EE_13	Porphyritic subvolcanic body	1.47	
EE_03	Clastic sedimentay rock	16.23	12.78
EE_11	Clastic sedimentay rock	9.33	

Note: LOI stand for loss on ignition, Av. stands for average

As observed in the petrography chapter and considering the LOI values mentioned above, rocks of KVF are variably altered and post magmatic element mobilization cannot be ruled out. Therefore, bivariate variation plots (Fig. 4.1) are used in this section to test for the mobility of elements and outline the mobile and immobile elements. Zirconium (Zr) was chosen for the horizontal axes because it is one of the most immobile elements (**Cann, 1970**), whereas selected HSFE, REE, LILE and major elements were plotted on the vertical axes of the bivariate variation plots.

In the plot of Zr (ppm) against Ba (ppm), the quartz-feldspar porphyries show a positive correlation and a slope of unity with a square coefficient of correlation (R^2) = 0.49. However, the amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and porphyritic subvolcanic bodies yielded a much greater scattered pattern and show R^2 of 0.37. Similarly, in the plot of Zr (ppm) against Gd (ppm), immobile behaviour is highly depicted by a linear trend with a slope of unity given by the KVF rock units. A significant positive correlation is given by the quartz-feldspar porphyries with higher R^2 of 0.74 and other KVF rock units also recorded a high R^2 of 0.66, thus suggesting Gd was relatively immobile during post magmatic processes that affected the KVF rock units. The quartz-feldspar porphyries show a poor correlation between Zr (ppm) and Nd (ppm) with R^2 = 0.38, whereas the amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and porphyritic subvolcanic bodies show an improved correlation between Zr (ppm) against Nd (ppm) and altogether recorded a positive R^2 of 0.64, therefore, Nd is immobile for the amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and porphyritic subvolcanic bodies and mobile for the quartz-feldspar porphyries. The KVF elements display a linear trend and significant positive correlation in the plot of Zr (ppm) against Nb (ppm). The quartz-feldspar porphyries and all the other KVF rock units grouped together display a pronounced correlation R^2 of 0.89 and 0.87, respectively. This gives us evidence that Nb is immobile and can be used for petrogenesis purposes, thus clearly

supporting that Niobium is one of the most immobile elements (**Cann, 1970; Hill et al., 2000; Kurtz et al., 2000**). Positive correlation is also witnessed in the plots of Zr (ppm) against Y and Th (ppm). Just like in the above-mentioned plots, the quartz-feldspar porphyries for Y and Hf plots indicate a significant positive correlation coefficient with R^2 of 0.81 and 0.96, respectively. The R^2 for the amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and porphyritic subvolcanic mafic bodies for Y and Hf is 0.57 and 0.97, respectively. Generally, plots of immobile incompatible trace elements display well defined positive correlation with little scattering of values (Fig. 4.1). The observed trends are basically typical of magmatic processes, such as variable degrees of partial melting. Therefore, suggestion is that the observed geochemical variations of the investigated KVF rocks are as a result of petrogenetic processes and are unlikely to result from alteration. The results support the fact that alteration did not significantly affect the mobility of the above assessed elements and their concentration can be used to infer petrogenetic processes (**Manya, 2016**).

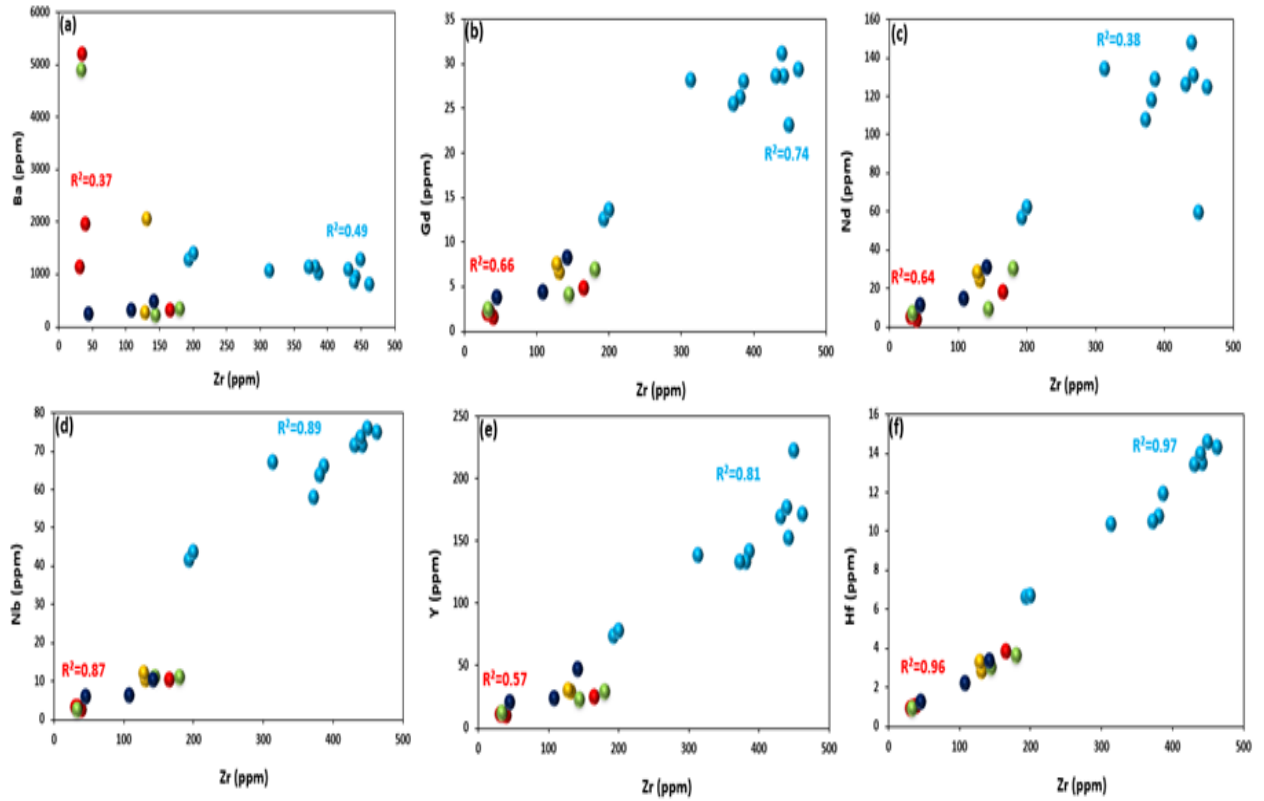


Fig. 4.1: Bivariate plots of Zr (ppm) against selected HFSE, REE, LILE and major elements for KVF rock units. (a) Zr (ppm) vs. Ba (ppm) showing a negative correlation. (b) Zr (ppm) vs. Gd (ppm) displaying a positive correlation. (c) Zr (ppm) vs. Nd (ppm) showing a positive correlation. (d) Zr (ppm) vs. Nb (ppm) showing a positive correlation. (e) Zr (ppm) vs. Y (ppm) showing a positive correlation. (f) Zr (ppm) vs. Th (ppm) showing a positive correlation. Quartz-feldspar porphyries (blue), amygdaloidal rocks (red), porphyritic mafic flows (yellow), pyroclastic rocks (green) and porphyritic subvolcanic bodies (navy blue).

The major elements generally show poor-to moderate correlation with Zr (low- to moderate R^2 values) and yielded much greater scattered patterns. The plot of Zr (ppm) against SiO_2 (wt. %) recorded R^2 of 0.64 for the quartz feldspar porphyries and a low R^2 of 0.05 for the amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and porphyritic subvolcanic mafic bodies. The plot of Zr (ppm) against Na_2O (wt. %) on the other hand yielded low R^2 for both quartz feldspar porphyries and the other magmatic rocks (0.08 and 0.05, respectively). R^2 0.07 and 0.28 were recorded in the plot of Zr (ppm) against K_2O (wt. %) for quartz feldspar porphyries

and other magmatic rocks, respectively. The plot of Zr (ppm) against TiO_2 (wt. %) however, recorded relatively high R^2 of 0.72 for the amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and porphyritic subvolcanic bodies whereas, the quartz feldspar porphyries yielded R^2 of 0.14.

According to the above results, SiO_2 (wt. %), Na_2O (wt. %), and K_2O (wt. %) are mobile for amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks, and porphyritic subvolcanic bodies, whereas TiO_2 (wt. %) is immobile for the aforementioned KVF rock units. However, SiO_2 (wt. %) is relatively immobile in quartz-feldspar porphyries, whereas Na_2O (wt. %), K_2O (wt. %) and TiO_2 (wt. %) are mobile in quartz-feldspar porphyries. As a result of the immobility of the aforementioned major elements, the above results cannot be used for petrogenetic purposes. To be more specific, only the TiO_2 (wt. %) can be used for petrogenetic purposes in amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks, and porphyritic subvolcanic bodies, whereas SiO_2 (wt. %) can be used for petrogenetic purposes in quartz-feldspar porphyries. Because the results for the rest of the aforementioned major elements are mobile, they should be taken with caution.

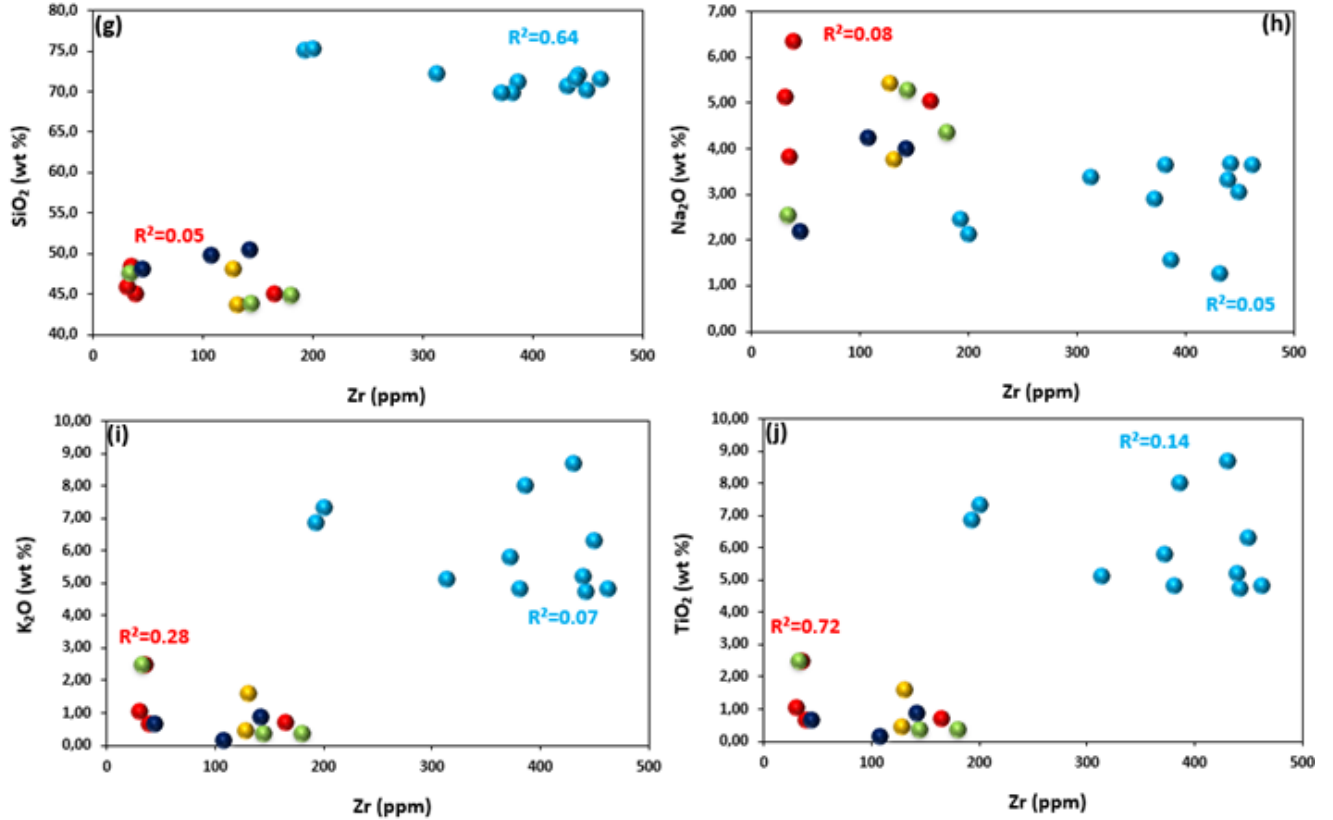


Fig. 4.1: Continued All major elements show a much greater scatter with Zr. (g) Zr (ppm) vs. SiO₂ (wt. %). (h) Zr (ppm) vs. Na₂O (wt. %). (i) Zr (ppm) vs. K₂O (wt. %). (j) Zr (ppm) vs. TiO₂ (wt. %).

4.2 Nomenclature of KVF rock units

Based on the Si contents, KVF rocks units can be discriminated into two end members including the ultra mafic- to mafic series (43.66 – 50.50 wt.% SiO₂, **Table 4.2**) and the felsic series with 69.84 -75.22 wt.% SiO₂ (**Table 4.2**). However, as elaborated in section 4.1, the SiO₂ content of ultra mafic- to mafic KVF units is likely to have undergone post crystallisation changes, and the yielded SiO₂ values are to be taken with caution. Furthermore, in the plot of immobile (as assessed in the **section 4.1** above) trace elements (e.g., Nb/Y vs. Zr/Ti, **Fig. 4.2**), amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and porphyritic subvolcanic bodies are mainly subalkaline basaltic in composition. The compositions of amygdaloidal rocks and porphyritic mafic flows is therefore consistent with the name “basalt” given to these units

within the KCM Project. Similarly, the porphyritic subvolcanic bodies are chemically and texturally consistent with the “dolerite” name given to these magmatic bodies within the KCM Project. On the other hand, quartz-feldspar porphyries are essentially rhyolitic/dacitic in composition, with however, three samples plotting in the andesite/andesite basalt. This composition is partly consistent with the generic “rhyolite” name used to refer to these units within the KCM Project. However, the texture (abundance of phenocrysts), as well as the chemical compositions (andesitic/andesite basaltic composition for some of them) of those rocks are inconsistent with rhyolite and are better referred in this study to as quartz-feldspar porphyries.

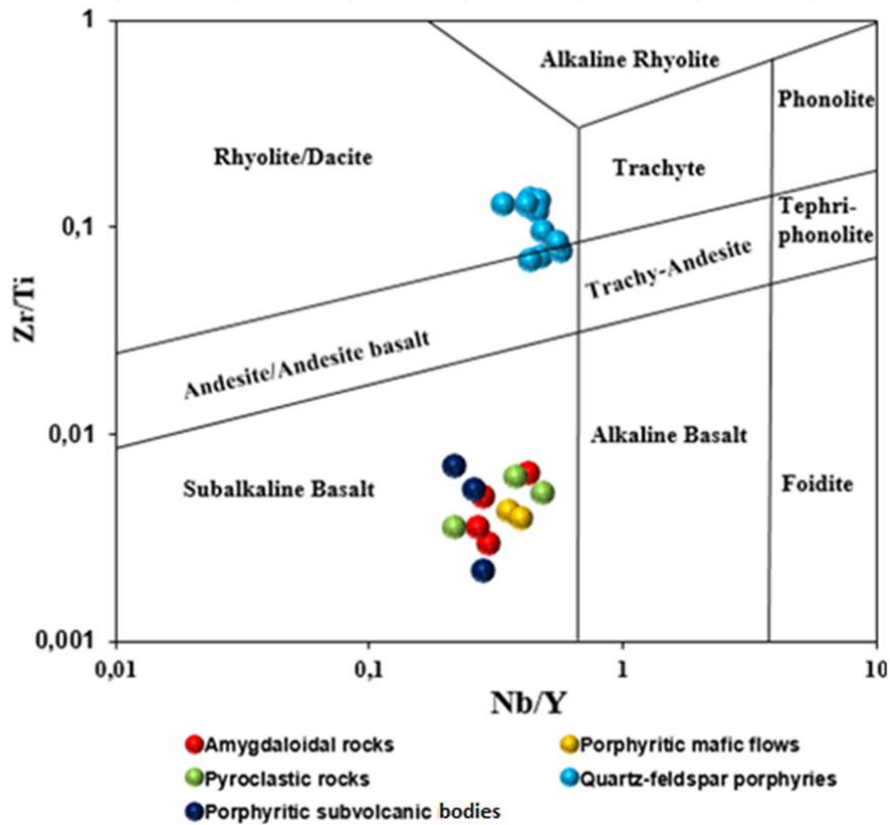


Fig. 4.2: Plot of Nb/Y vs. Zr/Ti widely used as an immobile proxy for the TAS diagram classifying the amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and porphyritic subvolcanic bodies into subalkaline basalt and the quartz-feldspar porphyries are classified into rhyolite/dacite to andesite/andesite basalt (modified after **Pearce, 1996**).

4.3. Major and minor-element compositions

Major and minor elements oxide concentrations along with major and minor oxide ratios are given in **Table 4.2**. Of note however, major element contents of KVF units are likely to have undergone post crystallisation changes as elaborated in section 4.1. The values reported here are therefore to be taken with caution. They are purely indicative and cannot be used for petrogenetic implications as already mentioned in section 4.1.

4.3.1. Amygdaloidal rocks

Subalkaline basaltic amygdaloidal rocks of KVF have a restricted range in SiO_2 contents varying from 44.94 to 48.40 wt. % and a restricted range in Al_2O_3 contents varying from 13.95 to 16.74 wt. %. The amygdaloidal rocks are characterized by TiO_2 contents of 0.80 - 2.59 wt. %, K_2O contents of 0.68 - 2.50 wt. % and Na_2O contents of 3.82 – 6.37 wt. %. The FeOT, MgO and CaO contents vary between 8.62 - 14.96 wt. %, 2.13 - 9.79 wt. % and 6.73 - 2.93 wt. %, respectively. The $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios for the amygdaloidal rocks range from 2.83 to 3.22 and from 5.69 to 17.44, respectively. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ values range from 1.51 to 9.37.

4.3.2. Porphyritic mafic flows

The subalkaline basaltic porphyritic mafic flows of the KVF have a restricted range in SiO_2 , TiO_2 and Al_2O_3 contents varying between 43.66 - 48.01 wt. %, 3.11 - 3.27 wt. % and 15.18 - 16.27 wt. %, respectively. Porphyritic mafic flows are characterized by K_2O contents of 0.43 - 1.60 wt. %, Na_2O contents of 3.77 - 5.44 wt. % and FeOT contents of 13.32 - 16.37 wt.%. The MgO and CaO contents vary from 6.04 to 10.32 wt. % and from 3.44 to 6.92 wt. %, respectively. The $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios for the porphyritic mafic flows range from

2.68 to 3.16 and from 2.36 to 12.65, respectively. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ values range from 4.64 to 5.23.

4.3.3. Pyroclastic rocks

Pyroclastic rocks of the KVF are also subalkaline basaltic in compositions and have a restricted range in SiO_2 contents varying from 43.81 to 47.59 wt. % and a restricted range in Al_2O_3 contents varying between 14.57 - 17.62 wt. %. The TiO_2 contents vary from 0.92 to 2.90 wt. %, K_2O contents from 0.38 to 2.47 wt. % and Na_2O contents range between 2.54 - 5.29 wt. %. The FeOT, MgO and CaO contents vary between 10.78 – 14.89 wt. %, 0.68 - 11.61 wt. % and 6.86 - 10.25 wt. %, respectively. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios range from 1.03 to 13.92 and from 5.40 to 18.74, respectively. The $\text{SiO}_2/\text{Al}_2\text{O}_3$ values range from 2.70 to 3.01.

4.3.4. Porphyritic subvolcanic bodies

Porphyritic subvolcanic bodies of KVF are subalkaline basaltic in composition and have a restricted range in SiO_2 , TiO_2 and Al_2O_3 contents spanning from 48.10 to 50.50 wt. %, 2.02 to 2.05 wt. % and 13.39 to 15.36 wt. %, respectively. Porphyritic subvolcanic bodies are characterized by K_2O contents of 0.13 - 0.89 wt. %, Na_2O contents of 2.19 - 4.23 wt. % and FeOT abundance of 12.89 - 14.11 wt. %. The MgO and CaO contents vary between 5.25 - 6.19 wt. % and 8.50 - 10.91 wt. %, respectively. The $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios range from 3.13 to 3.77 and 6.63 to 7.49, respectively. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ values range from 3.22 to 32.54.

4.3.5. Quartz-feldspar porphyries

Rhyolitic quartz-feldspar porphyries of the KVF have narrow ranges in SiO_2 , TiO_2 and Al_2O_3 contents spanning from 69.84 to 75.22 wt. %, 0.24 to 0.55 wt. % and from 12.05 to 12.84 wt. %, respectively. Quartz-feldspar porphyries are characterized by K_2O contents of 4.75 - 8.70 wt. %, Na_2O contents of 1.26 – 3.68 wt. % and FeOT 2.35 - 6.96 wt. %. The MgO and CaO contents vary between 0.05 - 0.86 wt. % and 0.36 - 1.05 wt. %, respectively. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios for the quartz-feldspar porphyries range from 0.14 to 0.77 and from 22.09 to 51.00, respectively. The $\text{SiO}_2/\text{Al}_2\text{O}_3$ values range from 5.47 to 6.15.

4.3.6. Clastic sedimentary rocks

Clastic sedimentary rocks of the KVF have narrow ranges in SiO_2 and Al_2O_3 contents varying from 53.21 to 55.24 wt. % and from 8.60 to 12.74 wt. %, respectively. The clastic sedimentary rocks are also characterized by TiO_2 contents of 0.48 - 0.79 wt. % and Na_2O contents of 0.31 – 0.81 wt. %. The FeOT, MgO and CaO contents varying between 4.42 - 6.55 wt. %, 0.84 - 2.73 wt. % and 18.34 - 27.81 wt. %, respectively. The $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios range from 4.34 to 6.19 and 0.13 to 0.34, respectively. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ values range from 10.89 to 26.54.

Their Al_2O_3 contents is relatively low (8.6 -12.74 wt. % and 10.67 on average), hence classified as arenite. In the plot of TiO_2 (wt. %) vs. Zr (ppm) the two clastic sedimentary rock samples showed an intermediate origin (**Fig.4.3**). The clastic sedimentary rocks of the KVF were compared to the sandstones of the D'kar and Ngwako Pan Formation which plotted towards the felsic and intermediate rocks field (**Kelepile et al., 2017**).

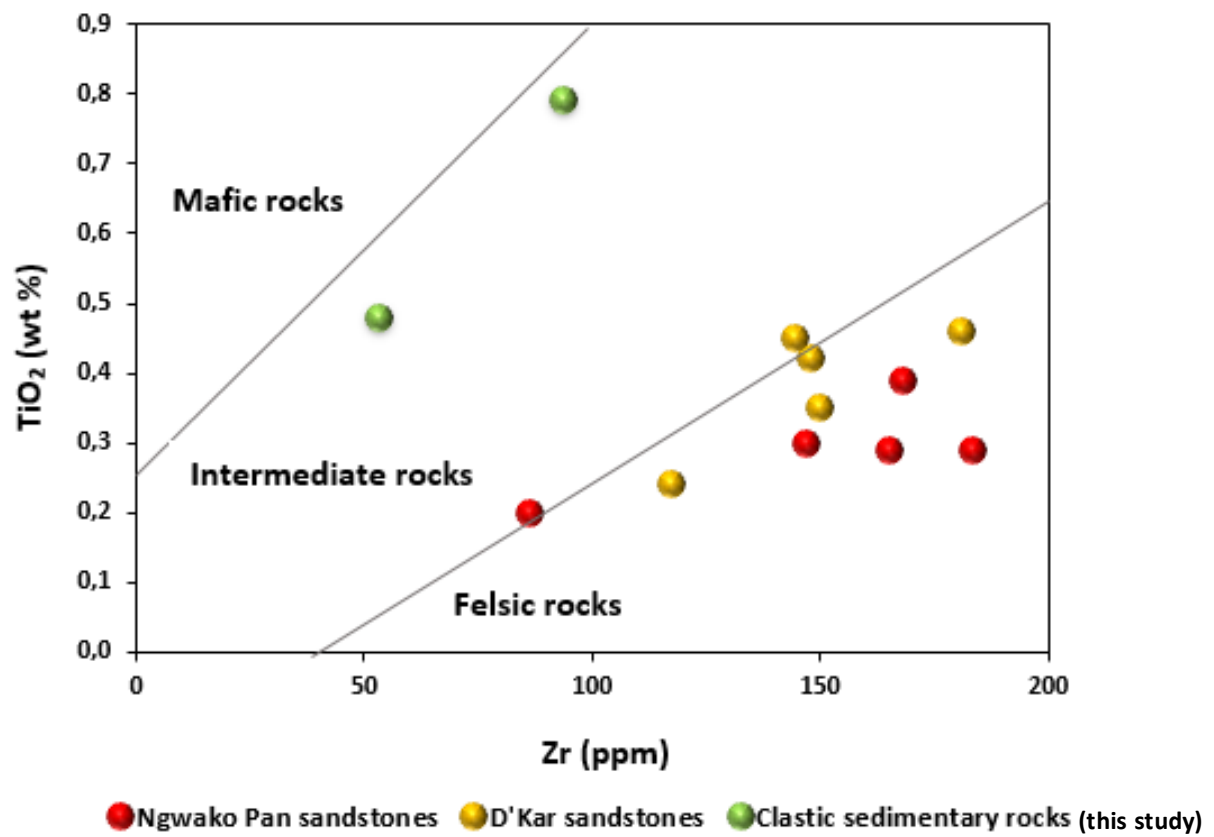


Fig. 4.3: TiO_2 (wt. %) vs. Zr (ppm) plot for sedimentary rock samples showing that clastic sedimentary rocks investigated in this study are of an intermediate origin. Also plotted are sandstones of the D'Kar and Ngwako Pan formations, which are of a felsic-to an intermediate origin (after **Hayashi et al., 1997**).

Table 4.2

Major, minor, trace element concentrations and major element ratios of the KVF units (amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks, porphyritic subvolcanic bodies, quartz-feldspar porphyries and clastic sedimentary rocks).

Analyte	Analytical technique	Amygdaloidal rocks					Porphyritic mafic flows			Pyroclastic rocks			
		EE_01	EE_02	EE_04	EE_05	Avg	EE_07	EE_08	Avg	EE_06	EE_09	EE_10	Avg
SiO ₂	XRF	44.94	45.81	48.40	45.08	46.06	43.66	48.01	45.84	47.59	43.81	44.93	45.44
TiO ₂	XRF	0.80	1.04	1.00	2.59	1.36	3.11	3.27	3.19	0.94	2.81	2.9	2.22
Al ₂ O ₃	XRF	13.95	16.17	16.74	14.74	15.40	16.27	15.18	15.73	17.62	14.57	15.65	15.95
FeOT	XRF	8.62	10.58	10.30	14.96	11.12	16.37	13.32	14.85	10.78	14.89	11.82	12.50
MnO	XRF	0.44	0.50	0.56	0.38	0.47	0.46	0.38	0.42	0.57	0.43	0.62	0.54
MgO	XRF	2.13	8.20	9.79	6.90	6.76	10.32	6.04	8.18	9.33	6.68	11.61	9.21
CaO	XRF	21.93	11.31	6.73	8.72	12.17	3.44	6.92	5.18	7.98	10.25	6.86	8.36
Na ₂ O	XRF	6.37	5.15	3.82	5.05	5.10	3.77	5.44	4.61	2.54	5.29	4.34	4.06
K ₂ O	XRF	0.68	1.06	2.50	0.72	1.24	1.6	0.43	1.02	2.47	0.38	0.38	1.08
P ₂ O ₅	XRF	0.09	0.11	0.09	0.77	0.27	0.9	0.92	0.91	0.09	0.82	0.84	0.58
Cr ₂ O ₃	XRF	0.04	0.05	0.03	0.04	0.04	0.05	0.02	0.04	0.03	0.02	-	0.03
TOTAL		100.0	100.0	100.0	100.0	100.0	100.0	99.9	99.9	99.9	100.0	100.0	100.0
Li	ICP-OES	20.7	92.6	99.6	55.5	67.10	88.3	43.7	66.00	79.9	54.5	99.9	78.10
Be	ICP-MS	0.3	0.4	0.2	1.3	0.55	1	1	1.00	0.2	0.9	1.6	0.90
V	ICP-OES	99.7	136	179	260	168.68	266	344	305.00	252	244	290	262.00
Cr	ICP-OES	183	310	309	359	290.25	350	187	268.50	278	189	138	201.67
Co	ICP-MS	19.7	52.5	55.5	73.6	50.33	99	75.3	87.15	50.6	74.4	110	78.33
Ni	ICP-MS	68.3	123	177	133	125.33	170	137	153.50	155	138	140	144.33
Cu	ICP-OES	68.5	29.3	8.4	12.6	29.70	24.7	<0.5	24.70	1.7	3.6	3.3	2.87
Zn	ICP-OES	181	499	637	362	419.75	593	349	471.00	573	383	640	532.00
Ga	ICP-MS	8.5	14.5	14.5	18	13.88	20.1	18	19.05	18.9	16.1	19.8	18.27
Rb	ICP-MS	22.3	41.3	103	19.4	46.50	52.5	12.2	32.35	103	10.6	14.7	42.77
Sr	ICP-OES	142	90.1	127	72.6	107.93	202	117	159.50	276	50	80.1	135.37
Mo	ICP-MS	3.73	2.56	3.07	3.82	3.30	2.48	4.1	3.29	2.81	2.91	2.34	2.69
Ag	ICP-MS	2.4	0.9	<0.3	0.4	1.23	<0.3	<0.3	-	<0.3	<0.3	<0.3	-
Cd	ICP-MS	0.12	0.11	0.09	0.09	0.10	0.06	0.06	0.06	0.04	0.06	0.05	0.05
Te	ICP-MS	0.2	0.17	0.11	0.13	0.15	0.11	0.07	0.09	0.13	0.06	0.05	0.08
Ba	ICP-OES	1960	1150	5210	324	2161.00	2060	271	1165.50	4900	225	349	1824.67
Ti	ICP-OES	0.39	0.58	0.56	1.46	0.75	1.37	1.69	1.53	0.54	1.59	1.68	1.27
Pb	ICP-MS	74.8	31.9	23.6	24.2	38.63	21.8	22.9	22.35	37.5	19.7	13.8	23.67
Bi	ICP-MS	4.28	1.37	0.59	1.05	1.82	0.47	0.36	0.42	0.53	0.34	0.29	0.39
U	ICP-MS	2.93	1.04	0.66	1.24	1.47	0.31	0.34	0.33	0.49	0.51	0.36	0.45
Th	ICP-MS	0.7	0.5	0.4	0.9	0.63	0.7	0.7	0.70	0.3	0.6	0.7	0.53
Zr	ICP-OES	39.2	30.8	34.8	165	67.45	131	128	129.50	33	144	180	119.00
La	ICP-MS	8.06	19.35	15.16	33.55	19.03	42.26	53.87	48.06	14.19	13.87	55.48	27.85
Ce	ICP-MS	6.62	16.96	14.36	29.70	16.91	40.47	49.50	44.99	13.24	13.74	55.07	27.35
Pr	ICP-MS	5.57	8.52	9.51	31.80	13.85	42.30	51.80	47.05	11.80	14.59	57.62	28.01
Nd	ICP-MS	6.50	8.17	9.67	29.67	13.50	40.00	47.33	43.67	11.67	15.50	51.00	26.06
Sm	ICP-MS	18.46	12.31	9.74	24.10	16.15	31.28	34.36	32.82	10.26	17.44	33.33	20.34
Eu	ICP-MS	9.12	9.93	19.05	19.18	14.32	27.62	29.93	28.78	21.77	15.51	27.35	21.54
Gd	ICP-MS	6.18	7.61	8.46	18.84	10.27	25.52	28.80	27.16	9.58	15.68	26.45	17.23
Tb	ICP-MS	5.91	7.38	8.23	16.67	9.55	21.73	23.42	22.57	8.65	14.77	21.31	14.91
Dy	ICP-MS	5.43	6.52	7.48	14.41	8.46	18.60	19.38	18.99	7.42	13.88	17.70	13.00
Ho	ICP-MS	5.15	5.85	6.69	13.09	7.69	16.30	16.43	16.36	6.96	12.53	15.46	11.65
Er	ICP-MS	5.24	6.05	6.33	13.14	7.69	14.86	15.19	15.02	6.57	12.24	14.86	11.22
Tm	ICP-MS	4.94	5.25	5.56	12.04	6.94	13.58	13.58	13.58	5.86	11.42	12.96	10.08
Yb	ICP-MS	4.78	5.26	5.26	11.96	6.82	13.40	13.88	13.64	6.22	11.96	12.92	10.37
Lu	ICP-MS	4.97	5.28	4.97	11.80	6.75	10.87	10.25	10.56	5.28	9.63	11.80	8.90
ΣREE		96.94	124.44	130.46	279.96	157.95	358.78	407.73	383.26	139.48	192.75	413.32	248.52
(ΣLREE)		60.51	82.85	85.94	186.85	104.04	249.45	295.61	272.53	92.51	106.32	306.31	168.38
(ΣHREE)		36.43	41.59	44.52	93.11	53.91	109.33	112.13	110.73	46.97	86.43	107.01	80.14
LREE/HREE		1.66	1.99	1.93	2.01	1.90	2.28	2.64	2.46	1.97	1.23	2.86	2.02
Eu/Eu*		0.74	1.00	2.09	0.89	1.18	0.97	0.95	0.96	2.20	0.94	0.91	1.35

Table 4.2 (continued.)

Quartz-feldspar porphyries													
Analyte	Analytical technique	EE_12	EE_14	EE_15	EE_16	EE_17	EE_18	EE_19	EE_20	EE_21	EE_22	EE_23	Avg
SiO ₂	XRF	71.6	72.11	70.23	70.7	71.18	69.86	71.55	69.84	75.13	72.25	75.22	71.79
TiO ₂	XRF	0.34	0.33	0.35	0.34	0.32	0.54	0.34	0.55	0.25	0.33	0.24	0.36
Al ₂ O ₃	XRF	12.32	12.4	12.84	12.34	12.05	12.27	12.33	12.15	12.3	12.19	12.24	12.31
FeOT	XRF	5.81	5.34	5.69	5.34	5.31	6.96	5.7	6.95	2.47	5.29	2.35	5.20
MnO	XRF	0.08	0.06	0.05	0.08	0.08	0.11	0.09	0.1	0.03	0.2	0.02	0.08
MgO	XRF	0.21	0.26	0.86	0.63	0.33	0.5	0.35	0.61	0.06	0.19	0.05	0.37
CaO	XRF	1.05	0.95	0.52	0.5	1.03	1.08	0.99	0.92	0.36	0.93	0.36	0.79
Na ₂ O	XRF	3.64	3.68	3.05	1.26	1.57	3.65	3.31	2.89	2.46	3.39	2.12	2.82
K ₂ O	XRF	4.84	4.75	6.29	8.7	8.02	4.84	5.21	5.8	6.85	5.12	7.32	6.16
P ₂ O ₅	XRF	0.05	0.05	0.05	0.05	0.04	0.13	0.05	0.13	0.02	0.04	0.02	0.06
Cr ₂ O ₃	XRF	0.07	0.07	0.07	0.06	0.06	0.06	0.09	0.06	0.07	0.07	0.07	0.07
TOTAL		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Li	ICP-OES	4.2	5.8	54.5	40.4	28.1	19.6	32.2	27	2.2	20.1	3.2	21.57
Be	ICP-MS	5.4	5.8	8.5	5.7	5.5	4.5	5.9	4.8	4.3	5.8	6.4	5.69
V	ICP-OES	15.1	13.8	18.1	19.5	15.4	22.2	13.1	19.5	12.5	13.3	17.3	16.35
Cr	ICP-OES	381	309	371	290	260	359	366	296	243	281	199	305.00
Co	ICP-MS	6.9	5.8	9.3	6.1	5	10	6	13.6	6.7	5.7	4.5	7.24
Ni	ICP-MS	8	8	7.5	7.7	5.1	7.3	7	7.5	6	39.3	8.7	10.19
Cu	ICP-OES	11	11.2	2.5	6.5	7.1	24.2	8.7	7.4	3.6	30.5	5.7	10.76
Zn	ICP-OES	36.3	46.5	28.7	109	51.4	99.4	59.7	84.6	9.5	12	5.1	49.29
Ga	ICP-MS	29.4	28.4	26.8	27	26.2	27.5	29.2	26.6	20.2	28.4	18.9	26.24
Rb	ICP-MS	174	153	330	529	482	223	290	340	252	161	252	289.64
Sr	ICP-OES	36	35.7	22.9	33.3	21.2	30.4	43.2	29.6	14.6	30.2	16.7	28.53
Mo	ICP-MS	38.7	39.5	41	39	34.3	35	43.5	35.6	38.5	38.5	36.3	38.17
Ag	ICP-MS	1.2	1	1	1	0.9	0.9	1.2	0.9	0.7	1	0.6	0.95
Cd	ICP-MS	0.08	0.09	0.05	0.07	0.05	0.06	0.09	0.09	0.09	0.08	0.08	0.08
Te	ICP-MS	0.07	<0.05	0.05	<0.05	0.07	<0.05	<0.05	0.06	<0.05	0.07	0.06	0.06
Ba	ICP-OES	822	961	1290	1090	1030	1140	847	1130	1290	1070	1400	1097.27
Ti	ICP-OES	0.19	0.18	0.18	0.17	0.16	0.3	0.17	0.25	0.12	0.16	0.12	0.18
Pb	ICP-MS	15.9	15.4	7.9	13.8	9.9	13.7	15.1	11.4	9	10.4	8.3	11.89
Bi	ICP-MS	0.39	0.14	0.19	0.2	0.1	0.16	0.34	0.16	0.1	0.2	0.14	0.19
U	ICP-MS	6.74	6.15	5.24	5.56	4.81	5.71	6.26	5	3.46	3.93	6.62	5.41
Th	ICP-MS	28.1	27.1	28.1	26.6	25.4	24.8	27.7	24.7	37.7	27.7	38.6	28.77
Zr	ICP-OES	462	442	449	431	386	381	439	372	193	313	200	369.82
La	ICP-MS	314.52	332.26	101.61	298.39	335.48	298.06	377.42	249.68	212.58	322.58	183.23	275.07
Ce	ICP-MS	320.54	301.98	108.66	259.90	310.64	253.71	361.39	222.77	150.99	323.02	155.94	251.78
Pr	ICP-MS	257.38	271.31	111.48	259.84	270.49	240.98	306.56	214.75	138.52	277.87	135.25	225.86
Nd	ICP-MS	208.33	218.33	99.33	210.00	215.00	196.67	246.67	180.00	95.00	223.33	103.83	181.50
Sm	ICP-MS	143.08	143.59	92.82	141.03	142.56	131.79	160.00	124.10	60.51	147.18	68.72	123.22
Eu	ICP-MS	68.03	70.75	53.74	70.48	70.61	66.67	75.92	65.17	23.81	70.07	23.40	59.88
Gd	ICP-MS	113.13	110.42	89.58	110.42	108.49	101.54	120.46	98.46	48.26	108.88	52.51	96.56
Tb	ICP-MS	101.48	97.26	96.62	100.00	98.52	90.08	108.23	89.03	45.78	95.15	48.10	88.20
Dy	ICP-MS	88.51	83.23	98.45	86.96	83.23	77.02	93.17	77.33	40.37	79.50	42.24	77.27
Ho	ICP-MS	81.89	76.74	98.61	80.36	76.74	71.31	85.52	71.17	38.30	72.70	39.42	72.07
Er	ICP-MS	83.81	77.62	104.29	81.90	77.62	73.33	86.67	73.33	39.90	73.33	41.10	73.90
Tm	ICP-MS	79.32	73.77	97.53	77.47	72.84	68.83	82.41	69.14	38.89	68.52	41.05	69.98
Yb	ICP-MS	79.43	74.64	95.22	76.56	73.68	69.38	81.82	68.90	39.71	69.86	42.11	70.12
Lu	ICP-MS	77.02	71.74	88.20	74.22	70.19	67.39	78.26	66.46	37.58	64.60	40.68	66.94
ΣREE		2016.46	2003.64	1336.13	1927.52	2006.11	1806.78	2264.48	1670.29	1010.22	1996.59	1017.56	1732.34
(ΣLREE)		1425.00	1448.65	657.22	1350.05	1453.29	1289.43	1648.41	1154.93	729.68	1472.93	722.87	1213.86
(ΣHREE)		591.46	554.99	678.91	577.47	552.82	517.34	616.06	515.36	280.54	523.66	294.69	518.48
LREE/HREE		2.41	2.61	0.97	2.34	2.63	2.49	2.68	2.24	2.60	2.81	2.45	2.38
Eu/Eu*		0.53	0.56	0.59	0.56	0.56	0.57	0.54	0.59	0.44	0.55	0.39	0.53

Table 4.2 (continued and end.)

		Porphyritic subvolcanic bodies				Clastic sedimentary rocks		
Analyte	Analytical technique	EE_27	EE_28	EE_13	Avg	EE_03	EE_11	AV
SiO ₂	XRF	48.1	49.74	50.5	49.45	53.21	55.24	54.23
TiO ₂	XRF	2.05	2.03	2.02	2.03	0.79	0.48	0.64
Al ₂ O ₃	XRF	15.36	14.02	13.39	14.26	8.6	12.74	10.67
FeOT	XRF	13.74	12.89	14.11	13.58	4.42	6.55	5.49
MnO	XRF	0.23	0.28	0.41	0.31	1.38	0.51	0.95
MgO	XRF	6.19	5.73	5.25	5.72	0.84	2.73	1.79
CaO	XRF	10.91	10.34	8.5	9.92	27.81	18.34	23.08
Na ₂ O	XRF	2.19	4.23	4.01	3.48	0.31	0.81	0.56
K ₂ O	XRF	0.68	0.13	0.89	0.57	2.41	2.38	2.40
P ₂ O ₅	XRF	0.2	0.53	0.85	0.53	0.17	0.15	0.16
Cr ₂ O ₃	XRF	0.26	0.04	0.01	0.10	0.02	0.03	0.03
TOTAL		99.9	100.0	99.9	99.9	100.0	100.0	100.0
Li	ICP-OES	23.1	24.5	20.7	22.77	9.1	26.7	17.90
Be	ICP-MS	0.2	0.5	0.6	0.43	5.8	0.4	3.10
V	ICP-OES	354	272	254	293.33	195	180	187.50
Cr	ICP-OES	398	287	171	285.33	149	244	196.50
Co	ICP-MS	65	59.5	61.4	61.97	10.6	22.8	16.70
Ni	ICP-MS	60.6	121	56	79.20	32.6	33.6	33.10
Cu	ICP-OES	223	35.5	180	146.17	28.5	2.3	15.40
Zn	ICP-OES	225	225	282	244.00	115	163	139.00
Ga	ICP-MS	20.4	16.5	21	19.30	14.5	32.7	23.60
Rb	ICP-MS	52.4	6.7	34	31.03	64	69.5	66.75
Sr	ICP-OES	148	163	149	153.33	303	746	524.50
Mo	ICP-MS	6.05	5.87	5.08	5.67	12.3	18.4	15.35
Ag	ICP-MS	<0.3	<0.3	0.3	0.30	0.7	<0.3	0.70
Cd	ICP-MS	0.55	0.05	0.5	0.37	0.21	0.16	0.19
Te	ICP-MS	<0.05	0.05	0.06	0.06	0.18	0.06	0.12
Ba	ICP-OES	243	326	478	349.00	1480	1040	1260.00
Ti	ICP-OES	1.2	1.21	1.21	1.21	0.39	0.25	0.32
Pb	ICP-MS	126	36.1	383	181.70	29.4	27.3	28.35
Bi	ICP-MS	0.1	0.21	0.13	0.15	1.5	0.25	0.88
U	ICP-MS	0.21	0.61	0.85	0.56	1.21	0.32	0.77
Th	ICP-MS	0.9	1.2	3.7	1.93	6.2	4.7	5.45
Zr	ICP-OES	44.7	108	142	98.23	93.5	53.3	73.40
La	ICP-MS	21.94	29.03	67.74	39.57	38.71	55.16	46.94
Ce	ICP-MS	20.30	21.78	56.68	32.92	34.78	42.20	38.49
Pr	ICP-MS	19.92	25.08	58.20	34.40	35.82	38.44	37.13
Nd	ICP-MS	19.00	24.17	51.50	31.56	29.33	32.33	30.83
Sm	ICP-MS	15.90	20.00	36.92	24.27	23.08	18.46	20.77
Eu	ICP-MS	16.46	16.87	30.48	21.27	15.24	15.10	15.17
Gd	ICP-MS	14.44	17.18	31.97	21.20	16.80	12.59	14.69
Tb	ICP-MS	13.29	15.40	28.27	18.99	14.14	9.92	12.03
Dy	ICP-MS	11.99	13.60	25.47	17.02	11.93	8.88	10.40
Ho	ICP-MS	11.14	12.67	24.51	16.11	10.45	7.24	8.84
Er	ICP-MS	10.86	12.19	23.76	15.60	10.29	7.52	8.90
Tm	ICP-MS	9.88	10.80	20.68	13.79	9.26	6.17	7.72
Yb	ICP-MS	10.05	11.00	20.10	13.72	9.09	6.70	7.89
Lu	ICP-MS	9.32	9.63	17.70	12.22	9.32	6.83	8.07
ΣREE		204.47	239.42	493.98	312.62	268.21	267.56	267.88
(ΣLREE)		127.95	154.12	333.49	205.19	193.75	214.29	204.02
(ΣHREE)		76.52	85.30	160.49	107.44	74.46	53.27	63.86
LREE/HREE		1.67	1.81	2.08	1.85	2.60	4.02	3.31
Eu/Eu*		1.09	0.91	0.88	0.96	0.76	0.97	0.87

The plot of $\text{FeOT} / (\text{FeOT} + \text{MgO})$ against SiO_2 (wt. %) (**Frost et al., 2001**) (Fig.4.4a) shows the amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and porphyritic subvolcanic bodies plot in the magnesian rock field. An exception is one sample from the amygdaloidal rocks, one sample from the pyroclastic rocks and one sample from the basaltic porphyritic subvolcanic bodies which plot in the ferroan rocks. The rhyolitic quartz-feldspar porphyries all plot in the ferroan rocks field. Magnesian rocks suggests I-type and arc-related magmas. Ferroan rocks on the other hand, are consistent with peraluminous S-type compositions, with melt derived from reduced sedimentary sources (**Frost et al., 2001**).

The KVF rocks shows a relatively low Al content, (up to 17.62 wt. % Al_2O_3). Therefore, the aluminum saturation index (ASI), A/CNK (molar $\text{Al}_2\text{O}_3 / \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O}$) is < 1 . ASI for the amygdaloidal rocks ranges from 0.35 - 0.91, porphyritic mafic flows ASI is 0.86 (exception is one sample with ASI of 1.31). Pyroclastic rocks ASI ranges between 0.67 - 0.98, basaltic porphyritic subvolcanic bodies ASI ranges from 0.70 - 0.81 and ASI of rhyolitic quartz-feldspar porphyries ranges between 0.75 - 0.89. In the plot of $\text{Al} / (\text{Ca} + \text{Na} + \text{K})$ against $\text{Al} / (\text{Na} + \text{K})$, the amygdaloidal rocks, pyroclastic rocks, porphyritic mafic flows (with an exception of one sample plotting towards the peraluminous field) and basaltic porphyritic subvolcanic bodies plot in the metaluminous field (Fig.4.4b). However, the rhyolitic quartz-feldspar porphyries plot on the peralkaline field. Peraluminous rocks suggest S-type rocks, peralkaline type suggests continental rift basin-related volcanicity, whereas metaluminous rock types come from igneous sources (I-type) (**Frost et al., 2001**, Fig.4.4b). In the plot of SiO_2 against oxides (Fig.4.5), the KVF rocks display negative correlation with Ca, Ti, Fe, Mg and Al, whereas K and Na are scattered.

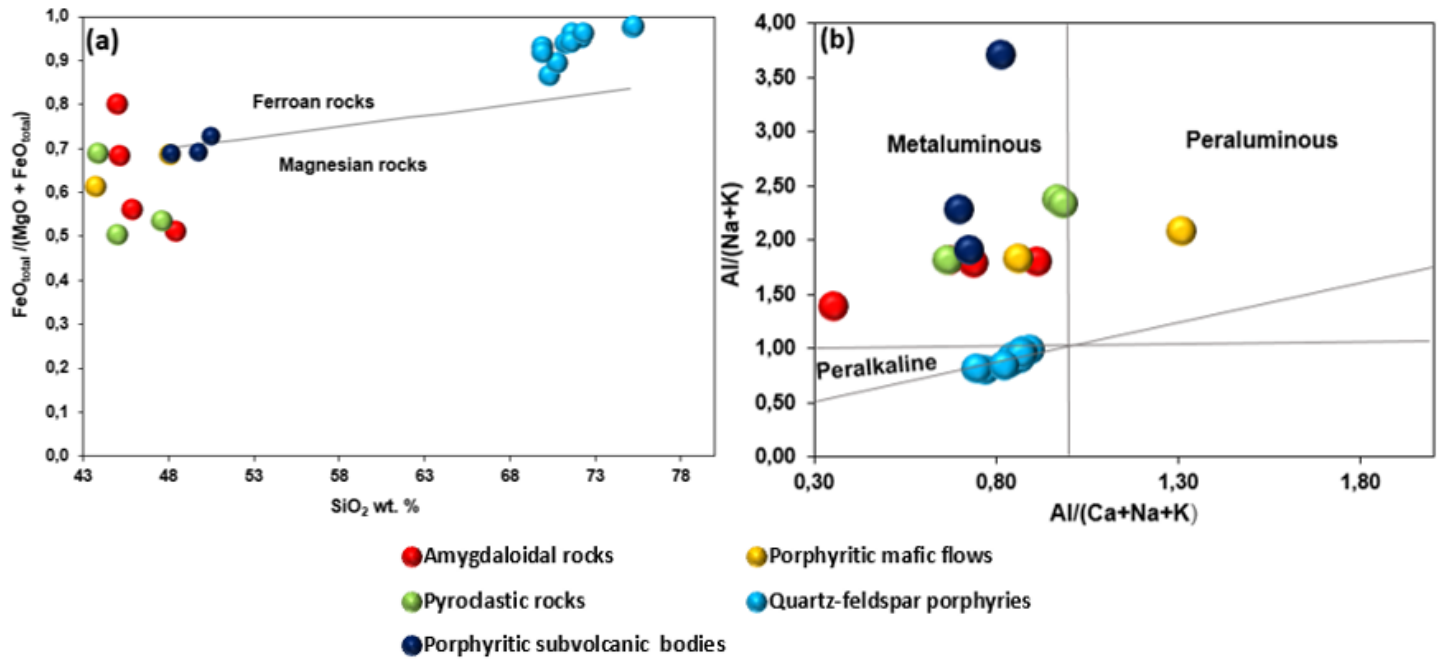


Fig. 4.4: Geochemical plots of major and minor elements from the KVF. (a) Amygdaloidal rocks (with an exception of one sample), porphyritic mafic flows, pyroclastic rocks (with an exception of one sample) and porphyritic subvolcanic bodies (with an exception of one sample) are magnesian rocks, whereas the quartz-feldspar porphyries are ferroan rocks (after **Frost et al., 2001**). (b) Plot of $\text{Al} / (\text{Ca} + \text{Na} + \text{K})$ vs. $\text{Al} / (\text{Na} + \text{K})$ showing the amygdaloidal rocks, pyroclastic rocks, porphyritic mafic flows (with an exception of one sample plotting towards the peraluminous field) and porphyritic subvolcanic bodies plot in the metaluminous field. However, the quartz-feldspar porphyries plot on the peralkaline field (after **Maniar and Piccoli, 1989**).

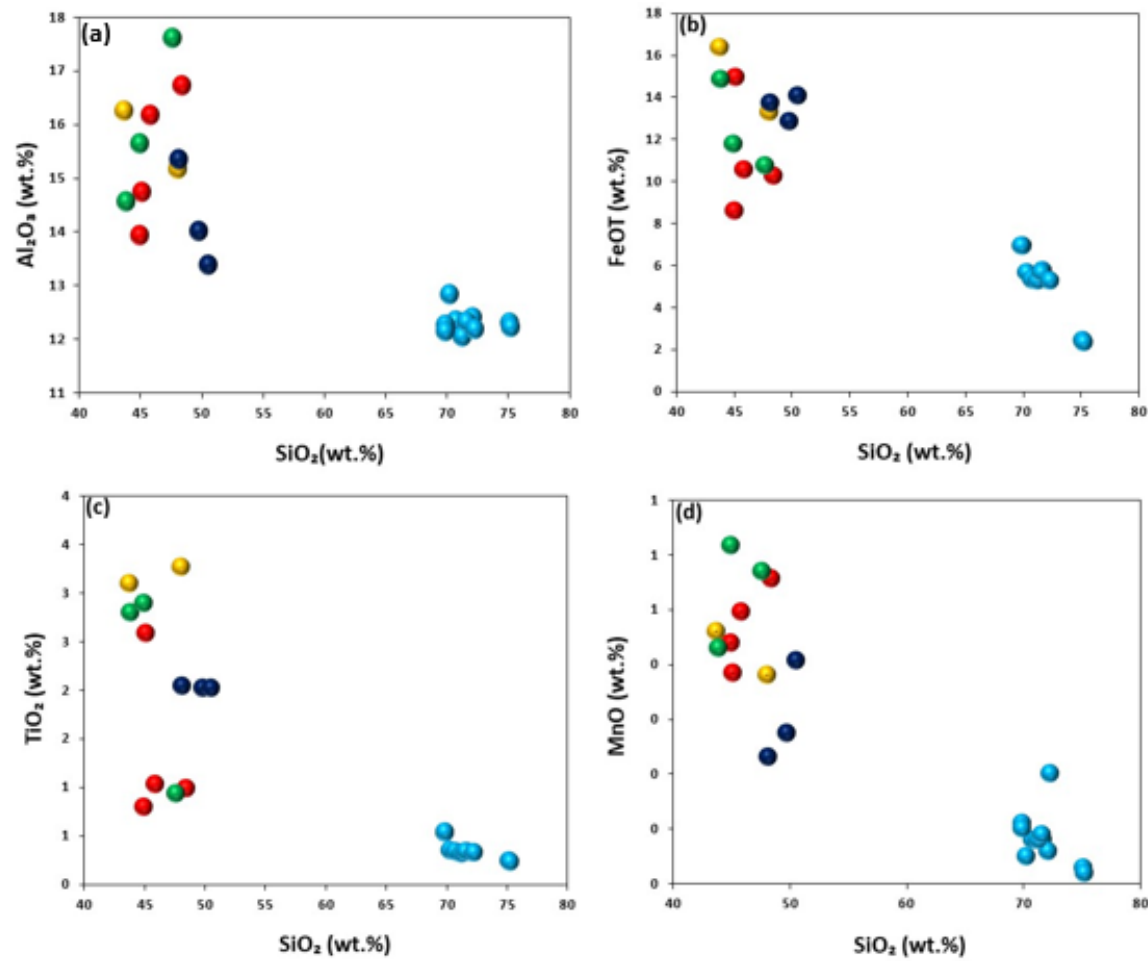


Fig. 4.5: Harker diagrams expressed as major oxides against SiO₂. (a) SiO₂ (wt. %) vs. Al₂O₃ (wt. %). (b) SiO₂ (wt. %) vs. Fe₂O₃ (wt. %). (c) SiO₂ (wt. %) vs. TiO₂ (wt. %). (d) SiO₂ (wt. %) vs. MnO (wt. %).

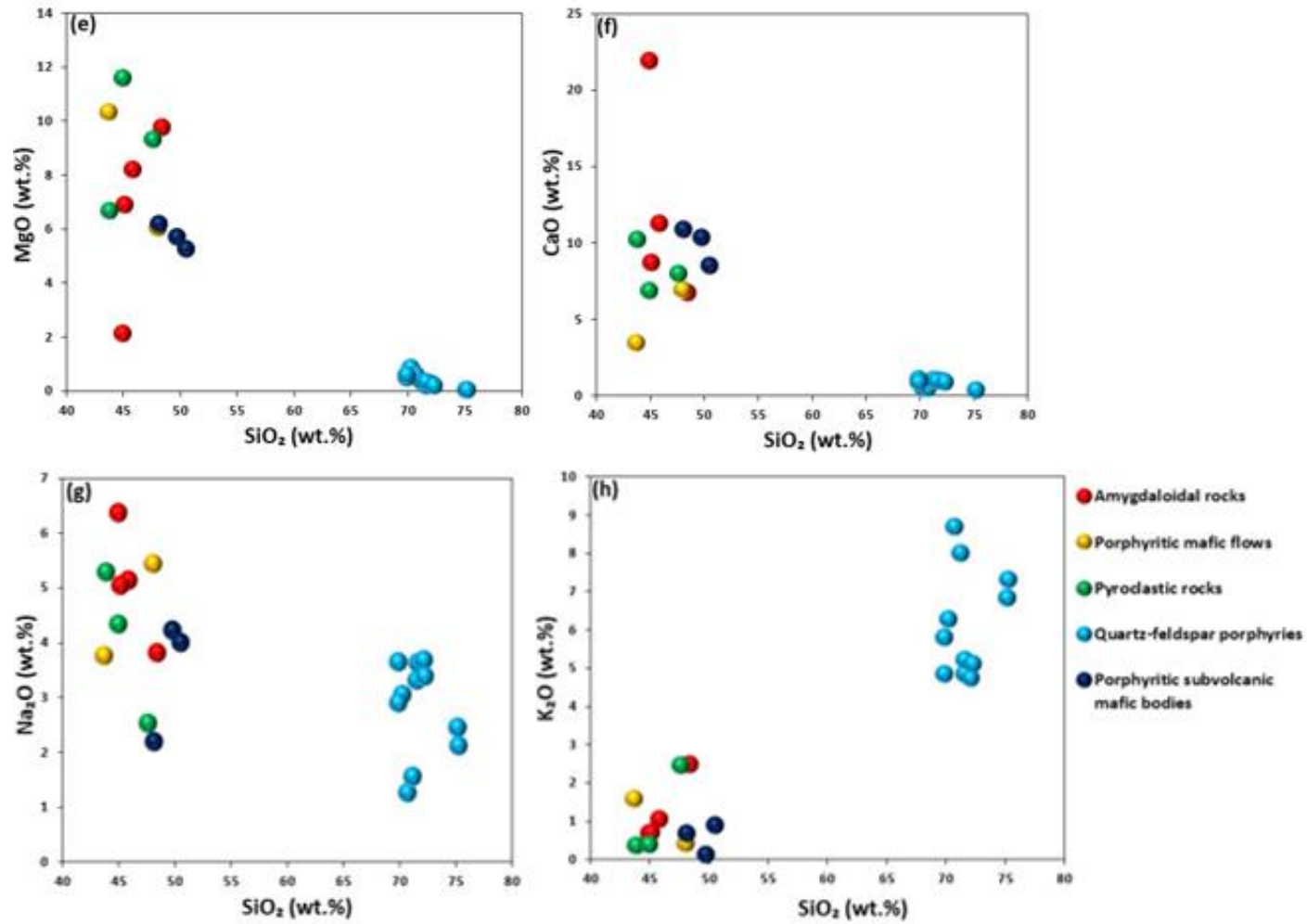


Fig. 4.5 continued: (e) SiO_2 (wt. %) vs. MgO (wt. %). (f) SiO_2 (wt. %) vs. CaO (wt. %) (g) SiO_2 (wt. %) vs. Na_2O (wt. %). (h) SiO_2 (wt. %) vs. K_2O (wt. %).

4.4. Trace-element compositions

Trace-element contents of the investigated samples are shown in **Table 4.2**. The paragraphs below report on the distribution of selected trace elements within the KVF rock units.

4.4.1. Amygdaloidal rocks

The Cr, Co and Ni contents in the amygdaloidal rocks of the KVF range between 183 - 359 ppm, 19.7 - 73.6 ppm and 68.3 - 177 ppm, respectively. The concentration of V in the amygdaloidal rocks is between 99.7 - 260 ppm. The amygdaloidal rocks of the KVF are relatively rich in large ion lithophile elements (LILE) and Ba, Rb and Sr concentrations vary from 324 to 5210 ppm, 19.4 to 103 ppm, and 72.6 to 142 ppm, respectively. The amygdaloidal rocks are however, relatively poor in high field strength elements (HFSE) such as Th, Zr, Ti and U. Their abundances span from 0.4 to 0.9 ppm, 30.8 to 165 ppm, 0.39 to 1.46 ppm and 0.66 to 2.93 ppm, respectively. The La content of the amygdaloidal rocks range between 8.06 – 33.55 ppm. The La/Co and La/Cr values range from 0.08 to 0.14 and from 0.01 to 0.03, respectively. The Th/Co ratio of the amygdaloidal rocks in the KVF range from 0.01 to 0.04. Moreover, the amygdaloidal rocks have an average Cr/Th ratio of 513.20.

The total REE contents (Σ REE) of the KVF amygdaloidal rocks range from 96.94 to 279.96 ppm (average 157.95 ppm). The amygdaloidal rocks of the KVF were normalized to chondrite and present a low to moderate LREE/HREE ratios (1.66 - 2.01, average 1.90), a flat LREE ($\text{La}_{\text{CN}}/\text{Sm}_{\text{CN}} = 0.44 - 1.57$; average 0.99) and are HREE-enriched with respect to LREE ($\text{Gd}_{\text{CN}}/\text{Yb}_{\text{CN}} = 1.29 - 1.61$; average 1.48). Amygdaloidal rock samples also show a negative-to a strong positive Eu anomaly ($\text{Eu}/\text{Eu}^* = 0.74 - 2.09$, average 1.18) and a slight negative to slightly positive Ce anomaly ($\text{Ce}/\text{Ce}^* = 0.88 - 1.09$, averaging 0.99) (Fig.4.9a).

4.4.2. Porphyritic mafic flows

The Porphyritic mafic flows of the KVF have Cr, Co and Ni contents ranging between 187 - 350 ppm, 75.3 - 99 ppm and 137- 170 ppm, respectively. The V content varies from 266 to 344 ppm. The porphyritic mafic flows are relatively rich in LILE for example, barium concentrations vary from 271 to 2060 ppm, Rb contents are between 12.2 and 52.5 ppm, while the Sr concentration varies from 117 to 202 ppm. The porphyritic mafic flows are however, relatively depleted in HFSE (Th, Zr, Ti and U). Their abundances are 0.7 ppm on average (there are only two samples for these KVF rock units and they both yielded a 0.7 ppm), 128 - 131 ppm, 1.37 - 1.69 ppm and 0.31 - 0.34 ppm, respectively. The La content of the porphyritic mafic flows range from 42.26 – 53.55 ppm. The La/Co and La/Cr ratios range from 0.13 to 0.22 and 0.04 to 0.09, respectively. The Th/Co values in the porphyritic mafic flows vary from 0.01 to 0.04. The Cr/Th ratio have an average value of 383.57.

The (Σ REE) in the porphyritic mafic flows is between 358.78 - 407.73 ppm (average 383.26 ppm). The chondrite-normalized REE patterns for the porphyritic mafic flows of the KVF are presented in Fig.4.9b. The samples are characterized by slightly high LREE/HREE ratios (ranging from 2.28 - 2.64; average 2.46), LREE enrichment relative to HREE ($La_{CN}/Sm_{CN} = 1.35 - 1.57$; average 1.46) and flat HREE profile ($Gd_{CN}/Yb_{CN} = 1.90 - 2.08$; average 1.99). The porphyritic mafic flows have a slight negative Eu anomaly, which ranges between 0.95 - 0.97, average 0.96 and a Ce anomaly which is slightly negative (0.96 - 0.98, average 0.97).

4.4.3. Pyroclastic rocks

When comparing pyroclastic rocks to amygdaloidal rocks and porphyritic mafic flows, the pyroclastic rocks of the KVF show higher contents of Cr, Co and Ni, which vary between 138

- 278 ppm, 50.6 - 110 ppm and 138 - 155 ppm, respectively. The pyroclastic rocks are also characterised by relatively high V contents, 244 - 290 ppm. The pyroclastic rocks of the KVF are rich in LILE with Ba, Rb and Sr contents ranging between 271 - 4900 ppm, 10.6 - 103 ppm and 50 - 276 ppm, respectively. The pyroclastic rocks are however, relatively HFSE-poor. Thorium, Zr, Ti and U abundances vary between 0.3 - 0.7 ppm, 33 - 180 ppm, 0.54 - 1.68 ppm and 0.36 - 0.51 ppm, respectively. The La content of the pyroclastic rocks ranges from 13.87 - 55.48 ppm. The La/Co and La/Cr values range from 0.06 to 0.16 and from 0.02 to 0.12, respectively. The Th/Cr ratios of the pyroclastic rocks in the KVF range from 0.00 to 0.01 and for Th/Co ratio is at 0.01. The pyroclastic samples are characterised by high Cr/Th ratio with an average value of 479.60.

In the pyroclastic rocks, Σ REE content ranges from 139.48 - 413.2 ppm. The pyroclastic rocks of the KVF were normalized to chondrite and present a low to moderate LREE/HREE ratios (1.23 - 2.86, 2.02 average), an enriched LREE relative to HREE ($La_{CN}/Sm_{CN} = 0.80 - 1.38$; 1.28 average) and are a flat HREE ($Gd_{CN}/Yb_{CN} = 1.31 - 2.05$; 1.63 average) relative to LREE. These samples show a slight negative-to a strong positive anomaly ($Eu/Eu^* = 0.91 - 2.20$, 1.35 average) and a slightly negative-to slightly positive Ce anomaly ($Ce/Ce^* = 0.95 - 1.02$, 0.99 averaging) (Fig.4.9c).

4.4.4. Quartz-feldspar porphyries

The Cr, Co and Ni contents in the rhyolitic quartz-feldspar porphyries of the KVF range between 199 - 381 ppm, 4.5 - 13.6 ppm and 6.00 - 39.3 ppm, respectively. The concentration of V in the quartz-feldspar porphyries is between 13.1 - 22.2 ppm. The quartz-feldspar porphyries of the KVF are relatively rich in large ion lithophile elements, with Ba, Rb and Sr

concentrations that vary from 822 to 1400 ppm, 153 to 529 ppm, and from 14.6 to 43.2 ppm, respectively. The quartz-feldspar porphyries are HFSE-rich. Thorium, Zr, Ti and U abundances span between 24.7 - 38.6 ppm, 193 - 462 ppm, 0.12 - 0.30 ppm and 3.46 - 6.74 ppm, respectively. The La contents of the quartz-feldspar porphyries range from 101.61 – 335.48 ppm. The La/Co and La/Cr values range from 3.39 to 20.80 and from 0.08 to 0.40, respectively. The Th/Cr and Th/Co ratios range from 0.07 to 0.19 and from 1.82 to 8.58, respectively. Moreover, the quartz-feldspar porphyries have an average Cr/Th ratio of 10.97.

In the felsic to intermediate discriminate plots of Nb + Y (ppm) vs. Rb (ppm), Yb + Ta (ppm) vs. Rb (ppm) and Yb (ppm) vs. Ta (ppm) and Y (ppm) vs. Nb (ppm) (Figs.4.6 a-d), the rhyolitic quartz-feldspar porphyries specifically plot towards the within-plate granites.

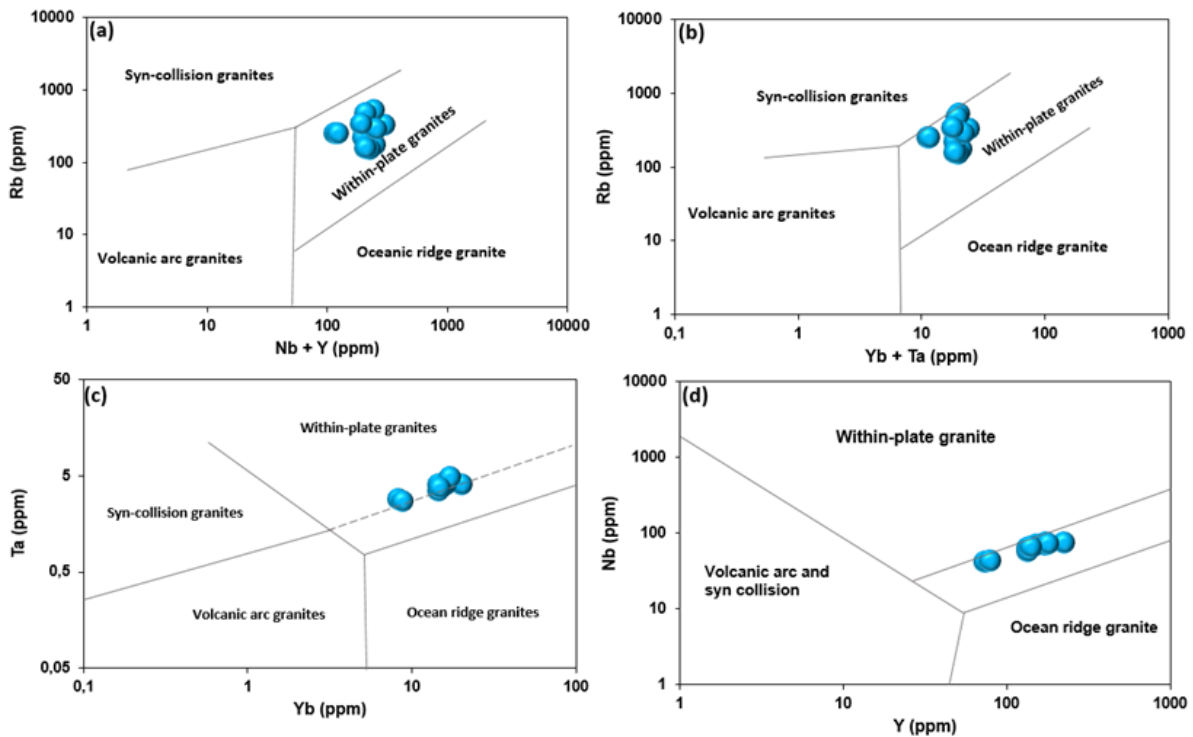


Fig. 4.6: Geochemical plot of trace elements from the KVF showing that the quartz-feldspar porphyries typically fall in the field of within-plate granites. (a) Nb (ppm) + Y vs. Rb (ppm) (b) Yb +Ta (ppm) vs. Rb (ppm) (c) Yb (ppm) vs. Ta (ppm) (d) Y (ppm) vs. Nb (ppm) (after **Pearce et al., 1984**).

The quartz-feldspar porphyries have a wide range of total REE, spanning from 1010.22 to 2264.48 ppm (average 1732.04 ppm). When normalized to chondrite (Fig.4.9e), the quartz-feldspar porphyries show a low to moderate LREE/HREE (0.97 - 2.81, average 2.38), enrichment of LREE ($(La_{CN}/Sm_{CN} = 1.38 - 1.83$; average 1.56) with respect to HREE and a flat HREE ($Gd_{CN}/Yb_{CN} = 1.44 - 1.59$; average 1.53) pattern. The quartz feldspar porphyry samples also show a negative Eu anomaly ($Eu/Eu^* = 0.39 - 0.59$, average 0.53) and a slightly negative- to slightly positive Ce anomaly ($Ce/Ce^* = 0.87 - 1.15$, average 1.03).

4.4.5. Porphyritic subvolcanic bodies

The basaltic porphyritic subvolcanic bodies of the KVF have Cr, Co and Ni contents ranging from 171 to 398 ppm, from 59.5 to 65 ppm and from 56 - 121 ppm, respectively. The V content varies between 254 - 354 ppm. The porphyritic subvolcanic bodies are relatively rich in LILE. Barium concentration varies from 243 to 478, Rb content changes from 6.7 to 52.4 ppm, while the Sr concentration varies from 148 to 163 ppm. The porphyritic subvolcanic bodies are relatively HFSE-rich with Th, Zr, Ti and U concentrations varying from 0.9 to 3.7 ppm, from 44.7 to 142 ppm, from 1.20 to 1.21 ppm and from 0.21 to 0.85 ppm, respectively. The La contents of the porphyritic subvolcanic bodies range from 21.94 – 67.74 ppm. The La/Co and La/Cr ratios range from 0.10 to 0.34 and from 0.02 to 0.12, respectively. The Th/Cr and Th/Co values vary from 0.00 to - 0.02 and from 0.01 to 0.06, respectively. The Cr/Th ratios have an average value of 242.54.

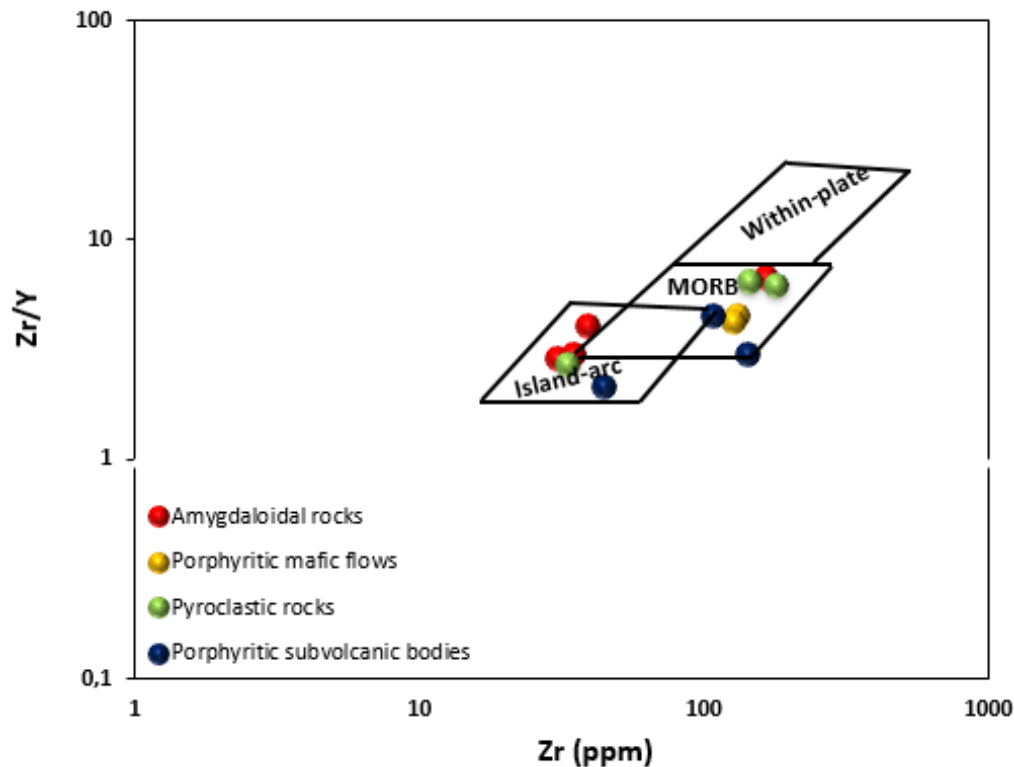


Fig. 4.7: In the ultra mafic-to mafic discriminate plot of Zr (ppm) vs. Zr/Y, the amygdaloidal rocks plot in the island-arc field, with an exception of one sample plotting towards the mid ocean ridge basalts (MORB). One sample from both the porphyritic subvolcanic bodies and pyroclastic rocks plot towards the island-arc field, whereas, two samples of both the mentioned KVF rock units plot in the MORB. The porphyritic mafic flows consistently plot in the field of MORB (after **Pearce and Norry, 1979**).

In the plot of Co (ppm) vs. Th (ppm), the essential of amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and porphyritic subvolcanic bodies plot in the calc-alkaline field, with an exception of one sample from the pyroclastic rocks plotting towards Island arc tholeiite. The quartz-feldspar porphyries are classified as High-k and Shoshonitic (Fig.4.8). The presence of different magmatic series within a single ore zone gives an indication that the different rock units found within the KVF are not cogenetic. Spider diagrams (Figs. 10 a-f) show uneven pattern with negative Yb anomalies, positive Pb and Th anomalies that are highly pronounced for ultra mafic-to mafic rock series and clastic sedimentary rocks. Nonetheless, the quartz-feldspar porphyries exhibit pronounced negative Yb and Sr anomalies.

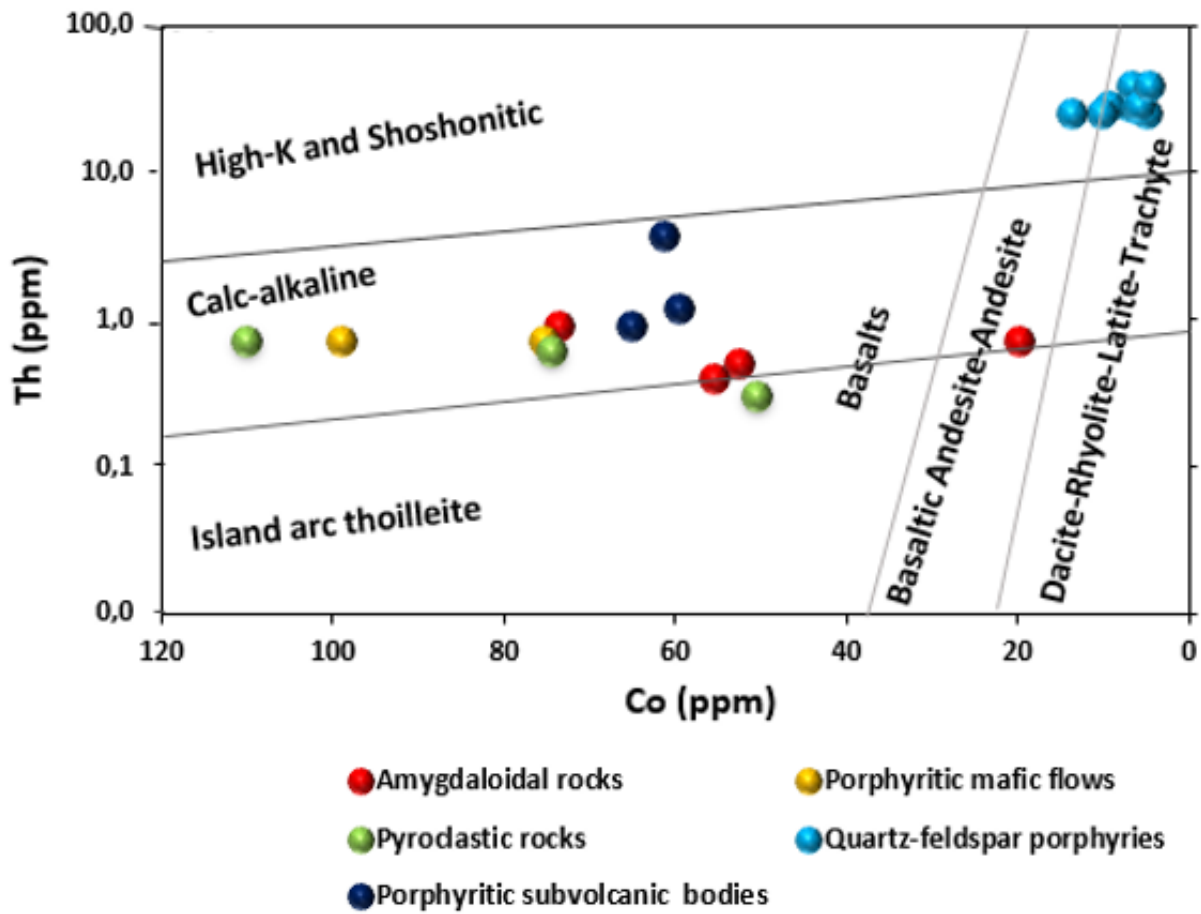


Fig. 4.8: Immobible trace element plot for volcanic rocks showing that basaltic amygdaloidal rocks, porphyritic mafic flows, porphyritic subvolcanic bodies and pyroclastic rocks are classified as calc-alkaline rocks with one sample from the pyroclastic rocks plotting on the Island arc thuilleite series. The essentially rhyolitic quartz- feldspar porphyries are classified as High-K and shoshonitic rocks (after **Hastie et al., 2007**).

In the porphyritic subvolcanic bodies ΣREE content ranges from 204.47 to 493.98 ppm (average 312.62 ppm). The chondrite-normalized REE patterns for the porphyritic subvolcanic bodies of the KVF are presented in Fig. 4.9e. The samples are characterized by low to moderate LREE/HREE ratios ranging from 1.67 to 2.08 (1.85 average), LREE enrichment with respect to HREE ($\text{La}_{\text{CN}}/\text{Sm}_{\text{CN}} = 1.09\text{--}351$; 2.28 average), coupled with flat HREE profile ($\text{Gd}_{\text{CN}}/\text{Yb}_{\text{CN}} = 0.94\text{--}1.56$; 1.38 average). The porphyritic subvolcanic bodies have a slight negative-to slight

positive Eu anomaly, which ranges between 0.88 - 1.09 (average 0.96) and a Ce anomaly, which is slightly negative (0.79 - 0.97, average 0.89).

4.4.6. Clastic sedimentary rocks

The Cr, Co and Ni contents in the clastic sedimentary rocks of the KVF range between 149 - 244 ppm, 10.6 - 22.8 ppm and 32.6 - 33.6 ppm, respectively. The concentration of V in the clastic sedimentary rocks is between 180 - 195 ppm. The clastic sedimentary rocks of the KVF are relatively LILE-rich (Ba, Rb and Sr). Their concentrations vary from 1040 to 1480 ppm, from 64 to 69.5 ppm and from 303 to 746 ppm, respectively. The clastic sedimentary rocks are also HFSE-rich, with Th, Zr, Ti and U abundances spanning from 4.7 to 6.2 ppm, from 53.3 to 93.5 ppm, from 0.25 to 0.39 ppm and from 1.21 to 0.32 ppm, respectively. The La contents of the clastic sedimentary rocks range from 38.71 – 55.16 ppm. The La/Co and La/Cr values range from 0.75 to 1.13 and from 0.07 to 0.08, respectively. The Th/Cr and Th/Co ratios range between 0.02 - 0.04 and 0.21 - 0.58, respectively. Clastic sedimentary rocks have an average Cr/Th ratio of 37.97.

Clastic sedimentary rocks have total REE values ranging from 267.56 to 268.21 ppm (averaging 267.88 ppm). When normalized to chondrite (Fig. 4.9f), the clastic sedimentary rocks show a moderate LREE/HREE (2.60 - 4.02, average 3.31), an enriched LREE ((La_{CN}/Sm_{CN} = 1.68 - 2.99; average 2.33) and a flat HREE (Gd_{CN}/Yb_{CN} = 1.85 - 1.88; average 1.86) patterns. The clastic sedimentary rocks were compared to the Ngwako Pan and D'Kar formations data obtained from **(Kelepile et al., 2017)**, which as well show a moderate LREE/HREE, an enriched LREE and a flat HREE. The samples show a slight negative Eu anomaly (Eu/Eu* = 0.76 - 0.97, average 0.87) and a slight negative Ce anomaly (Ce/Ce* = 0.89 - 0.98, average 0.93).

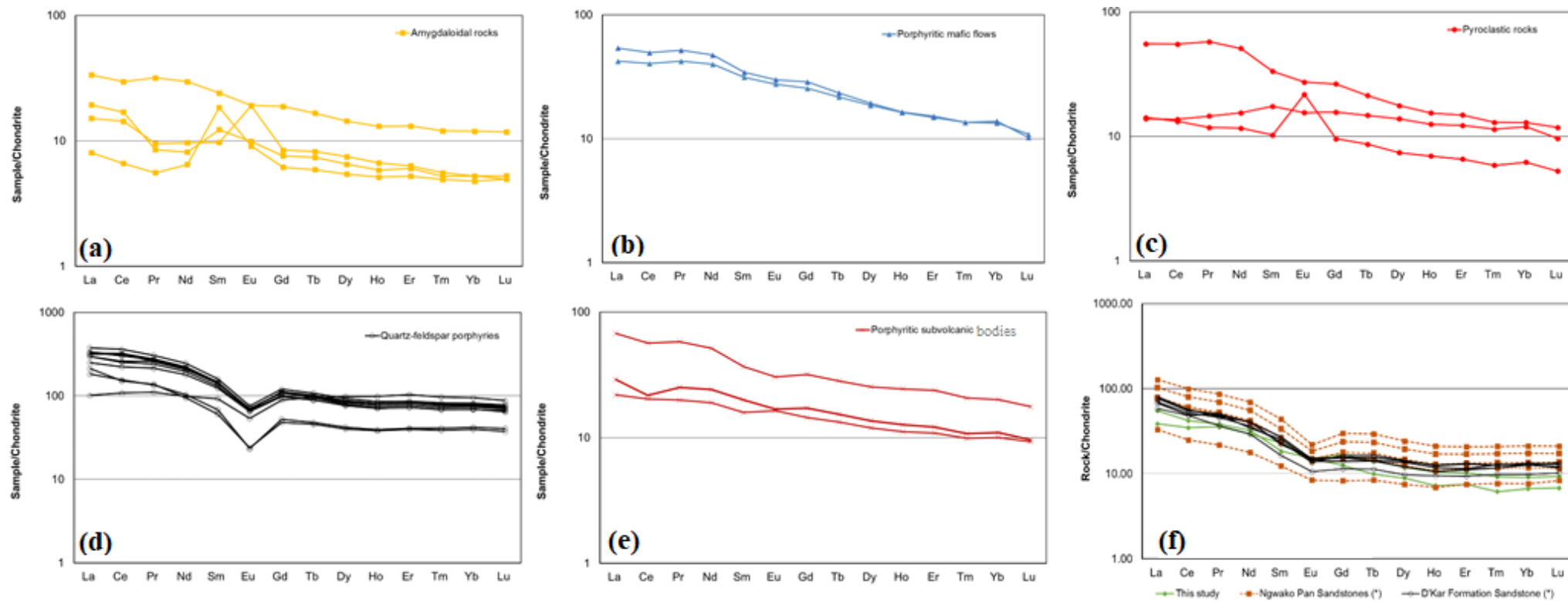


Fig. 4.9: Chondrite-normalised REE patterns of the studied KVF units. (a) Chondrite-normalised amygdaloidal rocks. (b) Chondrite-normalised porphyritic mafic flows. (c) Chondrite-normalised pyroclastic rocks. (d) Chondrite-normalised clastic sedimentary rocks (this study), Ngwako Pan and D'Kar formations for comparison purpose. (e) Chondrite-normalised quartz-feldspar porphyries (f) Chondrite-normalised porphyritic subvolcanic mafic bodies.

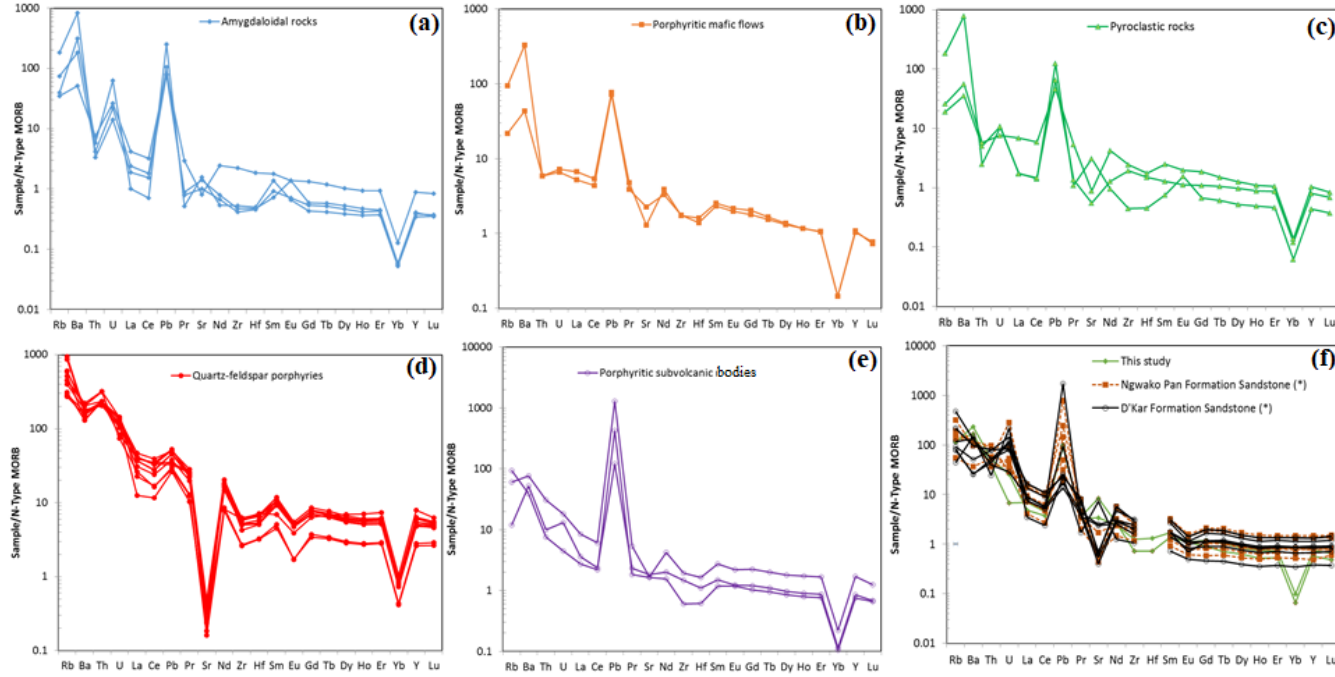


Fig. 4.10: MORB-normalised spider diagrams from (a) amygdaloidal rocks showing a pronounced negative Yb anomalies, positive Pb and Ba anomalies. (b) Porphyritic mafic flows showing a pronounced negative Yb anomalies, positive Pb and Ba anomalies. (c) Pyroclastic rocks displaying a pronounced negative Yb anomalies, positive Pb and Ba anomalies. (d) Quartz-feldspar porphyries exhibiting pronounced negative Yb and Sr anomalies, positive Pb and Th anomalies. (e) Porphyritic subvolcanic bodies (f) Clastic sedimentary rocks (this study) showing a pronounced negative Yb anomalies, positive Pb and Ba anomalies, whereas the Ngwako Pan and D'Kar formations show a pronounced positive Pb anomaly, positive U anomaly and negative Sr anomaly. Normalisation values are from **McDonough and Sun (1995)**.

4.5 Copper and silver quantities and implications for Cu-Ag source (s)

4.5.1 Copper and silver grades in the KVF rocks

This section describes the content of Cu and Ag, which are the elements of interest as far as this research is concerned. The highest Cu content in the KVF rocks is found within the basaltic porphyritic subvolcanic bodies, with values ranging from 35.5 to 223.0 ppm and 146.2 ppm on average. The amygdaloidal rocks follow with Cu content varying from 8.4 - 68.5 ppm with an average of 29.7 ppm. Clastic sedimentary rocks are characterized by Cu content of 2.3 – 28.5 ppm and 15.4 ppm on average, whereas porphyritic mafic flows have Cu content ranging between 0.5 - 24.7 ppm and 13.2 ppm on average. Rhyolitic quartz-feldspar porphyries on the other hand present an average of 10.8 ppm Cu content that ranges between 6.5 – 30.5 ppm. The lowest Cu content of the KVF rocks was measured in the pyroclastic rocks, ranging between 1.7 - 3.6 ppm and averages 3.45 ppm.

Whole rocks geochemistry also indicated that the KVF is relatively poor in Ag. The amygdaloidal rocks have Ag content ranging between 0.3 – 2.4 ppm and an average of 1.2 ppm. Rhyolitic quartz-feldspar porphyries yielded about 0.9 – 1.2 ppm of Ag and averaging 1.0 ppm, whereas Ag content in the basaltic porphyritic subvolcanic bodies, porphyritic mafic flows and pyroclastic rocks is less than 0.3 ppm. The clastic sedimentary rocks have Ag content 0.7 ppm on average.

Loss On Ignition (LOI), as mentioned in section 4.1, measures or estimates the magnitude of alteration of investigated rock samples. When considering the relationship between Cu-Ag content and LOI as depicted in **Table 4.3**, porphyritic subvolcanic bodies with the highest Cu content on average (146.20 ppm) and Ag content of less than 0.3 ppm yielded an average LOI value of 1.93 wt. %, amygdaloidal rocks with Cu content of 29.7 ppm and Ag content of 1.2

ppm yielded an average LOI value of 9.93 wt. %, clastic sedimentary rocks had an average Cu content of 15.4 ppm, a 0.7 ppm Ag content, and a LOI value of 12.78 wt. %. Porphyritic mafic flows with Cu and Ag content of 24.7 ppm and less than 0.3 ppm, respectively, yielded a LOI value of 4.19 wt. % on average, while quartz-feldspar porphyries with the second lowest Cu content (10.8 ppm) and an Ag content of 1.0 ppm yielded a LOI value of 0.37 wt. %. Pyroclastic rocks had the lowest Cu content on average of 2.87 ppm, Ag content of less than 0.3 ppm and LOI value of 6.13 wt. %. As a result, because there is no relationship or trend between metal content and LOI, it is clear that the Cu and Ag distribution, as observed is not due to alteration/weathering. Therefore, the Cu and Ag contents of investigated samples can be reliably used.

Table 4.3

Cu and Ag content (range and average respectively) in the different KVF units.

LITHOLOGY	Cu content (ppm)	Average Cu content (ppm)	Ag content (ppm)	Average Ag content (ppm)	Average LOI (wt. %)
Amygdaloidal rocks	8.4 - 68.5	29.7	2.4 - 0.4	1.2	9.93
Porphyritic mafic flows	0.5 - 24.7	24.7	< 0.3	< 0.3	4.19
Pyroclastic rocks	1.7 - 3.6	2.87	< 0.3	< 0.3	6.13
Clastic sedimentary rocks	2.3 – 28.5	15.4	0.7	0.7	12.78
Porphyritic subvolcanic bodies	35.5 - 223	146.2	0.3	0.3	1.93
Quartz-feldspar porphyries	2.5 – 30.5	10.8	1.2 - 0.9	0.95	0.37

4.5.2 Copper and Ag tonnage of the KVF

The KVF Cu-Ag quantities calculation was carried out in order to assess the total maximum Cu and Ag quantities likely to be sourced from the KVF rock units and then compare it to the total budget of Cu and Ag within the KCM Property. The formula's first step is to compute the input variables, followed by the output variables. The input variables are the Cu and Ag contents of the ultramafic-to mafic series (amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and porphyritic subvolcanic bodies) and the felsic series (quartz-feldspar porphyries), and the output variable is simply the maximum amount of Cu and Ag that could have been leached from both the ultramafic-to mafic series and the felsic series of the KVF, taking into account the density and volume of each rock unit (**Table 4.4**).

The Cu and Ag grade or concentration of both the ultra mafic-to mafic series and felsic series was obtained from ICP-OES and ICP-MS data measured, respectively. The quartz-feldspar porphyries averagely recorded Cu and Ag contents of 10.76 ppm and 0.95 ppm, respectively. The amygdaloidal rocks, porphyritic mafic flows, porphyritic subvolcanic bodies and pyroclastic rocks altogether compositionally classified as basaltic in composition yielded on average Cu and Ag content values of 53.69 ppm and 1.00 ppm, respectively. Basaltic units and quartz-feldspar porphyries have average densities of 2.9 g/cm³ and 2.4 g/cm³, respectively (**Charlier et al., 2011**). The volume of the basaltic units and quartz-feldspar porphyries was calculated using the area and thickness of the two rock units (**Table 4.4**). The total area of the KVF was calculated using ArcGIS, and its total thickness was obtained from (**Schwartz et al., 1995**).

The area was calculated in ArcGIS using the Calculate Geometry function in an attribute table for projected data files, where the target shapefile was re-projected (polygons in this case), a field to the target polygon's attribute table was added and the actual area of the KVF was

calculated which is 6762.80 km² (**Fig. 4.11**). As mentioned in the geological setting chapter, the KVF's total thickness is 2500 m and it is important to note that basaltic rocks account for a smaller proportion of the KVF area, as evidenced by the 1500 to 200 m thickness reported by **Schwartz et al. (1995)** and subsequent calculated average of 850 m. The remaining thickness (1650 m) is accounted for by the quartz-feldspar porphyries. As a result, the volume of both the basaltic rocks and the quartz-feldspar porphyries was calculated from the KVF area obtained and their individual thickness (**Table 4.4**). The weighted KVF Cu quantity formula used to calculate the KVF's Cu quantity is provided below;

$$M_{total} = \rho_b V_b G_b + \rho_q V_q G_q$$

Where, **M_{total}** denotes the total Cu quantity, **ρ** denotes density, **V** denotes volume, **G** denotes Grade, and **b** and **q** subscripts denote basaltic rocks and quartz-feldspar porphyries, respectively.

The Cu and Ag quantity of basaltic rocks calculated is 895 and 17 million tonnes, respectively. On the other hand, the Cu and Ag quantity of quartz-feldspar porphyries calculated is 288 and 25 million tonnes, respectively. Therefore, the total amount of Cu and Ag likely to be contained in the KVF is 1183 and 42 million tonnes, respectively. Considering that the total Cu and Ag budget of the KCM deposits is well over 500 million tonnes (**KCM Report, 2018**), then the calculated Cu and Ag amount is likely to have provided more than enough metal for most of the KCM Cu-Ag deposits after leaching.

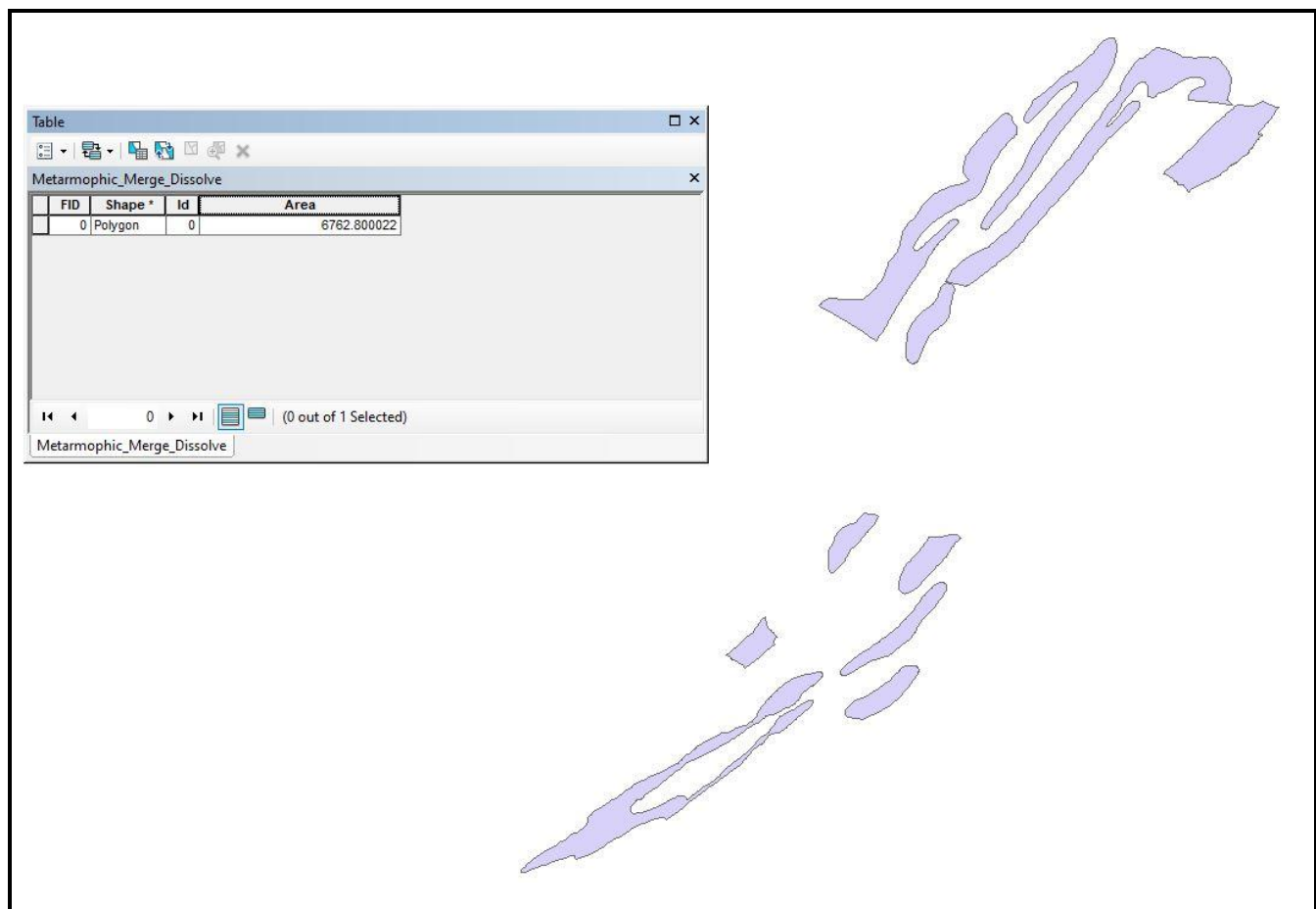


Fig. 4.11: A map showing the area (6762.80 Km²) of KVF calculated in ArcGIS using the Calculate Geometry function in an attribute Table for projected data files, where the target shapefile was re-projected (polygons in this case).

Table 4.4

Variables used for the calculations of the Cu and Ag quantities of the KVF.

Weighted KVF Cu and Ag quantity		
INPUT VARIABLES		
Parameters	Basaltic rocks	Quartz-feldspar porphyries
Cu grade (ppm)	53.69	10.76
Ag grade (ppm)	1.00	0.95
Density (g/cm ³)	2.9	2.4
Thickness (km)	0.85	1.65
Area (KVF) (km ²)	6762.80	6762.80
Volume (km ³)	5748.38	11158.62
Cu quantity (Mt)	895	288
Ag quantity (Mt)	17	25
OUTPUT VARIABLES		
Cu quantity of the KVF (Mt)		1183
Ag quantity of the KVF (Mt)		42

Note: The total amount of Cu and Ag in the KVF was calculated by adding the Cu and Ag amounts in the basaltic rocks and the quartz-feldspar porphyries. This was accomplished by multiplying the density in (t/m³) by the volume in (m³) and the Cu grade in (g/t), and then converting the final product from grams to million tonnes. The volume of the KVF rocks was calculated from the KVF area and the individual thickness of the KVF rock units.

The Cu and Ag quantities of the Ngwako Pan and D'Kar formations, which are also potential Cu and Ag sources within the KCM (**Hall et al., 2018, Kelepile et al., 2020**), were also calculated. Table 4.5 shows the parameters used in the calculations. The Cu and Ag grades of the Ngwako Pan and D'Kar formations, as well as their thicknesses, were obtained from **Kelepile et al. (2017) and Hall (2017)**, respectively. The thickness of each formation and the total area of the Ghanzi Group were used to calculate the volume of each formation. The Ghanzi Group and the KVF form the Ghanzi-Chobe Belt, a 500 km by 100 km belt with a total area of 50 000 km² (**Borg and Maiden, 1989**). The KVF area was determined to be 6762.80 km² (**Fig. 4.11**), so subtracting the KVF area from the Ghanzi-Chobe Belt area yielded the total area of the Ghanzi Group, which is 43 237.20 km². Sedimentary rocks, particularly sandstones, have an average density of 2.19 g/cm³. The D'Kar formation has a Cu and Ag content of 80 877.1 million tonnes and 71.0 million tonnes, respectively. The Ngwako Pan formation contains calculated 531 064.0 million tonnes of Cu and 94.7 million tonnes of Ag, respectively (**Table 4.5**).

Table 4.5

Variables used for the calculations of the Cu quantities of the D’Kar and Ngwako Pan formations.

Weighted Ngwako Pan and D’Kar formations Cu and Ag quantity			
INPUT VARIABLES			
Parameters	D’Kar formation	Ngwako Pan formation	
Cu grade (ppm)	569.42	2804.24	
Ag grade (ppm)	0.50	0.50	
Density (g/cm ³)	2.19	2.19	
Thickness (km)	1.5	2.0	
Area(km ²) (Ghanzi Group)	43 237.20	43 237.20	
Volume (km ³)	64 855.80	86 474.40	
Cu quantity (Mt)	80 877.12	531 064.00	
Ag quantity (Mt)	71.0	94.7	

Note: The total amount of Cu and Ag in the D’Kar and Ngwako Pan formations was calculated by multiplying the density in (t/m³) by the volume in (m³) and the Cu grade in (g/t), and then converting the final product from grams to million tonnes. The individual volumes were calculated from multiplying the Ghanzi group area and the individual thickness of D’kar and Ngwako Pan formations.

CHAPTER 5

DISCUSSION

5.1 Magma source(s)

The results presented above suggest that the KVF rock units did not derive and evolve from the same parental magma. In fact, the KVF rock units are of different magmatic series, with the felsic quartz-feldspar porphyries plotting in the high-K and shoshonitic field, whereas the ultra mafic-to mafic KVF volcanics are essentially calc-alkaline bodies, suggesting the different rock units found within the KVF are not cogenetic.

Furthermore, the ultra mafic-to mafic series (amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and porphyritic subvolcanic bodies) of the KVF are essentially MORB-derived, suggesting close genetical relationships between rocks of that series. Mid-ocean ridge basalt is a variety of submarine basalt which erupts in response to seafloor spreading, it is the most voluminous volcanic rock type on earth (**le Roex, 1998**). On the other hand, all quartz-feldspar porphyries are within-plate-derived magmatic bodies, indicating they all may have formed from the same magma. Rb/Sr values support the fact that quartz-feldspar porphyries generated from the crust. Thorium, Ta, Yb, and Hf data, as well as Y/Nb ratios (1.76- 2.93) of the investigated quartz-feldspar porphyries indicate their inclusive derivation from crustal protolith as crustal-derived rocks are known to have Y/Nb ratios greater than 1.2 (**Eby, 1990, Eby, 1992**). The felsic quartz-feldspar porphyries series of the KVF can also be regarded as a result of a relatively silica saturated magma source, although a mafic magma can still produce felsic rocks through crystal fractionation and crustal materials assimilation. However, higher

abundances of incompatible elements such as Th, is in favour of a felsic source, rather than a mafic one.

5.2 Magmatic evolution

The KVF rock units vary from subalkaline basaltic, through andesitic/andesite basaltic to rhyolitic/dacitic compositions (Fig. 4.2). A depletion in Ca, Fe, Mg, Fe, Mn, Ti, and P with silica increase, as displayed by quartz-feldspar porphyries supports the crystal fractionation processes during the evolution of these felsic- to intermediate volcanic suite. This is consistent with plagioclase (as widely observed in the rocks) and apatite (though not observed) fractionation. Plagioclase fractionation is further supported by the negative Eu anomaly characteristic of all quartz-feldspar porphyries. Apatite fractionation is depicted by decrease in P_2O_5 and CaO with silica increase. Furthermore, enrichment of K_2O over Na_2O displayed by the quartz-feldspar porphyries is indication of fractionation or incompatible LILE enrichment such as Ba, Rb and Th over HSE in most cases (**Esperanca et al., 1992**). In the ultra mafic-to mafic series, the fractionation trend is not clearly shown among all members. However, depletion in Al, Mg, and Ca with increase in silica can be clearly depicted in mafic porphyritic subvolcanic bodies, also suggesting fractionation of plagioclase. Furthermore, all the KVF rocks display an enrichment of LILE, reflecting the significant role of fractional crystallisation processes during the evolution of these volcanic rock units.

The studied KVF rock samples display a wide range of Rb/Sr ratios. Amygdaloidal rocks Rb/Sr ratios range from 0.16 to 0.81, porphyritic mafic flows from 0.10 to 0.26, pyroclastic rocks from 0.18 to 0.37, porphyritic subvolcanic bodies from 0.24 to 0.35 and quartz-feldspar porphyries from 4.29 to 17.26. These Rb/Sr values are higher than lower and middle continental

crust Rb/Sr ratios, which are 0.12 and 0.22, respectively (**Rudnick and Fountain, 1995, Wedepohl, 1995**). Given that the continental crust can be regarded as being vertically zoned with Rb/Sr increasing upward (**Blevin and Chappell, 1995**), the Rb/Sr values of the KVF rocks indicate on one hand contamination by the upper continental crust of the mantle-derived (as shown in section 5.1) parental magma of the mafic KVF volcanics (amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks and porphyritic subvolcanic bodies). The large range in Pb concentration as observed in the KVF mafic series (13.8- 383 ppm) further suggests crustal contamination as one process that affected the chemistry of these subalkaline rocks as they evolved. On the other hand, the elevated Rb/Sr values of the quartz-feldspar porphyries of the KVF once again support an upper crustal-derived magma.

5.3 Magma emplacement mechanisms

Textural evidences, such as crystal embayment and rounded crystals in quartz-feldspar porphyries indicate rapid magma ascent during the emplacement of the KVF quartz-feldspar porphyries. In fact, embayment of crystals reduces magma viscosity and loading mass, thus enabling its rapid ascent (**Annen et al., 2006; Petford, 2003**). Rounding of quartz and feldspar crystals likely related to mechanical abrasion of euhedral crystals will also contribute in reducing the loading mass of the magma, then promoting its rapid ascent. The presence of abundant plagioclase phenocrysts in rocks from the KVF further suggests low viscosity of magma. Indeed, plagioclase phenocryst growth is ascribed to the high-water content of the pre-eruptive magma (**Carr et al., 1982**). A high-water content in turn reduces magma viscosity and promotes its rapid ascent as already indicated above. The rate of magma ascent in turn influences the style of volcanic eruption (**Miwa et al., 2009**). In fact, rapid ascent typically

favours explosive eruptions because there is less time for outgassing, whereas slow ascent favours effusive eruptions (**Andujar and Scaillet, 2012**).

The presence of angular lithic fragments, notably in the pyroclastic rocks of the KVF strongly suggests that the eruption that resulted into KVF rock units was most likely explosive. On the other hand, eruption was also effusive as suggested by the presence of porphyritic mafic flows and amygdaloidal rock units. Numerous factors are likely to control the style of eruption. High viscosity of magma for example, inhibits the release of volatiles, thus increasing the likelihood of explosive gas escape (**Mangan et al., 2004**). However, if volatiles contained in the magma are lost during ascent, this will result in passive flow extrusion (**Cashman, 2004**). Furthermore, a volcanic eruption is effusive when the erupting magma is volatile-deficient, therefore, preventing fragmentation, which causes explosive eruptions (**Doubik and Hill, 1999**). However, if a magma is not beyond a specific permeability threshold, a shift from effusive to explosive eruption might occur and this shift probably better explains the presence of both effusive and explosive magmatic features within the KVF mafic series. Evidences of changes in the dynamic of the KVF rock emplacement can also be assessed by degassing activity, which hints are given by rock textures. The presence of vesicles and amygdales in some of the KVF rock units indicates that the magma was not degassed during eruption and instead micro-vesiculated (cf. **Savov et al., 2008**). On the other hand, the microlites observed might be the result of magmatic degassing on eruptive timeframe (**Szramek et al., 2006**). Likewise, flow banding may be related to increased degassing during magma ascent (**Stasiuk et al., 1996**). Change from a degassing magmatic system from a non-degassing one clearly indicates changes in the eruption style and/or activity (cf. **Duffell et al., 2003**).

The KVF displays disequilibrium features such as rounded, resorbed, and embayed quartz and plagioclase crystals, suggesting magma mixing/mingling. The skeletal growth in plagioclase

(**Fig. 3.10h**) further supports the KVF magmatic system experienced repeated episodes of disequilibrium and undercooling (cf. **Bennet et al., 2019**).

The texture exhibited by KVF rock units can also provide clues on the magma cooling rate. With the exception of amygdaloidal rocks with limited evidence of glass, the other KVF rocks exhibit no development of glass composition, suggesting slow magma cooling. Furthermore, virtually almost all KVF rocks have a porphyritic texture, indicating that the magma body was cooled in stages. Cooling slowly when deep under the surface and then rising to the surface to cool faster. However, the lack of glassy groundmass may also suggest that the KVF experienced devitrification, which is likely to occur as a result of extra slow cooling or reheating of the primary volcanic glass (**Lofgren, 1971**). But, in the absence of devitrification textures such as spherulite, the devitrification process cannot be confidently envisaged.

The petrological and geochemical characteristics of the KVF's clastic sedimentary rocks are comparable to those of the D'Kar and Ngwako Pan formations (see geological setting section). Sandstones of the D'Kar and Ngwako Pan formations are classed as subarkoses and arkoses and are chemically and texturally immature-to submature (**Kelepile et al., 2017**). The textural and chemical characteristic of both D'Kar and Ngwako Pan formations are comparable to the investigated KVF clastic sedimentary rocks, suggesting the KVF clastic rocks and rocks from the D'Kar and Ngwako Pan formations derived from the same source. Worthy of note is that the probable source of sandstones of both the D'Kar and Ngwako Pan formations were located in the Paleoproterozoic basement rocks and the Mesoproterozoic Kgwebe volcanic rocks (**Kelepile et al., 2017**). If the KVF intercalated clastic rocks and rocks from D'Kar and Ngwako Pan Formations derived from the same source as above argued, then the KVF clastic rocks also derived from the Mesoproterozoic KVF volcanics. This suggests simultaneous volcanism and sedimentation processes, whereby clastic sedimentary rocks development involved sediments

obtained from erosion of KVF volcanics and their subsequent transport, sedimentation and lithification while volcanism is still operating. Such a scenario would suggest not only a long-life volcanic activity with episodic magma pulses, but also a rapid erosion rate, which requests a favourable tectonic setting. The tectono-magmatic conditions at which that can occur is beyond the objective assigned to this and will therefore not be discussed further.

5.4 Source (s) of Cu and Ag in the KCM Cu-Ag deposits

The KVF contains 1183 million tonnes of Cu and 42 million tonnes Ag and considering that the total Cu +Ag budget of the KCM deposits is estimated over 500 million tonnes (**KCM Report, 2018**), the calculated KVF Cu + Ag quantity is likely to provide enough metal to the KCM copper deposits and therefore can account for the total metal budget at the KCM property. However, considering that all the Cu and Ag contained in the KVF are unlikely to have been leached, the possibility of other Cu-Ag cannot be ruled out. The Cu-Ag may have been sourced from Ngwako Pan and D'Kar formations as pointed out by previous studies (**Kelepile et al., 2020**). Calculation done in section 4.5 indicate the Ngwako Pan and D'kar formations altogether are likely to contain significant Cu and Ag, up to 611 941.1 and 166 million tonnes, respectively. It is probably on that regard that **Hall et al. (2018)** suggested two source rocks for the Kalahari Copper Belt's base metals. Those included the red bed sandstones of the Ngwako Pan Formation and the basaltic rocks of the underlying KVF and associated ultra mafic-to mafic intrusive rocks of the Umkondo Large Province, which are found south of the Kalahari Copper Belt. Moreover, the base metals could have been derived from concealed and currently unknown deep magmatic bodies in which metals were transported along deformation structures developed within the overlying sedimentary strata.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This study aimed at investigating the possibilities of the KVF being the source of Cu and Ag in the Khoemacau Mining Project. This was attained by assessing the contents of Cu-Ag of the Kgwebe Volcanic rocks, investigating the mineralogy of the KVF rock units and assessing whether the KVF could have accounted for the total Cu-Ag budget in the Khoemacau Mining Project. The following conclusions derived from the results obtained and the preceding discussion:

- (1.) Amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks, porphyritic subvolcanic bodies, quartz-feldspar porphyries, and clastic sedimentary rocks are the identified rock types that constitute the KVF;
- (2.) KVF rock units were classified into two end members including the ultra mafic-to mafic series (amygdaloidal rocks, porphyritic mafic flows, pyroclastic rocks, and porphyritic subvolcanic bodies) and the felsic series (quartz-feldspar porphyries);
- (3.) Felsic suites of the KVF are crustal derived, while the more mafic counterparts are mantle-derived. Likewise, whereas the ultra mafic-to mafic series are volcanic arc and MORB-derived, the felsic series are consistently within-plate- derived;

- (4.) Magma differentiated by the means of fractional crystallisation, magma mixing and crustal contamination (especially the ultra mafic-to mafic KVF suites);
- (5.) Magma ascent was rapid and led to both effusive and explosive eruption styles;
- (6.) Emplacement of the KVF volcanics was synchronous with sedimentation as witnessed by the intercalation of clastic sedimentary rocks within the KVF volcanics;
- (7.) The Cu and Ag contents of KVF rock units are sufficient to account for the total metal budget of KCM Property, and significant amount of Cu and Ag is likely to have been leached/sourced from the KVF rock units;
- (8.) Additional Cu-Ag may have been sourced from other lithologies and especially from the Ngwako Pan and the D'kar formations as pointed out by previous studies and the calculations conducted in this study.

In terms of recommendations, it is critical to assess which quantity of copper and silver could have been leached from both the KVF and the Ngwako Pan and the D'kar formations. The physico-chemical conditions under which the leaching process may have taken place are also to be outlined. Those include, the temperature, the salinity, redox conditions of the mineralizing hydrothermal fluids, as well as the fluid/rock ratio that could have led to optimal leaching of Cu and Ag from each of the potential rock source identified.

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