

**PEDOLOGICAL ASPECTS OF EARTHENWARE POTTERY-
MAKING SOILS FROM KWENENG DISTRICT, BOTSWANA**

By

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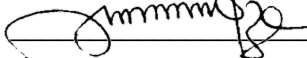
**A Thesis Submitted to the Faculty of Sciences in Partial Fulfilment of the Requirements for
the Award of the Degree of Master of Science in Environmental Science of BIUST**

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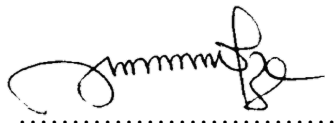
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I, Yvette Matshameko, declare that this thesis is my own original work and that it has not been presented and will not be presented to any other university for a similar or any other degree award.

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CERTIFICATION

The undersigned certifies that he has read and hereby recommends for acceptance by the Faculty of Sciences a dissertation titled: Pedological aspects of earthenware pottery-making soils from Kweneng District, Botswana, in fulfilment of the requirements for the degree of Master of Science in Environmental Science of the BIUST.

A handwritten signature in black ink, appearing to read 'Peter N. Eze', is written above a horizontal dotted line.

Dr Peter N. Eze

Date: 08 February, 2021
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ABSTRACT

Ethnopedological and pedological investigations have been largely centred on agricultural land uses and associated practices. However, indigenous peasants have also relied on soil resources to eke their livelihood in other activities including non-commercial pottery making. Clayey soils, weathered sandstone and other materials are traditionally used in the Kweneng District of Botswana for earthenware pottery. This study bridges the gap in the dearth of information on the pedological characteristics of these pottery-making soils against the traditional soil knowledge. The objectives of this study are: (i) to characterize the soils using their morphological, physico-chemical and mineralogical properties; (ii) to assess the degree of chemical weathering of the soils; (iii) to quantify the operating pedogenic processes and (iv) to classify the soils following USDA *Soil Taxonomy* and correlate it to WRB system. Soil samples were collected from two profile pits each sited in Letlhakeng, Takatokwane pan, and two excavations in Khudumolapje and Letlhakeng respectively. Standard pedological parameters, such as structure, colour, bulk density, porosity, pH, electrical conductivity, organic matter content, carbonate contents and magnetic properties were determined using routine laboratory procedures. The total elemental composition and clay mineralogy analysis were done using the x-ray fluorescence spectroscopy and x-ray diffractometry. Chemical index of alteration (CIA), chemical index of weathering (CIW) and index of compositional variability (ICV) were used to assess chemical weathering intensities. Molecular pedogenic ratios were used to quantify pedogenesis in the soils. The soil colour spanned grey to greenish at Takatokwane, brown reddish in Letlhakeng, and brownish gray in Khudumolapje. Sandy texture dominated the particle size distribution of the soils, with most having more than 60 % sand and less than 30 % clay. These soils are moderate to highly porous (20 - 40 %). The soil pH ranged from 7.0 to 9.6 with high CEC ($< 20 \text{ Cmol kg}^{-1}$) for Takatokwane and medium CEC ($12\text{-}20 \text{ Cmol kg}^{-1}$) in Letlhakeng. Element abundance followed $\text{SiO}_2 > \text{Al}_2\text{O}_3 > \text{Fe}_2\text{O}_3 > \text{TiO}_2$ in all the soil profiles. The clay mineral assemblages of the soils are smectite, sepiolite, vermiculite, kaolinite, montmorillonite and illite. Variations in the properties of these soils could be mainly attributed to the differences in topography. The degree of weathering of the soils are generally incipient as they had $\text{ICV} > 1$ and CIA values < 60 . The dominant pedogenic processes in the soils include hydrolysis, lessivage, leaching, eluviation, illuviation and gleization. Based on USDA Soil Taxonomy system, the soils qualified as Aridisols with subgroups of Natrargids and Petrocalcids at Takatokwane and Letlhakeng respectively with the WRB correlations as Gleyic Arenosols (Aridic) and Calcisols (Loamic, gleyic, aridic). Site-specific pedological studies of this kind would continue to provide insights into the best management practices needed for the sustainable use of soil resources.

Keywords: Pedogenesis; Weathering; Clay mineralogy, Letlhakeng; Takatokwane

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CHAPTER ONE

INTRODUCTION

1.1 Introduction

Soil is an open system which results from the complex interactions between environmental factors (climate, organism, relief, organism, parent material and time) and the specific processes of formation (Silva et al., 2019). Pedogenesis (soil formation) is strongly influenced by the five soil forming factors. Soil properties often express some of the characteristics of the parent material and climate hence providing insight into the environmental and climate conditions in which they formed. Improved understanding of soil formation and properties can provide insights into ways of ensuring sustainable soil use and management (Arnold, 2005; Khomo, 2008).

Many pedological studies have been focused on the genesis, classification as well as the productivity of the agricultural soils while non-agricultural soils remain poorly covered in research programs and publications (Cabral et al., 2015). Pottery making in Southern Africa dates back to over 2000 years ago (Thebe and Sadr, 2017). This is a socio-cultural and economic practice or activity which is done mostly using indigenous knowledge and wisdom of the local people. The south-eastern Botswana is well known for both ancient and contemporary pottery making as it is a practice which started in the early 19th century. Batswana (people originating from Botswana) use earthenware vessels for different purposes which include cooking, decoration and for rituals.

1.2 Statement of the problem

Many of the pedological and ethnopedological studies in Botswana are mainly focused on agricultural soils while neglecting some of the soils that peasants rely on to improve their economic lifestyles, such soils are used in both traditional and commercial pottery. Previous studies on the earthenware pottery-making soils from Botswana focused on the art of making pots (e.g. Thebe et al., 2009; Pikirayi and Lindahl, 2013; Thebe and Sadr, 2017), relationship between pottery and language (e.g. Thebe and Sadr, 2017), the choice of collecting clay for pottery making as well as some religious and cultural rituals to be observed when using clay for pottery making (e.g. Thebe et al., 2009), and the clay mineralogy of pottery making soils (e.g. Ekosse and Fouche, 2006). Extensive literature search shows that there is scarcity of scientific information on the pedology of soils utilized in earthenware pottery from Botswana and the Kweneng district was no exception.

1.3 Justification of the study

Most of the rural peasants in Kweneng District rely on income from pottery making to sustain their lives. Pottery making is a good economic activity in Kweneng district (Banyatsi, *pers comm*, March 2019) and to improve this sector, then the soils used in pottery making should be comprehensively studied beyond just the local knowledge. There is dearth of scientific published information on the properties of earthenware pottery making soils which leaves this commercial practice with gaps in scientific knowledge of the raw material. The scientific study of earthenware pottery making soils will aid in improving the quality of the products, as well as assisting potters with supplement scientific information regarding their raw material. This study will also play a huge role in the provision of documented scientific literature in pedological investigations of Kweneng district. The clay soil used for pottery making has interesting and

unique qualities that can be studied such as the physico-chemical properties, mineralogy and geochemical properties, therefore by studying these properties of clay we can have a better understanding of the soils that are used for earthenware pottery making as well as provide better insight that can be helpful to potters in Botswana.

1.4 Aims and objectives of the study

The overarching aim of this study is to improve our understanding of the pedological aspects of earthenware pottery-making soils from Kweneng district.

The specific objectives are:

- (i) to characterize the pottery making soil using their morphological, physico-chemical, geochemical, and clay mineralogical properties;
- (ii) to assess the degree of weathering of the soils;
- (iii) to quantify the pedogenic processes operational in the soil environments; and
- (iv) to classify the soils following USDA *Soil Taxonomy* and correlate it to WRB system.

CHAPTER TWO

LITERATURE REVIEW

2.1 Pedogenic models

Pedologists have developed various models aimed at explaining the mechanisms and processes of soil formation. These models include; (i) functional-factorial model, (ii) process-systems model and (iii) the energy model. Pedogenic models are important as they aid in putting soil information into perception and offer understanding of the system interrelationships, the process connections and the nuances of pedogenesis (McBratney et al., 2008).

2.1.1 *The mechanistic model (also known as the functional-factorial model)*

Developed by Hans Jenny in 1941, this model defines the soil as a system using the five factors of soil formation:

$$S = f(cl, o, r, p, t \dots) \quad \text{(Equation 2.1)}$$

Where s = soil, cl = climate, r = relief, p = parent material and t = time, the dots indicate additional factors which may be of local importance but not universal such as inputs of eolian dust and sulphate deposition in acid rain (Schaetzl and Anderson, 2007).

The mechanistic model implies that soils are a function of the four environmental-landscape factors; climate, organisms, relief and parent material which act over time as seen in equation 2.1 (Johnson and Schaetzl, 2015). It has led to studies that allow one of these five soil forming factors to vary whilst the others are held constant in order to determine the consequence of the varying factor on soil formation (e.g Hillel, 2008; Harrison and Strahm, 2008; Brevik et al., 2016). The recognition of the relationships between soil forming factors is important because it is one possible source of detailed soil pattern (McBratney et al., 2008). Through this model,

Jenny demonstrated that we would be able to predict the exact soil principles by specifying the state of the entire soil system (Schaetzl and Anderson, 2007). Jenny's theory is mostly based on classical thermodynamics. The *cl,o,r,p,t* factors were then later classified into active and passing soil forming factors by Joffie (1949). Climate and organisms make up the active soil forming factors which are responsible for providing energy needed to act on the parent material in order to form soil. The passive factors of soil formation are made up of relief, parent material and time, they give soil forming conditions and mass which then serves as a base on which the active soil forming factors work for the development of soil in due time (Singh, 2015). The advantages of Jenny's model are that it is observable, measurable and vary spatially which makes it suitable for soil mapping. Another good thing about it is that it is easy to understand and the fact that it's a factorial model attempts to describe the soil system characteristics using external variables. The shortcomings of this model is that it reveals very little about the soil system dynamics and pedogenic processes (Schaetzl and Anderson, 2007).

2.1.2 *Processes-based model*

In 1959, Simonson developed the processes model which concentrates on the processes that formed soil (Sebastian et al., 2008; Brevik et al., 2016). Simonson processes-based method is mostly useful in examining and describing characteristics of a soil profile (Brevik et al., 2016). This model is of the view that soil formation consists of two steps, (i) accumulation of parent material and (ii) differentiation of the parent material into horizons (Schaetzl and Anderson, 2007). According to this model, soil is regarded as an open system with additions, removals of materials from the profile, translocation and transformation within the soil profile;

$$s = f(\text{additions, removals, translocations, transformation}) \quad (\text{Equation 2.2})$$

In the year 1978, Simonson further expanded this theory to that additions and losses take place in the soil as a whole while translocations are additions and losses that happen amongst horizons within a distinct pedon. The four sets of processes concurrently occur in all soils. The development of each horizon is due to these processes. The benefit of Simonson's model is that it is adaptable to computer simulations used in pedogenesis as it classifies each of the four sets of processes. The process-system based model has formed the conceptual backbone on a branch of pedology which is focused on mass balance calculations. The shortcoming of the model is that it cannot be used when interpreting soil variability (Schaetzl and Anderson, 2007). The difference between the Simonson and Jenny models is that while the process-systems model centres on processes that occur internally within the soil profile, the functional factor model emphasises on the external factors influencing pedogenesis.

2.1.3 Energy model.

In view of the strengths and weaknesses of mechanistic and process-based models, Runge (1973) attempted to blend the factorial model with the processes model and came up with the energy model (Equation 2.3). To formulate this equation (Equation 2.3), Runge highlighted and combined two factors from Jenny's model, climate and relief to a single intensity factor defined as the amount of available water for leaching (w). He then combined the parent material and organisms factors and defined them as organic matter production (o) lastly he include time (t) factor (Schaetzl and Anderson, 2007). This model states that energy is the principal driving factor for soil formation (Sebastian et al., 2008). In this model, the external factors drive the internal processes (Schaetzl and Thompson, 2015; Brevik et al., 2016). The main source of energy in Runge's model is gravity which is responsible for water flow in and on the soil,

another source is derived from vegetation which utilizes water during transpiration. This model is written as;

$$s = f(o, w, t) \quad \text{(Equation 2.3)}$$

Where s = soil, o = organic matter and t = time.

2.2 Factors of soil formation

As noted earlier, soil formation is strongly influenced by state factors including climate, organism, relief, parent material, and time. The complex interaction of these factors is responsible for the nature and properties of soils found at any location.

2.2.1 Climate

Temperature and precipitation are the two active climatic parameters that are considered by pedologists when studying soil genesis (Singer, 2015). High temperature and high moisture content due to precipitation tends to increase the rate of bedrock and sediment weathering and also influences the occurrence and extent of soil chemical reactions, soil pH and the decomposition of organic matter (Pidwirny, 2006). Rainfall is responsible for leaching away soluble materials and iron-rich minerals from uppermost horizons into the lower ones while evaporation can bring about the accumulation of salt compounds mostly in the surface horizons. Precipitation and temperature also direct the subsequent behaviour of chemical elements in the soil solution, element movement is influenced by pH of solutions which in turn relies on the quantities of infiltrating water (Tardy et al., 1976). Another major key role of rainfall in soil genesis is that it determines the nature of the soil as it influences the type of climate, for example in arid and semi-arid climates saline soils are most prospectively to form while humid and warm climates are prone to the development of red laterite and lateritic soils. Climate indirectly exerts

the control of plants and animals which supply energy in the form of organic matter (Singh, 2015).

2.2.2 *Organism*

The living organisms play a role in the processes involved in pedogenesis including profile mixing, accumulation of organic matter as well as biogeochemical nutrient cycling (Pidwirny, 2006). Macro-organisms such as snails, moles, rodents, termites, earthworm and centipedes cause mixing of the soil material which delays horizon differentiation hence delaying the process of soil development. On the other hand, microorganisms found in the soil such as fungi, bacteria, protozoa, and nematodes assist in the breakdown of organic matter, and indirectly play a role in decomposition of mineral matter by the production of organic acids. The constant decomposition of soil mineral and organic matter helps in the transportation and deposition of these constituents in the different soil layers hence leading to the development of soil (Singh, 2015). Organisms such as bacteria, fungi, animals, humans and vegetation are the major determinants which have an effect on the physical and chemical environments of the soils (Moazallahi and Farpoor, 2012). Vegetation constitutes second component of soil solid which is organic matter. The organic matter produced, has an influence on soil properties by improving the water holding capacity, reducing tendency of crust formation as well as soil erosion. Flora is a source of food for organisms in the soil and it acts as an indicator of soil health.

2.2.3 *Topography*

Topography describes the landscape and the shape on which soil is found (Singer, 2015) and the configuration of the land surface. The difference in slope, position on the slope and the slope aspect tend to create different conditions for soil formation. The topography passively plays a role as a soil forming factor by altering weathering and soil properties indirectly through its

effect on water and mass movements (Jenny, 1941). In most cases, soils formed from comparable parent material under identical climatic conditions often present dissimilarities due to their position on the landscape. Soils on relatively high land areas and steep slopes are well aerated with good drainage and normal pedological evolution while those on flat-lying areas and depressions are mostly characterised by inefficient drainage, temporary or permanent waterlogged soil and pedological evolution which comes differently (Tardy et al., 1976; Singh, 2015), generally formation of soil is poor on steep slopes due to erosion while the gently sloping flat land is ideal for the development of soil. Horizon differentiation is rapid on flat lands as compared to uplands and lowlands due to the higher rate of water percolation and soil constituents leaching (Singh, 2015).

2.2.4 Parent material

Soil parent material is the initial material for pedogenesis at time zero ($t = 0$). Soil tends to inherit its parent material's primary minerals, physical and chemical properties which then become the initial properties of the soil until it undergoes some soil forming processes (Jenny, 1941). An insight of the unique conditions that lead and facilitate soil formation can be seen from the soil properties which express the characteristics of the components of the parent material (Arnold, 2005). The soil parent material may be alluvial, colluvial, lacustrine, till or eolian and can also be a combination of these (Khomu, 2008; Singh 2015). It is possible to have soil forming in various sequences of parent material which results in the discontinuities in the soil pedon (Moazallahi and Farpoor, 2012). The parent rock has an effect on the rate of soil development as different materials react differently to bioclimatic factors of soil formation (Targulian and Krasilnikov, 2007; Tsozué et al., 2017).

2.2.5 *Time*

Soil formation is a natural phenomenon which requires thousands of years to become a mature pedon. Pedologic time is the period of time that is taken by the nature from the parent stage of a parent material to the stage formation of a mature soil (Singh, 2015). Time of a pedogenic process is not a constant value as it is based on the reflection of the intensities of the pedogenetic processes of the environment (Figure 2.1) (Targulian and Krasilnikov, 2007). Time has a temporal influence in all the other four factors of soil formation. Several soil processes become steady state with time when soil reaches its old age (Pidwirny, 2006). Younger soils tend to adopt some characteristics from their parent material, but as the age advances, the addition of organic matter, moisture exposure and any other environmental factors may change its features. As time goes on, soils are buried deeper below the surface while undergoing transformation.

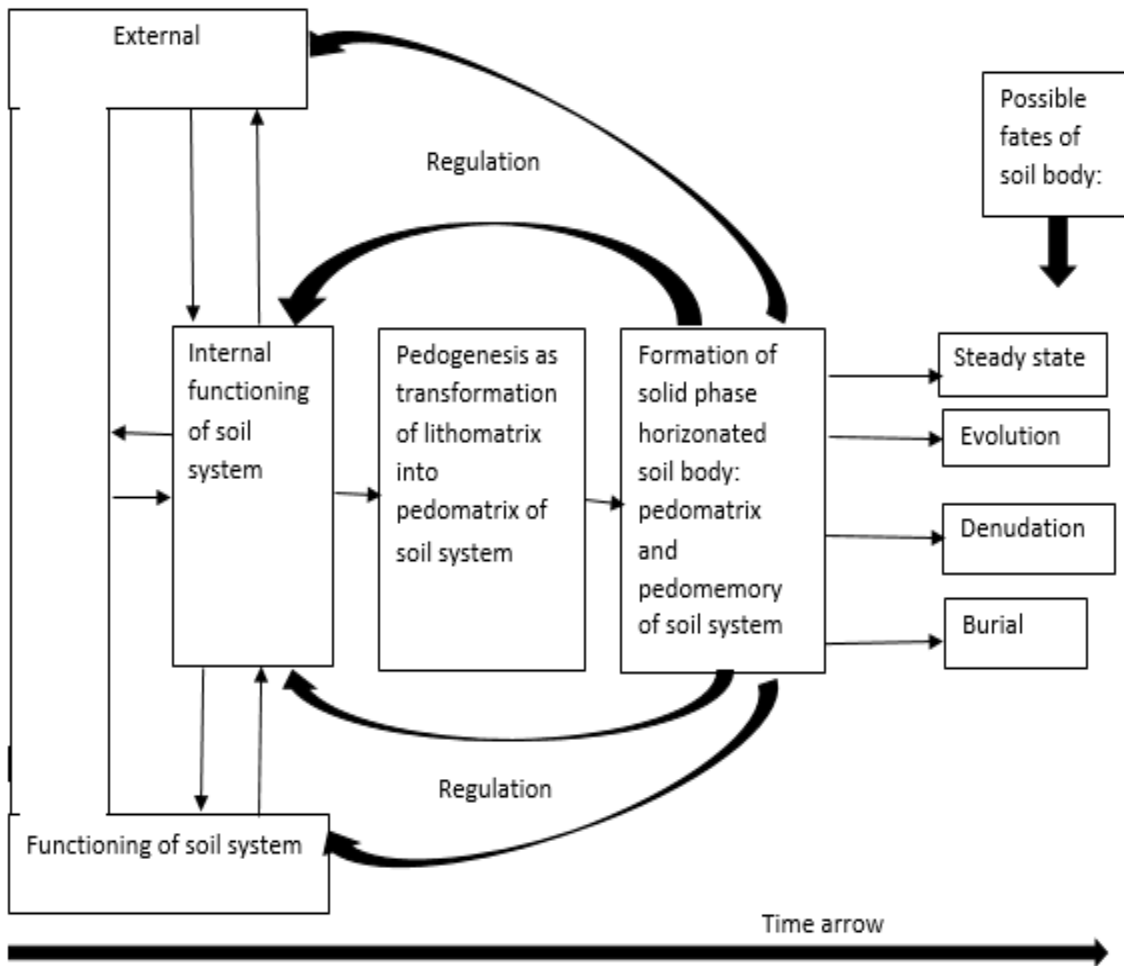


Figure 2.1: Soil system behaviour in time (Adapted from Targulian and Krasilnikov, (2007))

Pedogenesis can be seen as an incorporation of precise pedogenic processes (SPP) with each being capable of generating a certain set of solid-phase pedogenic features. These SPPs can be grouped into; soil weathering, transformation, translocation, leaching, pedoturbation, gains and losses (Targulian and Krasilnikov, 2007) Soil external functions are dependent on the quality and or magnitude of the pedogenic products which are subject to modification during pedogenesis.

2.3 Molecular weathering indices and quantitative pedogenic ratios

Weathering is a general term given to the process by which rocks are broken down to form soils. Variables such as climate, biological activity, parent material and topography influence the rate of weathering. The determination of quantifiable characterization of weathering in a soil is key in predicting and assessing the soil evolutionary phase (Yousefifard et al., 2012). Various pedogenic processes (redox processes, primary minerals dissolution, transport of materials, ion exchange and the formation of secondary minerals) are responsible for the movement of elements during weathering (Xin et al., 2010; Şenol et al., 2017). The distribution of elements in the pedon is used to determine the weathering nature and degree (Nesbitt and Young, 1982; Mohanty and Nanda, 2016).

Chemical weathering is one of the key processes responsible for modifying the surface of the earth as it utilizes important controls on geochemical cycling of elements. Both precipitation and temperature accelerate soil chemical weathering and cause alkaline and alkaline earth metal (Ca, Mg, Na and K) depletion (Mohanty and Nanda, 2016). The use of mass balance plots are of great importance as they provide a way of accounting for what happens to the elements during soil evolution by measuring the gains, losses as well as transformations that develop of time (Brimhall and William, 1987).

The chemical indices are mostly used for characterizing weathering of the profiles as well as assessing the degree of chemical weathering changes (Price and Velbel, 2003). In a review done by (Price and Velbel, 2003), weathering indices utility was evaluated using the following criteria;

Chemical weathering index is supposed to be easy to use and should contain some elements common in soil analyses so that it can be widely applicable and comparable with other studies. The incorporation of elements with a wide range of mobility in the weathering environment should be considered. It is also important for a weathering index to exhibit chemically appropriate trends with an increase in weathering. Useful weathering index is supposed to be applicable to soil, rock types and rocks and it ought to be able to yield values for the unweathered material that is different from the values of weathered material irrespective of the type of rock. It is ideal that a chemical weathering index ought not to assume that any element is immobile, instead the least mobile elements are the ones that should be used (Price and Velbel, 2003).

2.3.1 Chemical Weathering Indices

Chemical index of alteration (CIA) was developed by Nesbitt and Young (1982) to be used in the reconstruction of paleoclimate from the early Proterozoic sediments of the Huronian supergroup. It is a measure of the breakdown of feldspars and other minerals through the removal of base cations (mostly Na and Ca) for the production of clays (Nesbitt and Young, 1982). This index has been used in different paleosols studies because the CIA is an interpretation of the level of conversion of feldspars which mostly dominate the upper crust to clay e.g. kaolinite (Price and Velbel, 2003). According to Nesbitt and Young (1982), incipient weathering is indicated by values ranging between 50 and 60 while 60-80 is an indication of intermediate weathering and values greater than 80 indicate extreme weathering. Low CIA values are an indication of near or absence of chemical weathering hence reflecting cold and/or arid conditions while the high CIA infer the removal of unstable or mobile cations such as Ca, Na and K in relation to the highly

immobile (Al, Ti) during weathering (Lamine and Ishiga, 2016; Nadłonek and Bojakowska, 2018). CIA can be calculated using the molecular proportions from the formula:

$$[Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100 \quad (\text{Equation 2.4})$$

CaO* is the amount in silicate only

Chemical index of weathering (CIW) was developed by Harnois (1988). It is similar to the CIA as it also measures the extent of the conversion of feldspars to clay but different in the sense that it eliminates the K₂O from its equation. CIW mostly yields high values for rocks rich in K-feldspar since it has no justification for the aluminium associated with K-feldspar (Price and Velbel, 2003). CIW can be calculated from the equation:

$$\frac{Al_2O_3}{(Al_2O_3 + CaO^* + Na_2O)} \times 100 \quad (\text{Equation 2.5})$$

CaO* is the CaO residing only in the silicate fraction.

Plagioclase index of alteration this was proposed by Fedo et al. (1995) to act as an alternative to the CIW. Due to the abundance of plagioclase in silicate rocks, the PIA can be used when there is need for monitoring plagioclase weathering (Price and Velbel, 2003; Fiantis et al., 2010). Values of 50 are attained in non-weathered rocks and those close to 100 are attained in clay minerals such as kaolinite, gibbsite and illite (Nadłonek and Bojakowska, 2018). PIA values can be calculated from the formula:

$$\frac{Al_2O_3 - K_2O}{Al_2O_3 + CaO^* + Na_2O - K_2O} \times 100 \quad (\text{Equation 2.6})$$

Where CaO* is the CaO residing only in the silicate fraction

2.3.2 *Pedogenic ratios*

Molecular geochemical ratios have been successfully used to quantify pedogenic processes in soils and palaeosols (Sheldon and Tabor, 2009). The Al/Si ratio is considered to be a measure of clayeyness because the Al accumulates in clay minerals relative to a silicate mineral parent. Calcification takes place when evapotranspiration exceeds precipitation hence causing the upward movement of dissolved alkaline salts from the groundwater. At the same time, the movement of rain water causes a downward movement of the salts. This results in the deposition of the translocated cations in the B horizon (Pidwirny, 2006). The salinization process can be defined as the accumulation of soluble salts of the Na and K which are mobile elements in a soil (Sheldon and Tabor, 2009). Salinization process functions in a similar way to calcification. It differs from calcification in the sense that the salt deposits occur at or very near the soil surface. Salinization also takes place in much drier climates (Pidwirny, 2006). The rate of salinization is related to the mean annual temperature of a location. The amount of a given base divided by Ti is an expression of leaching. The Ti/Al ratio is predominantly useful as a provenance indicator because the Ti contents may be variable among different type of rocks or soil even when Al contents are relatively constant (Sheldon and Tabor, 2009).

2.4 Earthenware pottery-making soils

Pottery making is widely practiced in the Southern African region. In Botswana the pots (Figure 2.2) are used for storage, sold to locals and tourists as well as for ritual purposes (Thebe et al., 2009).



(a)



(b)

Figure 2.2: Photos of local pottery (a and b)

Raw material extraction is one of the first important technical procedures for making pots (Cabral et al., 2015; Thebe and Sadr, 2017b). According to a study done by (Thebe and Sadr, 2017) which was focused on the potter's choice of raw material in the south eastern part of Botswana, potters prefer using clay for their craft which are in situ clay which is weathered from the local bedrock, clay form alluvial deposits, at different depths below the ground surface and

some of the clay came from the termite mounds. The choice of clay used also depends on the pottery object to be made (Cabral et al., 2015).

Peasants often differentiate soils used based on their morphological properties including texture and consistency which are mostly similar to the ones used by scientists in the field (Cabral et al., 2015). Clays are differentiated from other fine grained soils by their different size and mineralogy (Pikirayi and Lindahl, 2013). Clays are the most commonly used soils in the production of pottery because of their unique physical and chemical characteristics which include; plasticity, colour, particle size and to some extent their smell and taste (Thebe et al., 2009).

The mineralogy of the pottery making soils influences the characteristics of the soils, the mineralogical attributes presented by clay samples can maximize its use for application (Adeagbo et al., 2016). The type of minerals found in a clay sample can be used to account for the strength of the pots made from it. Southern Africa has different coloured clay soils (Ekosse and Fouche, 2006). In Botswana, the colours range from white, red, and brown, grey to green. The difference in these colours could be due to the factors that led to the formation of the soil as well as the presence of some elements such as iron oxide, manganese and calcite (Adeagbo et al., 2016; Thebe and Sadr, 2017). A lot of artisans have raised complaints concerning the quality of products; cracks, melting of pieces and heterogeneous coloration (Hicham et al., 2016).

CHAPTER THREE

MATERIAL AND METHODS

3.1 Description of the study area

Geographically, the study area falls within latitudes 23°54'09.2 and 24°06'37.7 S and longitudes 24°57'07.7 and 25°01'13.4 E and the elevation ranges from 1034 to 1074 m above sea level (Figure. 3.1). Profile pits and excavations exposed in the dry valley of Letlhakeng (Figure.3.2), Takatokwane pan (Figure. 3.3), Letlhakeng and Khudumolapje excavation (Figure. 3.4) were identified with the help of a local potter.

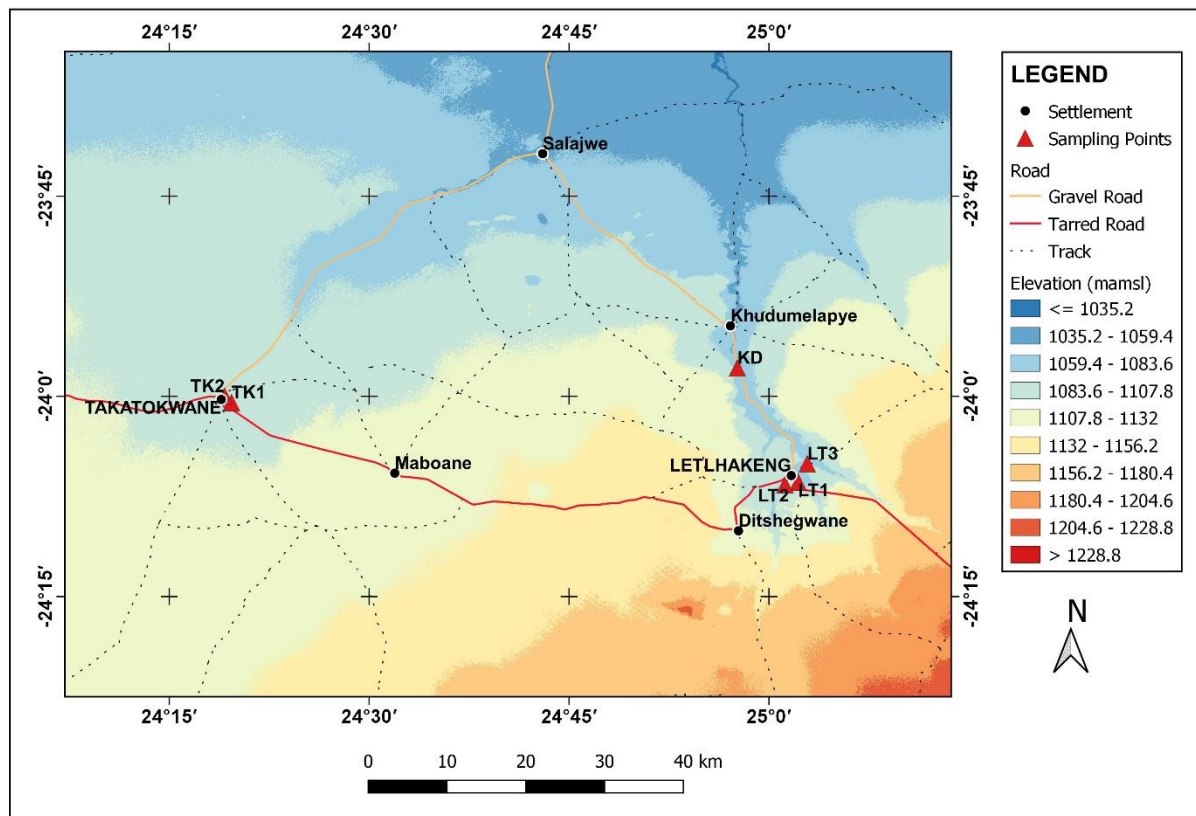


Figure 3.1: Map of study location showing the sampled points.

Under the Koppen classification system, the Kweneng district falls under semi-arid climate. It is characterised by hot summers with annual mean temperature of 28.4 degrees Celsius and cold winters with an annual mean temperature of 3.5 degrees Celsius. This area receives an average of 300 mm of rainfall annually. The area is characterized by short dry winters and records high temperatures with low rainfall in summer.

Kweneng District is characterised by savannah type of vegetation mainly consisting of *Ziziphus Mucronata*, *Terminalia Sericea*, *Acacia Tortius* and *Boscia Albirrnc* thorn shrubs and grass (Letlhakeng Development Plan, 2002). The land use at the study location is extraction of rocks and soil used for road construction and pottery making. In this district, subsistence arable farming is a predominant practice. Surficial geology of the study area is predominantly medium to coarse grained feldspathic sandstone (Kweneng Formation) of the Karoo supergroup (Letlhakeng Development Plan, 2002).



Figure 3.2: Landscape of Takatokwane pan



Figure 3.3 Landscape of Letlhakeng valley

3.2 Field methods and soil sampling

Selection of the studied profiles and excavations was based on their use for pottery making as identified with the assistance of local potters. The four soil profiles in Letlhakeng and Takatokwane were dug to a measurement of approximately 1 m x 1 m x 2 m unless where rock outcrop or high water table were encountered. Field description for all the soil profiles was done in accordance with the guideline for soil profile description (FAO, 2006). Soil samples were collected from each genetic horizon of the profiles and were then taken to the laboratory for laboratory analyses. Undisturbed core samples were collected for bulk density analysis. An identified parent material sample (background sample) of the study area was collected for total elemental analysis.

3.3 Laboratory analyses

Analyses of soil samples were carried out in the Soil Science laboratory of the Botswana International University of Science and Technology (BIUST) following air drying and passing of the soils through 2 mm metallic sieve to remove gravels and large roots. Particle size distribution was done using the Bouyoucos hydrometer method (Bouyoucos, 1962) with sodium hexametaphosphate as soil dispersant. Bulk density and porosity were done using the core method based on the procedure out-lined in ISO (2017). For the computation of porosity from bulk density, equation 3.1 was used.

$$\text{Soil porosity (\%)} = 1 - \left(\frac{(\text{soil bulk density})}{2.65} \right) \times 100 \quad (\text{Equation 3.1})$$

Organic matter content was determined using the loss on ignition (LOI) method (Ball, 1964) in a furnace at 550 °C and 1000 °C and calculated from equation 3.2.

$$OM(\%) = \left(\frac{(\text{pre ignition weight} - \text{post ignition weight})}{\text{pre igniton weight}} \right) \times 100 \quad (\text{Equation 3.2})$$

After OM determination, the calcium carbonate content of the soils were derived from equation 3.3.

$$\text{Carbonate content (\%)} = \left(\frac{d-e}{c-a} \right) \times 100 \quad (\text{Equation 3.3})$$

where **a**; mass of crucible, **c**; mass of sample – crucible, **d**; mass of sample + crucible after 550 °C, **e**; mass of sample + crucible at 1000 °C

Both pH and electrical conductivity were determined using a 1:2.5 soil water ratio. Soil pH was also measured in potassium chloride (KCl). The exchangeable base cations and Cation Exchange Capacity (CEC) were determined using the ammonium acetate extraction method buffered at a

pH of 7. The base cation concentration was then determined using the Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). COLE rod method by Schafer and Singer (1976) was used to determine the Coefficient of linear extensibility ($COLE_{rod}$).

Total elemental analyses on soil and the parent rock material were done using the X-ray fluorescence (XRF) at the Minerals Geochem laboratory of SGS, Randfontein, South Africa. The Borate Fusion Method was used to determine the major rock-forming oxides reported in %. A sample that weighed 0.7 g was mixed with lithium tetraborate flux and fused to form a homogenous glass bead. Following the borate fusion was the analysis of the glass bead on the WDXRF Spectrometer. The loss on ignition (LOI) at 1000 °C was done separately by gravimetry. The sodium peroxide fusion method was used to determine the trace and minor elements. 0.2-2.0 g sample was weighed into a crucible containing NaO_2 and NaOH. The mixture was then fused. The sample was then leached, acidified and made up to volume and analysed by ICP-OES.

Clay mineralogical study of the fine-earth fraction (< 0.002 mm) was accomplished by systematic particle size separation. Samples were air-dried, dispersed in sodium hexametaphosphate, and the clay fraction of < 0.002 mm were separated by repeated centrifugation and decantation after settling in a cylinder. X-ray diffraction (XRD) spectra were obtained for smeared slides from 5° to 70° 2θ and increment of 0.0205° using the Bruker D8 Advance XRD machine. The clay mineralogical patterns were obtained for samples untreated, heated at 550 °C for two hours and glycolated smeared mount samples. The peaks were then used to identify the clay minerals in each sample.

3.4. Evaluation of chemical weathering and pedogenesis

Geochemical molecular indices used to quantify weathering and pedogenesis in the soils are presented in Table 3.1. Mass balance was used to evaluate the elemental redistribution in the soil profiles as they were undergoing weathering. A calculation of the geochemical mass balance was used to compute the net result of pedogenic weathering. The formula, equation (3.4), assumes that an immobile element behaves conservatively and corrects mobile element concentrations for volumetric strain during weathering and pedogenesis (Chadwick et al., 1990; Du et al., 2010).

$$\tau_{i,j} = \left(\frac{C_{i,p}}{C_{i,w}} \right) \left(\frac{C_{j,w}}{C_{j,p}} \right) - 1 \quad \text{Equation (3.4)}$$

Where C is the concentration (weight percentage), “i” is the immobile element, “j” is the element of interest, w is the weathered material and p is the parent material. If $\tau_{i,j} = -1$, then it means that element “i” is depleted completely during chemical weathering. This equation is a useful means for estimating elemental loss or gain within a profile. The mass-balance equations have several imperative assumptions, it assumes that there should be a genetic relationship between regolith and its parent material. Another assumption is that since the calculations are highly based on immobile elemental concentrations, then the reference element should be conservative in its real sense. Titanium (Ti) was the selected immobile element for this study which is highly resistant to chemical weathering.

Table 3.1: Molecular weathering indices and pedogenic ratios used for environmental interpretation

Ratio/Index	Formula (Pedogenic process)	Rationale	Normal value	Strong effect
Index of compositional	$(\text{Fe}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2 + \text{CaO}^* + \text{MgO} + \text{MnO} + \text{TiO}_2) / \text{Al}_2\text{O}_3$	It approximates the magnitude of chemical weathering.	-	-
Chemical Index of Alteration (CIA)	$(\text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{K}_2\text{O} + \text{Na}_2\text{O}) \times 100$ (Redistribution of elements)	Interpreting the extent of conversation of feldspars which mostly dominate the upper crust to clay e.g. kaolinite (Prince and Velbel, 2003).	-	-
Chemical Index of Weathering (CIW)	$\text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{NaO}) \times 100$	Similar to CIA, different as it eliminates K_2O from formula.	-	-
Plagioclase Index of Alteration (PIA)	$(\text{Al}_2\text{O}_3 - \text{K}_2\text{O}) / (\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} - \text{K}_2\text{O}) \times 100$	Alternative to CIW, needed for monitoring plagioclase weathering.	-	-
$\sum \text{Bases}/\text{Al}$	$\text{CaO} + \text{MgO} + \text{K}_2\text{O} + \text{Na}_2\text{O} / \text{Al}_2\text{O}_3$ (Hydrolysis)	During soil formation, some rock-forming alkaline earth elements are lost as compared to Al.	< 2	> 10
Clayeyness	$\text{Al}_2\text{O}_3 / \text{SiO}_2$ (Hydrolysis)	High values indicate more clayey soil.	< 0.1	> 0.3
Trace element leaching	Ba/Sr (Leaching/Hydrolysis)	Sr is more soluble than Ba (Sheldon and Tabor, 2009)	-	> 10
Calcification	$\text{CaO} + \text{MgO} / \text{Al}_2\text{O}_3$ (Calcification)	In comparison with Al, alkaline earth elements are lost during soil formation.	< 2	> 10
Salinization	$\text{K}_2\text{O} + \text{Na}_2\text{O} / \text{Al}_2\text{O}_3$ (Salinization)	Accumulation of mobile elements Al and Na in soil.	< 1	> 1
Provenance	$\text{TiO}_2 / \text{Al}_2\text{O}_3$ (Acidification)	Al is lost through chemical weathering while Ti is mostly lost by physical weathering.	-	-

CHAPTER FOUR

RESULTS

4.1 Macro-morphological properties

4.1.1 *Takatokwane pan*

The two soil profiles studied in Takatokwane are designated as TK1 and TK2 and the macromorphological properties are presented in Table 4.1. Seven genetic horizons were identified in the approximately 154⁺ cm deep TK1. Based on the FAO (2006) guidelines of soil profile description, the horizons were designated as A, AB, Btss1, Btss2, C, 2AB and 2Btss (Figure 4.1a; Table 4.1). The soil horizons boundaries were clear with smooth to wavy. The uppermost (0 -74 cm) horizons of TK1 are dominantly grey to light grey in colour while at 74 -145 cm the soil was white in colour and the lowest horizon (145-155⁺ cm) was greenish in colour (Figure 4.1a and Table 4.1). The soils had moderately angular blocky to sub angular blocky structure. TK1 had moist friable consistency, roots were present only in the upper most horizons (0 – 50 cm) and there was slight to strong reaction with dilute hydrochloric (HCl) acid throughout the whole profile. .

Similar to TK1, seven distinct genetic horizons were also identified in TK2 which had a depth of approximately 142⁺ cm. The horizon designation keyed out as A, Btss1, Btss2, C, 2AB, 2Btss and Btgss (Figure 4.1b). The horizon boundaries were clear with smooth to wavy horizon. The upper most horizons (0 - 84 cm) of TK2 had colours spanning brown and light grey with increasing depth at 84 - 128 cm. At the depth of 128 - 142⁺ cm, TK2 was greenish. The profile had friable moist consistency, few roots in the upper horizons (0 – 36 cm) and no roots at depth below (36 – 142⁺ cm) (Table 4.1). This soil has a weak to strong angular to sub angular blocky structure. The soil in this profile had a strong reaction with HCl throughout the whole profile in exception of the A (0 - 14 cm) horizon.

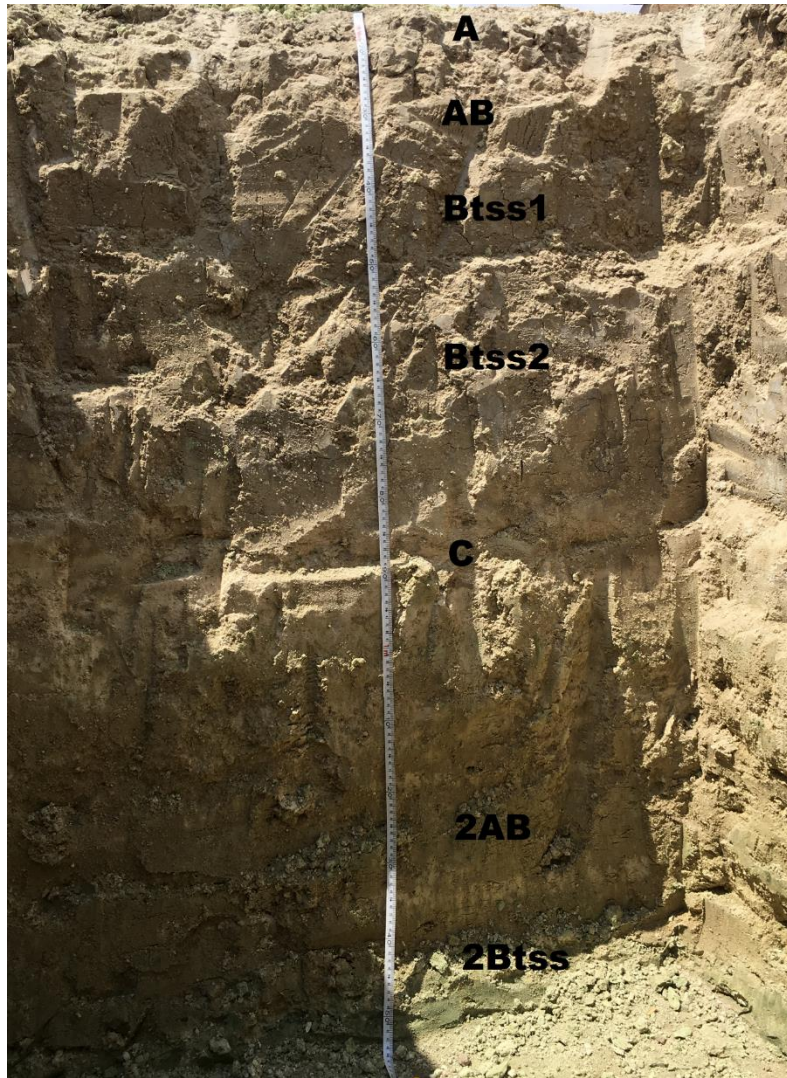
4.1.2 *Letlhakeng valley*

The two pedons at Letlhakeng are represented as LT1 and LT2. LT1 had a depth of about 190⁺ cm deep with seven distinct genetic horizons designated as A, AB, Bk, BCk1 and BCk2 (Figure 4.1c). The horizon boundaries of this profile were clear with wavy to irregular. In the uppermost horizons (0-85 cm), colours ranged from brown to light brownish grey, while the two bottom horizons of depth 85-190⁺ cm were pale red. The soil had strong subangular to angular blocky structure throughout the whole profile. The profile had a moist friable to firm consistency, there were common to few roots present in the profile. Throughout the whole profile there was a strong to slight effervescence when the soil was reacted with HCl. Carbonate nodules as well as mottles were present in LT2 from a depth of 52 cm (Table 4.1).

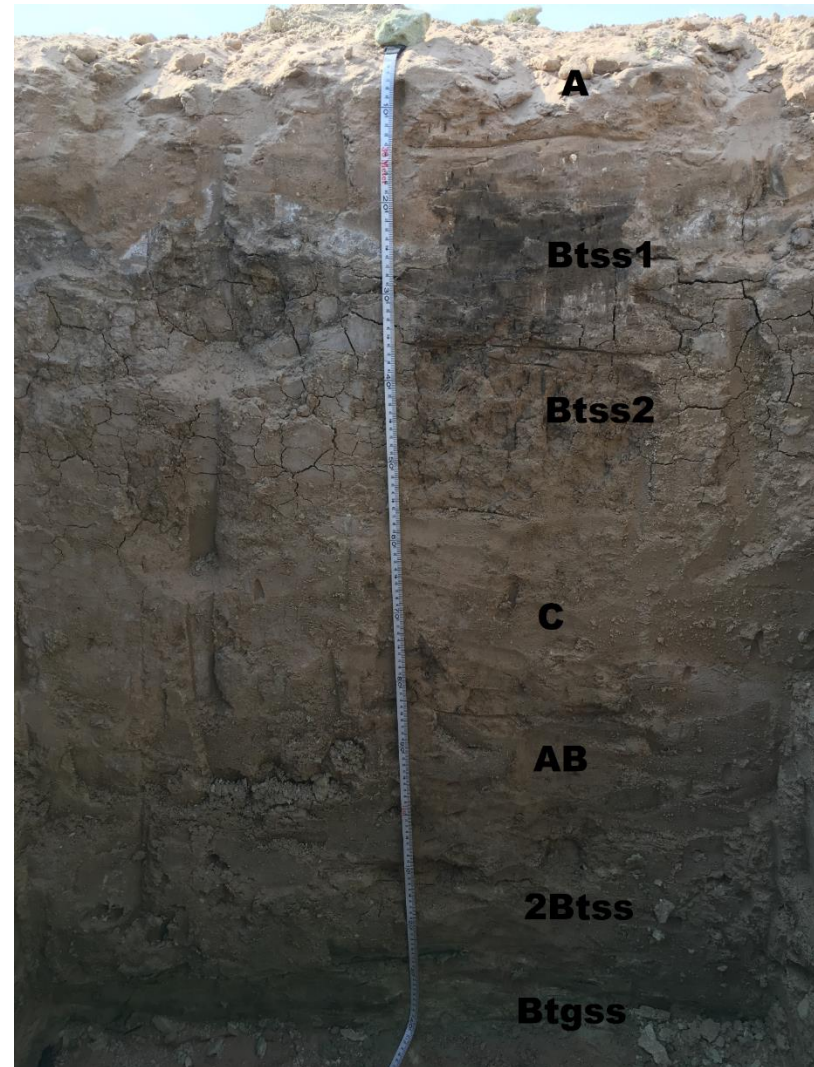
With a depth of ~200⁺ cm, LT2 had five genetic horizons. These horizons were classified as A, AB, Bk1, Bk2 and BCk (Figure 4.1d; Table 4.1). The horizon boundaries were clear and smooth. The soil colour varied from weak to pale red soil throughout the whole profile. Here, the soil structure was moderate to strongly subangular to angular blocky. The soils had moist friable consistency; there were traces of roots in the whole soil profile. When reacted with HCl there was a slight to strong effervescence. Carbonate nodules were observed at depth 90-137 cm.

4.1.3 *Exposed cuttings*

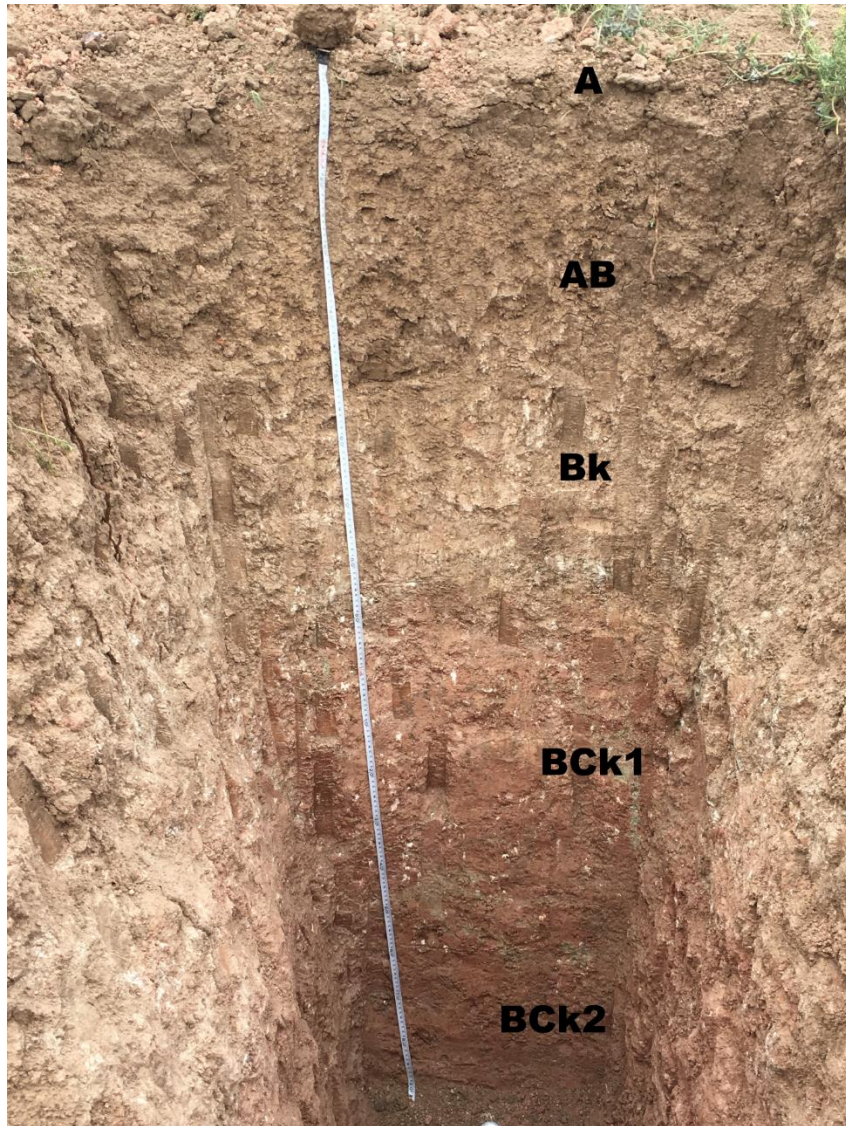
Two excavations, one in Letlhakeng (LT3) and another in Khudumolapje (KD) showed morphological properties presented in Table 4.1. Both have lithified horizons designated as Cm1 and Cm2 (Figure 4.1e and f; Table 4.1). The depths of the excavations stood at 400 cm⁺ for both LT3 and KD1. While LT3 was conspicuously white, the colour of KD ranged from yellowish (top) to greenish (bottom).



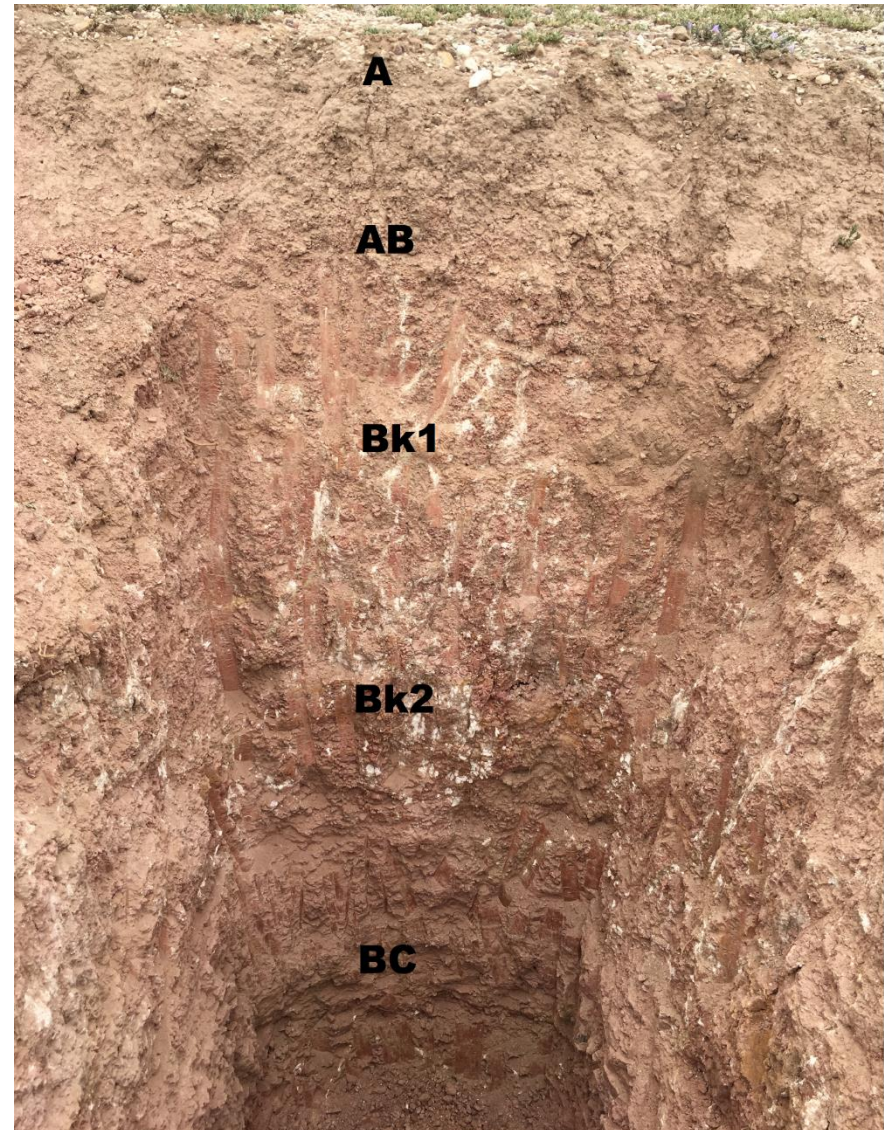
(a)



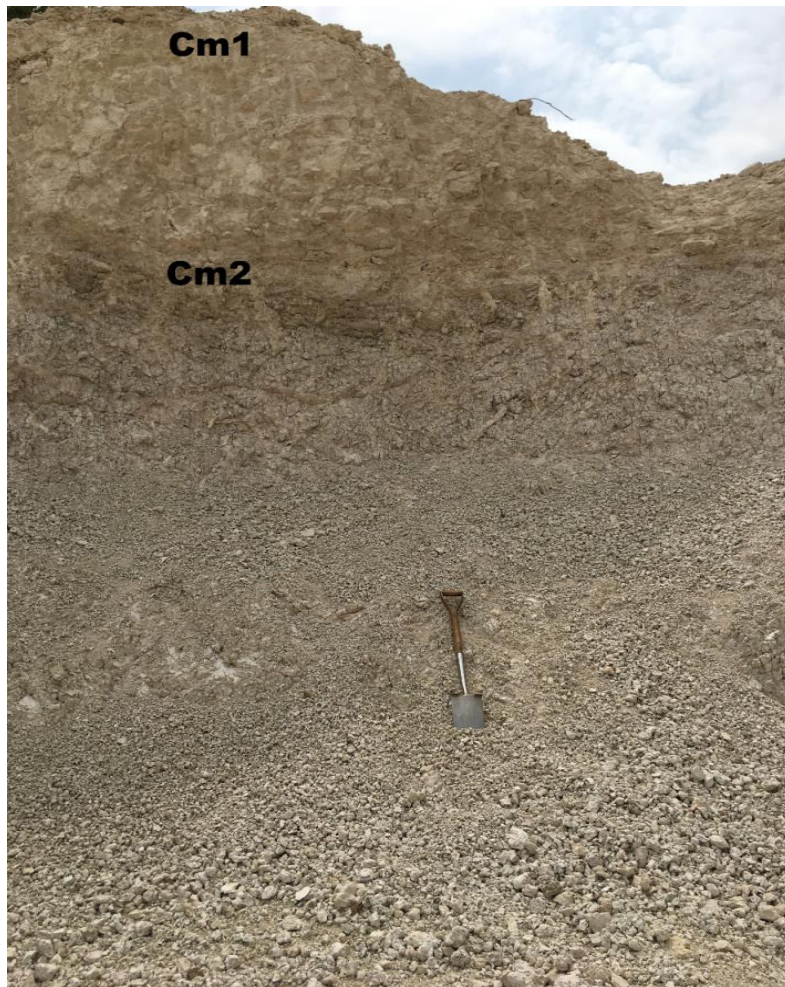
(b)



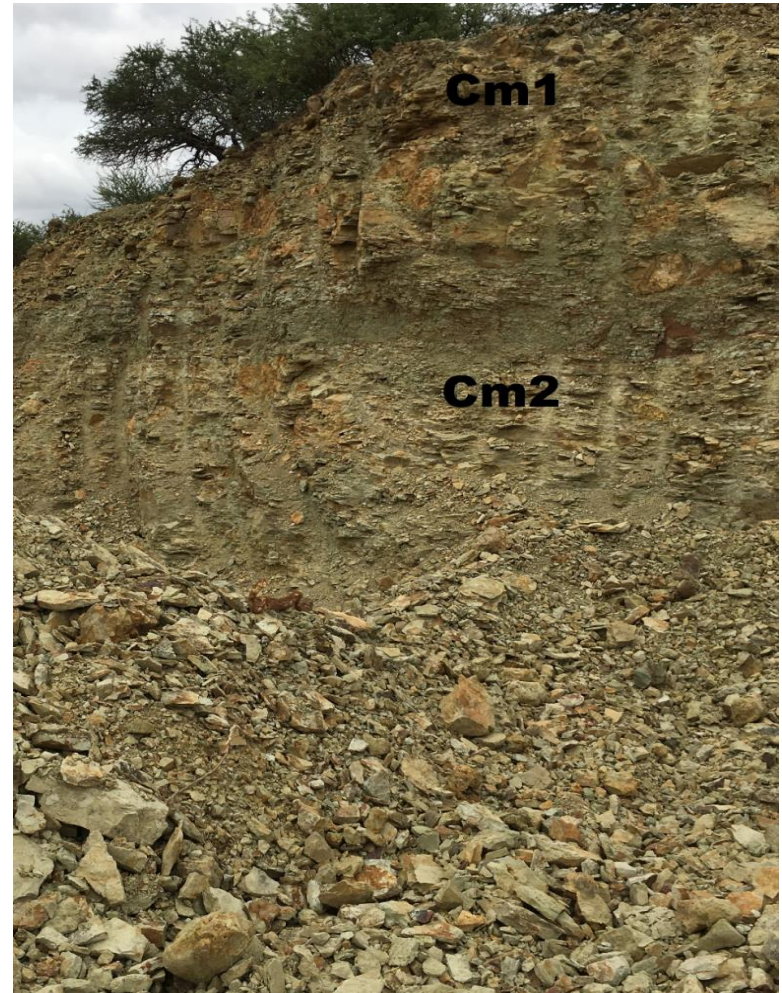
(c)



(d)



(e)



(f)

Figure 4: Photos of the studied pedons: (a) TK1; (b) TK2; (c) LT1; (d) LT2; (e) LT3; (f) KD1

Table 4.1: Macromorphological properties of the pedons

Horizon	Depth (cm)	Colour (dry)	Colour (moist)	Structure	Boundary	Consistency (moist)	Roots	Reaction (HCl)	Other Features
Takatokwane 1									
A	0-20	2.5Y 7/1 (Light grey)	2.5Y 5/1 (Grey)	1gr	cs	Friable	Common	ST	-
AB	20-36	10YR 7/2 (Light grey)	10YR 6/2 (Light brownish grey)	1sbk	cw	Friable	None	ST	-
Btss1	36-50	7.5YR 5/3 (Brown)	7.5YR 5/2 (Brown)	2abk	cw	Friable	Few	ST	-
Btss2	50-74	10YR 7/1 (Light grey)	10YR 6/2 (Light brownish grey)	2sbk	ac	Friable	None	ST	-
C	74-98	10YR 8/1 (White)	10YR 8/2 (Very pale brown)	2abk	cs	Friable	None	ST	-
2AB	98-145	10YR 1/8.5 (White)	10YR /8 (Very pale brown)	2abk	cs	Friable	None	SL	-
2Btss	145-155	5GY 5/4 (Greenish grey)	5GY 4/2 (Greyish green)	3abk	cw	Firm	None	SL	-

Table 4.1: Macromorphological properties of the pedons

Horizon	Depth (cm)	Colour (dry)	Colour (moist)	Structure	Boundary	Consistency (moist)	Roots	Reaction (HCl)	Other Features
Takatokwane 2									
A	0-14	7.5YR 5/4 (Brown)	7.5YR 4/3 (Brown)	1gr	cs	Friable	Few	VS	-
Btss1	14-36	7.5YR 5/3 (Brown)	7.5YR 4/3 (Brown)	2sbk	aw	Friable	Few	ST	-
Btss2	36-56	10YR 6/2 (Light brownish grey)	10YR 5/2 (Greyish brown)	3abk	cs	Friable	None	ST	-
C	56-84	10YR 8/2 (Very pale brown)	10YR 5/3 (Brown)	2sbk	cs	Friable	None	ST	-
AB	84-104	10YR 7/1 (Light grey)	10YR 6/2 (Light brownish grey)	1abk	cs	Friable	None	ST	-
2Btss	104-128	10YR 7/2 (Light grey)	10YR 6/2 (Light brownish grey)	2abk	cw	Friable	None	ST	-
Btgss	128-142	Gley1 7/10Y (Light greenish grey)	Gley1 5/5G.1 (Greenish grey)	3abk	cw	Firm	None	ST	-

Table 4.1: Macromorphological properties of the pedons

Horizon	Depth (cm)	Colour (dry)	Colour (moist)	Structure	Boundary	Consistency (moist)	Roots	Reaction (HCl)	Other Features
Letlhakeng 1									
A	0-15	7.5YR 5/2 (Brown)	7.5YR 5/3 (Brown)	1gr	cw	Friable	Common	ST	-
AB	15-52	10YR 5/3 (Brown)	10YR 4/3 (Brown)	3sbk	cs	Friable	Few	ST	-
Bk	52-85	10YR 7/1 (Light grey)	10YR 6/2 (Light brownish grey)	3sbk	cw	Friable	Few	ST	Carbonate nodules
BCK1	85-158	10R 7/3 (Pale red)	10R 5/3 (Weak red)	2abk	ci	Firm	Few	SL	Mottles
BCK2	158-190	10R 6/3 (Pale red)	10Y 5/4 (Weak red)	3abk	ci	Firm	None	SL	Carbonate nodules
Letlhakeng 2									
A	0-25	10R 8/2 (Pinkish white)	10R 7/2 (Pale red)	2sbk	cs	Friable	Common	SL	-
AB	25-43	10R 8/3 (Pink)	10R 7/3 (Pale red)	3sbk	cw	Firm	Few	SL	-
Bk1	43-90	10R 7/4 (Pale red)	10R 5/4 (Weak red)	2abk	aw	Firm	Few	ST	-
Bk2	90-137	10R 5/4 (Weak red)	10Y 4/4 (Weak red)	3abk	cs	Firm	Very Few	ST	Carbonate nodules
BCK	137-200	10R 7/4 (Pale red)	10Y 5/6 (Pale red)	3abk	cs	Friable	Moderately Few	SL	-

Table 4.1: Macromorphological properties of the pedons

Horizon	Depth (cm)	Colour (dry)	Colour (moist)	Structure	Boundary	Consistency (moist)	Roots	Reaction (HCl)	Other Features
Letlhakeng 3									
Cm1	~10	N/9.5 (White)	7.5YR 2/8 (Pinkish white)	-	-	Firm	-	None	-
Cm2	~400	N/8.5 (White)	2.5Y 1/8 (White)	-	-	Firm	-	None	-
Khudumolapje									
Cm1	~10	2.5Y 7/6 (Yellow)	10YR 5/6 (Yellowish brown)	-	-	Firm	-	None	-
Cm2	~300	Gley1 10Y/8 (Light greenish grey)	10Y_5GY 5/2 (Greyish green)	-	-	Firm	-	None	-

gr: granular, abk: angular blocky, sbk: sub angular blocky, c: clear, s, smooth, w: wavy, i: irregular, VS: very slightly effervescent, SL: slight effervescent, ST: strong effervescent

4.2 Physico-chemical and mechanical properties

4.2.1 *Takatokwane pan*

There were variations in the physico-chemical properties of the pottery-making soils as shown in Table 4.2 and 4.3. The particle size distribution results (Table 4.2) of TK1 indicates that the profile had a higher percentage of sand than clay and silt, with values of the separates varying between 38.0 to 81.1 %, 15.0 to 49.2 % and 3.9 to 20.0 % respectively. The soils had sandy loam to sandy clay loam textured with only the 2Btss horizon having clay texture. The bulk density values ranged from 2.12 to 2.37 g/cm³ while porosity ranged between 10.6 and 22.3 %. The pH (H₂O) for the TK1 ranged from 9.0 to 10.3, while pH (KCl) ranged from 7.8 to 9.6. Electrical conductivity in this profile was fluctuating and ranged between 1.92 and 6.45 dS/m. The cation exchange capacity (CEC) varied between 27.21 and 168.11 Cmol (+)/kg. Organic matter content fluctuated between 2.88 to 9.81 % with the upper horizons showing a higher amount of organic matter than the ones at the bottom (Table 4.3). COLE_{rod} values ranged between 0.03 (moderate hazard class) and 0.11 (high hazard class). Calcium Carbonate (CaCO₃) content ranged between 1.35 and 3.16 % in this soil profile

The TK2 profile had 38.0 to 89.0 %, 8.9 to 53.2 % and 1.5 to 15.8 % of sand, clay and slit particles respectively with texture of sandy loam to sandy clay loam. However, Btss2 was different from the rest as it had clay texture (Table 4.2). Bulk density and soil porosity, were both fluctuating between 1.83 to 2.14 g/cm³ and 19.2 to 30.9 %, respectively. The TK2 soil profile had pH (H₂O) that fluctuated between 9.1 and 10.0 and pH (KCl) ranging between 7.8 and 9.0 (Table 4.2). Electrical conductivity in this profile was fluctuating and ranged between 2.52 to 5.74 dS/m. CEC varied between 31.71 to 88.28 Cmol (+)/kg. The organic matter content fluctuated between 1.23 to 11.06 %. The measured COLE_{rod} values varied between the high to moderate hazard class (0.06 and 0.20) (Table 4.3) with an exception of the Btss2

horizon which was in the very high hazard class (0.20). CaCO_3 content varied between 0.85 to 8.91 %.

4.2.2 *Letlhakeng valley*

LT1 particle size distribution analysis resulted in silt, clay and sand particles which varied between 4.0 to 15.9 %, 23.9 to 31.9 % and 56.1 to 68.3 % respectively (Table 4.2). The whole soil profile had a sandy clay loam texture. Bulk density and soil porosity were both fluctuating throughout this profile, the bulk density values ranged between 1.58 and 2.09 g/cm^3 while those of porosity ranged between 21.1 to 40.4 %. In LT1, the measured pH (H_2O) and pH (KCl) ranged and fluctuated between 8.3 to 9.0 and 7.1 to 7.3 respectively. The electrical conductivity increased with an increase of depth and ranged from 0.11 to 0.18 dS/m. The CEC varied between 9.23 to 158.70 Cmol (+)/kg . Organic matter content obtained in LT1 ranged between 6.55 to 7.40 %. COLE_{rod} values were fluctuating between 0.08 (high hazard class) and 0.18 (very high hazard class). CaCO_3 values ranged between 4.0 and 7.32 % (Table 4.3).

The LT2 profile had the amounts of sand varying between 56.2 to 66.9 %, clay varying between 25.3 to 31.8 % and silt varying between 7.8 to 16.8 %. The whole soil profile had a sandy clay loam texture. As the depth increased, bulk density also increased from 1.40 to 1.79 g/cm^3 while the soil porosity decreased from 47.2 to 23.5 % (Table 4.2). This profile also had both pH in water and pH (KCl) fluctuating and ranged between 7.7 to 8.6 and 7.0 to 7.5 respectively. Electrical conductivity measured was fluctuating between 0.08-0.75 dS/m. The CEC varied between 6.85 to 20.87 Cmol (+)/kg . The measured value of organic matter content in LT2 fluctuated and ranged between 5.88 to 7.69 %. The COLE_{rod} values increased with an increase in depth ranging between 0.12 (high hazard class) and 0.15 (very high hazard class). (Table 4.3). The CaCO_3 obtained was fluctuating in the profile and it ranged between 5.29 to 10.77 %.

4.2.3 *Exposed cuttings*

The exposed cutting are made of lithified soils. Both qualified as palaeosols as they show properties suggesting they formed during a geological time different from today. They are buried palaeosols which got exposed by human cutting activities in search of pottery making and road construction materials. The LT3 and KD profiles had pH (H₂O) ranging between 8.3 and 8.4 while pH (KCl) ranged between 7.1 and 7.4. Their EC varied between 0.06 and 0.10 dS/m with CEC of 29.73 Cmol (+)/kg. The organic matter content in these two profiles ranged between 3.17 and 8.79 % while the CaCO₃ was between 0.62 and 3.50 %.

Table 4.2: Physical and chemical properties of the soil

Horizon	<u>Particle size</u>				<u>BD</u>	<u>Porosity</u>	<u>pH</u>		<u>EC</u>	<u>Cations</u>				
	Silt	Clay	Sand	Texture	g/cm ³	(%)	H ₂ O	KCl	dS/m	Ca ⁺	Mg ²⁺	K ⁺	Na ⁺	CEC
	------(%)-----				------(Cmol+/kg)-----									
Takatokwane 1														
A	14.8	19.2	66.0	SL	-	-	9.0	7.8	6.45	13.24	3.32	7.56	144.00	168.11
AB	3.9	28.1	68.0	SCL	-	-	10.2	9.3	4.60	9.69	1.87	1.87	68.23	85.40
Btss1	12.8	49.2	38.0	C	2.12	20	10.2	9.2	4.29	6.78	0.74	4.96	57.15	69.35
Btss2	8.8	35.2	56.0	SL	2.26	14.7	10.2	9.2	3.64	5.52	0.65	2.81	32.32	41.30
C	4.8	17.2	78.0	SL	2.06	22.3	10.1	9.4	1.92	11.68	7.75	2.21	23.68	45.31
2AB	3.9	15.0	81.1	LS	2.37	10.6	10.3	9.6	3.85	4.50	0.47	1.46	20.78	27.21
2Btss	20.0	23.2	56.8	SCL	2.29	13.6	10.1	9.5	3.89	7.72	1.23	5.27	99.91	114.13
Takatokwane 2														
A	2.0	8.9	89.1	S	1.83	30.9	9.4	8.5	2.52	7.70	0.67	1.52	21.82	31.71
Btss1	3.2	20	76.8	SL	2.05	22.6	9.2	7.8	3.12	8.76	4.17	3.64	33.68	50.22
Btss2	8.8	53.2	38.0	C	1.91	27.9	9.1	7.9	4.65	7.59	4.41	3.75	36.68	54.42
C	2.0	21.2	76.8	SCL	2.01	24.2	9.4	8.1	4.31	11.08	4.85	6.29	75.17	97.40
AB	4.4	13.2	82.4	LS	1.95	26.4	9.7	8.2	4.21	7.81	1.56	3.90	46.60	59.87
2Btss	1.5	23.2	75.3	SCL	2.14	19.2	9.8	8.4	4.42	9.72	2.66	3.83	52.55	68.76
Btgss	15.8	20.9	63.3	SCL	1.72	25.1	10.0	9.0	5.74	6.96	0.78	3.69	78.86	88.28

Horizon	<u>Particle size</u>				BD g/cm ³	Porosity (%)	<u>pH</u>		EC μS/cm	Ca ⁺	<u>Cations</u>			CEC
	Silt	Clay	Sand	Texture			H ₂ O	KCl			Mg ²⁺	K ⁺	Na ⁺	
	-----	(%)	-----								-----	(Cmol+/kg)	-----	
Letlhakeng 1														
A	6.0	25.9	68.1	SCL	1.58	40.4	8.7	7.1	0.11	17.86	4.92	1.19	0.26	24.22
AB	4.0	27.7	68.3	SCL	2.09	21.1	8.3	7.3	0.12	0	7.78	0.99	0.55	9.32
Bk	12.0	31.9	56.1	SCL	1.74	34.3	8.5	7.2	0.13	0	9.99	0.91	0.95	11.85
BCK1	15.6	25.4	59.0	SCL	1.63	38.5	9.0	7.2	0.13	11.05	3.17	6.40	138.09	158.7
BCK2	15.9	23.9	60.2	SCL	1.88	29.1	9.0	7.3	0.18	0	14.77	0.77	4.74	20.29
Letlhakeng 2														
A	7.8	25.3	66.9	SCL	1.40	47.2	8.4	7.5	0.10	14.62	4.94	1.03	0.28	20.87
AB	12.0	31.8	56.2	SCL	1.56	41.1	8.4	7.0	0.80	0	5.88	0.73	0.24	6.85
Bk1	13.9	25.8	60.3	SCL	1.66	37.4	8.6	7.2	0.10	0	8.26	0.62	0.93	9.81
Bk2	11.9	27.8	60.3	SCL	1.79	23.5	8.5	7.2	0.20	0	10.23	0.69	1.71	12.63
BCK	16.8	29.4	63.8	SCL	-	-	7.7	7.1	0.75	0	11.42	0.67	3.24	15.32
Letlhakeng 3														
Cm1	~10	-	-	-	-	-	8.4	7.4	0.06	-	-	-	-	-
Cm2	~400	-	-	-	-	-	8.4	7.4	0.10	-	-	-	-	-
Khudumolapje														
Cm1	~10	-	-	-	-	-	8.4	7.2	0.08	14.91	12.75	1.37	0.7	29.73
Cm2	~300	-	-	-	-	-	8.3	7.1	0.09	-	-	-	-	-

SL:Sandy loam, C: clay, LS: loam sand, SL: sandy loam, BD: bulk density, CEC: cation exchange capacity

Table 4.3: Organic matter, COLE and CaCO₃ content of the soils

Horizon	Organic matter (%)	<u>COLE</u> COLE _{rod}	Hazard class	CaCO ₃ (%)
Takatokwane 1				
A	7.30	-	-	2.11
AB	9.81	0.11	High	2.26
Btss1	9.72	0.09	High	2.06
Btss2	7.06	0.09	High	2.22
C	2.88	0.03	Moderate	1.35
2AB	4.91	0.05	Moderate	2.83
2Btss	4.95	0.10	High	3.16
Takatokwane 2				
A	1.23	-	-	0.85
Btss1	5.77	0.09	High	1.70
Btss2	11.06	0.20	Very high	3.11
C	7.09	0.09	High	4.01
AB	5.71	0.06	Moderate	2.07
2Btss	4.59	0.07	Moderate	1.91
Btgss	5.09	0.09	High	8.91
Letlhakeng 1				
A	6.70	0.10	High	5.60
AB	7.40	0.18	Very high	6.97
Bk	6.99	0.16	Very high	7.32
BCK1	6.55	0.11	High	7.13
BCK2	6.77	0.08	High	4.03
Letlhakeng 2				
A	7.69	0.12	High	8.99
AB	7.02	0.10	High	9.43
Bk1	6.82	0.15	Very high	8.59
Bk2	7.06	-	-	5.29
BCK	5.88	-	-	10.77
Letlhakeng 3				
Cm1	3.17	-	-	0.62
Cm2	7.14	-	-	3.50
Khudumolapje				
Cm1	8.79	-	-	1.48
Cm2	6.03	-	-	1.59

4.3 Geochemistry

Results of the total elemental composition of the soils are presented in Tables 4.4 (major oxides), 4.5 (rare earth elements) and 4.6 (trace elements)). The dominant major oxide in both TK1 and TK2 was SiO₂ (57.70- 96.1 %) followed by CaO (0.60- 12.70 %), Al₂O₃ (0.97- 10.40 %), MgO (0.39-5.52 %) and Fe₂O₃ (0.66- 12.70 %). LT1 and LT2 generally had SiO₂ (53.50- 71.40 %), other major oxides such as Al₂O₃ (4.57- 10.70 %), CaO (3.83- 12.9 %), Fe₂O₃ (1.31- 4.47 %) and MgO (0.68- 1.37 %) were also present (Table 4.4). The major oxide abundance in LT3 and KD consisted of SiO₂ (64.7- 88.0 %), CaO (1.13- 3.06 %), Al₂O₃ (2.68- 11.0 %), MgO (1.25- 2.71 %) and Fe₂O₃ (1.91- 6.21).

The Rare Earth Elements (REE) concentrations were presented in Table 4.5. The REE concentrations of TK1 and TK2 were; Ce (7.3- 73.9 ppm), La (4.2- 34.9 ppm), Dy (0.63-4.41 ppm) and Pr (0.92- 8.19 ppm) while LT1 and LT2 had concentrations of; Ce (25.8- 76.3 ppm), La (13.3- 42.2 ppm), Dy (1.83- 5.79 ppm) and Pr (3.12- 8.86 ppm). REE concentrations of LT3 and KD were; Ce (20.4- 116.0 ppm), La (6.4- 38.0 ppm), Dy (0.85- 14.00 ppm) and Pr (1.51-10.0 ppm).

Trace elements were also analysed and the data was presented in Table 4.6. In TK1 and TK2 the concentrations were; Rb (9.60- 99.90 ppm), Ba (142-1180 ppm), Sr (24- 649 ppm) and Pb (17- 32 ppm) while those in LT1 and LT2 were; Rb (25.9- 89.3 ppm), Ba (268- 3460 ppm), Sr (69- 154 ppm) and Pb (13- 58 ppm). The concentrations of trace elements in LT3 and KD exposed cuttings were; Rb (24.2- 91.0 ppm), Ba (131.0- 36.9 ppm), Sr (18-121 ppm) and Pb (16-48 ppm).

The results presented in Figure 4.2 show the R² value as well as the correlation of selected major oxides in order to establish the relationship between the concentration of these oxides

in the parent material versus that in the soil horizons, the CaO and SiO₂ correlation was 0.813 while that of SiO₂ and Al₂O₃ was 0.6989 and that of TiO₂ and SiO₂ was 0.5693.

Table 4.4: Major oxides of elements, ICV, CIA, CIW and PIA values of the soils

Horizon	Depth	Al ₂ O ₃	CaO	Fe ₂ O ₃	K ₂ O	MgO	MnO	Na ₂ O	P ₂ O ₅	SiO ₂	TiO ₂	ICV	CIA	CIW	PIA
	(cm)	-----(%)-----													
Takatokwane 1															
A	0-20	2.73	4.79	1.68	0.84	2.99	0.04	1.87	0.08	78.2	0.22	4.6	26.7	29.1	22.1
AB	20-36	3.14	7.17	1.82	0.99	4.59	0.04	1.48	0.07	69.2	0.22	5.2	24.6	26.6	19.9
Btss1	36-50	3.05	6.82	2.01	0.93	4.59	0.04	1.42	0.06	70.2	0.23	5.3	25.0	27.0	20.5
Btss2	50-74	2.09	4.43	1.56	0.68	3.26	0.03	1.02	0.04	79.3	0.18	5.3	25.4	27.7	20.6
C	74-98	0.97	2.53	0.73	0.36	1.92	0.02	0.63	0.02	90.3	0.15	6.5	21.6	23.5	16.2
2AB	98-145	1.66	3.49	1.53	0.72	2.80	0.03	0.96	0.03	82.6	0.16	5.8	24.3	27.2	17.4
2Btss	145-155	10.4	2.54	3.02	4.10	2.68	0.03	2.63	0.12	67.4	0.47	1.5	52.9	66.8	54.9
Takatokwane 2															
A	0-14	1.02	0.60	0.66	0.22	0.39	0.02	0.57	0.02	96.1	0.15	2.56	42.3	46.6	40.6
Btss1	14-36	3.08	3.56	1.29	0.91	2.28	0.03	0.88	0.07	80.9	0.23	2.98	36.5	41.0	32.8
Btss2	36-56	3.15	8.11	1.54	1.04	5.52	0.04	1.22	0.09	66.2	0.21	5.61	23.3	25.2	18.4
C	56-84	2.42	6.60	1.15	0.83	3.95	0.03	1.10	0.07	74.3	0.18	5.72	22.1	23.9	17.1
AB	84-104	2.29	3.94	1.14	0.83	2.68	0.02	1.09	0.05	82.8	0.18	4.31	28.1	31.3	22.5
2Btss	104-128	2.04	3.03	0.99	0.82	2.02	0.02	1.01	0.04	85.0	0.17	3.95	29.6	33.6	23.2
Btgss	128-142	5.57	12.70	1.90	2.57	3.07	0.03	1.73	0.08	57.7	0.28	4.00	24.7	27.9	17.2

Horizon	Depth	Al ₂ O ₃	CaO	Fe ₂ O ₃	K ₂ O	MgO	MnO	Na ₂ O	P ₂ O ₅	SiO ₂	TiO ₂	ICV	CIA	CIW	PIA
	(cm)	-----(%)-----													
Letlhakeng 1															
A	0-15	4.57	16.1	1.31	0.81	0.68	0.04	0.52	0.067	62.7	0.27	4.32	20.8	21.6	18.4
AB	15-52	7.96	9.53	2.31	1.30	1.21	0.05	0.36	0.093	64.8	0.46	1.91	41.6	44.6	40.2
Bk	52-85	9.13	13.0	3.72	1.61	1.22	0.04	0.45	0.104	54.8	0.50	2.25	37.7	40.6	35.9
BCk1	85-158	10.7	10.3	2.94	1.86	1.54	0.05	0.59	0.139	59.0	0.51	1.66	45.6	49.6	44.8
BCk2	158-190	7.02	3.83	4.47	0.52	1.70	0.09	0.66	0.024	71.4	0.63	1.70	58.4	61.0	59.1
Letlhakeng 2															
A	0-25	6.27	12.0	2.42	1.18	1.01	0.04	0.31	0.106	62.0	0.39	2.77	31.7	33.7	29.3
AB	25-43	7.90	12.8	2.67	1.41	1.16	0.04	0.39	0.112	58.5	0.46	2.40	35.1	37.5	33.0
Bk1	43-90	9.01	11.5	2.74	1.54	1.37	0.05	0.47	0.113	59.6	0.46	2.01	40.0	42.9	38.4
Bk2	90-137	10.4	10.3	3.90	1.85	1.37	0.05	0.48	0.134	57.3	0.55	1.78	45.2	49.1	44.2
BCk	137-200	10.3	12.9	3.43	1.89	1.29	0.25	0.50	0.147	53.5	0.55	2.02	40.3	43.5	38.6
Letlhakeng 3															
Cm1	~10	2.68	2.48	1.19	0.48	1.25	0.02	0.20	0.015	88.0	0.24	2.19	45.9	50.0	45.1
Cm2	~400	8.45	3.06	3.09	1.01	2.54	0.05	0.27	0.018	70.6	0.49	1.24	66.1	71.7	69.1
Khudumolapje															
Cm1	~10	11.0	1.13	6.21	2.05	2.71	0.13	0.59	0.036	64.7	0.44	1.21	74.5	86.5	83.9
Cm2	~300	11.9	1.09	2.85	3.39	2.51	0.09	0.79	0.019	70.4	0.55	0.95	69.3	86.4	81.9

Table 4.5: Rare Earth Elements (REE) content of the soils

Horizon	Depth	Ce	Dy	Er	Eu	Gd	Ho	La	Lu	Nd	Pr	Sm	Tb	Tm	Yb
	(cm)	----- (ppm) -----													
Takatokwane 1															
A	0-20	19.8	1.41	0.78	0.51	1.99	0.26	11.0	0.10	9.5	2.4	1.8	0.25	0.09	0.9
AB	20-36	22.3	1.57	0.81	0.61	1.97	0.28	12.3	0.11	10.8	2.69	2.1	0.26	0.08	0.9
Btss1	36-50	20.2	1.35	0.85	0.55	1.88	0.23	10.8	0.10	9.2	2.37	1.7	0.24	0.08	0.8
Btss2	50-74	15.0	1.03	0.56	0.38	1.05	0.17	7.9	0.08	7.0	1.75	1.3	0.18	0.05	0.6
C	74-98	13.5	1.01	0.60	0.31	1.00	0.18	7.3	0.07	6.4	1.59	1.2	0.16	0.06	0.7
2AB	98-145	14.7	1.08	0.69	0.49	1.30	0.20	7.5	0.09	6.7	1.67	1.3	0.16	0.07	0.8
2Btss	145-155	73.9	4.14	2.46	1.76	5.53	0.78	34.9	0.31	31.9	8.19	6.1	0.85	0.31	2.4
Takatokwane 2															
A	0-14	7.3	0.63	0.41	0.18	0.52	0.1	4.2	<0.05	3.5	0.92	0.7	0.06	<0.05	0.4
Btss1	14-36	20.0	1.44	0.82	0.49	1.73	0.23	11.2	0.1	9.6	2.40	2.0	0.26	0.09	0.8
Btss2	36-56	21.8	1.39	0.85	0.55	1.52	0.25	11.5	0.08	10.2	2.64	2.0	0.26	0.08	0.8
C	56-84	17.4	1.14	0.67	0.42	1.39	0.21	9.6	0.06	7.9	2.06	1.5	0.19	0.07	0.7
AB	84-104	15.4	1.05	0.62	0.34	1.21	0.18	8.3	0.07	6.9	1.78	1.3	0.16	0.06	0.7
2Btss	104-128	14.8	0.94	0.6	0.28	1.28	0.17	8.6	0.06	6.7	1.69	1.2	0.15	0.05	0.6
Btgss	128-142	53.0	4.41	2.34	1.46	5.76	0.81	30.0	0.27	27.5	6.80	5.5	0.82	0.28	2.2

Horizon	Depth	Ce	Dy	Er	Eu	Gd	Ho	La	Lu	Nd	Pr	Sm	Tb	Tm	Yb
	(cm)	----- (ppm) -----													
Letlhakeng 1															
A	0-15	29.4	1.83	1.03	1.51	2.18	0.32	15.2	0.14	13.1	3.33	2.5	0.34	0.13	1.1
AB	15-52	52.2	3.36	1.98	1.34	4.44	0.66	25.1	0.25	22.5	5.83	4.5	0.62	0.24	2.0
Bk	52-85	62.6	3.77	2.20	1.52	4.89	0.68	29.3	0.28	26.3	6.99	5.2	0.73	0.29	2.2
BCk1	85-158	68.3	4.90	2.81	3.06	6.34	0.95	35.9	0.34	32.2	8.20	6.3	0.92	0.36	2.8
BCk2	158-190	25.8	2.36	1.48	0.77	2.77	0.43	13.3	0.18	12.8	3.12	2.7	0.40	0.17	1.4
Letlhakeng 2															
A	0-25	44.0	2.90	1.79	0.8	3.83	0.55	22.2	0.24	19.2	4.96	3.8	0.55	0.22	1.9
AB	25-43	53.9	3.35	1.97	1.28	3.87	0.63	26.6	0.27	23.7	6.14	4.7	0.63	0.25	2.1
Bk1	43-90	56.6	3.74	2.09	1.72	4.58	0.68	28.6	0.27	24.4	6.42	5.0	0.67	0.27	2.1
Bk2	90-137	75.1	5.01	2.79	1.81	6.19	0.92	39.3	0.35	35.2	8.84	6.9	0.96	0.37	2.8
BCk	137-200	76.3	5.79	3.33	1.83	7.21	1.08	42.2	0.39	34.6	8.86	7.0	1.02	0.44	3.1
Letlhakeng 3															
Cm1	~10	16.9	0.85	0.56	0.25	0.95	0.16	6.4	0.06	5.8	1.51	1.1	0.14	<0.05	0.6
Cm2	~400	58.7	3.17	1.86	0.81	3.95	0.58	26.1	0.23	20.2	5.28	4.1	0.56	0.23	1.8
Khudumolapje															
Cm1	~10	20.4	1.76	1.17	0.50	1.87	0.33	11.3	0.14	10.2	2.58	2.1	0.30	0.12	1.2
Cm2	~300	116	14.00	8.30	3.71	11.9	2.84	38	1.06	40.8	10.0	10.2	2.15	1.15	7.8

Table 4.6: Trace Element composition of the soils

Horizon	Depth	Ba	Cr	Cu	S	Sr	V	Zn	Co	Ga	Nb	Ni	Pb	Rb	Th	U	Y	Zr
	(cm)	----- (ppm) -----																
Takatokwane 1																		
A	0-20	316	28	11	495	363	23	23	3.7	4	5	16	32	31.2	4.0	3.87	8.3	<0.01
AB	20-36	436	34	14	719	672	62	23	4.6	4	5	38	25	33.5	4.2	3.15	8.8	<0.01
Btss1	36-50	382	30	14	547	649	56	24	3.9	4	4	18	24	29.6	3.7	3.09	7.9	<0.01
Btss2	50-74	295	28	<10	331	468	41	14	2.8	3	4	17	21	22.5	3.0	2.90	6.2	<0.01
C	74-98	229	21	<10	452	417	32	14	2.3	2	4	12	17	18.7	3.3	4.01	6.0	<0.01
2AB	98-145	508	23	<10	436	333	39	12	2.3	2	4	12	15	19.3	3.1	2.68	6.7	0.03
2Btss	145-155	1180	36	<10	692	350	165	41	6.4	13	11	15	25	99.9	10.8	3.19	21.8	0.02
Takatokwane 2																		
A	0-14	142	17	<10	<0.1	24	<10	<10	1.7	1	2	10	19	9.6	1.5	0.75	4.0	0.02
Btss1	14-36	321	32	11	321	259	21	22	3.3	4	4	16	35	27.6	3.1	2.22	8.0	0.01
Btss2	36-56	407	36	15	469	619	39	29	5.0	4	4	25	19	31.1	3.8	2.58	8.0	0.02
C	56-84	356	29	16	591	542	22	29	4.1	3	4	18	22	25.2	3.2	2.16	6.9	<0.01
AB	84-104	278	20	32	440	300	20	17	3.3	3	4	14	13	23.6	3	1.64	6.4	0.01
2Btss	104-128	243	21	<10	462	230	24	20	3.0	3	3	13	18	21.5	2.8	1.38	5.7	<0.01
Btgss	128-142	935	23	11	678	514	82	25	4.5	7	6	20	19	53.3	6.1	2.51	23.8	0.01

Horizon	Depth	Ba	Cr	Cu	S	Sr	V	Zn	Co	Ga	Nb	Ni	Pb	Rb	Th	U	Y	Zr
	(cm)	----- (ppm) -----																
Letlhakeng 1																		
A	0-15	2100	26	<10	635	85	21	28	5.8	6	5	25	22	33.6	3.9	1.2	10.6	0.01
AB	15-52	1150	41	15	313	94	45	45	7.3	10	9	24	20	65.0	8.6	1.83	19.0	<0.01
Bk	52-85	1130	42	12	612	139	72	68	8.5	12	10	27	28	74.1	10.5	2.42	19.9	<0.01
BCk1	85-158	3460	34	14	871	154	59	41	6.3	14	12	24	20	83.6	11.5	2.41	27.1	0.01
BCk2	158-190	268	139	41	149	69	87	33	17.4	8	6	37	13	25.9	4.0	0.92	13.0	0.02
Letlhakeng 2																		
A	0-25	351	36	15	373	74	35	36	7.4	8	8	24	21	54.6	7.4	1.95	16.8	0.01
AB	25-43	1000	35	15	526	82	47	44	7.6	10	9	25	30	63.4	9.0	2.14	18.3	0.02
Bk1	43-90	1750	39	13	613	161	48	33	6.9	11	10	25	58	70.4	9.4	3.38	20.9	<0.01
Bk2	90-137	1260	41	16	427	116	57	51	8.4	14	12	24	36	88.4	12.6	2.83	25.2	0.03
BCk	137-200	1030	39	43	305	130	57	45	11.8	14	12	28	32	89.3	12.1	2.61	33.6	0.03
Letlhakeng 3																		
Cm1	~10	131	29	11	69.2	18	20	13	4.8	4	5	16	16	24.2	3.1	0.82	5.5	0.02
Cm2	~400	226	49	18	172	41	58	32	10.1	11	9	22	26	60.8	9.2	1.43	17.7	0.02
Khudumolapje																		
Cm1	~10	3690	42	18	655	121	106	66	12.1	6	5	25	26	24.6	3.3	0.88	10.1	0.03
Cm2	~300	1180	49	16	449	120	67	60	11.7	14	10	27	48	91.0	18.1	2.88	82.6	0.02

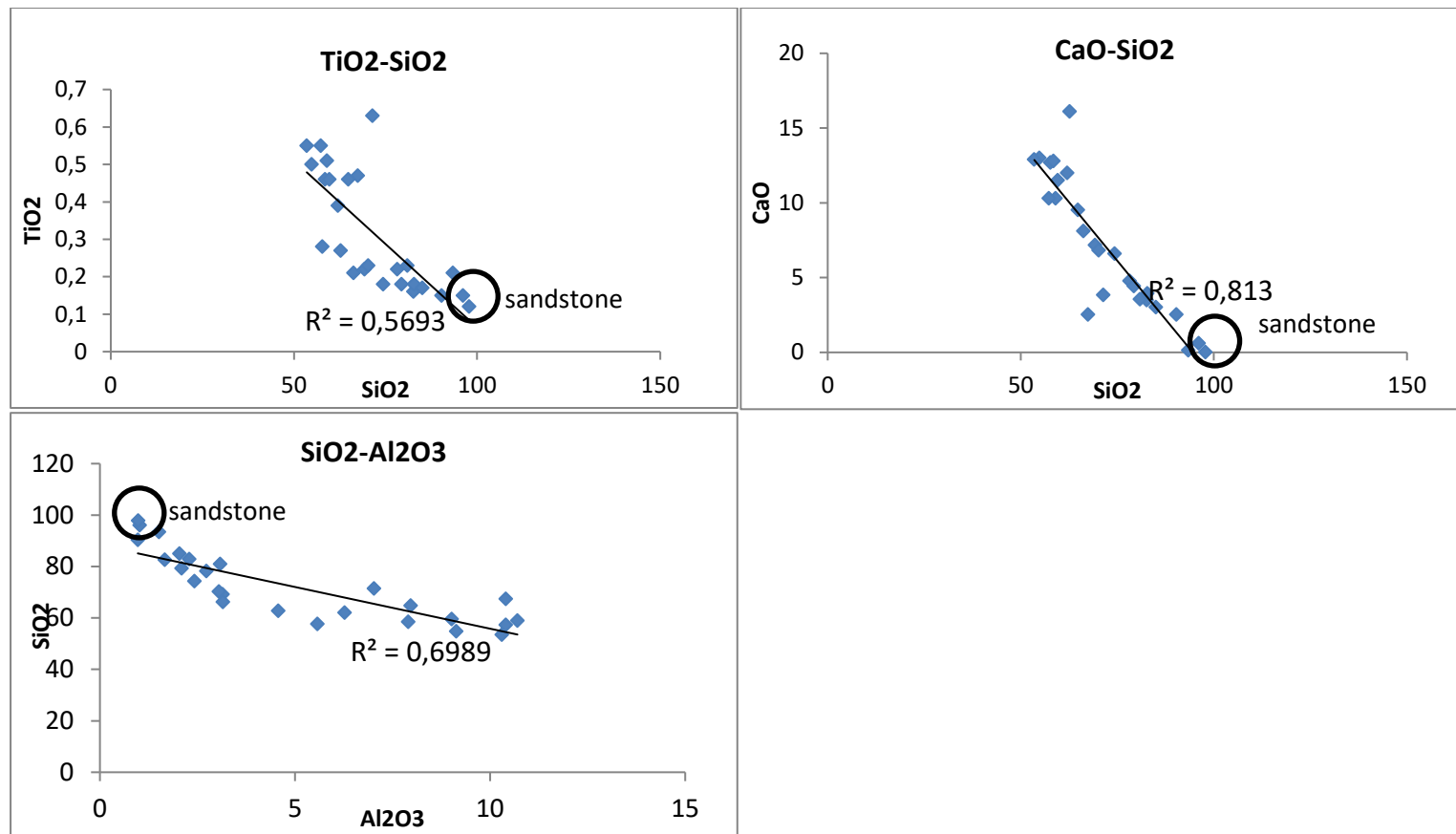


Figure 4.2: Correlations of SiO₂, TiO₂, CaO and Al₂O₃ in the soil profiles and the parent material.

4.4 Geochemical weathering indices and pedogenic ratios

The four weathering indices (Index of compositional variability, Chemical index of alteration, chemical index of weathering and Plagioclase index of alteration) were used to quantify the degree of weathering in the soils and the results are presented in Table 4.4 and Figures 4.3. TK1 profile had ICV, CIA, CIW and PIA which varied between 1.5 to 6.5, 21.6 to 52.9, 23.5 to 66.8 and 17.4 to 54.9 respectively. TK2 had ICV, CIA, CIW and PIA values which ranged from 2.56 to 5.72, 22.1 to 36.5, 23.9 to 46.6 and 17.1 to 40.6 respectively. In the LT1 profile the ICV, CIA, CIW and PIA values varied from 1.70 to 4.32, 20.8 to 58.4, 21.6 to 61.0 and 18.4 to 59.1 respectively. LT2 profile had the ICV, CIA, CIW and PIA ranging between 1.78 to 2.77, 35.1 to 45.2, 33.7 to 49.1 and 29.3 to 44.2 respectively.

To quantitatively assess pedogenesis in the soils, a selected pedogenic indices were used and the results are presented in Figure 4.4. Base loss, Clayeyiness, salinization, calcification, provenance and Ba/Sr leaching in TK1 ranged between 1.2 to 5.6, 0.01 to 0.15, 0.65 to 1.02, 0.50 to 4.59, 0.05 to 0.15 and 0.59 to 3.37 respectively while those in TK2 ranged between 1.8 to 5.2, 0.01 to 0.10, 0.58 to 0.84, 0.97 to 4.36, 0.05 to 0.15 and 0.66 to 5.92 respectively. In LT1, the indices were; base loss (1.0 to 4), clayeyiness (0.07 to 0.18), salinization (0.17 to 0.29), calcification (0.79 to 3.67), provenance (0.05 to 0.06) and Ba/Sr leaching (3.88 to 24.71) while LT2 had values ranging between; base loss (1.4 to 2.3), clayeyiness (0.10 to 0.19), salinization (0.22 to 0.24), calcification (1.12 to 2.07), provenance (0.05 to 0.06) and Ba/Sr leaching (4.47 to 10.87) (Figure 4.4).

The behaviour of nine elements (Ca, Fe, Mn, K, Mg, Na, Al, Si and P) was observed for the four pedons in Takatokwane and Letlhakeng as seen in Figure 4.5. The enrichment and depletion factors calculated for these profiles showed that for TK1, Si was depleted on the upper horizon and enriched at the C and 2AB horizons, it was then depleted again at the bottom horizons at depth 98-155⁺ cm. Fe, Al and Mn were enriched and only depleted at the

C horizon. There was an enrichment of K throughout the whole profile. In the TK2 soil profile, there was depletion of Si down the profile, the elements K, Mn, Fe, Al and Mg showed a depletion in the upper horizon (A). With an increase in depth, there was enrichment of Al, Ca, Fe, K, Mg, Na and P. At the AB horizon there was depletion of Mn that took place. Both the LT1 and LT2 profiles showed a depletion of the elements Si, Fe, Mn and Na and an enrichment of the Al, Ca, K, P and Mg elements. At the BCk2 of LT1, there was a depletion of K and P.

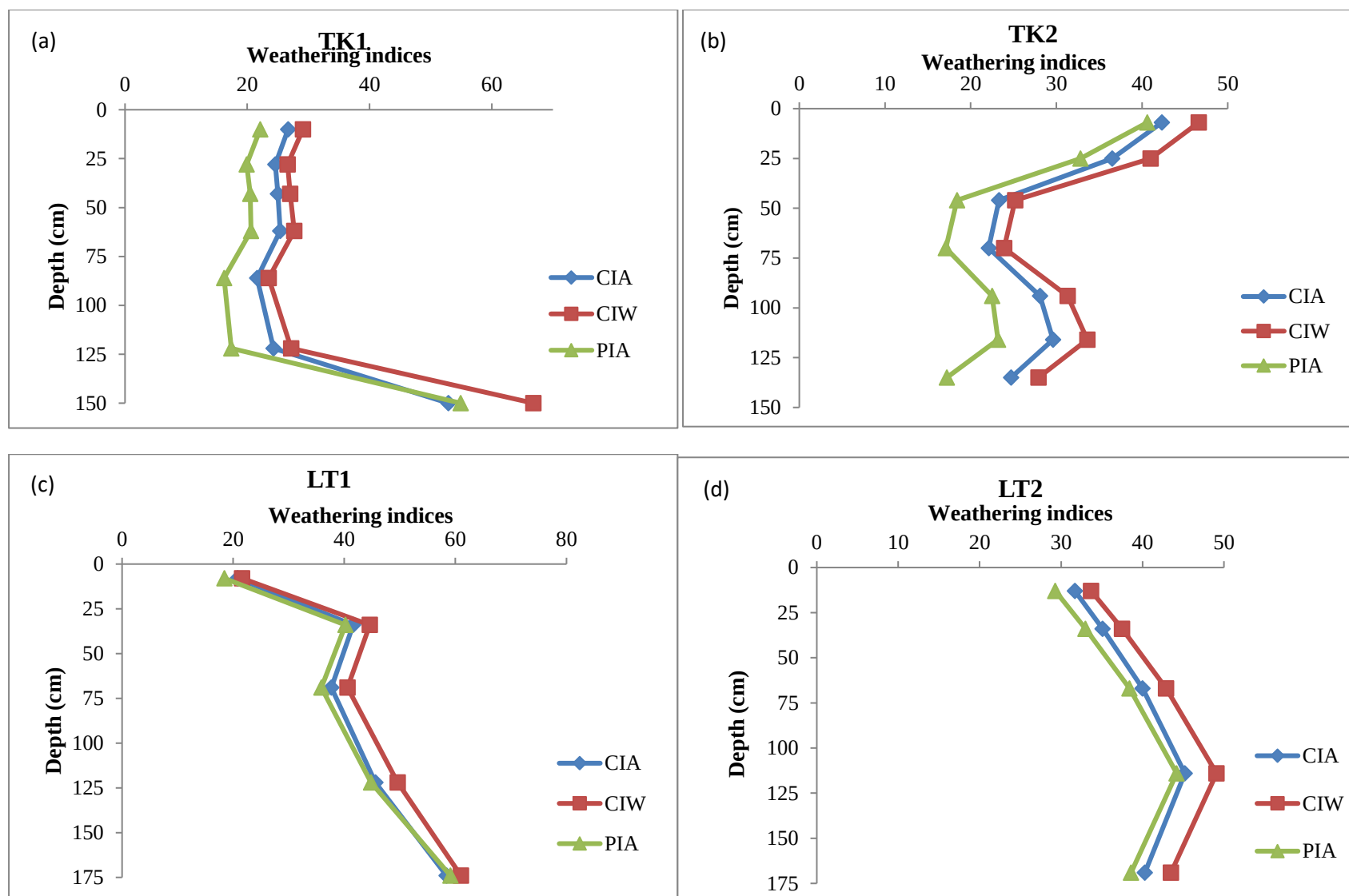


Figure 4.3: Weathering intensities of the soil; CIA, CIW and PIA for (a) TK1, (b) TK2, (c) LT1 and (d) (LT2)

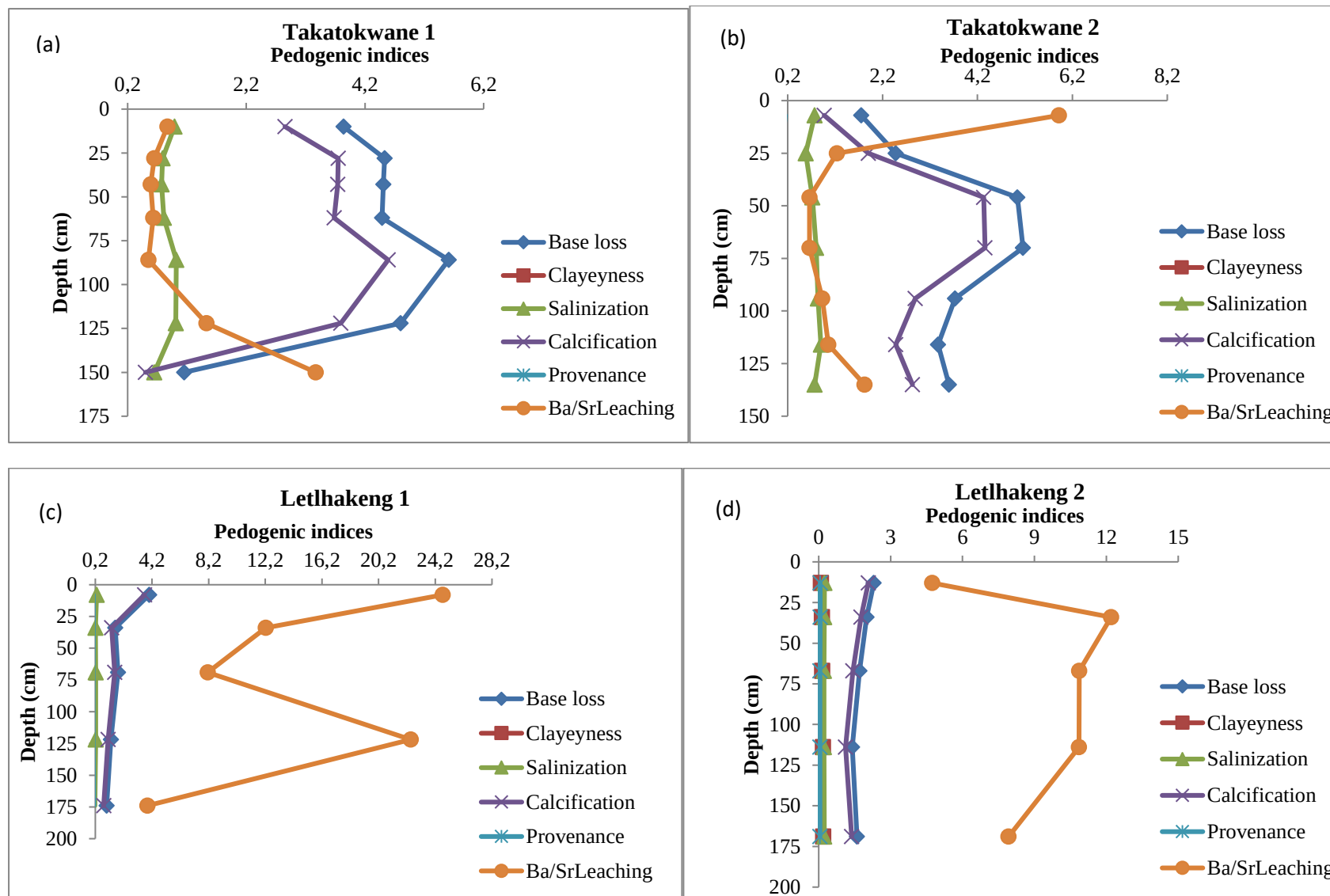
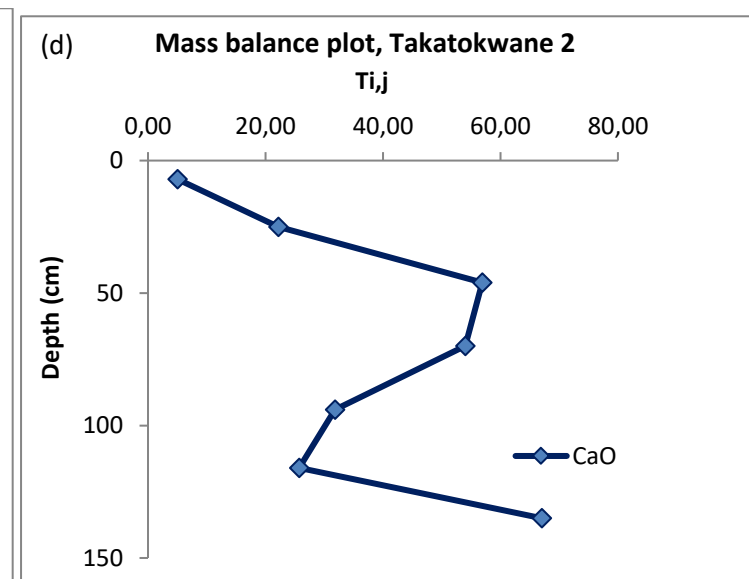
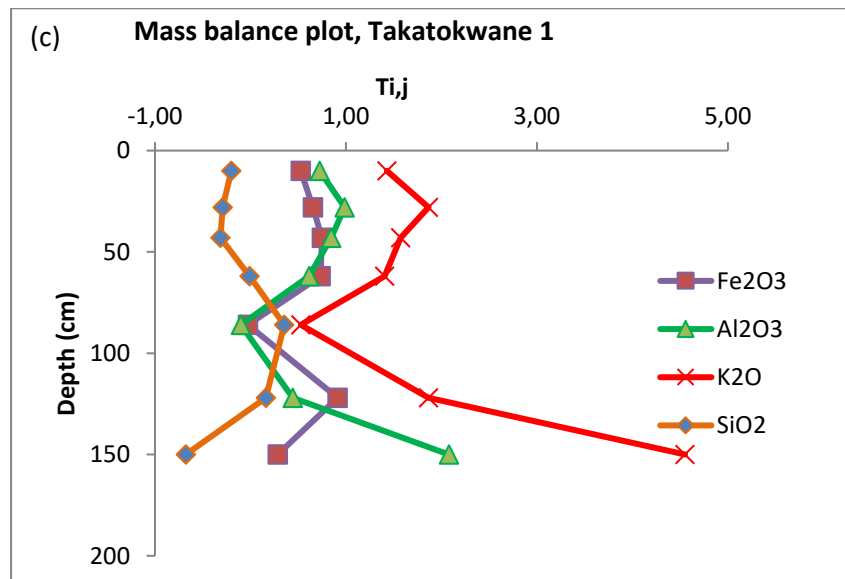
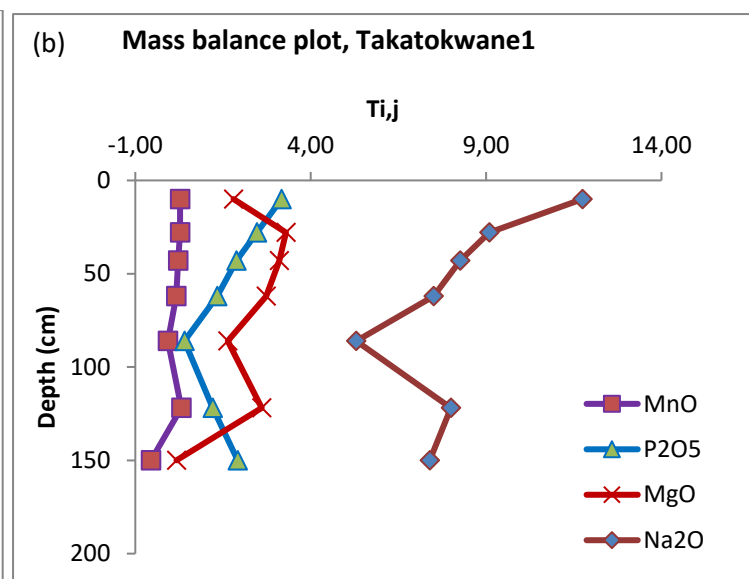
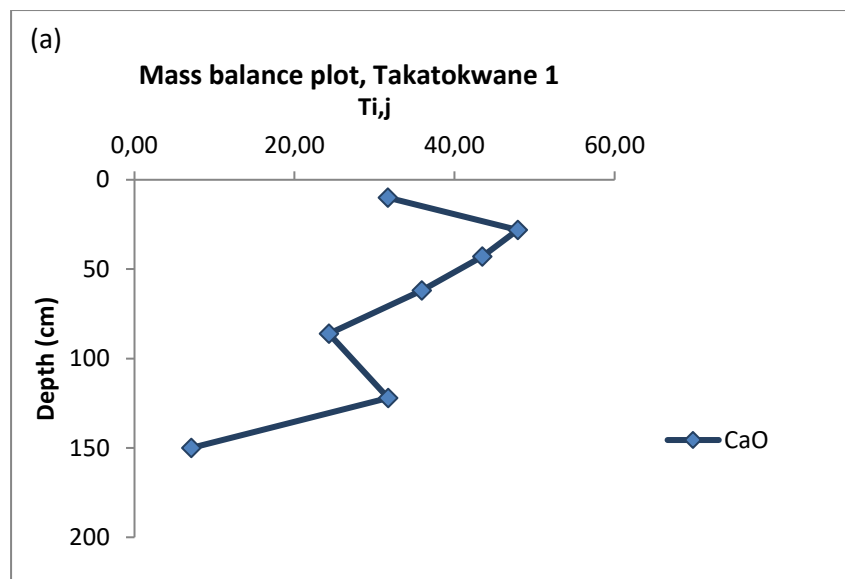
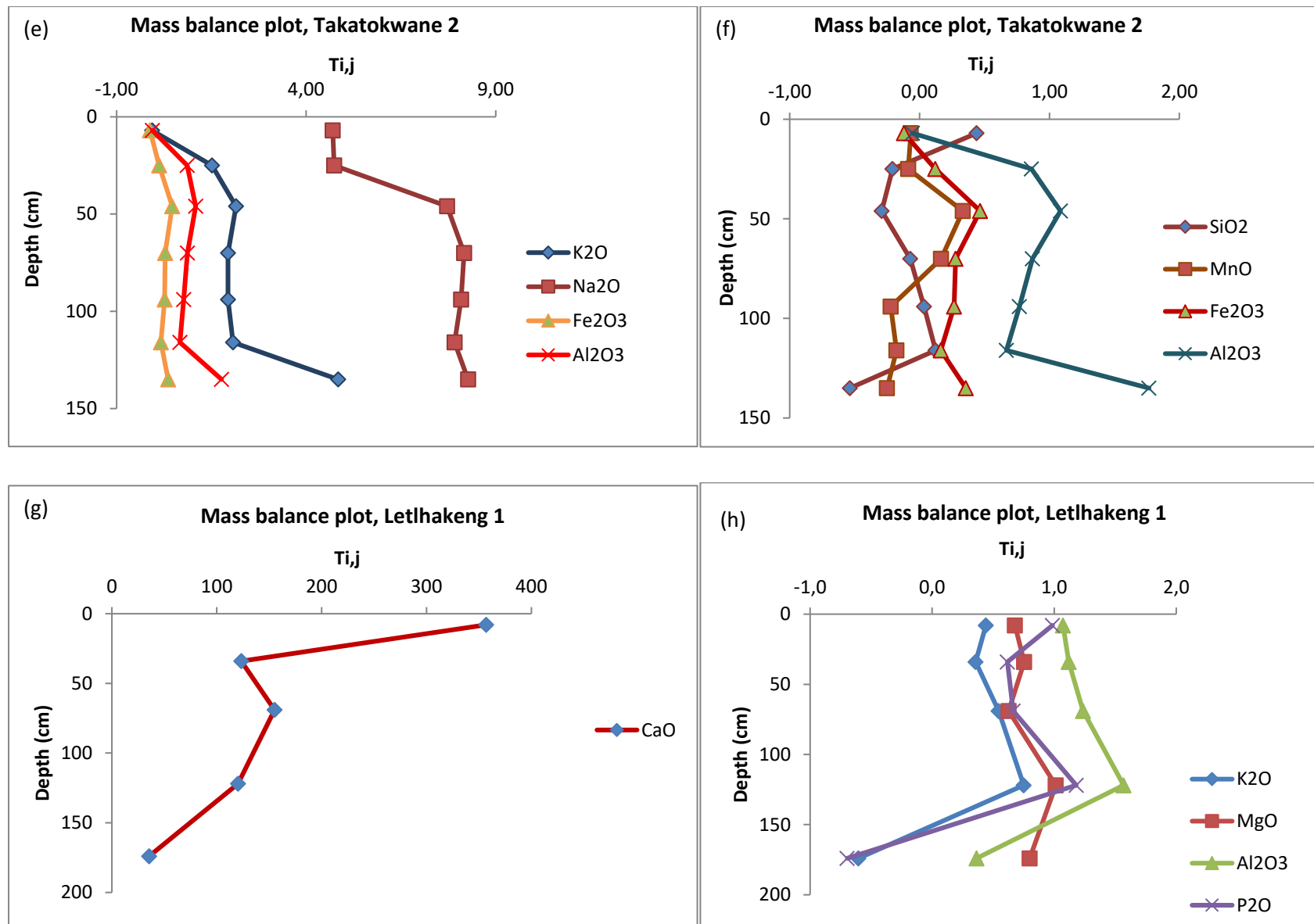


Figure 4.4: Depth plot of quantitative pedogenic ratios for (a) TK1, (b) TK2, (c) LT1 and (d) LT2





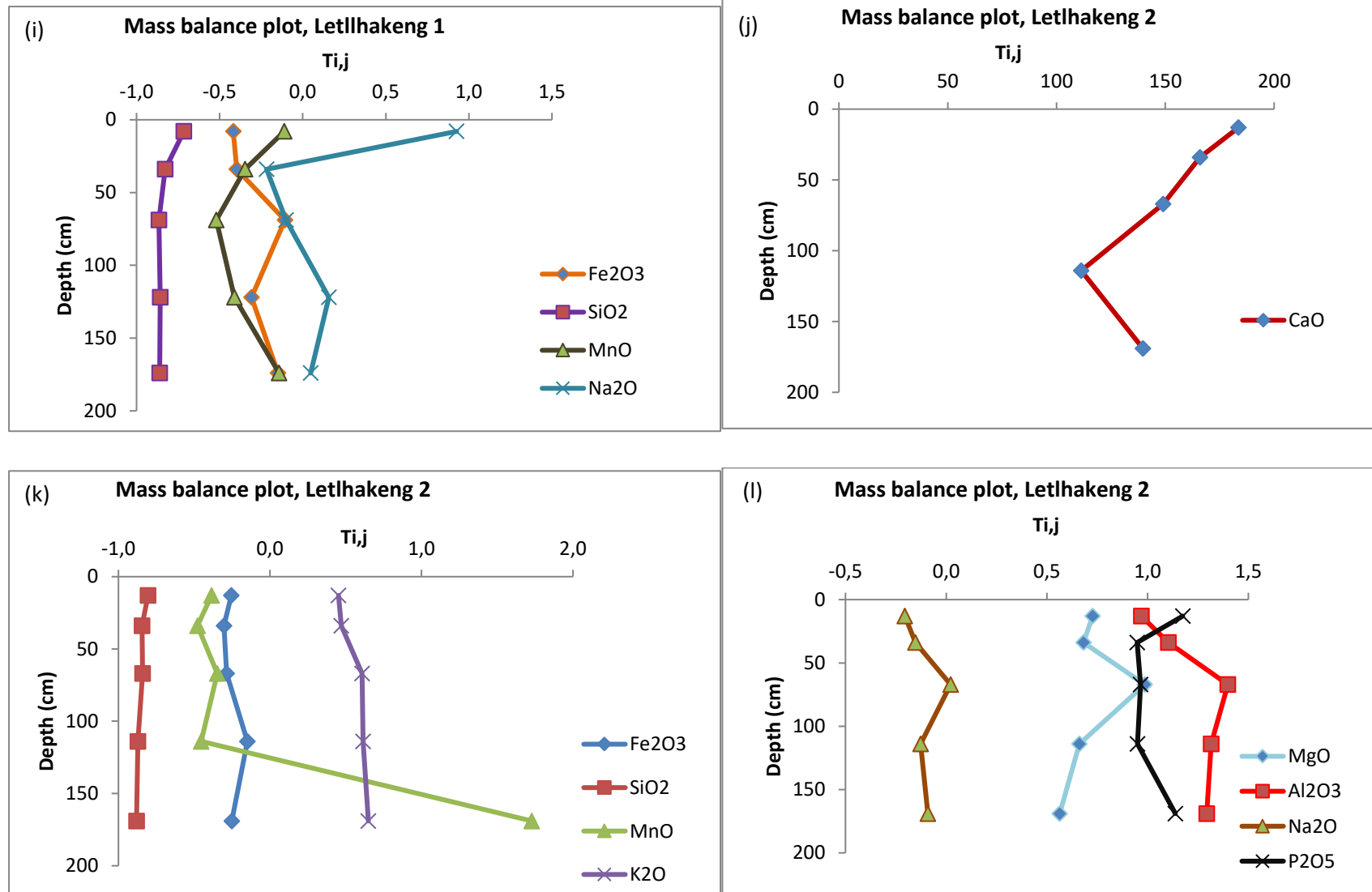


Figure 4.5: Element mobility in the TK1 (a, b and c), TK2 (d, e and f), LT1 (g, h and i) and LT2 (j, k and l) profiles.

4.5 Clay Mineralogy

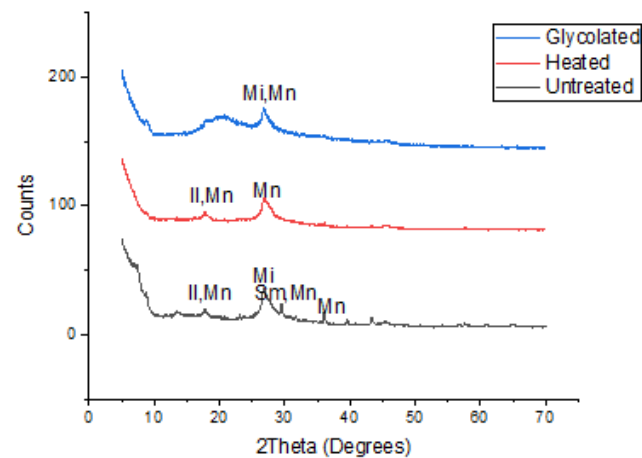
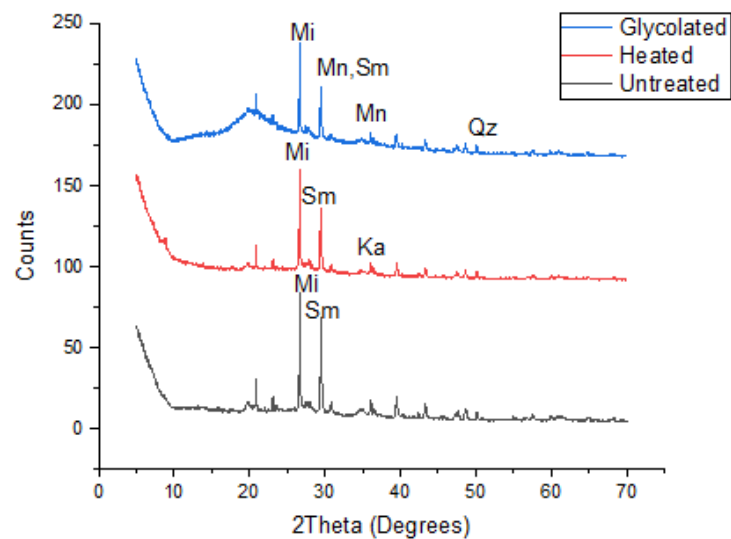
Clay mineralogical analysis was done and the diffractograms the mineral assemblages of all the horizons were presented in Figure 4.6.

In TK1 (Figure 4.6), with the exception of the A horizon all the other horizons in this profile had illite, mica, montmorillinite and smectite. TK1 showed the presence of vermiculite which was identified in the AB horizon. Quartz and smectite minerals were identified in the A, Btss2, C and 2AB horizons. The minerals illite, mica, smectite and montmorillinite were identified in all the horizons of TK2 (Figure 4.6), sepiolite was found in the Btss1 and C horizons while kaolinite was found in the Btss2, C and 2AB horizons of this profile.

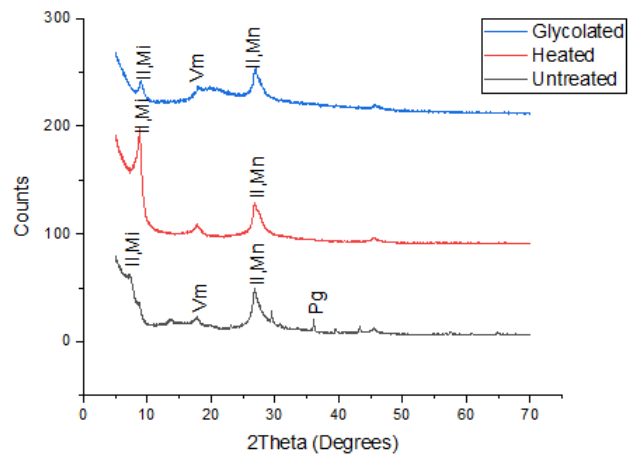
In LT1 profile, the minerals sepiolite, smectite, kaolinite, illite, mica and montmorillinite were identified in all horizons and only dickite was identified in the Bk horizon (Figure 4.6). LT2 (Figure 4.6) profile had all horizons containing the minerals illite, mica, sepiolite, smectite, kaolinite, montmorillinite and quartz with dickite identified in the A horizon of this profile while vermiculite mineral was found in the Bk2 horizon.

The mineralogical identification results of LT3 were presented in Figure 4.6, for both the Cm1 and Cm2 horizons, the minerals identified were sepiolite, smectite, illite and mica while kaolinite and montmorillinite were only identified in the Cm1 horizon. The KD profile showed the presence of sepiolite, illite, mica smectite and vermiculite (Figure 4.6).

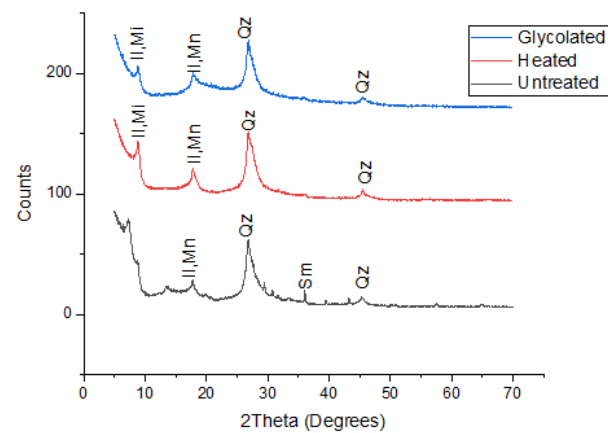
TAKATOKWANE 1



a. A

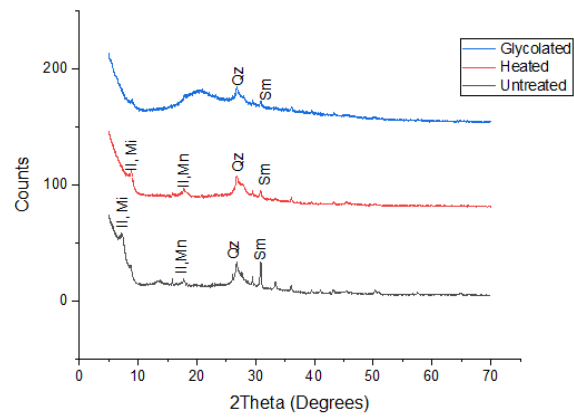


b. AB



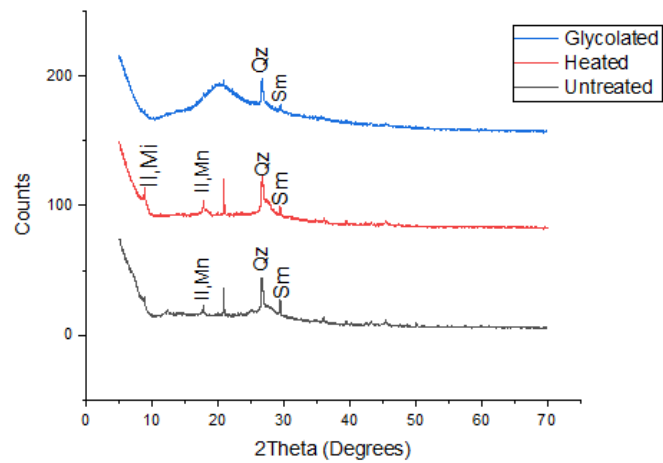
c. Btss1

d. Btss2

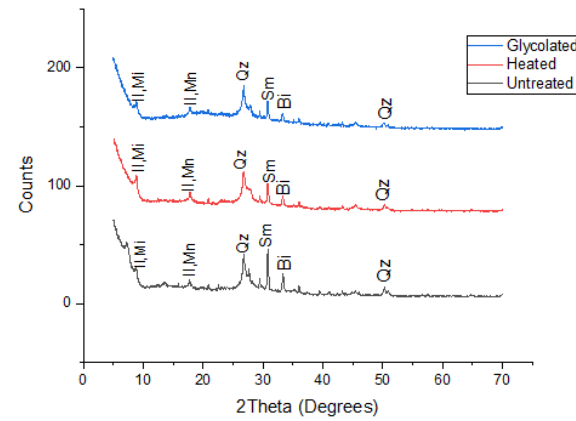


e. C

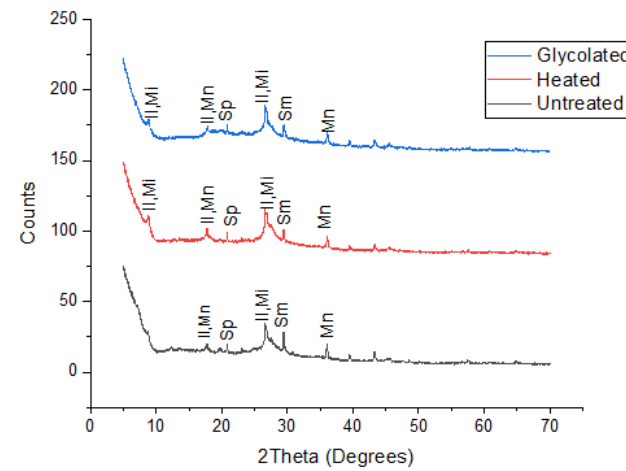
TAKATOKWANE 2



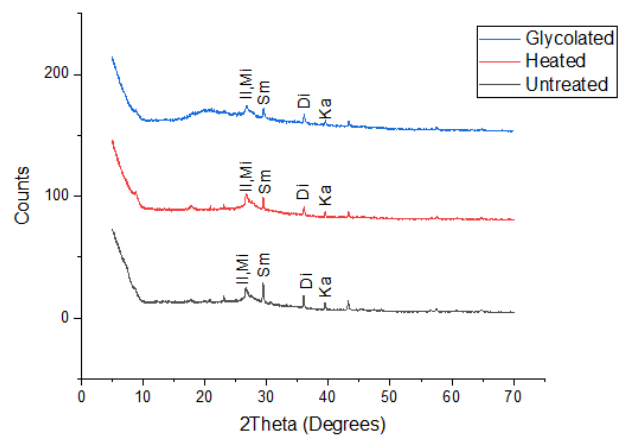
a. A



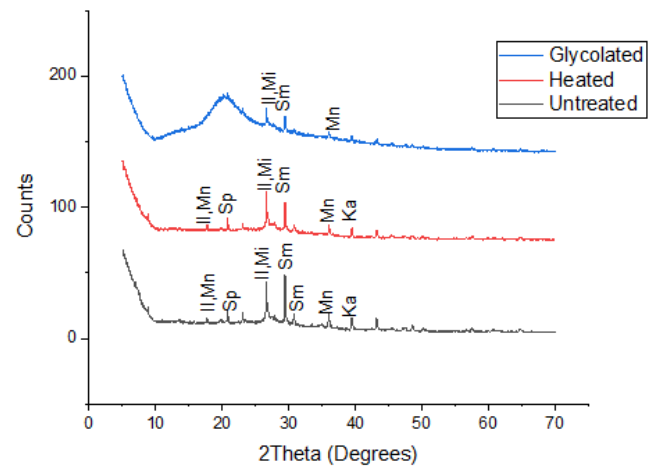
f. 2AB



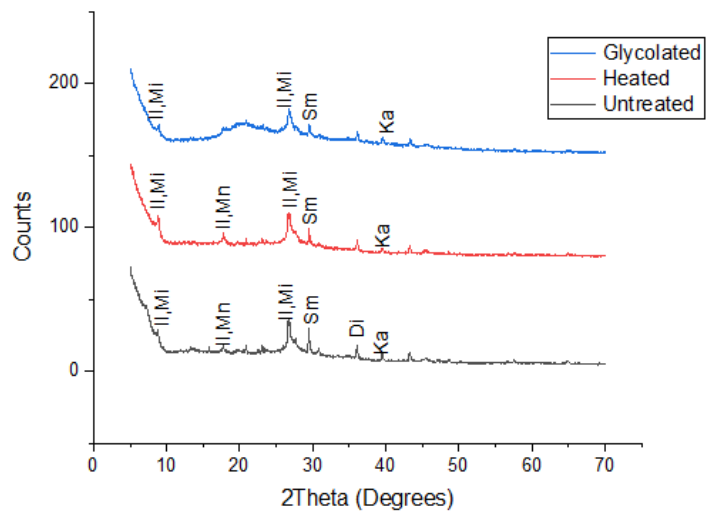
b. Btss1



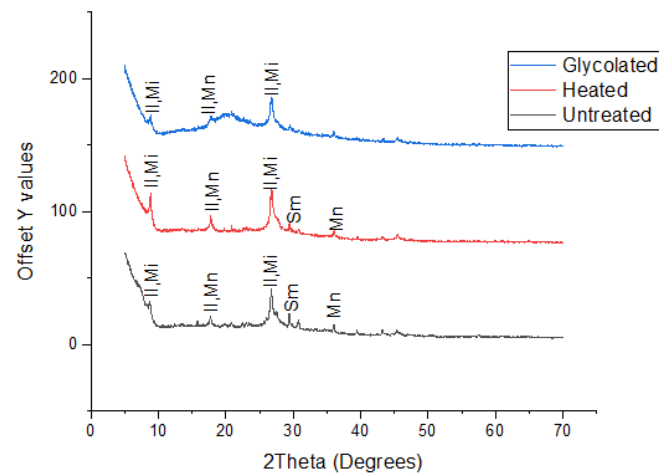
c. Btss2



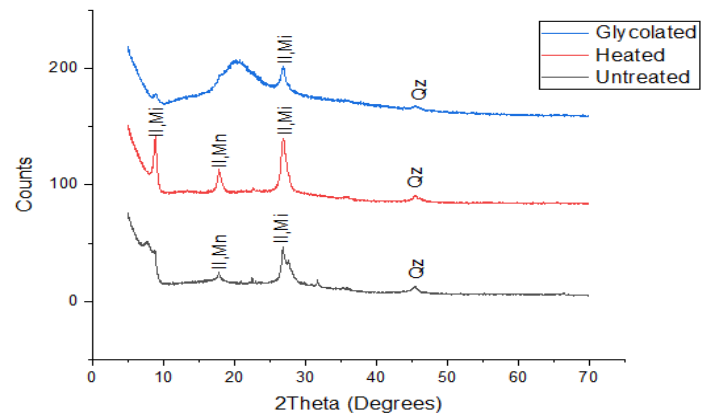
d. C



e. AB

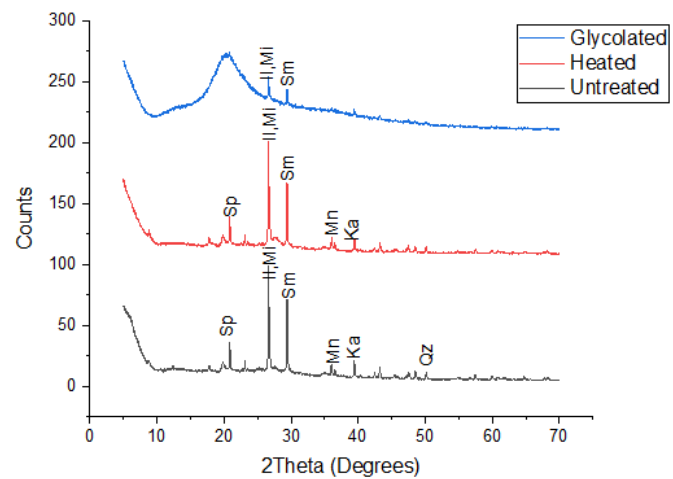


f. 2Btss

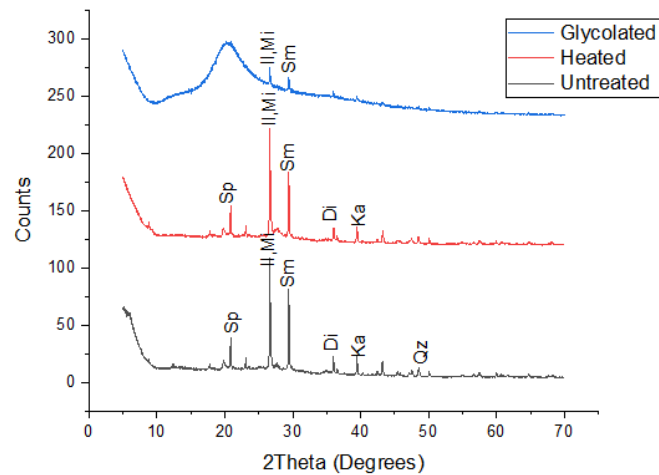


g. Btgss

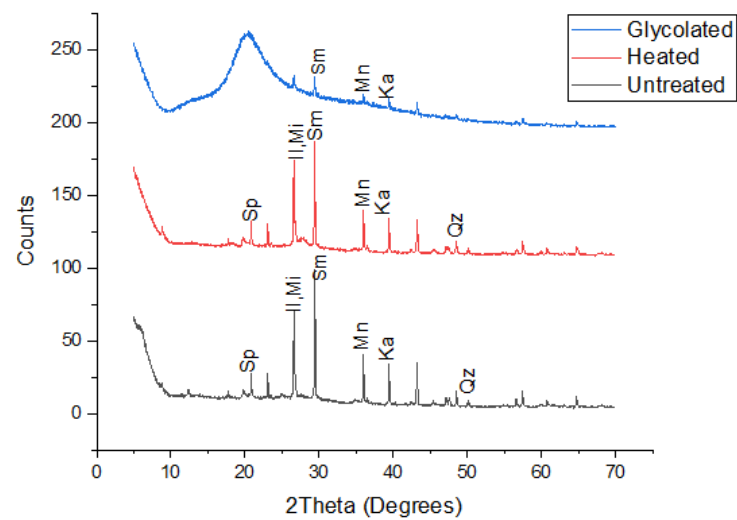
LETLHAKENG 1



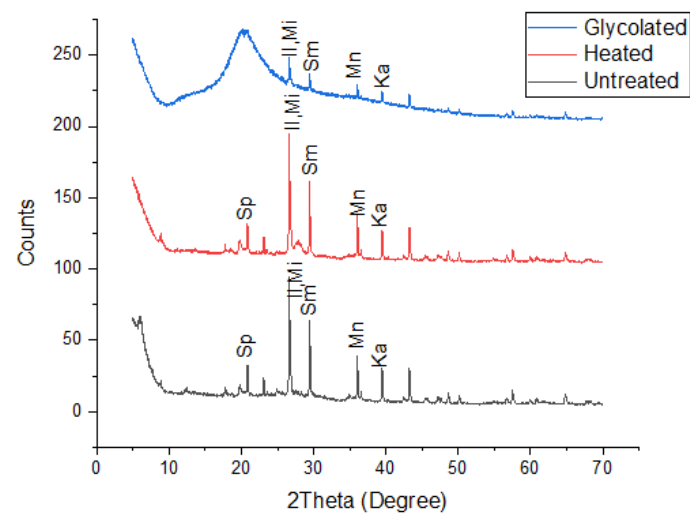
a. Ap



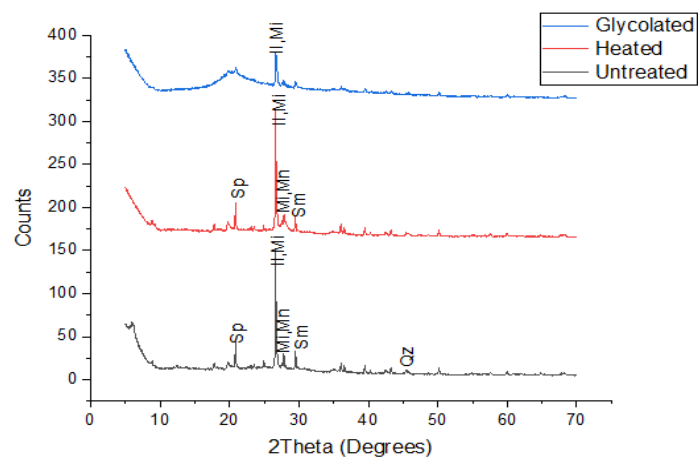
b. AB



c. Bk

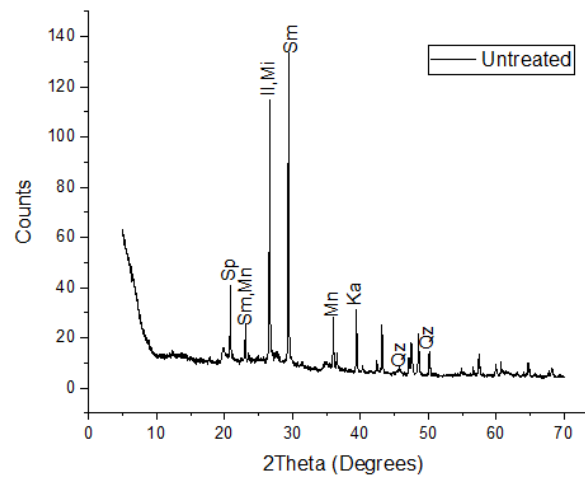
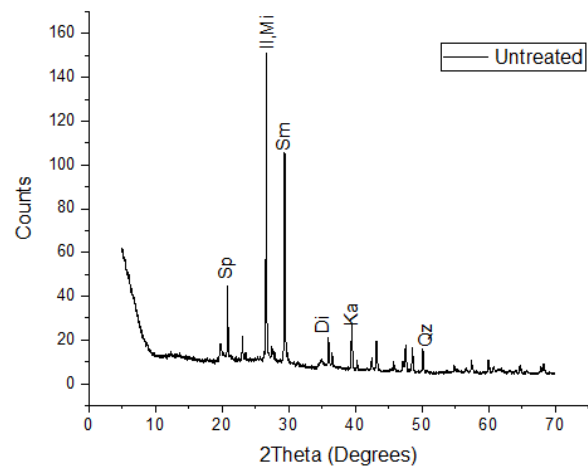


d. BCK1

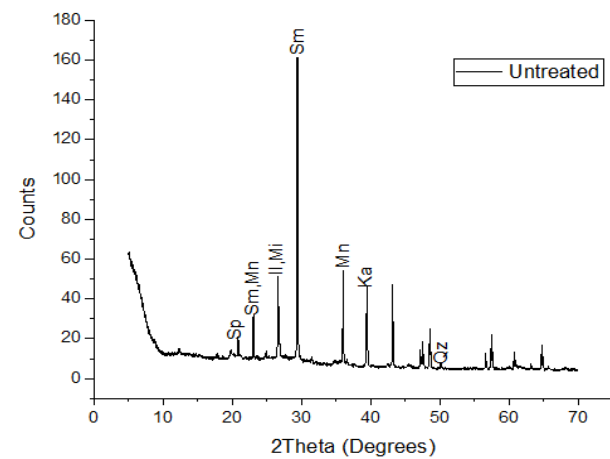


e. BCK2

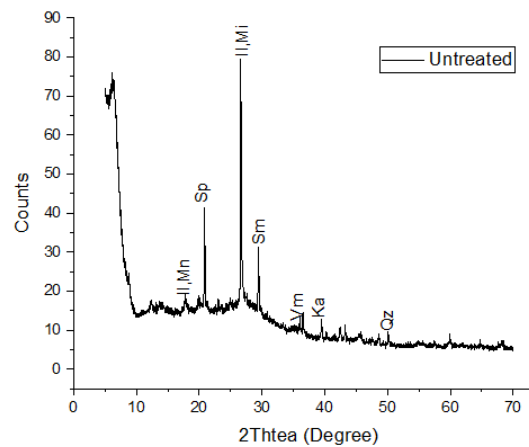
LETLHAKENG 2



a. Ap

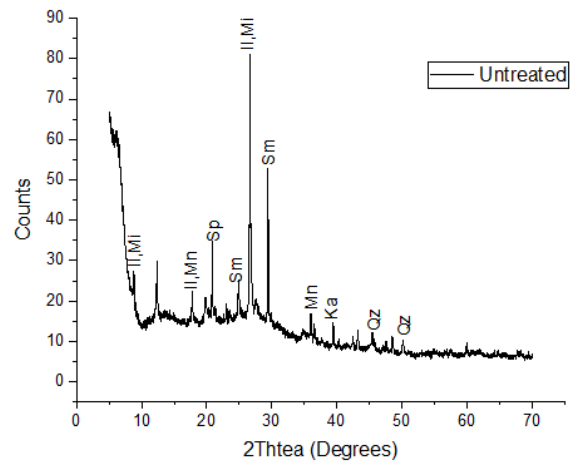


b. AB



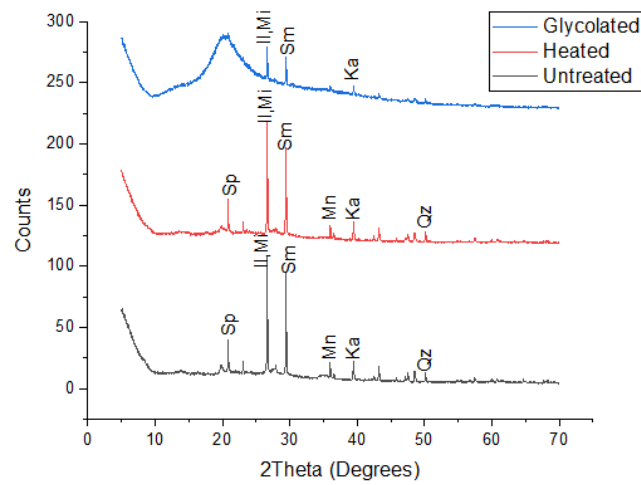
c. Bk1

d. Bk2

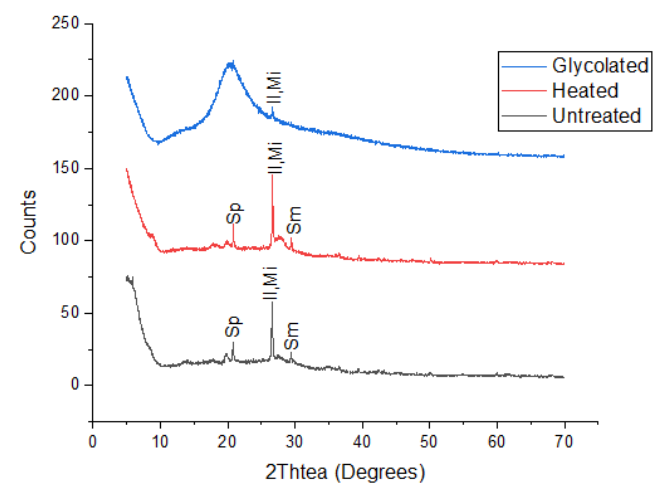


e. Bck

LETLHAKENG 3

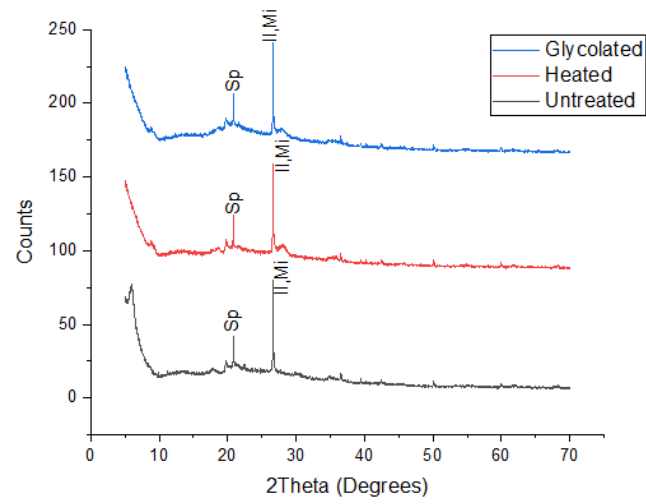


a. Cm1

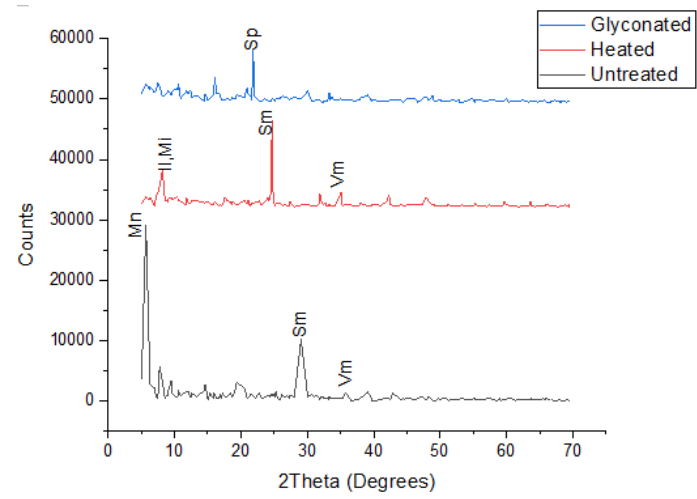


b. Cm2

KHUDUMOLAPYE



a. Cm1



b. Cm2

Figure 4.6: Diffractograms of the soil samples: (TK1: a-f), (TK2: a-g), (LT1: a-e), (LT2: a-e), LT3: a-b) and (KD: a-b)

4.6 Soil classification

4.6.1 Takatokwane pan

Using the soil orders of the USDA *Soil Taxonomy* (Table 4.7), the Takatokwane soils fall under the Aridisols order in the suborder group of Argids and great group of Natrargids. The family series for these soils was Loamy, smectitic isothermic. In reference with the World Reference Based (WRB) criteria (Table 4.8), the Takatokwane profiles were deep sandy loam clay soils which were classified as Gleyic Arenosols (aridic). This classification was due to the argic diagnostic horizons as well as the aridic, gleyic, and shrink swell diagnostic properties of these soils. The soils were made up of mineral diagnostic material with abruptic, arenic, aridic, clayic, gleyic and loamic principal qualifiers.

4.6.2 Letlhakeng pan

Based on the USDA *Soil Taxonomy*, the Letlhakeng soils were then classified as Aridisols with a suborder group of Calcids, great group of Petrocalcids and family series of Fine-loamy, smectitic, isothermic soils (Table 4.7). In line with the WRB classification (Table 4.8), the Letlhakeng soils were classified as Calcisols (Loamic, rhodic, aridic) due to the presence of the calcic diagnostic horizon which had aridic properties with calcaric and mineral material. The principal qualifiers identified were gleyic, petrogleyic and protic.

Table 4.7: Soil classification using USDA *Soil Taxonomy*

Class	Takatokwane	Letlhakeng
Order	Aridisols	Aridisols
Suborder	Argids	Calcids
Greatgroup	Natrargids	Petrocalcids
Subgroup	Typic Natrargids	Typic Petrocalcids
Family	Loamy, smectitic, hyperthermic	Fine-loamy, smectitic, hyperthermic
Name	Loamy, smectitic, hyperthermic Typic Natrargids	Fine-loamy, smectitic, hyperthermic Typic Petrocalcids

Table 4.8: Soil classification using the World Reference Based

Profiles	FAO/WRB
Takatokwane	Gleyic Arenosols (Aridic)
Letlhakeng	Calcisols (Loamic, rhodic, aridic)

CHAPTER FIVE

DISCUSSION

5.1 Ethnopedology

Local potters in Takatokwane are more interested in acquiring their raw materials (pottery-making soils) in the upper 50 cm of the soil profile because of tedious labour and longer time involved in digging deeper (Banyatsi, *pers comm*, 2019). They use indigenous skills to discern the type of soil that could be suitable for their craft. Pottery making in the Kweneng District is still largely at peasant level. In addition to depth distribution, another major driver of the choice of pottery making soil is colour. The red soils are preferred for pottery such as flower vase, plates, pots, etc, while white coloured materials are used for wall painting and where used for pottery is more valued and priced. To maximize profit and productivity, local potters often combine soils with differing colours. More emphasis tend to be placed on physical properties than chemical properties when choosing pottery-making soils probably because the former are visible while the latter is not. TK1 and TK2 are well used because of their high plastic clay content which makes them more mouldable. Their high COLE values (Table 4.3) is an indication of their high extensibility as they exhibit shrink swell characteristics (COLE values ranged from 0.02 to 0.11). Tall et al., 2017 reported that COLE values between 0.03 and 0.06 indicated medium shrink swell potential of the soil while those between 0.06 and 0.09 indicated high and those > 0.09 showed very high shrink swell potential, therefore this makes the Takatokwane soils mouldable. At Letlhakeng, soils from LT1 and LT2 are highly sought after because of their reddish colour (Table 4.1). The reddish-pinkish colour observed in the Letlhakeng soil could be a possible indication of the presence of oxides of iron in the soil and good drainage. In the Letlhakeng pedons as the depth increased, the soil colour became redder (LT1: 10YR 5/3 $>$ 10R 7/3 and LT2: 10YR 8/2 $>$ 10R 8/2 $>$ 10R 7/4 $>$ 10R 7/4). As reported by (Lucke and Sprafke, 2015) red colour in soil

could be an indication of the presence of oxidized iron or hematite. LT3 is used by the local potters because of its white colour. Illite mineral is known for its white colour and LT3 has lots of illite (Figure 4.6). Researchers have reported the extensive use of illite clay in pottery making (e.g. Kuwahara et al., 2001; Stevenson et al., 2006). KD (Figure 4.1(f)) on the other hand has an interesting combination of high clay content and iron oxides. When processed, they have the capability of producing good quality pottery.

5.2 The influence of climate, topography and parent material on soil properties

Sampling soils by landform gives invaluable insight into the stability, parent material and topographic factors (Briggs et al., 2006). Assessment of variability in soil properties can help explain the relationship between soil properties in a particular landform. With respect to landscape topography, TK1 and TK2 formed on a bottom (flat) slope of a pan. This position makes it possible for accumulation of colluvial and transported materials from the surrounding environments. Drainage is impeded in the Takatokwane pan. It exhibited some water logging characteristics at the lower horizons (145 – 155⁺ cm at TK1 and 128 – 142⁺ cm at TK2) which were seen in the grey to greenish colours (Table 4.1) of the soil, this suggests that gleying occurred in the pan. The light grey soil horizons (0 – 74 cm at TK1) indicate the domination of quartz and uncoated mineral grains in the soil. The few or non-existent presence of roots in the studied area could be attributed to the fact that steady accumulation of materials from the adjacent places wouldn't allow sufficient time for plant growth as plants need geomorphic stable landscape to grow. The low intensity and availability of the kaolinite mineral in TK1 and TK2 (Figure 4.6) can be attributed to the fact that the samples were collected on a land of low relief, Şenol et al., (2017) reported similar results that kaolinite tends to be more concentrated in areas of high relief as opposed to low lands. LT1 and LT2 formed on lower (foot) slope of Letlhakeng valley. Sheet erosion is evident at the pedons and this could be responsible for the removal of soil constituents such as organic matter and clay

from the topsoil. Spatial differences in pH, organic matter and clay content are caused by pedogenic processes that are affected by topographically changed hydrological and temperature regimes (Vasu et al., 2016).

The nature of parent material has a strong influence in the texture of soils. The observed difference in soil texture in the genetic horizons of TK1, TK2, LT1 and LT2 generally reflects that the soils were formed from sandstone parent material as these soils exhibit a dominance of sand, which was evident from the particle size analysis results (Table 4.1). Working in similar environments, Eze and Meadows (2014) reported that soils formed from sandstone developed into predominantly sand soils. The light greyish colours observed in some of the TK1 and TK2 profiles are clear evidence of quartz dominance in the sandstone (Hajpál and Török, 2004). Major elements distribution is a reflection of compositional change that occurs during the chemical weathering process in the soil. The major elemental composition analysis (Table 4.4) indicated that the SiO₂ concentration in both Takatokwane and Letlhakeng pedons was very high (> 55 %). Generally the parent material could be the primary contributing factor in the variation of silica content in the soil. Rajeshwar and Mani (2018) reported similar results in which their samples had high SiO₂ content inherited from the parent material. The presence of the clay minerals illite and mica (Figure 4.6) in Takatokwane and Letlhakeng soils might be because they were inherited from the parent material. Illite can also be formed authigenically (Şenol et al., 2017). Illite and kaolinite minerals can be an indication of the weathering of feldspars (Ozaytekin et al., 2018).

The semi-arid climate of the Kweneng District could be a contributing factor to the alkaline pH results (Table 4.2). The presence of calcium carbonate in these profiles also contributes to the high alkalinity in the soils and is also responsible for cementation of the soil particles. The semi-arid climate is highly favourable for the formation of smectite mineral which could be a possible reason for the occurrence of smectite in almost all the studied profiles. High

cation exchange capacity values can also be an indicator of the presence of smectite in clays (Tsozué et al., 2017; Ozaytekin et al., 2018), the CEC values (Table 4.2) of the A and Btss1 horizon of the TK1 profile were 168.11 and 114.13 Cmol/kg respectively hence the presence of smectite. Similar results have been reported by (Tsai et al., 2007; Tsozué et al., 2017). The dissolution process can transform montmorillonite into sepiolite. The alkalinity and the semi dry environment of the study location favours the formation of sepiolite hence why it was found in all the four sampling locations (Tsozué et al., 2017). The illite mineral can be transformed to smectite which could be why there is variation of illite and smectite minerals in some of the soil profiles (e. g TK1, LT2 and KD) (Moazallahi and Farpoor, 2012). Batezelli et al., (2019) reported that mineral compositions associated with smectite and sepiolite are an identification of soils that formed under arid to semi-arid environments. Various researchers (Lavkulich and Bulmerl, 1994; Moazallahi and Farpoor, 2012; Malavath and Mani, 2017; Şenol et al., 2017; Tsozué et al., 2017) have reported the presence of sepiolite, smectite, montmorillonite, mica, kaolinite, vermiculite and quartz and have demonstrated that these minerals are highly associated with arid to semi-arid environments as it is the case with the area of this study.

Organic matter content (1.20 – 11.30 %) in both Letlhakeng and Takatokwane was low to moderately high (Solutions, 2013) as the soils contained high amount of sand and low clay content. Hicham et al., (2016) reported that the existence of organic matter during manufacturing of earthenware products offers various advantages as it serves as a binding agent that gives the wet clay more energy, it also helps to increase the plasticity of the clay mineral after a few days of rotting into a moisturized clay mineral. The low clay content also resulted in TK1 and TK2 having slightly saline soil (EC values were < 6.45 dS/m). Ouhadi and Goodarzi (2007) reported that soils with low clay content tend to have moderate salinity.

5.3 Chemical weathering and pedogenic intensity

Chemical breakdown of the primary minerals can result in the net loss of some mobile elements such as Ca, Mg, K and Na as well as the accumulation of different clay minerals such as kaolinite, vermiculite, mica and smectite (Yousefifard et al., 2012). The mass balance of elements was computed for this study so as to understand the mobility of the major elements throughout the profiles. The values that fall below zero were interpreted to imply elemental loss while values greater than zero signified elemental enrichment (Xin et al., 2010; Yousefifard et al., 2012 and Tsozué et al., 2017). The loss of Si (Figure 4.5) which can be referred to as desilication, is a very significant process in soil development. Desilication primarily results in the leaching of SiO_2 and enrichment of quartz, secondary Al and Fe oxides (Eze et al., 2010). In the two TK1 and TK2 pedons, there was Al lost in the horizons. The depletion of Al during the development of soil has been documented by other researchers (e.g. Taboada et al., 2006; Jin et al., 2010 and Yousefifard, 2012). Unlike in TK1 and TK2, there was a gain of the Al element in the LT1 and LT2 profiles (Figure 4.5). Tsozué et al., (2017) elucidated that Al is pH dependent and forms strong complexes with soil organic matter, if it undergoes oxidation it might lead to the mobility of Al in the soil profile. The enrichment of Na which was observed in some of the TK1 and TK2 horizons can be attributed to the presence of montmorillonite mineral (Figure 4.6) which contains Na and Mn in its structure. The accumulation of Na can also be attributed to the dry season or low precipitation in the study area, these results are similar to those of (Tsozué et al., 2017). K element was enriched in the TK1, TK2 and LT2 profiles and was depleted with depth in the LT1 profiles. Yousefifard et al., (2012) reported that the presence of K in the soil can provide a good proxy measure of K-feldspar quantity in the parent material as well as in the soil profile. Significant enrichment of Fe was observed in the LT1 and LT2 pedons (Figure 4.5). (Xin et al., 2010) reported similar results of Fe accumulating with depth in the soil profile,

this Fe enrichment was attributed to the weathering of biotite in the soil. The results of Fe enrichment in this study, agrees with other results reported by Guan et al., (2001); Tijani et al., (2006) and Yousefifard et al., (2012).

In this study, ICV, CIA, CIW and PIA (Table 4.4) were used to measure the degree of chemical weathering as well the maturity of the soil. ICV values were generally greater than 1 in all the studied profiles (TK1, TK2, LT1, LT2, LT3 and KD) which implies that the soil is young, immature and mainly dominated by primary silicate minerals (Fig 4.6). The CIA values recorded in all pedons were below 50 which entails that they had undergone a low-to-moderate weathering and pedogenesis. This classification was based on (Nadłonek and Bojakowska, 2018) whereby values ranging from 44-66: low-to-moderate degree of weathering, 50-60: incipient (beginning) weathering, 60-80: intermediate weathering, > 80: extreme weathering. The low CIA values can be used to show near or absence of chemical alteration and thus may reflect cold and/or arid conditions (Lamine and Ishiga, 2016) as it is with the study area. Tuncay et al., (2019) reported that since CIW does not account for aluminium associated with K-feldspar, it is highly likely to generate high values for K-feldspar rich rocks or soil regardless of their chemical weathering status. If the CIA classification is performed for CIW (because these two indices display a similar behaviour), then it is evident that all the profiles fall under the low-to-moderate degree of weathering categorization. Figure 4.3 shows a strong relationship between CIA, CIW and PIA, based on this relationship we can establish that these indices are all in strong agreement that the soils had undergone low to moderate weathering and pedogenesis. The minimal occurrence of kaolinite mineral also indicates that the soil has not undergone intense weathering as this mineral is mostly associated with extreme weathering especially that of feldspars (Wilson, 2006).

Due to pedogenic processes operating over various periods of time (Abdelfattah, 2013), soils vary in their processes within and across landforms (Gessler et al., 2000; Vasu et al., 2016). In this study pedogenic indices (clayeyiness, salinization, base loss, calcification, provenance and leaching) were evaluated so as to quantitatively describe the pedogenic processes that took place in the soil (Figure 4.4). Σ Base/Al value is used to infer the hydrolysis pedogenic process as well as leaching. It is evident from this study that in both Takatokwane profiles, the values fell between the threshold values 2 and 10 (Sheldon and Tabor, 2009) which then suggests moderate hydrolysis while the profiles in Letlhakeng showed little hydrolysis as the values were > 2 , however the A horizons in LT1 and LT2 profiles seemed to exhibit more hydrolysis than horizons below them, the values obtained can also indicate a slow process of salinization as well as moderate hydrolysis (Mohanty and Nanda, 2016; Srivastava et al., 2019). Generally the LT1 and LT2 salinization ratios were below 1 which implies that there was very low accumulation of salt, this could also be a reason why the soil was non saline with an EC of < 2 (Table 4.2). Low salinization values imply that the soil is dry and well drained while high values signify that evaporation exceeds precipitation (Mohanty and Nanda, 2016). Accumulation of salt in soils can also be determined by calcification ratio (Retallack, 1997). Similarly to the salinization ratio, the calcification ratio values (Figure 4.4) also suggested that the soil had insignificant accumulation of soluble salts.

Clayeyiness is a measure of the amount of clay mineral formation which is marked by high Al content in clay as compared to the original rock (Mohanty and Nanda, 2016), it is also used to infer hydrolysis (Srivastava et al., 2019). For pedons TK1, TK2, LT and LT2 the values obtained were closer to zero which indicates that they contain more particles of sand than that of clay (Table 4.2 and Figure 4.4). In both TK1 (Btss1 horizon) and TK2 (Btss2 horizon) profiles, at depths 36-50 cm showed a noticeable difference in the particle size analysis results as they were identified as clay particles (> 49 % of clay), this difference can infer that

the processes of illuviation and lessivage occurred. Quenard et al., (2011) described the soil forming process of lessivage as a vertical transfer of fine particles ranging from less than 2 μm to 10 μm from a superficial horizon. The low calcification values obtained from this study suggest moderate to low precipitation in a semi-arid environment, this is the case with the Kweneng District as it receives very low annual rainfall. The pedogenic ratio Ba/Sr determines the intensity of leaching, it is indirectly linked with the climate change in the region, both soil profiles in Takatokwane showed insignificant amount of leaching as they fall below the < 2 threshold. While the Letlhakeng profiles were highly leached probably because of their texture and landscape position. The translocation of soluble nutrients in the different horizons of LT1 and LT2 could have resulted in high leaching rate. Vasu et al., (2016) reported that the intensity of these pedogenic processes varies with landforms and as such areas in low lands are highly prone to leaching as it is the case with Letlhakeng. Leaching and environments with high temperatures speeds up weathering and promotes the formation of kaolinite (Moazallahi and Farpoor, 2012) therefore this explains the kaolinite that was found in the LT1 and LT2 soil profiles as they had a high rate of leaching than the other soil profiles.

5.4 Soil classification of Takatokwane and Letlhakeng

The Takatokwane and Letlhakeng soils were both classified as Aridisols at order level (Table 4.7) in reference to the USDA Soil Taxonomy (Soil Survey Staff, 2014) due to being in the aridic soil moisture regime, having natric horizon (Takatokwane), calcic and petrocalcic horizons (Letlhakeng). Takatokwane Aridisols qualified as Argids at suborder level because it had an argic and natric horizon which also led to them being classified as Natrargids at great group level and Typic Natrargids at subgroup level as these horizons were within the 100 cm of the soil surface. On the other hand, Letlhakeng qualified as Calcids at suborder level because of its calcic and petrocalcic horizons which also qualified them as Petrocalcids

great group and Typic Petrocalcids at subgroup level as these horizons were present within the 100 cm of the soil surface. At family level, the Takatokwane particle size class was loamy as the horizons of this profile had less than 35 % clay (Table 4.1) by weight in the fine earth fraction while the Letlhakeng particle size class at family level was fine loamy as it had 18 % to less than 35 % clay in the fine earth fraction. Still at family level, both Takatokwane and Letlhakeng were in the smectitic mineralogical class as they both had more smectite (montmorillonite included) (Figure 4.7) minerals present in their soils than other clay minerals and they both qualified to be in the hyperthermic moisture regime (at the depth of 50 cm below the surface of the soil, the average yearly temperature is 22 °C or higher with the difference between averages of winter and summer soil temperature being 6 °C or more). The Takatokwane soil was then classified up to the family level as loamy, smectitic, hyperthermic Typic Natrargids while Letlhakeng was classified as fine-loamy, smectitic, hyperthermic Typic Petrocalcids. In line with the World Reference Based, (2014) classification (Table 4.8), Takatokwane was classified as Gleyic Arenosols (aridic). Arenosols are soils that have an average texture class of loamy sand or coarser (Table 4.1) in horizons thicker than 15 cm to and soil depth of 100 cm. Takatokwane was also classified in the Arenosols reference group as it had gleyic properties (principal qualifiers) and aridic properties (sub qualifiers). Letlhakeng soils were classified as Calcisols (loamic, rhodic, aridic). They qualified to be in the Calcisols reference soil group as they had a petrocalcic horizon with loamic, rhodic and aridic properties (all sub qualifiers).

CHAPTER SIX

CONCLUSION

Earthenware pottery-making soils from the Kweneng District of Botswana were studied to improve our understanding of the pedological characteristics with respect to indigenous knowledge of soils among the local potters. It was found that pottery-making soils in this region consist of both modern soils (e.g. LT1, LT2, TK1 and TK2) and palaeosols (e.g. LT3 and KD). Plasticity, colour and depth are the most considered factors by the local potters in choosing the raw materials. While the modern soils are obtained by digging the soils, the paleosols are mined from excavations. The texture of the soils is dominantly sandy clay loam with alkaline soil pH and high bulk densities. The clay mineralogy of the soils consisted mainly of smectite, illite and montmorillonite. In Takatokwane, the grey-greenish soils are of high interest to potters as they have a fair amount of highly plastic clays which is suitable for pottery. Letlhakeng potters are mainly drawn to the red soils because of their colour and ease to mould. The soil from Letlhakeng excavation is highly enriched in illite clays which bestows a characteristic of white colour and well sought after for painting. Geochemical molecular ratios used to assess chemical weathering and pedogenesis in these soils infer incipient (weak) weathering and pedogenesis – an indication that the area still holds the potential to yield more clayey soils for pottering making in the future. The dry semi-arid climate prevailing in the area and the predominantly quartzitic sandstone parent material are the leading factors responsible for slow rate of pedogenesis in the area. Based on abundance, the pottery-making soils are not only found in the upper soils horizons as the local potters believe, they exist at depths greater than 100 cm. Therefore, potters could go deeper to obtain the raw materials for their craft. Further investigation on the pottery-making soils from the Kweneng District should focus on micromorphology, mechanical properties including Atterberg limits, porosity tests, flexural and compressive strength tests.

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