



MINERAL WEATHERING, PEDOGENESIS AND CHARACTERIZATION OF EXPANSIVE SOILS FROM SEROWE, CENTRAL BOTSWANA

By

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I, Itumeleng Nkonga, 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/thesis titled: Mineral Weathering, Pedogenesis and Characterization of Expansive Soils from Serowe, Central 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 over a faint, light grey watermark that says 'Type text here'.

.....
Prof. Peter N. Eze

Date: 16 August, 2022

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I owe you all!

Abstract

Expansive soils tend to be fairly high in natural fertility and their unique morphology makes them quite interesting. Soils found in Serowe, Central Botswana, commonly exhibit variable degrees of periodic shrinking and swelling which often leave visible cracks and sometimes undulating micro-topography (gilgai) on the landscape. The use of expansive soils is often constrained due to severe management problems often associated with their physico-chemical properties. Therefore, basic site-specific pedological research is pivotal to understanding some of the unresolved edaphological and environmental aspects of expansive soils. The overarching aim of this study is to undertake a pedological investigation of the expansive soils from Serowe, which hitherto have been poorly studied. The main objective of this study is to advance our understanding on the pedology of the soils from Serowe. Specific objectives include to: (i) characterize the soils using macromorphological, physical, chemical, mechanical and mineralogical properties; (ii) evaluate mineral weathering intensities of the soils; (iii) identify the pedogenic processes responsible for their formation; and (iv) provide an updated high resolution classification of the soils in accordance to FAO-WRB system and USDA *Soil Taxonomy*. Five representative soil profiles (SP1, SP2, SP3, SP4 and SP5) were randomly sited on flat to undulating landscapes and samples were collected from each genetic horizon for laboratory analysis. Selected pedological parameters including particle size distribution, pH (H₂O and KCl), bulk density, porosity, organic matter, calcium carbonates contents, electrical conductivity, cation exchange capacity, coefficient of linear extensibility (COLE) and Atterberg limits were determined using routine laboratory procedures. X-ray fluorescence spectrophotometer and x-ray diffractometer were used for total elemental composition and clay mineral analysis respectively. Geochemical ratios including CIA, CIW, and ICV were used to assess mineral weathering; mass-balance plots for elemental redistribution and pedogenic ratios for quantitative pedogenesis. *In-situ* observations showed that all the soils have vertic properties and were generally very deep (>150 cm). By the virtue of their colour, the soils qualified as dark and chromic. With the exception of SP3, all other soil profiles had sandy clay loam texture with sand content ranging from 60.2 to 85.0 %, silt 0.2 to 15.0 % and clay content 20.8 to 33.8 %. SP3 and SP5 had consistently subangular blocky structure while SP1, SP2 and SP4 had subangular blocky structure on the top horizons (<25 cm) and angular blocky structure in the subsurface horizons. The bulk density values ranged from 1.14 to 1.67g/cm³ with medium to high porosity (20 – 40 %). pH (H₂O) values ranged from 6.9 to 8.0. The electrical conductivity values ranged from 0.07 to 0.40 dS/m. CEC values for all profiles were medium to high (> 12 Cmol/kg). The COLE rod values were high to very high (0.4 - 0.8). Elemental dominance for profiles SP1, SP2, SP3 and SP4 was: SiO₂ > Al₂O₃ > Fe₂O₃ > CaO > MgO, whereas SP5 had SiO₂ > Al₂O₃ > CaO > Fe₂O₃ > MgO. The soils were young and immature with ICV > 1 with incipient to moderate weathering (50 – 80 %) except four horizons;

SP1 (A and Ak), SP2 (Bt) and SP3 (Bsstb) which showed intense weathering (> 80%). The soils had mixed mineralogy consisting of smectite, nontronite, montmorillonite, vermiculite, illite, mica, sepiolite, palygorskite, chlorite, chrysotite and kaolinite. Local environmental factors including parent material and topography exerted the most influence on the pedoclimate which led to the pedogenesis of these soils via humification, clay-humic complexation, profile homogenization by vertic pedoturbation, calcification, hydrolysis, and salinization. In line with WRB system, SP1, SP2 and SP4 were Grumic, gleyic Vertisols (Calcric, mesotrophic) whereas SP3 and SP5 are Vertic, gleyic Acrisols (Abruptic) and Vertic, gleyic Alisols respectively. The *Soil Taxonomy* correlation were Glayey, smectitic, hyperthermic haplusterts for SP1, SP2 and SP4, and were fine-silty, mixed, hyperthermic haplargirds for SP3 and SP5. Application of the recommended practices would go a long way in ensuring sustainable management of the soil resources given its huge agronomic potentials.

Keywords: Land use; Vertisols; *Soil Taxonomy*; Clay mineralogy; Semi-arid climate

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CHAPTER ONE

INTRODUCTION

1.1. Background information

Soil is a natural resource of great importance to humankind. Consisting of air, water, mineral and organic matter, soils provide ecosystem services that make life on earth possible. Functions of the soil include provision of food, fibre and fuel, water purification and soil contaminant amelioration, flood regulation, nutrient cycling, source of pharmaceuticals and genetic resources, climate regulation, carbon sequestration, cultural heritage, provision of construction materials, foundation for human infrastructure and habitat for organisms (FAO, 2015). The immense and diverse roles played by soils in our society have continued to make it a key focal point for developmental policies, especially in developing economies.

In a well-thought out plan to increase global soil awareness, the Food and Agriculture Organization of the United Nations declared 2015 to 2025 as the international decade of soils. Being a non-renewable resource (meaning that soil loss and degradation is not recoverable within human lifespan), well detailed characterization of the soil resources is very important if we must achieve the Millennium Development Goals (MDG) of eradicating extreme poverty and hunger (MDG1) and ensuring environmental sustainability (MDG7) (FAO, 2000). Gaining improved understanding of the properties (physical, chemical, mechanical, biological and mineralogical), due to mineral weathering and the pedogenesis of soils is pivotal in formulating best management practices.

The expansive ‘black cotton’, also referred to as shrink-swell, soils, swell when wet and shrink when dry. The semi-arid climate in Botswana aggravates swelling and shrinking problems in some areas including Serowe. Sometimes the presence of expansive soils is overlooked and their potential expansiveness underestimated (Yitagesu et al., 2009).

1.2. Statement of Problem

Expansive soils, due to their nature and properties, have severe management problems in agriculture (Nachtergaele et al., 2001; Syers et al., 2001) especially water management and conservation. Their shrinking and swelling activities may also pose environmental hazards. The loss of fertilizers, pesticides, and other toxic organic and inorganic compounds through overland conveyance and/or transmission along cracks and other macropores may lead to contamination of surface water and groundwater and negatively impact the quality of the soil, water, and air (Van Dijk et al., 2013). Moreover, the expansive soils cause damage to buildings, roads, pipelines, and other structures each year. The occurrence of the expansive soils, presents a significant geotechnical and structural engineering challenges the world over, with costs associated with expansive behaviour estimated to run into several billions annually (Jones and Jefferson, 1998). In Botswana, evidence of such destructions are prominent at the Serowe Integrated Sports Service Stadium and some surrounding residential houses. The stadium was built on expansive black cotton soil of thickness varying from 8-12 meters and covering an area of approximately 4 km² (BOPA, 2007). The multi- million Pula stadium revealed glaring cracks shortly after its completion in 2001 due to inherent soil properties. The persistent cracking of the facility led to its abandonment in 2007 (Botlhale, 2010). This, in turn called for refurbishments of the stadium which is quite a lot of work and consequently capital intensive as well.

1.3. Justification of the study

Despite the enormous importance of soils, not much has been done with regards to pedological investigation of the Vertisols soils from Serowe. Only preliminary studies of engineers and farmers exist as per their requirements and such reports are not published. These soils contribute to costly damages (cracks in structures or buildings) that could occur within a few months after construction (Jones and Jefferson, 1998). Moreover, despite being considered the most prolific because of their high natural fertility and agricultural benefit (Moustakas, 2012), expansive soils

do, nevertheless, present complications in their management as they are hard and cloddy when dry, and very sticky when wet (Jutzi, 1988). Therefore, to get the best out of them, they have to be well studied at a site scale.

1.4. Aim and objectives of the study

The overarching aim of this research is to advance our understanding on the pedology of the soils from Serowe.

The specific objectives are:

- i. characterize soils using their macromorphological, physical, chemical, mechanical and mineralogical properties;
- ii. evaluate mineral weathering intensities of the soils;
- iii. identify the pedogenic processes responsible for their formation;
- iv. provide an updated high resolution classification of the soils in accordance to FAO-UNESCO, WRB systems and USDA *Soil Taxonomy*.

CHAPTER 2

LITERATURE REVIEW

2.1. Molecular weathering indices and quantitative pedogenic ratios

Weathering refers to physical disintegration and chemical decomposition that converts primary minerals into a more stable form (Yousefifard et al., 2012). This is one of the major factors that leads to soil formation, conveys balance between the release of elements from weathering and loss of elements due to leaching as moderated by new elements forming from the products of weathering (Bockheim et al., 2005). This approach has led to the use of various geochemical indices in the aim to calculate the gains and losses of the weathering products. From the four broad soil forming processes of Simonsons (1995), transformation is the only one that leads to the formation of clay minerals through chemical weathering (oxidation, hydration, hydrolysis and carbonation) of parent materials and transformation of fresh organic matter into decay resistant organic compounds (humus).

Molecular indices sometimes called chemical weathering indices are commonly used for characterizing weathering profiles (Price et al., 2003; Ohta et al., 2007; Taboada et al., 2016) and determining their weathering intensity (Ohta et al., 2007; Eze and Meadows 2014a; Eze et al., 2016). To achieve this, it is essential to incorporate the appropriate chemical weathering such as Chemical Index of Alteration (CIA), Chemical Index Weathering (CIW), Weathering Index of Parker (WIP) and others.

2.1.1. Chemical Index of Alteration (CIA) = $100 \times [Al_2O_3 / (Al_2O_3 + CaO + Na_2O + K_2O)]$

CIA was proposed by Nesbitt and Young (Price et al., 2003) who denoted it as:

$$(CIA) = 100 \times [Al_2O_3 / (Al_2O_3 + CaO + Na_2O + K_2O)] \quad (\text{Equation 2.1})$$

It is interpreted as the measure of the extent of conversion of feldspar (which dominates the upper crust) to clays and has been used in numerous soil and paleosol studies (e.g. Duzgoren-Aydin et al., 2002; Eze and Meadows, 2014b). Index values for CIA increase with progressive weathering but Ca, Na and K must decrease as the intensity of weathering increases. High CIA values reflect the removal of mobile cations whereas low CIA values reflect near absence of chemical weathering (Rieu et al., 2007). The index does not account for mineralogical dissolution of unweathered parent rock with mixed mineralogy and (Babechuk et al., 2014) also outlined that this index is incapable of adequately quantifying the stages of advanced chemical weathering. However, it is most widely used accompanied by the A-CNK ternary diagrams to allow for the graphical interpretation of the proportional chemical alterations which is hence more effective in discerning the degree of chemical weathering (Marra et al., 2017).

2.1.2. Chemical Index of Weathering (CIW)

Harnois (1988) proposed a new chemical index of weathering that can be applied to modern soils and Precambrian paleosol. Although expressed as a ratio between immobile oxide and a group of mobile oxides, its mobile component is limited to CaO and Na₂O (Duzgoren-Aydin et al., 2002). Price and Velbel (2003) have reasoned that this index is similar to CIA except that it eliminates K₂O from the equation which means any aluminum associated with K-feldspar is not accounted for thus it may yield very high values for K-feldspar rich rocks whether they are chemically weathered or not (Price and Velbel, 2003). Harnois (1988) also outlined that K₂O is not incorporated because during weathering it may be leached or may accumulate in the residue. This index is not a good indicator for the degree of weathering in granitic rocks (DuzgorenAydin et al., 2002).

$$(CIW) = [Al_2O_3 / (Al_2O_3 + CaO + Na_2O)] \times 100 \quad (\text{Equation 2.2})$$

2.1.3. Weathering Index of Parker (WIP)

This index was developed by Parker in 1970 and is also known as Parker's index (Harnois, 1988; Price and Velbel, 2003; Ohta and Arai, 2007; Babechuk et al., 2014; Sun et al., 2018) and is denoted by the equation:

$$(WIP) = [(Na/0.35 + Mg/0.9) + (K/0.25 + Ca/0.7)] \times 100 \quad (\text{Equation 2.3})$$

It is based on the proportions of the highly mobile alkali and alkaline earth elements (Na, K, Mg and Ca), taking into account their individual mobility based on their bond strengths with oxygen. WIP is superior in the regard that it is designed to reflect on the collective decomposition of multiple mineral phases as compared to CIA. However, its application to highly weathered materials is uncertain. WIP is the most appropriate application to weathering profile on heterogeneous (and homogeneous) parent rocks (Price and Velbel, 2003).

2.2. Pedogenic models

Pedology, the scientific study of soil formation (pedogenesis), morphology and classification, is a key area of research in soil science discipline (Hartemink and Bockheim, 2013). The nature and properties of soils vary in space and time due to the differences in the processes and factors that trigger their formation. There are many existing views of soil formation among soil scientists (Johnson and Watson-Stegner, 1987) and these varied views of soils are, in effect different theoretical bases for their study. Various models of soil formation have been developed by pedologists, which include and not limited to; (i) Jenny's functional-factorial model, (ii) Simonson's processes system model and (iii) Runge's energy model. These models have played an important role in soil classification and mapping with functional-factorial models of

Dokuchaev (1883) and Jenny (1941) being among the first developed to explain soil formation (Brevik et al., 2016).

2.2.1. Jenny's functional-factor model

The many specific influences on soil formation can be reduced to five: climate, organisms, topographic relief, parent material and time, easily remembered by the acronym "CLORPT" (Jenny, 1941; Buol et al., 1997). Each of these models of pedogenesis provide invaluable information for the characterization and interpretation of soil properties: energy process model provides understanding of the relationships between variables in soil formation; materials flux models give insight about the rates of development of soil features; and factor models provide clues about the role of selected environmental influences on soil formation (Retallack, 2001).

As already stated above soils form as a result of the distinctive interaction (Soil Survey Staff, 1975) of the soil-forming factors "CLORPT": climate (cl), biotic factors or organism (o) relief or topography (r), lithology or parent material (p), time (t), and others (Hartemink and Bockheim, 2013; Singh, 2015) as in equation 2.3 below. These soil-forming factors led to the formalization and development of the function of soil formation by Jenny (1941) and has now become a popular concept in pedology (Bockheim et al., 2005):

$$S = f(cl, o, r, p, t \dots) \quad (\text{Equation 2.4})$$

where; s = soil, cl = climate, o = organism, r = relief, p = parent material and t = time.

2.2.2. Simonson's process-systems model

Soil formation is a complicated natural process of soil origination from rocks under the influence of soil-forming factors in the natural or anthropogenic ecosystem. According to Simonson's

model, processes leading to soil formation can be broadly grouped into four namely: addition or gain of water, mineral and organic matter in the soil, loss or removal of the above materials from the soil, transformation of mineral and organic materials within the soil and transfer of energy and matter (mineral and organic). These processes operate mainly under the influence of the soil forming factors and promote horizon differentiation (Singh, 2015) (as demonstrated in Fig. 1.1). During soil formation, the soil profile slowly deepens and develops characteristic layers called horizons. These layers (vertical-section of the soil) reflect the combined effects of the particular set of genetic factors responsible for the soil development (Soil Survey Staff, 1975). To characterize these horizons, the master horizons (O, A, E, B, C, R) and sub-horizons (e.g., p, t, g, h, w, o...) designation take an important lead. In addition, physical and chemical properties of soils: soil colour, organic matter content (its accumulation, decomposition, humification), texture (amount of clay, silt and sand, as distinct from its mineralogy), structure, moisture content, clay mineralogy etc. are important to soil classification as well as are used in-suitability and interpretations of soil genesis.

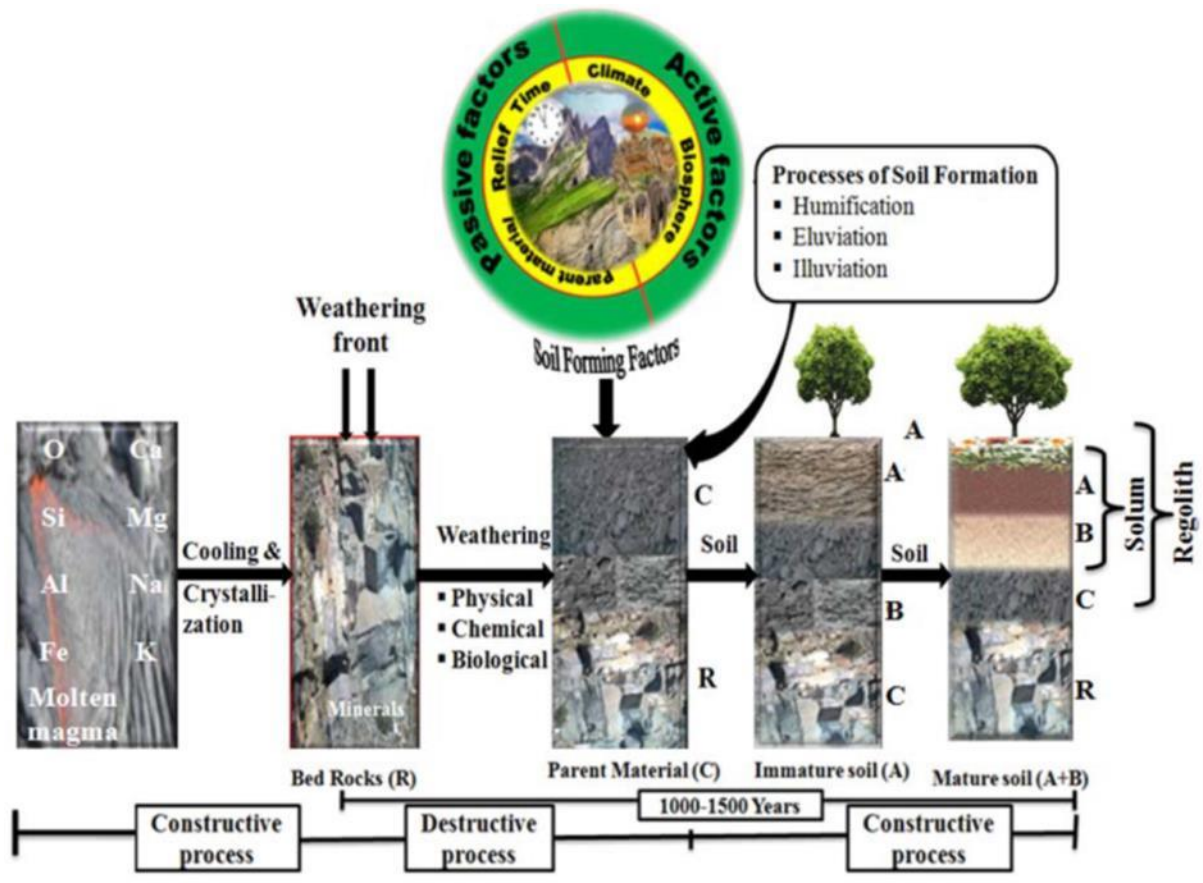


Figure 1.1: Summary of stages of soil formation from Singh (2015)

2.2.3. Runge's Energy Model

Runge's model was described as a hybrid between the models of Jenny and Simonson where external factors are responsible for internal soil processes and its focus is on the energy transfer through and losses from the soil system (Brevik et al., 2016). This energy process model viewed the soils as energy transformers, which means a body of material changed by the continuing efforts of natural processes. Heat from the Sun is the primary source of energy in soils and it far exceeds (by about 7500 times) heat flow from deep within the crust generated by the decay of radioactive elements (Retallack, 2001). The pattern of energy flow through soils can be as complex as the flow of material. The environmental factor model on the other hand views the soil as an environmental product shaped over time by climate, organisms and geomorphological processes from whatever initial material.

2.3. Factors of soil formation

2.3.1. Climate

Climatic factors are regarded as the “active” (Fig. 1) and most influential soil formation factors. The soil clay mineralogy, in time responds sensitively to the climatic factors primarily; rainfall and temperature that interact with the permeability of the parent material ((Hartemink and Bockheim, 2013). This interaction benefits the decomposition of minerals in the parent material. Temperature influences the chemical reactions involved in soil formation. Van’t Hoff’s law states that “with every 10 °C rise in temperature, the speed of chemical reaction increases by a factor of two or three (Simonson, 1995). This process applies to weathering of minerals which release soluble components and thus help in soil genesis.

2.3.2. Organism

Vegetation constitutes the soil organic matter which is the most important indicator of soil health. The decomposition of organic matter produces soluble organic acids which help in breakdown of the minerals present in parent rock, resulting in the release of essential plant nutrients (Singh, 2015). Moreover, microorganisms such as bacteria, fungi, actinomycetes, protozoa and nematodes also play a vital role in the decomposition of organic matter and indirectly it also contributes to the decomposition of mineral matters through production of organic acids. As such, these decompositions contribute to the movement and deposition of these soil constituents in the different layers contributing to the formation of the soil. Soil properties are influenced by organic matter content in the soil by improving water and nutrient holding capacity, colloidal properties of soil and reducing tendency of crust formation and soil erosion by wind and water (Singh, 2015). Literature also suggest that plant residues return large amounts of metallic cations and silica to soils which may contribute greatly to the formation of clay (McCauley 2009).

2.3.3. Relief (Topography)

Relief depicts local variation of the slope as the topography reflects the elevation of the ground surface on a large scale. This factor greatly affects soil clay mineralogy through concentrating water hence chemical weathering processes (hydrolysis, hydration, oxidation or reduction), leaching and seepage. Soil formation of steep slopes is very poor due to erosion and the low slopes are ideal for soil development (Singh, 2015). Soil organic matter and clay are suspended with water flowing uplands and deposited in the lowlands which therefore affect the soil formation. The impact of topography is clearly evident in lowland soils which are typically darker, with a higher content of pH, EC, clay and organic matter given that transported materials accumulate in lowlands.

2.3.4. Parent material

Parent material as loose unconsolidated mass of mineral matter formed upon the weathering of rocks which serves as the raw material of soil formation upon which other factors will serve to transform. It is the chief influencer on physical and chemical properties of the soil.

Parent material is categorized by deposition agent as: alluvium by water, marine by ocean, lacustrine by lake, dune/ loesses and aeolian by wind, colluviums by gravity action and till/ moraine by ice. In terms of distinguishing taxa in soil taxonomy, parent material is considered the second most important factor after the climatic factor (Bockheim et al., 2014)

2.3.5. Time

Soil formation is a natural process that takes thousands of years to develop a mature pedon. The period devoted by nature from the stage of parent material to the stage of formation of mature soil (horizons A, B, C) is known to be pedological time (Singh, 2015). As one of the soil forming factors, Jenny (1941) regards time, as well as parent material and relief/topography as passive

factors. There are variations in the rate of development among soils. The longer the soils take to develop when other factors are in place brings about the formation of more clay minerals.

2.4. Vertisols

Vertisols are clayey soils (≥ 30 percent clay content) (Boettinger et al., 2014) with slickensides, deep wide cracks and high bulk densities (Bockheim et al., 2014). Hartemink and Bockheim (2013), refer to them as the shrinking and swelling dark clay soils. This is mainly for the reason that they are very common in swelling clays that undergo marked changes in moisture content (Soil Survey Staff, 2014). Their slickensides result directly from the swelling of clay minerals and shear failure. Vertisols are viewed to be greatly skewed to the semi-arid tropics and subtropics with necessary constraints for their formation associated with clayey smectite-rich parent material (Kabala et al., 2015; Kovda et al., 2017) or neo-genesis or alteration of primary minerals after sedimentation (Pal et al., 2009) and alternations of the moisture regimes.

Shrink-swell phenomena in soils entail complex and dynamic processes in order to better explain Vertisols genesis and behaviour and its vertic intergrades. A broad variety of investigations into the creation of soils of vertical character and unusual properties emphasize pedoturbation or churning as the fundamental process (Pal et al., 2006; Moustakas, 2012). In some soils, even though micro morphological study, it is often difficult to find convincing evidence that the higher clay content within the B horizon results from obtaining silicate layer clays by illuviation (Soil Survey Staff, 1975). A variety of parent materials; igneous, metamorphic-sedimentary rocks as well as their deposits, are attached to the formation of Vertisols.

The semi-arid climate in Botswana has largely contributed to swelling and shrinking problems in some areas because smectite is generally thought to form during weathering in seasonally wet and dry climates (Kovács et al., 2013). Evidence of these destructions in Botswana, is justified by the Serowe Integrated Sports Service Stadium and some residential houses. The stadium was

built on the expansive black cotton soil of the thickness varying from 8-12 meters and some one-kilometer-wide and two kilometers in length (BOPA, 2007). It revealed glaring cracks immediately after its completion in 2001 due to peculiar soil properties, this led to its abandonment in 2007 (Botlhale, 2010). Sometimes the presence of expansive soils can be overlooked and their potential expansiveness can be underestimated (Yitagesu et al., 2009).

2.6. Soil Classification

Soil classification has been a fundamental area of research since the emergence of the soil science discipline dating as far as the 19th century (Hartemink and Bockheim, 2013) and further states that it is largely based on how the soils formed. There are several national classification systems, most of which group the soils according to their genesis with some taking into account the factors of soil formation (Bockheim et al., 2014). However, the concern on their usefulness leads to the development of the Soil Taxonomy in 1949. The United States Department of Agriculture Soil Taxonomy and Food and Agriculture Organization (FAO)/World Reference Base (WRB) are currently widely used in the international field of soil classification, soil analysis, scientific review and soil mapping on different scales (Brevik et al., 2016). It is difficult to extensively use only one system since some goals have not yet been adjusted.

2.6.1. USDA Soil Taxonomy

Soil Taxonomy, United States Department of Agriculture (USDA) classification system) is a detailed categorical system that has defined quantitative boundary values for each unit at each level (Bockheim et al., 2014). The publication of its original edition was in 1975 with the main objective as outlined by Soil Survey Staff, (1975) being the establishment of hierarchical classes to provide a full understanding of the relationship among soils and between soils and the soil forming factors responsible for their characteristics. Originally, soil survey was the mandate for

the development of this classification system but during the last few decades, it has advanced to serve the purposes of communication in pedology.

The USDA Soil Taxonomy system provides high resolution classification categorically as shown in Table 2.1. The soils are classified hierarchically from highest to lowest system in today's soil taxonomy: orders, suborders, great groups, subgroups, families and series (Soil Survey Staff, 2014) and the twelve Orders are namely: Spodosols, Entisols, Oxisols, Alfisols, Ultisols, Mollisols, Inceptisols, Gelisols, Vertisols, Aridisols, Andisols and Histosols.

Table 2.1: Soil Taxonomy categories reported in 2010 as adopted from (Bockheim et al., 2014).

Category	Diagnostic horizon
Order	12
Suborders	65
Great groups	344
Subgroups	~1800
Series	~23,000

This classification system's primary soil formation factor is climate, being the temperature and moisture regimes. These climatic conditions are used to distinguish two soil taxonomy orders: Aridisols (dry or arid to semi-arid soils) and Gelisols (very cold soils). The soil-temperature regimes are linked to geographic crop adaptation. To determine which agricultural crops or plants are best adapted to a particular place, the system uses the mean annual soil temperature (MAST) (like thermic, hyperthermic, mesic) as noted by (Bockheim et al., 2014).

During the different days of the year or seasonally, the moisture content of the soil may vary. The soil may be saturated, amount of water enough to cause leaching or no leaching possible, evapotranspiration may also occur hence leaving precipitated carbonates and more soluble salts (Soil Survey Staff, 1975). The various moisture regimes (examples: ustic, xeric, aridic, udic) are defined by the period that the soil is either moist or dry in the moisture control section whereas the aquic moisture regime is periodically saturated (Boettinger et al., 2014).

Parent material as the second most important factor in *Soil Taxonomy*, is used to determine to determine three soil orders: Histosols (organic matter origin), Andisols (from pumice, glass and short-range minerals) and partly for some Entisol suborders derived from fluvial deposits or sandy materials (Bockheim et al., 2014). Vertisols are reported to require materials with 30 percent or more shrink-swell clay hence the parent material is an important identifier for such. This will play a vital role in the classification of the soils of the study area as they have been observed to have the shrink-swell behaviour. Finally, other factors such as relief is significant in pedogenesis, organisms (worms and humans) are also recognized for their activity in soil formation. Time also important in pedogenesis but is not recognized directly in this classification system.

2.6.2. FAO/WRB Systems

WRB aimed at reaching an international agreement on the global recognition of major soil groupings and standards for their classification and identification. Instead of the six levels recognized for soil taxonomy which emerged in different concepts of major soil divisions, the WRB varies from only 2 hierarchical levels. It uses number of first-level Reference Soil Groups (32RGSs) maintain a more conventional Russian approach to soil classification, reflecting the impact of parent material and climate influences on soil-forming processes (Brevik et al., 2016). Instead of the six levels recognized for soil taxonomy which emerged in different concepts of major soil divisions, the WRB varies from only 2 hierarchical levels. At second point, when the

RSGs come with a set of quantitatively specified quality qualifications, the soils are distinguished by their secondary characteristics.

CHAPTER THREE

MATERIALS AND METHODS

3.1. Geographical and Environmental Setting of the study location

The study area, Serowe, is in the Central District of Botswana. It is situated on the eastern Hardveld of Botswana, about 300 km northeast of the capital city Gaborone (Fig. 3.1).

Geographically, Serowe is located within 26° 07'37'' and 26° 54'10'' East and 22° 14'10'' and 22° 30'33'' South, covering an area of 244048 ha (Mweso, 2003). The geology of the study area is composed of basalts of the stormberg series (on the south) and post Karoo dolerites (on the north side), karoo sandstones and basalt are also found on the western portion of the study area (Denbow, 1979) as shown in Fig. 3.2.

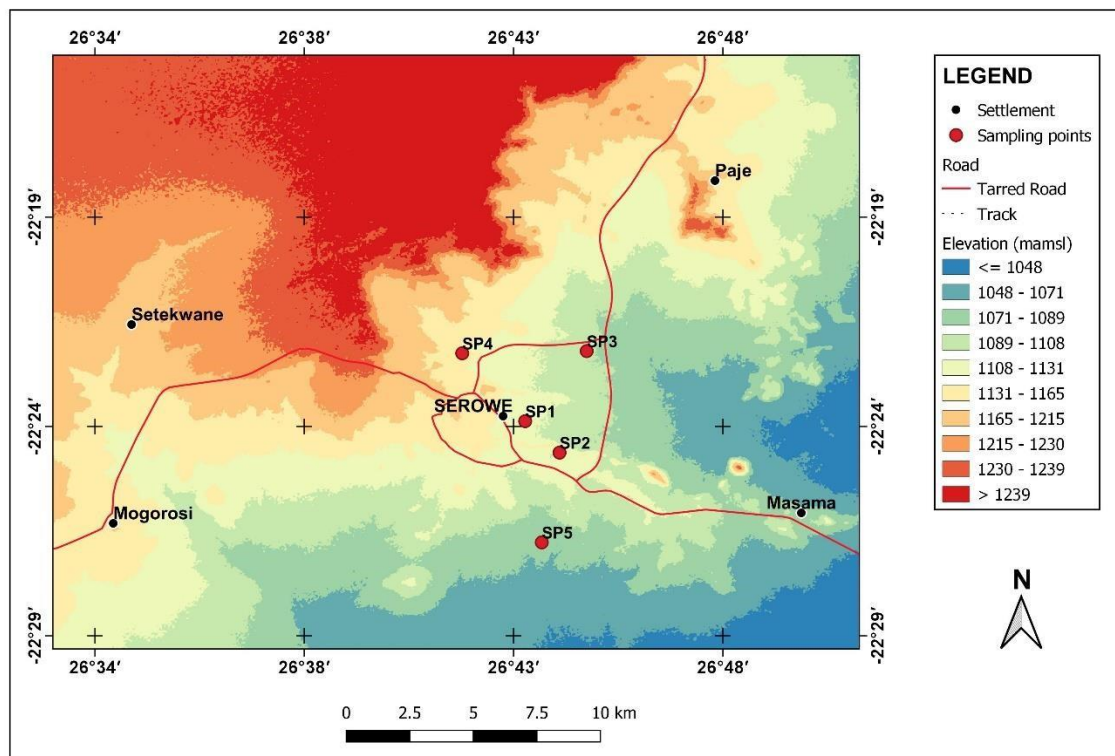


Figure 3.1: Map of Botswana showing location of the study area.

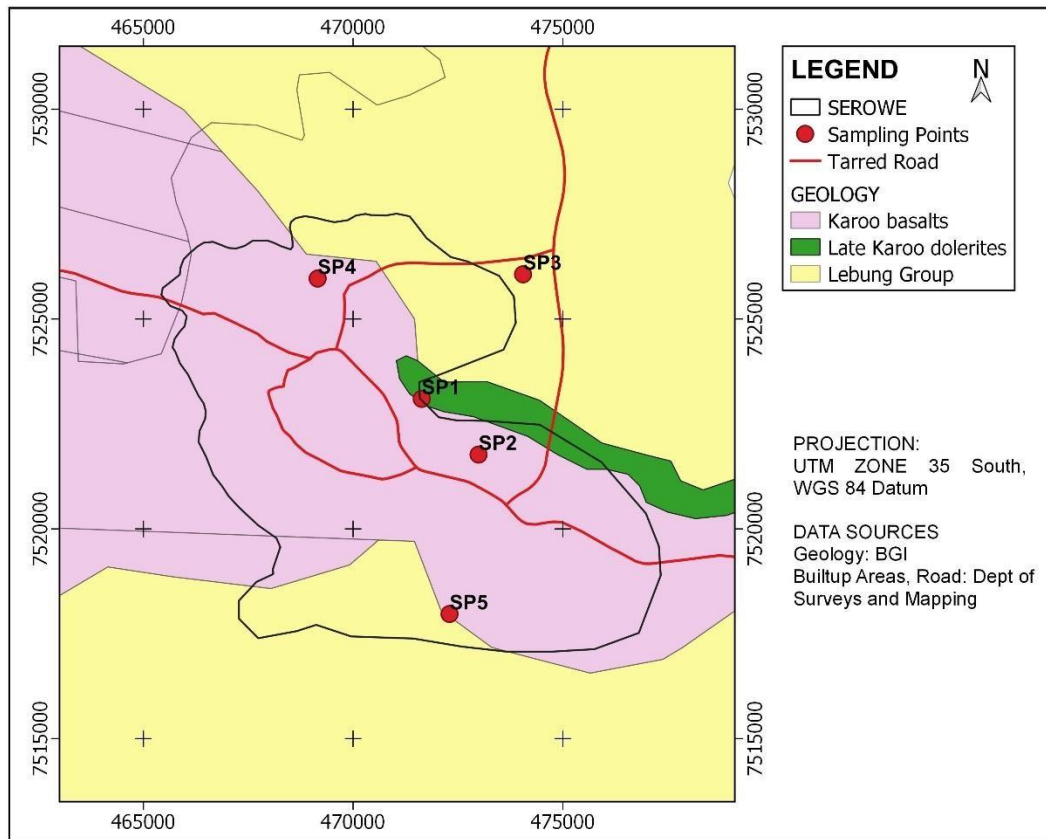


Figure 3.2: Geology of the study area.

The climate of Serowe is characterized as semi-arid (cold dry winters with moist warm summers) with mean annual rainfall of 477 mm. The summer season begins from October to April whereas the winter season stretches from May to August. In general, the mean maximum temperature ranges between 22°C and 31°C while the mean minimum temperature lies between 5°C and 19°C (March, 2002). The month of November, December and January experience higher temperatures, and the lowest temperatures are observed in June, July and August.

Serowe is characterized by a gentle slope ranges from 1000 to 1250 meters above sea level (Fig. 3.1.) (March, 2002; Mweso, 2003) with lower elevation in the east and south east while the highest elevation is found in the vicinity of the escarpment edge (with an average slope of 5% and it gradually reduces to 1% in the east and southeast) (March, 2002). Some rock outcrops

exist at the escarpment and along river valleys below the escarpment otherwise in other areas the rocks are covered by Kalahari sands and superficial deposits.

Three main physiographic units have been distinguished in the study area namely: sand-veld, escarpment and hard-veld. The sand-veld is composed of dense tree, shrubs and grasses. Denser and taller vegetation is generally along the strip of the escarpment contrary to the shallowness of the soils in the study area (Mweso, 2003). There is an occurrence of dense stand of *Cenchrus ciliaris* (Buffalo grass), surrounded by denser woodland dominated by *colophospermum mophane* and *Terminalia* on sandveld whilst *Zizipus mucronata* and *Acacia* species on the hardveld (Denbow, 1979; Mweso, 2003). A low resolution soil map (1:1000000) shows Serowe has different soil types, which are spatially variable thus influencing the soil moisture distribution. According to (Mweso, 2003), the main soil types are Ferralic Arenosols (mainly on plateau), Calcic Luvisols, Pellic Vertisols, Eutric Nitosols (mainly in peneplain) and Endoleptic Regosols on hillslopes.

3.2. Site selection, soil sampling and field description

This study involved an extensive fieldwork to identify areas in Serowe with abundance of shrink swell soils. After a thorough reconnaissance survey, five sampling points were selected (see Fig 3.1). Profile pits measuring 2 m by 1 m were dug. The soil profiles were described following the Guidelines for Soil Profile Description (FAO, 2006). Both disturbed and undisturbed soil samples were collected from all the genetic horizons of the profile pits, bagged and shipped to the laboratory for further analysis. The soil samples were air dried and passed through 2mm sieve prior to laboratory analysis.

3.3. Laboratory Analysis

Particle size distribution was determined using a modified Bouyoucos Hydrometer method of Bouyoucos (1962). Soil pH (H₂O and (KCl) and electrical conductivity (EC) were done in the ratio 1:2.5 and 1:5 (soil to water) respectively using the pH and EC probe meter. EC was measured in dS/m. Bulk density was measured in g/cm³ using the core sampler method and particle density and porosity (%) were also obtained as follows:

$$\text{Bulk density} = \frac{\text{weight of soil sample}}{\text{bulk volume of soil}} \quad (\text{Equation 3.1})$$

$$\text{Particle density} = \frac{\text{weight of soil sample}}{\text{volume of soil}} \quad (\text{Equation 3.2})$$

$$\text{Soil porosity} = \left[1 - \left(\frac{bd}{pd} \right) \right] \times 100 \quad (\text{Equation 3.3})$$

Loss on Ignition (LOI) (at 550° and 950° in a furnace) method Ball (1964), was used to measure the organic matter content of the soil and calcium carbonate content through calculations by calculation using the formula provided below. Cation exchange capacity (CEC) measured in cmol+/kg, was also determined using the Inductively coupled plasma-optical emission spectrometry (ICPOES) after being digested with Ammonium acetate (1N NH₄AOc) at pH7 Schollenberger and Simon (1945).

$$L.O.I(\%) = \left[\left(\frac{W_s - W_a}{W_s - W_c} \right) \right] \times 100 \quad (\text{Equation 3.4})$$

$$CaCO_3 = \left(\frac{W_{CO_3} - W_a}{W_s - W_c} \right) \quad (\text{Equation 3.5})$$

where; W_s: mass of crucible + sample; W_a: mass of crucible + sample after 550°C; W_c: mass of crucible; W_{CO₃}: mass of CO₃.

The clay mineralogy was analyzed by X-ray Diffractometer (XRD) using a Bruker D4 Endeavor AXS instrument operating with a cobalt radiation source. The data collection range was from 5° to 70°, with increment of 0.2° and data collection time of 23 min per sample. The obtained XRD patterns were processed using the Bruker Origin software package for clay mineral identification. Orientated clay samples were placed on glass slides and subjected to treatments including heating at 550° C in a furnace for 40 minutes, ethylene glycol solvation and oven dried at 60 °C. The soil samples were analyzed for major oxides, trace and rare earth elements using X-ray Fluorescence (XRF) Spectrometer at SGS Geochemistry laboratory, Pretoria, South Africa. Major elements mass balance plots, index of compositional variability (ICV), molecular weathering indices and pedogenic ratios were used to characterize the weathering intensity and the pedogenesis of the soils by incorporating the formula as shown below:

Mass balance calculation as proposed by Brimhall and Dietrich (1987); Chadwick et al., (1990);

$$\tau_{i,j} = \left(\frac{C_{i,p}}{C_{i,w}} \right) \left(\frac{C_{j,w}}{C_{j,p}} \right) - 1 \quad \text{(Equation 3.6)}$$

Where: $C_{i,w}$: concentration of immobile element (i) in weathered material; $C_{i,p}$: concentration of immobile element (i) in parent material; $C_{j,w}$: concentration of element of interest (j) in weathered material; $C_{j,p}$: concentration of element of interest (j) in parent material.

Index of compositional variability (ICV),

$$ICV = \frac{(Fe_2O_3 + K_2O + Na_2O + CaO + MgO + MnO + TiO_2)}{Al_2O_3} \quad \text{(Equation 3.7)}$$

Table 3.2: Weathering indices (in molecular proportions) adopted from (Taboada et al., 2016)

Index	Formula	Optimum	Optimum	Reference
		fresh value	weathered value	
WIP	$[(\text{Na}/0.35 + \text{Mg}/0.9) + (\text{K}/0.25 + \text{Ca}/0.7)] \times 100$	>100	0	Parker (1970)
CIW	$[\text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O})] \times 100$	≥ 50	100	Harnois (1988)
CIA	$100 \times [\text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})]$	≥ 50	100	Nesbitt and Young (1984)
PIA	$100 \times [(\text{Al}_2\text{O}_3 - \text{K}_2\text{O}) / (\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})]$	≥ 50	100	Fedo et al., (1995)

Atterberg limits and Coefficient of Linear Extensibility (COLE) (done in triplicates) measurements were done using Casagrande mechanical device and COLE rod method of Schafer and Singer (1976) respectively. COLERod calculations were done according to equation 3.8 below.

$$\text{COLERod} = (lm - ld) / ld \quad (\text{Equation 3.8})$$

COLERod = coefficient of linear extensibility using rod lengths, lm = moist rod length, ld = dry rod length.

Quantitative assessments of weathering and pedogenesis were done using molecular geochemical and pedogenesis ratios as detailed in Table 3.2 and 3.3 respectively.

Table 3.3: Pedogenic ratios used to assess pedogenic processes of the expansive soils (Sheldon & Tabor, 2009).

Ratio	Pedogenic process (Formula)	Rationale value	Normal effect	Strong
$\sum \text{Bases/Al}$	Hydrolysis ($\text{CaO} + \text{MgO} + \text{K}_2\text{O} + \text{Na}_2\text{O}/\text{Al}_2\text{O}_3$)	Common rock-forming alkaline and alkaline earth elements are lost compared to Al during pedogenesis	< 2	> 10
Salinization	Salinization ($\text{K}_2\text{O} + \text{Na}_2\text{O}/\text{Al}_2\text{O}_3$)	Soluble salts (alkali elements) not removed from the soil horizon (Nesbitt and Young, 1984)	< 1	> 1
Clayeyness	Hydrolysis ($\text{Al}_2\text{O}_3/\text{SiO}_2$)	Al accumulates as clay, hence higher clayeyness values means highly weathered or clayey the soil is.	< 0.1	> 0.3
Provenance	Acidification (pH) ($\text{TiO}_2/\text{Al}_2\text{O}_3$)	Ti is most readily lost by physical weathering, whereas Al is lost by chemical weathering (Sheldon, 2006)	-	-
Calcification	Salinization ($\text{CaO} + \text{MgO}/\text{Al}_2\text{O}_3$)	Alkaline earth elements are easily lost compared to Al during pedogenesis (Retallack, 2007)	< 2	> 10
Trace element leaching	Leaching/hydrolysis (Ba/Sr)	Ba is less soluble than Sr (Retallack, 2001; Sheldon and Tabor, 200)	-	> 10

CHAPTER FOUR

RESULTS

4.1. Macromorphology

This research consisted of five profile pits: SP1, SP2, SP3, SP4 and SP5, which were dug, sampled and studied for various soil properties in the field and further in the laboratory. SP1, SP2, SP4 and SP5 had six horizons each whereas SP3 had 8 horizons (Fig. 4.1). Based on the FAO (2006), soil profile description guidelines horizon designation for the profiles keyed out as: SP1 (A, Bk1, Bk2, Bk3, Bss1, Bss2), SP2 (Ap, Bss1, Bss2, Bss3, Bkss, Bt), SP3 (Ap, Bss, 2Ab, Bb, Bssb, Bsstb1, Bsstb2, Bsstb3), SP4 (A, Bkss1, Bkss2, Bk, Bksst1, Bksst2) and SP5 (Ap, Bt1, Bt2, Bk, Bkkm1, Bkkm2) as shown in Table 4.1.

The depth of these pedons ranged from 170⁺ cm to 190 cm. variations in colour (moist) was observed for all the profiles; SP1 was dominated by a hue of Gley 2 with dark bluish and greenish gray colour while SP2 had predominantly a reddish colour. SP3 was dark brown and yellowish brown with a hue of 7.5YR and 10YR and the deepest horizon (173-185⁺ cm) had a moist colour being black. The dominating hue for profile SP4 was 7.5YR with soil colours being very dark gray and brown. The black to light gray colour with a hue of 2.5Y were observed in SP5. For these profiles, the upper most horizons for SP1, SP2 and SP5 were characterized by strong sub-angular blocky structure whereas it is weak and medium subangular blocky structure for SP4 and SP3 respectively (Table 4.1).

For SP1, all the horizons except topsoil had a very strong wedge structure. For SP2 and SP4, their subsoils (13 – 149 cm) and (25 – 121 cm) respectively were predominantly wedge in structure. SP3 and SP5 had a sub angular blocky structure throughout the whole profile.

Different strengths of the structure were observed as follows: SP3 was weak at 58 – 92 cm and 4 – 143 cm, medium at 0 – 20 cm, 92 – 124 cm and 143 – 160 cm, strong at 20 – 58 cm, 160 – 173 cm and 173 – 185 cm which was the deeper most horizons while SP5 had a strong structure at 0 – 153 cm and very strong at 153 – 185 cm⁺.

Roots were observed at depth of 0 – 40 cm and 94 – 170⁺ cm in SP1 0 – 46 cm in SP2 0 – 143 cm in SP3, 0 – 75 cm and 121 – 164 cm in SP4 whereas all horizons in SP5 had roots. The most common boundary was gradual smooth for SP1, SP3 and SP4, clear smooth for SP2 gradual smooth and abrupt smooth for SP5. Moist soil consistency was very firm throughout the whole profile in SP4 and also in SP1 (0 – 136 cm), SP2 (0 – 127 cm), SP3 (0 – 58 cm) and SP5 (7 – 96 cm), whereas a firm moist soil consistency was observed at 136 – 170⁺ cm, 127 – 190 cm, 124 – 185⁺ cm and both 0 – 7 and 96 – 185⁺ cm in SP1, SP2, SP3, SP4 and SP5 respectively. A loose moist soil consistency was observed in only one profile pit SP3 at 58 – 124 cm.

The most dominant field texture in all profile pits was clay. It was observed at 0 – 136 cm in SP1, 0 – 127 cm in SP2, 0 – 58 cm and 124 – 185 cm⁺, all horizons in SP4 and 0 – 96 in SP5. Silty clay was observed in the remaining horizons of SP1, SP2 and SP3 while as well as sandy clay was observed in SP5. Gravel was only observed in SP3 at 58 cm – 92 cm and in SP5 at 96 cm – 185⁺ cm depth. It was absent in SP1, SP2 and SP4. No reaction with HCl was observed in the uppermost horizon for all profile pits as well as in SP2 at 81 cm – 127 cm and 149 – 190⁺ cm whereas all other horizons reacted with HCl.

Slickensides and vertic properties were observed at 20 – 65 cm and 94 – 170⁺ cm respectively in SP1. In SP3 slickenside, charcoal and vertic properties were observed at 20 – 58 cm, 124 – 160 cm, 170 – 185⁺ cm, 160 – 173 and 92 – 124 cm respectively. Vertic properties and

slickenside were the most common factors in all profile but were more pronounced in SP2 (13 – 127 cm), SP4 (25 – 75 cm and 121 – 186⁺ cm) and SP5 (7 – 32 cm). Carbonates dominated SP2 (127 – 149 cm) while their combination with cementation dominated SP5 at (96 – 153 cm and 168 – 185⁺ cm). Slickensides were the most common features in all the profiles.

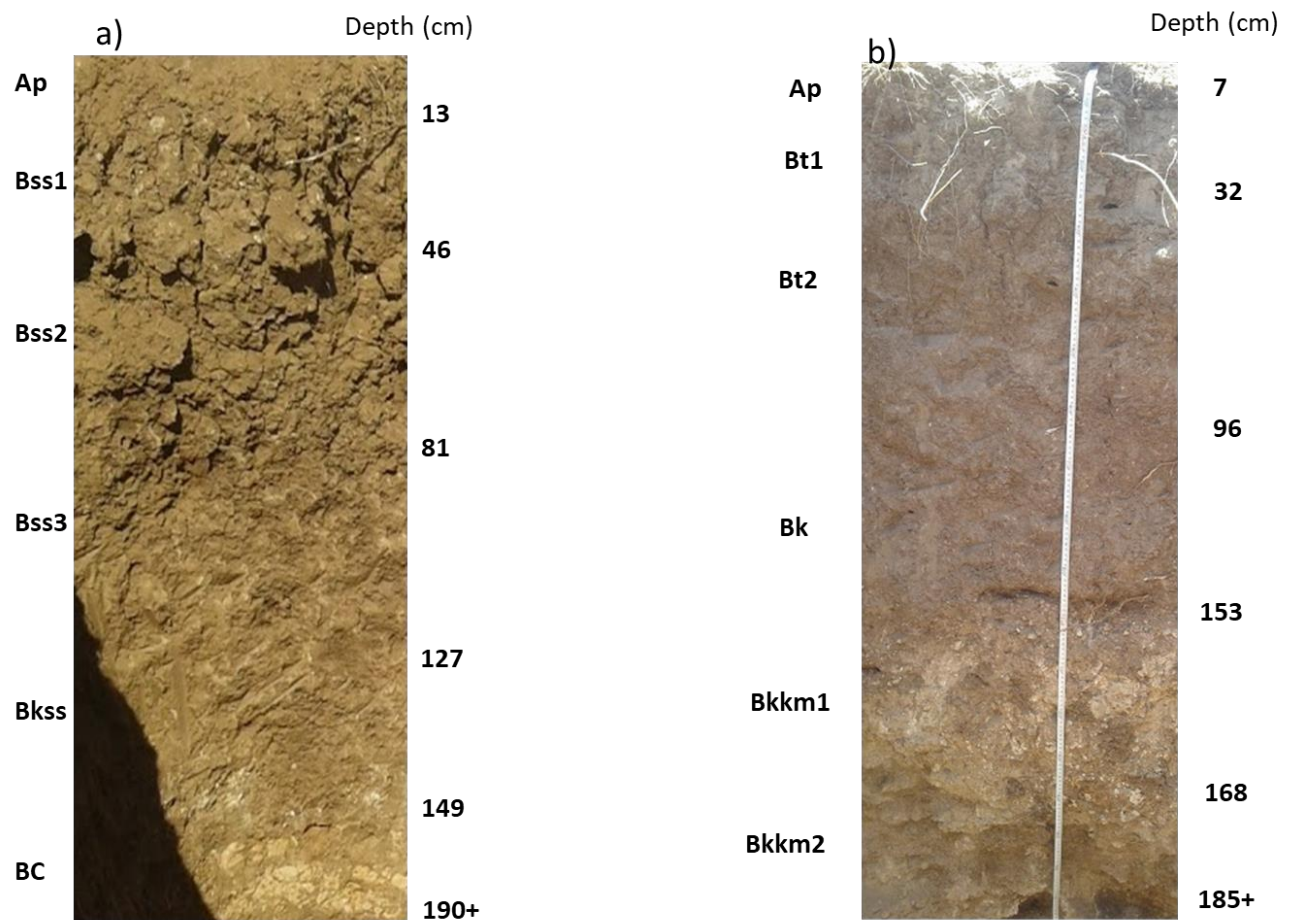


Figure 4.1: Representative profiles SP2 (a) and SP5 (b)

Table 4.1: Macromorphological characteristics of the expansive soils

Horizon	Depth (cm)	Colour (Dry)	Colour (Moist)	Structure ¹	Root	Boundary ²	Consistency (moist)	Field texture	Gravel (>2mm)	React HCl	Other features
SP 1											
A	0-20	Gley2 5/10G Greenish gray	Gley2 4/10B D.bluish gray	3sbk	frequent	cs	very firm	clay	absent	no	—
Bk1	20-40	Gley2 3/5PB V.D.bluish gray	Gley2 2.5/5PB Bluish black	4wedge	common	gs	very firm	clay	absent	yes	slk
Bk2	40-65	Gley2 5/10B Bluish gray	Gley2 3/10B V.D. bluish gray	4wedge	absent	gw	very firm	clay	absent	yes	slk
Bk3	65-94	Gley2 4/5BG D.bluish gray	Gley2 4/10BG D.greenish gray	4wedge	absent	gw	very firm	clay	absent	yes	—
Bss1	94-136	Gley2 5/10Y Greenish gray	Gley2 5/10Y Greenish gray	4wedge	few	gs	very firm	clay	absent	yes	vertic, slk
Bss2	136-170+	Gley2 7/10Y L.Greenish gray	Gley2 5/5GY Greenish gray	4wedge	few	gs	firm	silty clay	absent	yes	vertic, slk

¹ B – brownish; D – dark; G – grayish; L – light; R – reddish; V – very² 1 – weak; 2 – medium; 3 – strong; 4 – very strong; abk – angular blocky; sbk – sub-angular blocky³ a – abrupt; c – clear; i – irregular; g – gradual; s – smooth; w – wavy⁴ slk – slickenside; cem – cementation

NB: Slope <4 % for all the profiles

Horizon	Depth	Colour		Structure ¹	Root	Boundary ²	Consistency	Field	Gravel	React	Other
	(cm)	(Dry)	(Moist)				(moist)	texture	(>2mm)	HCl	features
SP 2											
Ap	0-13	2.5YR 4/4 R. brown	2.5YR 3/4 D. R brown	3sbk	frequent	cs	very firm	clay	absent	no	—
Bss1	13-46	10R 5/2 Weak red	5YR 4/3 R. brown	4wedge	common	gs	very firm	clay	absent	yes	vertic, slk
Bss2	46-81	2.5YR 5/4 R. brown	2.5YR 4/4 R. brown	4 wedge	none	gs	very firm	clay	absent	yes	vertic, slk
Bss3	81-127	5YR 4/4 R. brown	2.5R 4/4 R. brown	4 wedge	none	cs	very firm	clay	absent	yes	vertic, slk
Bkss	127-149	5YR 6/4 L.R. brown	5YR 5/4 R. brown	3 wedge	none	cw	firm	silty clay	absent	yes	carbonates
Bt	149-190+	5YR 7/6 R. yellow	5YR 5/6 Y. Red	2sbk	none	cs	firm	silty clay	absent	no	—

¹B – brownish; D – dark; G – grayish; L –light; R – reddish; V – very

²1 – weak; 2 – medium; 3 – strong; 4 – very strong; abk – angular blocky; sbk – sub-angular blocky

³a – abrupt; c – clear; i – irregular; g – gradual; s – smooth; w – wavy

⁴slk – slickenside; cem – cementation

NB: Slope <4 % for all the profiles

Horizon	Depth (cm)	Colour (Dry) (Moist)		Structure ¹	Root	Boundary ²	Consistency (moist)	Field texture	Gravel (>2mm)	React HCl	Other features
SP 3											
Ap	0-20	7.5YR 3/2 D. brown	7.5YR 2.5/2 V.D. brown	2sbk	frequent	cs	very firm	clay	absent	no	—
Bss	20-58	7.5YR 4/1 D. gray	7.5YR 3/2 D. brown	3sbk	common	gs	very firm	clay	absent	yes	slk
2Ab	58-92	10YR 5/3 Brown	10YR 4/4 D.Y. brown	1sbk	few	gs	loose	silty clay	present	yes	—
Bb	92-124	10YR 6/4 L.Y. brown	10YR 4/2 D.G. brown	2sbk	few	cw	loose	silty clay	absent	yes	vertic, slk
Bssb	124-143	10YR 5/4 Y. brown	10YR 3/2 V.D.G. brown	1sbk	few	cw	firm	clay	absent	yes	slk
Bsstb1	143-160	10YR 4/2 D.G. brown	10YR 2/2 V.D. brown	2sbk	none	as	firm	clay	sent	yes	slk
Bsstb2	160-173	10YR 4/4 D.Y. brown	10YR 3/2 V.D.G. brown	3sbk	none	cs	firm	clay	absent	yes	charcoal
Bsstb3	173-185+	10YR 2/1 Black	Gley1 2.5/N Black	4sbk	none	gs	firm	clay	absent	no	slk

Horizon	Depth	Colour		Structure ¹	Root	Boundary ²	Consistency	Field	Gravel	React	Other
	(cm)	(Dry)	(Moist)				(moist)	texture	(>2mm)	HCl	features
SP 4											
A	0-25	7.5YR 4/1 D. gray	7.5YR 3/1 V.D gray	1sbk	frequent	cs	very firm	clay	absent	no	—
Bkss1	25-45	7.5YR 4/2 Brown	7.5YR 4/1 D. gray	2 wedge	common	gs	very firm	clay	absent	yes	slk
Bkss2	45-75	7.5YR 4/2 Brown	7.5YR 3/2 D. brown	2 wedge	common	gs	very firm	clay	absent	yes	slk
Bk	75-121	7.5YR 5/1 Gray	7.5YR 3/1 V.D. gray	4 wedge	none	gs	very firm	clay	absent	yes	—
Bksst1	121-164	7.5YR 6/1 Gray	10YR 4/2 D.G. brown	4abk	few	cs	very firm	clay	absent	yes	vertic, slk
Bksst2	164-186+ G. brown	10YR 5/2 Brown	10YR 5/3	3abk	none	gs	very firm	clay	absent	yes	vertic, slk

¹B – brownish; D – dark; G – grayish; L –light; R – reddish; V – very

²1 – weak; 2 – medium; 3 – strong; 4 – very strong; abk – angular blocky; sbk – sub-angular blocky

³a – abrupt; c – clear; i – irregular; g – gradual; s – smooth; w – wavy

⁴slk – slickenside; cem – cementation

NB: Slope <4 % for all the profiles

Horizon	Depth	Colour		Structure ¹	Root	Boundary ²	Consistency	Field	Gravel	React	Other
	(cm)	(Dry)	(Moist)				(moist)	texture	(>2mm)	HCl	features
SP 5											
Ap	0-7	2.5Y 3/1 V.D. gray	2.5Y 2.5/1 Black	3sbk	frequent	cs	firm	clay	absent	no	—
Bt1	7-32	2.5Y 5/1 Gray	2.5Y 4/2 D.G. brown	3sbk	common	gs	very firm	clay	absent	yes	slk
Bt2	32-96	2.5Y 6/2 L.B. gray	2.5Y 5/1	3sbk	few	gs	very firm	clay	absent	yes	—
Bk	96-153	2.5Y 7/2 L. gray	2.5Y/ 6/2 L.B. gray	3sbk	few	gi	firm	sandy clay	present	yes	carbonates, cem
Bkkm1	153-168	2.5Y 8/3 Pale brown	7.5YR 4/3 brown	4sbk	few	as	firm	sandy clay	present	yes	cem
Bkkm2	168-185+	2.5Y 7/2 L. gray	2.5Y 4/2 D.G. brown	4sbk	few	as	firm	sandy clay	present	yes	cem

¹B – brownish; D – dark; G – grayish; L –light; R – reddish; V – very

³a – abrupt; c – clear; i – irregular; g – gradual; s – smooth; w – wavy

²1 – weak; 2 – medium; 3 – strong; 4 – very strong; abk – angular blocky; sbk – sub-angular blocky

⁴slk – slickenside; cem – cementation

NB: Slope <4 % for all the profiles

4.2. Physico-chemical and mechanical properties

There were variations in the physico-chemical and mechanical properties of the expansive soils of Serowe (Tables 4.2 and 4.3). The particle size distribution procedure was carried out to determine the percentage of the soil content of sand, silt and clay and to determine the textural class of the soil as a whole. The results of the particle size distribution (Table 4.2) designate that the profiles had higher percentage of sand than silt and clay with separates values varying between 63.2 to 98.8 %, 0.2 to 22.2 % and 6.8 to 33.8 % respectively. This clearly indicates that the most dominant textural class, sandy clay loam makes about 90% of the expansive soils from Serowe. SP1, SP2 and SP4 had 30 % or more of clay content to the depth of at least 120 cm. In this research, the knowledge of the percentage clay is considered very important. The bulk density and porosity results ranged from 1.04 to 1.67g/cm³ and 37 to 60.8 % respectively. As the soil bulk density increases, porosity decreases and vice-versa. Fluctuating organic matter content values ranged from 2.4 to 11.6 %. The results decreased with increasing depth in SP5. The pH (H₂O) of all representative sampled expansive soils from Serowe ranged from 6.9 to 8.7 with the lowest (6.9) and highest (8.7) values were obtained from SP1 and SP2 respectively. For SP3 and SP4, the pH values were only around 7 (7.5 and 7.9). The resulting pH values increased down the profile for SP1 and SP2 but fluctuated for SP3, SP4 and SP5. The electrical conductivity (EC) values ranged from 0.07 to 1.11dS/m with a fluctuating trend. All profiles except SP2 resulted in an EC of less than 1dS/m. Organic matter values ranged between 2.4 to 11.6 %. The cation exchange capacity (CEC) values for all the five profiles range from 14.11 to 56.9 cmol+/kg with the lowest and highest values obtained from SP5 and SP2 respectively as shown in Table 4.2 below. The values fluctuated for SP1 and SP2 with calcium declining with increasing depth for SP2. From the depth of 58cm, the level of Mg increased with depth. Calcium was absent in SP4 for all horizons except the deepest horizon, which also yielded higher CEC values.

It was also absent from 0-96 cm depth in SP5. It decreased with increasing depth from 96-185⁺ cm. Potassium also decreased in the same profile with increasing depth.

COLE rod values for all the five profiles ranged from 0.030 to 0.268. They fluctuated for SP3 and SP4 with a range of 0.030 to 0.235 and 0.070 to 0.268 respectively as shown in Table 4. SP1 values increased with depth from 0 to 94cm depth, the same trend was achieved in the whole SP2 profile. As for SP5, the values ranged from 0.052 to 0.103 and declined with increasing depth. At 153⁺ cm, the COLE rod procedure was not achievable because the soil was coarse.

Table 4.2: Physical and chemical properties of expansive soils from Serowe

Horizon	Depth (cm)	Particle size				ρ g/cm ³	Porosity (%)	pH		σ dS/m	OM (%)	Cations				CEC
		Sand	Silt	Clay	Texture			H ₂ O	KCl			Na ⁺	K ⁺	Mg ⁺	Ca ⁺	
		------(%)-----						1:2.5	1:2.5			------(cmol+/kg)-----				
<u>SP1</u>																
A	0-20	64.2	4.0	31.8	SCL	1.39	47.5	6.9	6.1	0.07	7.1	0.50	1.08	10.69	12.26	24.53
Bk1	20-40	63.2	3.0	33.8	SCL	1.29	51.3	7.7	6.5	0.10	5.9	1.30	0.61	14.33	14.77	31.01
Bk2	40-65	63.2	3.0	33.8	SCL	1.64	38.1	7.9	6.7	0.14	5.2	1.88	0.37	13.79	12.18	28.23
Bk3	65-94	66.2	3.8	30.0	SCL	1.64	38.1	8.1	6.8	0.22	5.7	3.43	0.41	14.74	12.03	30.60
Bss1	94-136	71.4	5.8	22.8	SCL	1.57	40.8	8.1	6.9	0.25	6.0	4.40	0.55	15.78	13.13	33.87
Bss2	136-170 ⁺	72.4	0.8	26.8	SCL	1.04	60.8	8.2	7.0	0.23	7.0	3.50	0.43	14.59	11.87	30.39
<u>SP2</u>																
Ap	0-13	65.2	2.8	32.0	SCL	1.48	44.2	8.1	6.9	0.12	5.3	1.30	1.47	13.32	14.88	30.96
Bss1	13-46	70.0	0.8	29.2	SCL	1.67	37.0	8.2	7.0	0.59	5.8	21.81	0.53	17.05	11.76	51.15
Bss2	46-81	68.0	1.2	30.8	SCL	1.64	38.1	8.5	7.1	1.09	5.7	27.10	0.47	16.65	10.03	54.26
Bss3	81-127	66.0	1.2	32.8	SCL	1.66	37.4	8.5	7.2	1.11	5.9	30.08	0.51	16.87	9.50	56.95
Bkss	127-149	64.0	11.2	24.8	SCL	1.39	47.5	8.6	7.3	0.92	4.4	18.71	0.31	14.43	7.41	40.87
Bt	149-190 ⁺	67.8	5.6	26.6	SCL	1.52	42.6	8.7	7.4	0.67	3.2	12.14	0.27	12.24	6.52	31.16

ρ : Bulk density; σ : electrical conductivity; SL - sandy loam; LS - Loamy sand; SCL - sandy clay loam

Horizon	Depth	<u>Particle size</u>				ρ	Porosity	<u>pH</u>		σ	OM	<u>Cations</u>				
		Sand	Silt	Clay	Texture			H ₂ O	KCl			Na ⁺	K ⁺	Mg ⁺	Ca ⁺	CEC
		(cm)	-----(-%)-----					g/cm ³	(%)			1:2.5	1:2.5	dS/m	(%)	
<u>SP3</u>																
Ap	0-20	59.0	22.2	18.8	SCL	1.37	48.3	7.4	6.6	0.19	11.6	0.67	3.64	13.75	0.00	18.06
Bss	20-58	60.2	15.0	24.8	SCL	1.34	49.4	7.6	6.7	0.10	8.0	0.48	0.67	13.57	0.00	14.73
2Ab	58-90	81.0	12.2	6.8	LS	1.46	44.9	7.9	7.1	0.07	3.1	0.27	0.22	8.42	11.39	20.30
Bb	90-124	85.0	5.2	9.8	LS	1.49	43.8	7.7	7.0	0.07	2.4	0.40	0.24	10.48	12.17	23.29
Bssb	124-143	84.2	6.0	9.8	LS	1.39	47.5	7.5	6.8	0.08	3.4	0.50	0.48	14.50	15.51	30.88
Bsstb1	143-160	74.2	5.0	20.8	SCL	1.22	54.0	7.7	6.6	0.10	5.0	0.41	0.45	14.31	15.16	30.34
Bsstb2	160-173	73.0	0.2	26.8	SCL	1.20	54.7	7.8	6.4	0.11	5.3	0.53	0.44	14.54	15.37	30.88
Bsstb3	173-185 ⁺	64.0	5.2	30.8	SCL	1.15	56.6	7.8	6.7	0.11	8.6	0.59	0.59	16.27	0.00	17.44

ρ : Bulk density; σ : electrical conductivity; LS - Loamy sand; SCL - sandy clay loam

Horizon	Depth (cm)	Particle size			Texture	ρ g/cm ³	Porosity (%)	pH		σ dS/m	OM (%)	Cations				CEC
		Sand	Silt	Clay				H ₂ O	KCl			Na ⁺	K ⁺	Mg ⁺	Ca ⁺	
		------(%)-----						1:2.5	1:2.5			------(cmol+/kg)-----				
SP4																
A	0-25	74.4	2.6	23.0	SCL	1.40	47.2	7.6	6.8	0.12	8.6	0.46	0.95	16.90	0.00	18.30
Bkss1	25-45	69.4	0.6	30.0	SCL	1.29	51.3	7.8	6.9	0.14	8.0	4.10	0.49	17.87	0.00	22.45
Bkss2	45-75	68.1	0.5	31.4	SCL	1.22	54.0	7.5	6.9	0.40	7.8	4.39	0.54	18.40	0.00	23.33
Bk	75-121	67.4	2.6	30.1	SCL	1.19	55.1	7.5	6.9	0.29	6.1	4.09	0.60	18.97	0.00	23.65
Bksst1	121-164	69.8	2.4	27.8	SCL	1.14	57.0	7.4	7.0	0.30	6.9	3.47	0.57	18.42	0.00	22.46
Bksst2	164-185 ⁺	76.4	0.6	23.0	SCL	1.41	46.8	7.4	7.0	0.25	8.5	2.99	0.49	18.13	15.06	36.67
SP5																
Ap	0-7	75.8	4.4	19.8	SCL	1.55	41.5	7.3	7.0	0.13	11.4	0.31	2.28	11.52	0.00	14.11
Bt1	7-32	75.8	3.6	20.6	SCL	1.30	50.9	7.5	7.0	0.10	8.5	0.79	0.59	12.67	0.00	14.05
Bt2	32-96	70.8	7.4	21.8	SCL	1.23	53.6	7.6	7.0	0.18	8.1	1.01	0.56	14.79	0.00	16.35
Bk	96-153	83.2	3.2	13.0	SCL	1.14	57.0	7.8	7.1	0.10	6.9	0.94	0.43	15.82	15.18	32.36
Bkkm1	153-168	70.8	1.2	8.0	SCL	1.62	38.9	8.3	7.2	0.09	5.1	1.45	0.37	15.83	14.20	31.85
Bkkm2	168-185 ⁺	98.8	0.2	1.0	SCL	1.35	49.1	8.4	7.3	0.10	4.7	1.21	0.27	14.75	12.20	28.42
ρ : Bulk density; σ : electrical conductivity; LS - Loamy sand; SCL - sandy clay loam																

Table 4.3: Mechanical properties and calcium carbonate content of the soils.

Horizon	COLE		Atterberg Limits			CaCO ₃ (%)
	COLE rod	Hazard class	LL	PL (%)	PI	
<u>SP1</u>						
A	0.054	moderate	30.07	15.95	14.12	0.8
Bk1	0.150	very high	37.10	21.85	15.25	2.1
Bk2	0.172	very high	41.77	22.45	19.32	2.9
Bk3	0.249	very high	42.60	26.36	16.24	3.6
Bss1	0.128	very high	46.60	22.08	24.52	3.9
Bss2	1.181	very high	53.58	23.54	30.04	4.7
<u>SP2</u>						
Ap	0.084	high	31.96	16.17	15.79	4.0
Bss1	0.159	very high	50.96	25.07	25.89	5.4
Bss2	0.173	very high	64.58	25.92	38.66	4.8
Bss3	0.230	very high	61.35	52.34	9.01	3.7
Bkss	0.243	very high	49.09	23.60	25.49	3.6
Bt	0.259	very high	36.17	19.18	16.99	1.3
<u>SP3</u>						
Ap	0.126	very high	53.56	31.80	21.76	1.5
Bss	0.145	very high	42.10	28.04	14.06	4.7
2Ab	0.030	low	21.06	-	-	7.0
Bb	0.077	high	25.60	12.72	12.88	0.8
Bssb	0.036	low	20.60	-	-	0.9
Bsstb1	0.122	very high	39.46	20.41	19.05	1.5
Bsstb2	0.177	very high	37.97	29.22	8.75	1.6
Bsstb3	0.235	very high	53.56	26.90	26.66	1.4

Horizon	COLE		Atterberg Limits			CaCO ₃
	COLE rod	Hazard class	LL	PL (%)	PI	(%)
<u>SP4</u>						
A	0.121	very high	42.41	29.21	13.20	2.6
Bkss1	0.071	high	45.85	36.81	9.04	2.7
Bkss2	0.255	very high	48.38	29.00	19.38	2.1
Bk	0.129	very high	50.98	27.61	23.37	2.5
Bksst1	0.183	very high	45.35	21.08	24.27	2.2
Bksst2	0.268	very high	42.92	20.82	22.10	1.1
<u>SP5</u>						
Ap	0.103	very high	41.88	21.38	20.50	2.9
Bt1	0.074	high	38.61	22.37	16.24	6.2
Bt2	0.052	medium	43.00	27.11	15.89	6.9
Bk	0.070	high	38.92	25.87	13.05	6.8
Bkkm1	-	-	-	-	-	3.7
Bkkm2	-	-	-	-	-	4.2

COLE – Coefficient of Linear Extensibility; LL – Liquid limit; PL – Plastic limit; PI – Plasticity Index

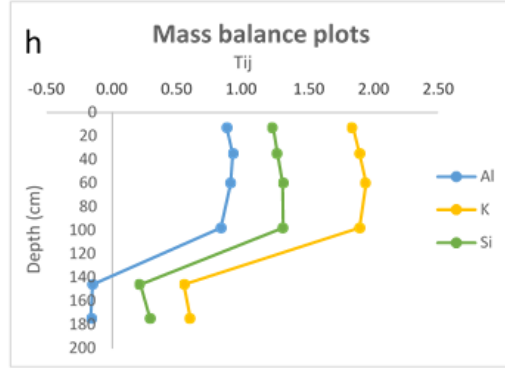
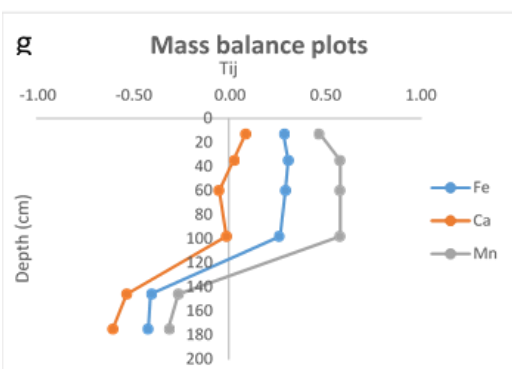
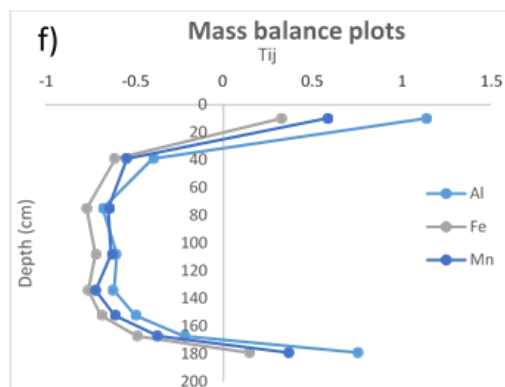
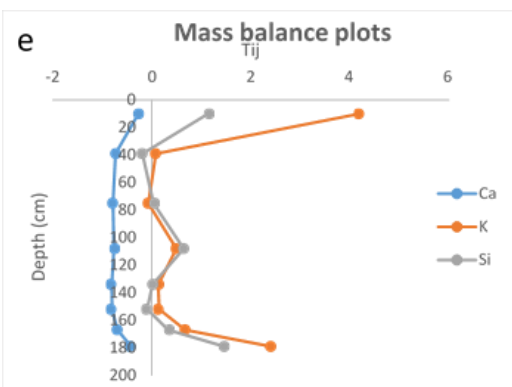
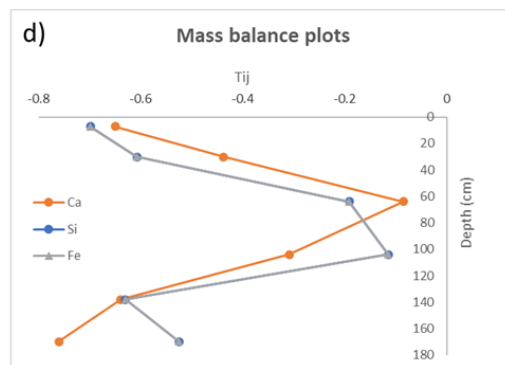
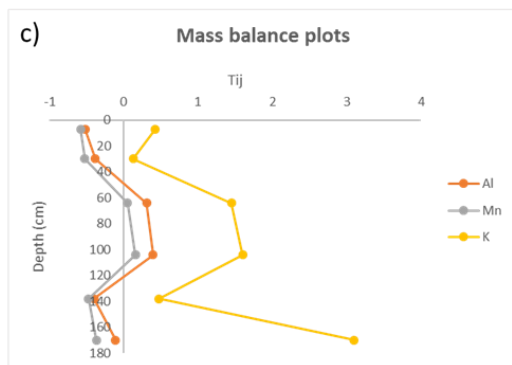
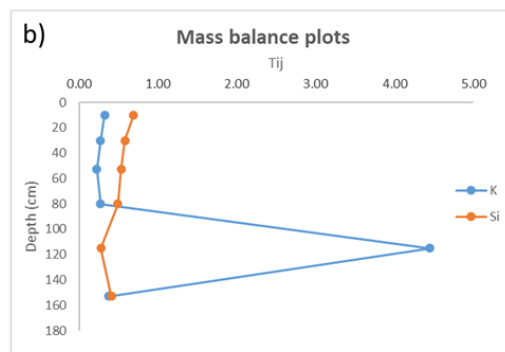
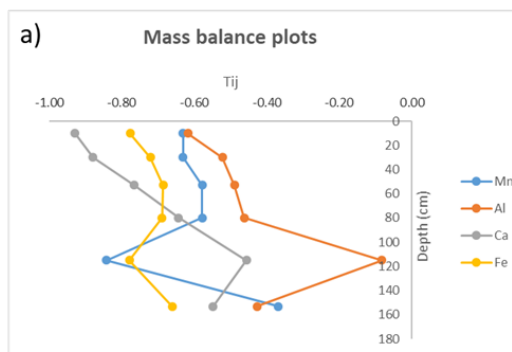
4.3. Geochemistry

To quantify the weathering degree in soils, the following geochemical indices namely; Index of compositional variability (ICV), chemical index of alteration (CIA), chemical index of weathering CIW, plagioclase index of alteration (PIA) and weathering index of Parker (WIP) were used and the results are shown in Figure 4.3 and Table 4.4. SP1 values for ICV, CIA, CIW, PIA and WIP varied between 1.11 to 1.70, 58.40 to 77.09, 64.40 to 84.25, 49.34 to 69.82 and 4.94 to 20.07 respectively, SP2 had 1.37 to 1.90, 54.12 to 67.35, 55.77 to 83.40, 51.15 to 60.36 and 9.02 to 15.20 respectively, SP3 had 1.39 to 1.95, 59.00 to 71.82, 66.44 to 80.23, 52.33 to 67.65 and 9.79 to 17.03 respectively, SP4 had 1.61 to 1.70, 63.55 to 65.76, 70.08 to 74.08, 60.10 to 62.97 and 15.23 to 17.55 respectively and lastly SP5 had 2.15 to 3.50, 32.27 to 53.77, 34.28 to 59.71, 30.68 to 50.13 and 23.39 to 31.70.

Quantitative assessment of the soil pedogenesis was done using selected pedogenic ratios as presented in Table 4.5. A similar range of values per ratio for all the profiles was recorded. Base loss, clayeyness, salinization, calcification, provenance and B/Sr leaching for all the profiles ranged from 0.47 to 2.73, 0.06 to 0.23, 0.13 to 0.24, 0.31 to 2.54, 0.05 to 0.87 and 0.67 to 10.62 respectively. Also the least and highest recorded values were in profiles SP1 and SP5 respectively for all ratios except for Ba/Sr leaching which was in SP5 and SP3 respectively.

Six major elements (Al, Ca, Fe, K, Mn, and Si) enrichment and depletion for the five pedons are as shown in Fig. 4.1. According to the results shown in the mass balance plots for SP1; Al, Ca, Fe and Mn were depleted while K and Si were enriched with a major shift observed at a depth of 115 cm depth. In SP2, there was a depletion for all elements except K, with a major shift around 110 cm deep for all except Ca. An enrichment with decrease in depth which finally

led to a depletion which fluctuated between depth of 40 – 170cm in SP3. Beyond the latter depth, an increase in enrichment was observed. Ca was the only element that was depleted throughout the whole pedon. For SP4, there was an increase in enrichment for all elements except Ca. At 100 cm depth, a major shift for all elements was observed which led to a decreasing gain with depth and finally a depletion for four elements (Al, Ca, Fe and Mn). SP5 pedon had a fluctuation in enrichment for Ca, K, Si. A depletion was also registered in the subsoil for Al, Fe and Mn which decreased with depth and finally became enriched.



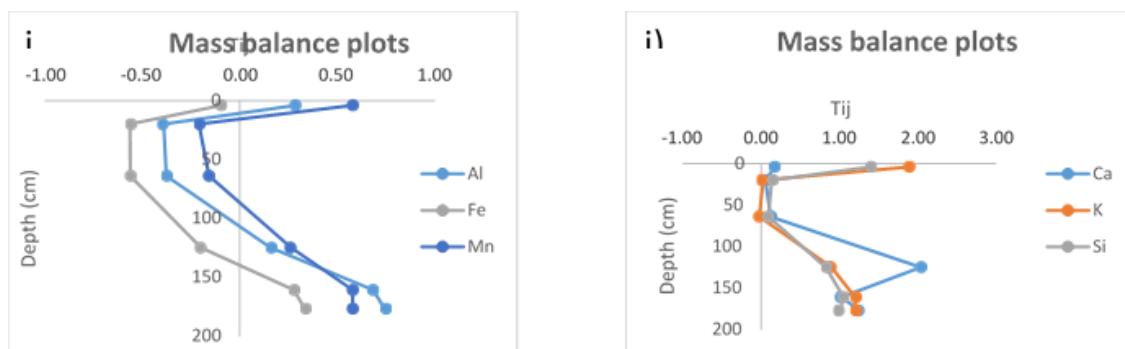


Figure 4.2: Elemental mass balance plots in SP1 (a and b), SP2 (c and d), SP3 (e and f), SP4 (g and h) and SP5 (i and j) profiles.

Table 4.4: Major oxides and molecular weathering indices

Horizon	Major Oxides												Molecular Weathering Indices				
	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	V ₂ O ₅	ZrO ₂	ICV	CIA	CIW	PIA	WIP
	%																
	SP1																
A	5.08	0.68	3.16	0.53	0.89	0.07	0.3	0.032	84.2	0.55	0.01	0.03	1.22	77.09	83.83	69.04	4.94
Bk1	6.34	1.16	3.95	0.51	1.25	0.07	0.34	0.025	78.7	0.6	0.02	0.02	1.24	75.93	84.25	69.82	6.06
Bk2	6.79	2.26	4.45	0.49	1.4	0.08	0.38	0.023	76.4	0.63	0.02	0.04	1.43	68.45	74.84	63.51	7.83
Bk3	7.14	3.44	4.41	0.51	1.57	0.08	0.44	0.023	74.3	0.66	0.02	0.03	1.56	61.93	67.34	57.50	9.96
Bss1	12.20	5.25	3.14	2.18	1.72	0.03	0.68	0.15	63.7	0.57	0.01	0.02	1.11	60.07	69.32	49.34	20.07
Bss2	7.61	4.36	4.81	0.55	1.92	0.12	0.51	0.026	70.2	0.69	0.02	0.03	1.70	58.40	64.40	54.18	12.02
	SP2																
Ap	6.41	3.38	4.28	0.57	1.56	0.08	0.65	0.028	76.7	0.59	0.02	0.02	1.73	58.22	65.29	53.04	10.70
Bss1	8.21	5.44	5.57	0.45	2.31	0.09	1.07	0.023	65	0.64	0.02	0.02	1.90	54.12	55.77	51.15	15.20
Bss2	8.71	4.42	5.74	0.49	2.41	0.10	1.26	0.023	66.7	0.67	0.02	0.01	1.73	58.53	66.22	55.24	14.55
Bss3	9.29	3.34	6.28	0.52	2.41	0.11	1.38	0.023	65.3	0.73	0.03	<0.01	1.59	63.94	73.42	60.36	13.47
Bkss	8.02	3.49	5.25	0.59	2.24	0.10	1.21	0.021	70.9	0.6	0.02	0.02	1.68	60.26	69.55	55.82	13.29
Bt	5.92	1.16	3.37	0.82	1.39	0.06	0.89	0.018	82.8	0.42	0.01	<0.01	1.37	67.35	83.40	58.02	9.02

Horizon	-----Major Oxides-----												Molecular Weathering Indices				
	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	V ₂ O ₅	ZrO ₂	ICV	CIA	CIW	PIA	WIP
	_____ % _____																
SP3																	
Ap	14.2	3.55	9.41	1.04	3.03	0.15	1.55	0.188	53.3	1.02	0.04	0.01	1.39	69.81	79.16	64.70	17.03
Bss	12.00	3.93	8.34	0.65	2.76	0.13	1.33	0.087	60.9	0.93	0.04	0.02	1.51	67.00	74.92	63.37	15.08
2Ab	6.38	3.17	4.9	0.56	2.05	0.10	0.96	0.052	77.5	0.69	0.03	0.03	1.95	57.63	66.44	52.57	11.79
Bb	5.31	2.28	3.96	0.60	1.64	0.07	0.81	0.037	81.9	0.64	0.02	0.02	1.88	59.00	69.62	52.33	9.79
Bssb	7.65	2.83	5.10	0.68	1.96	0.08	1.09	0.048	75.9	0.71	0.02	0.03	1.63	62.45	72.66	56.90	12.05
Bsstb1	10.00	2.86	6.60	0.69	2.27	0.11	1.11	0.055	68	0.83	0.03	0.03	1.45	68.21	77.43	63.51	12.54
Bsstb2	10.30	2.98	7.25	0.67	2.25	0.12	1.14	0.057	66.40	0.81	0.03	0.02	1.48	68.26	77.23	63.82	12.69
Bsstb3	11.70	2.82	8.10	0.68	2.63	0.13	1.09	0.063	61.30	0.86	0.04	0.01	1.39	71.82	80.23	67.65	12.79

Horizon	Major Oxides												Molecular Weathering Indices				
	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	V ₂ O ₅	ZrO ₂	ICV	CIA	CIW	PIA	WIP
	%																
SP4																	
A	12.50	5.25	9.11	0.57	3.53	0.14	1.35	0.088	55.7	0.93	0.03	0.01	1.67	63.55	70.08	60.65	17.56
Bkss1	12.80	4.94	9.29	0.58	3.49	0.15	1.41	0.086	56.5	0.91	0.04	<0.01	1.62	64.88	71.81	61.94	17.28
Bkss2	12.70	4.59	9.18	0.59	3.54	0.15	1.45	0.090	57.5	0.91	0.03	0.01	1.61	65.70	73.07	62.97	16.99
Bk	12.20	4.77	8.99	0.58	3.41	0.15	1.37	0.079	57.6	0.90	0.04	0.01	1.65	64.48	71.56	61.42	16.84
Bksst1	11.30	4.53	8.41	0.62	3.24	0.14	1.32	0.068	60.6	0.93	0.04	0.02	1.70	63.59	71.08	60.10	16.32
Bksst2	11.10	3.82	8.25	0.64	3.1	0.13	1.32	0.064	64.3	0.97	0.04	0.02	1.64	65.76	74.08	61.97	15.23
SP5																	
Ap	8.56	5.68	6.42	0.58	3.58	0.15	1.10	0.096	59.9	0.88	0.04	0.01	2.15	53.77	59.71	50.13	17.55
Bt1	8.11	10.20	6.2	0.41	3.81	0.15	1.03	0.084	56.5	0.84	0.04	0.02	2.79	41.06	44.09	38.99	23.39
Bt2	8.28	10.80	6.22	0.39	3.95	0.16	1.09	0.080	54.3	0.81	0.03	0.02	2.83	40.27	43.22	38.38	24.49
Bk	7.70	14.70	5.69	0.38	4.86	0.12	1.08	0.065	45.5	0.70	0.03	<0.01	3.58	32.27	34.28	30.68	31.01
Bkkm1	11.20	9.79	9.06	0.44	6.77	0.15	2.13	0.065	51.1	0.99	0.05	<0.01	2.62	47.54	53.19	45.67	29.35
Bkkm2	11.60	10.90	9.47	0.44	7.04	0.15	2.29	0.079	50.0	10.1	0.06	<0.01	2.70	45.98	51.38	44.23	31.70
R (Basalt)	13.3	9.67	14.2	0.4	5.57	0.19	2.54	0.379	49.8	3.53	0.07	0.02	2.71	51.33	56.96	49.79	28.86

Table 4.5: Pedogenic Ratios

Horizon	Pedogenic Ratios				Provenance	Ba/Sr
	ΣBase/Al	Clayeyness	Salinization	Calcification		
SP1						
A	0.47	0.06	0.16	0.31	0.11	7.28
Bk1	0.51	0.08	0.13	0.38	0.09	6.47
Bk2	0.67	0.09	0.13	0.54	0.09	2.91
Bk3	0.83	0.10	0.13	0.70	0.09	4.92
Bss1	0.81	0.19	0.23	0.57	0.05	9.00
<u>Bss2</u>	<u>0.96</u>	<u>0.11</u>	<u>0.14</u>	<u>0.83</u>	<u>0.09</u>	<u>2.97</u>
SP2						
Ap	0.96	0.08	0.19	0.77	0.09	2.45
Bss1	1.13	0.13	0.19	0.94	0.08	2.14
Bss2	0.99	0.13	0.20	0.78	0.08	2.59
Bss3	0.82	0.14	0.20	0.62	0.08	2.83
Bkss	0.94	0.11	0.22	0.71	0.07	3.55
<u>Bt</u>	<u>0.72</u>	<u>0.07</u>	<u>0.29</u>	<u>0.43</u>	<u>0.07</u>	<u>4.55</u>
SP3						
Ap	0.65	0.27	0.18	0.46	0.07	2.10
Bss	0.72	0.20	0.17	0.56	0.08	2.49
2Ab	1.06	0.08	0.24	0.82	0.11	2.33
Bb	1.00	0.06	0.27	0.74	0.12	10.6
Bssb	0.86	0.10	0.23	0.63	0.09	3.89
Bsstb1	0.69	0.15	0.18	0.51	0.08	2.13
Bsstb2	0.68	0.16	0.18	0.51	0.08	2.27
Bsstb3	0.62	0.19	0.15	0.47	0.07	2.25

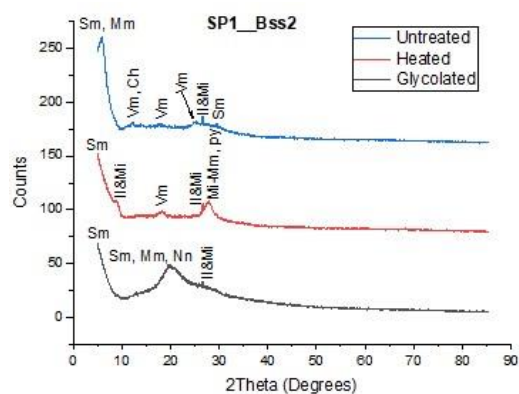
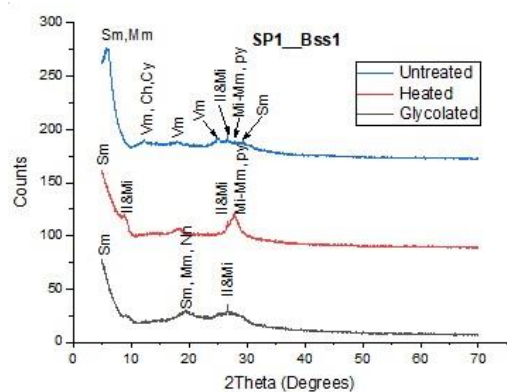
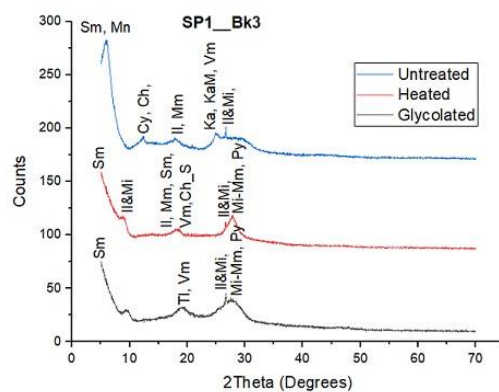
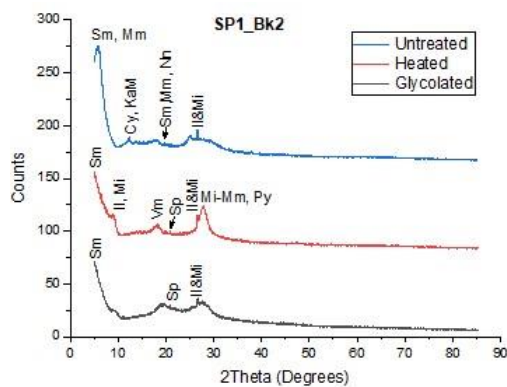
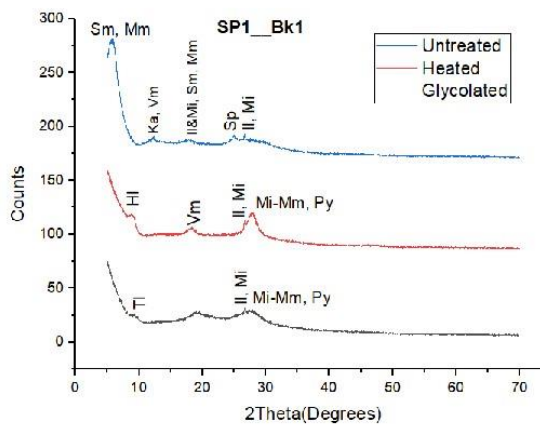
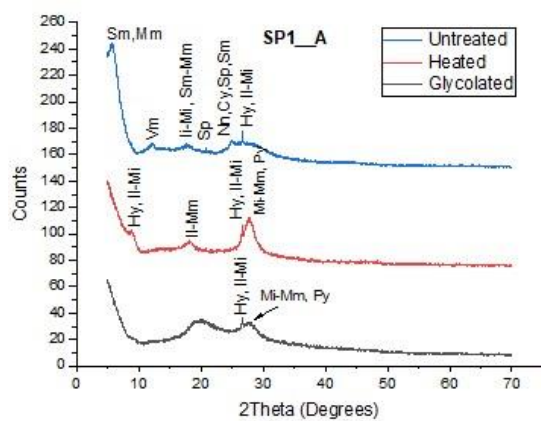
Horizon	Pedogenic Ratios				<u>Provenance</u>	<u>Ba/Sr</u>
	<u>ΣBase/Al</u>	<u>Clayeyness</u>	<u>Salinization</u>	<u>Calcification</u>		
SP4						
A	0.86	0.22	0.15	0.70	0.07	2.24
Bkss1	0.81	0.23	0.16	0.66	0.07	1.67
Bkss2	0.80	0.22	0.16	0.64	0.07	1.98
Bk	0.83	0.21	0.16	0.67	0.07	2.02
Bksst1	0.86	0.19	0.17	0.69	0.08	1.88
<u>Bksst2</u>	<u>0.80</u>	<u>0.17</u>	<u>0.18</u>	<u>0.62</u>	<u>0.09</u>	<u>2.27</u>
SP5						
Ap	1.28	0.14	0.20	1.08	0.10	2.89
Bt1	1.91	0.14	0.18	1.73	0.10	1.21
Bt2	1.96	0.15	0.18	1.78	0.10	1.23
Bk	2.73	0.17	0.19	2.54	0.09	0.67
Bkkm1	1.71	0.22	0.23	1.48	0.09	0.77
<u>Bkkm2</u>	<u>1.78</u>	<u>0.23</u>	<u>0.24</u>	<u>1.55</u>	<u>0.87</u>	<u>0.70</u>

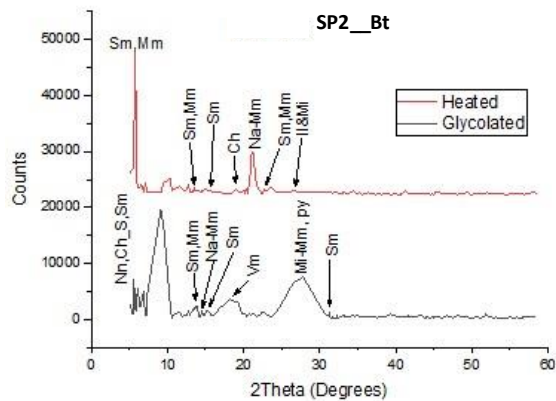
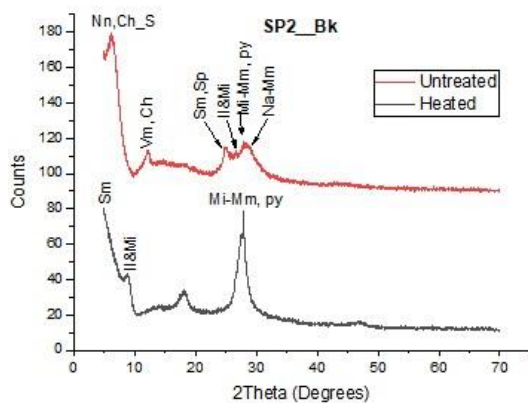
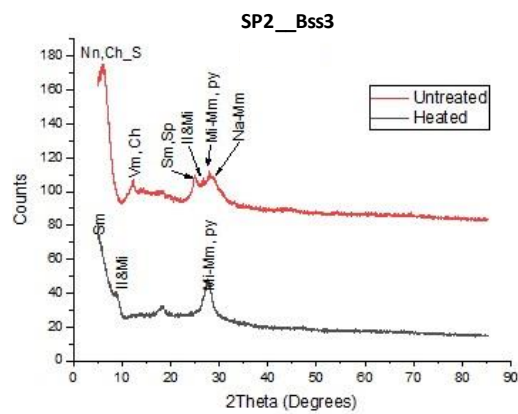
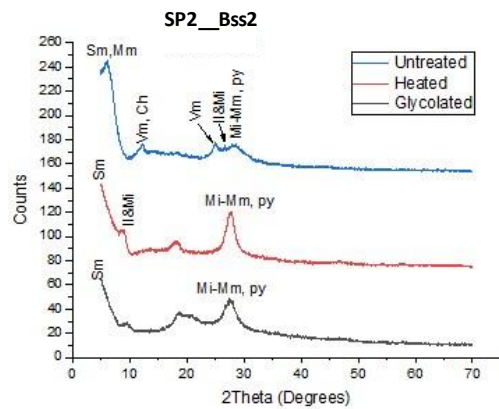
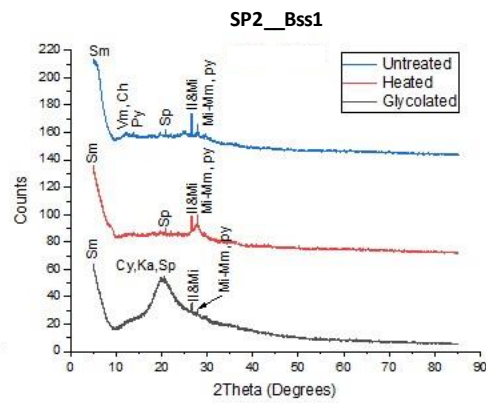
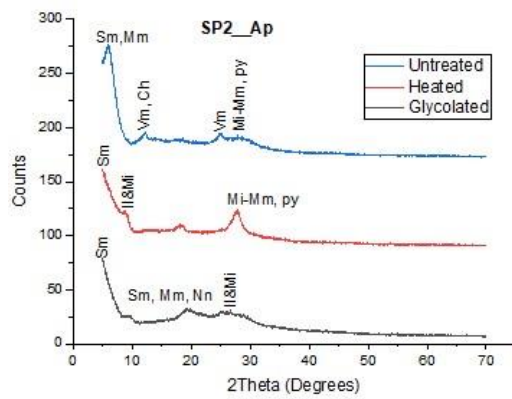
4.4. Clay Mineralogy

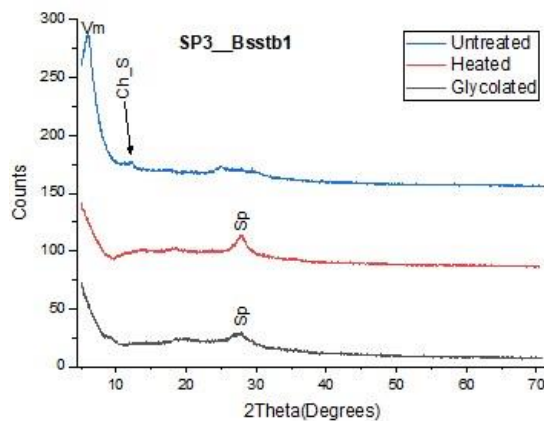
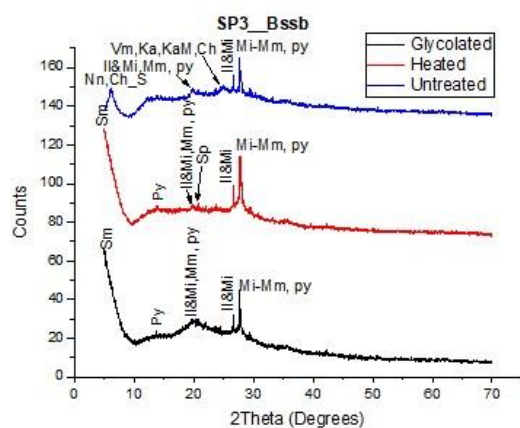
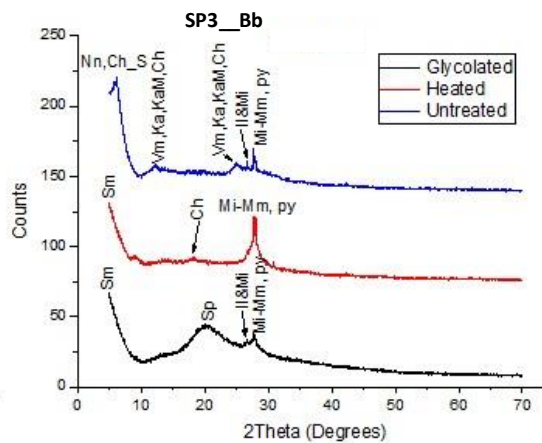
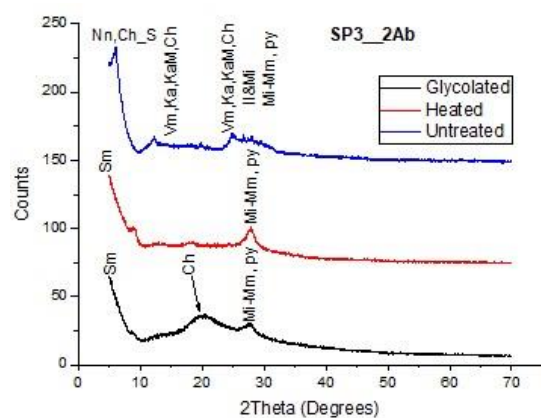
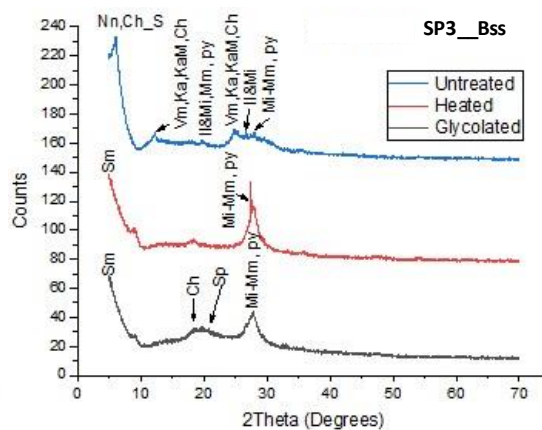
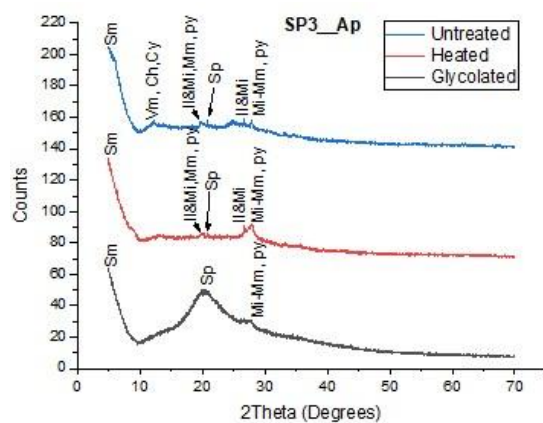
The diffractograms of the mineral assemblages were presented in Figure 4.1. Various clay minerals were found in the different horizons of the five pedons. In SP1 and SP2, all the horizons had the following clay minerals; montmorillonite, smectite, vermiculite, palygorskite, illite and mica. Sepiolite was only present in the first three horizons. Chrysotite and kaolinite were also present except in horizon Bk1 and A, Bss2 respectively in SP1, whereas kaolinite was identified only in horizon Bss1.

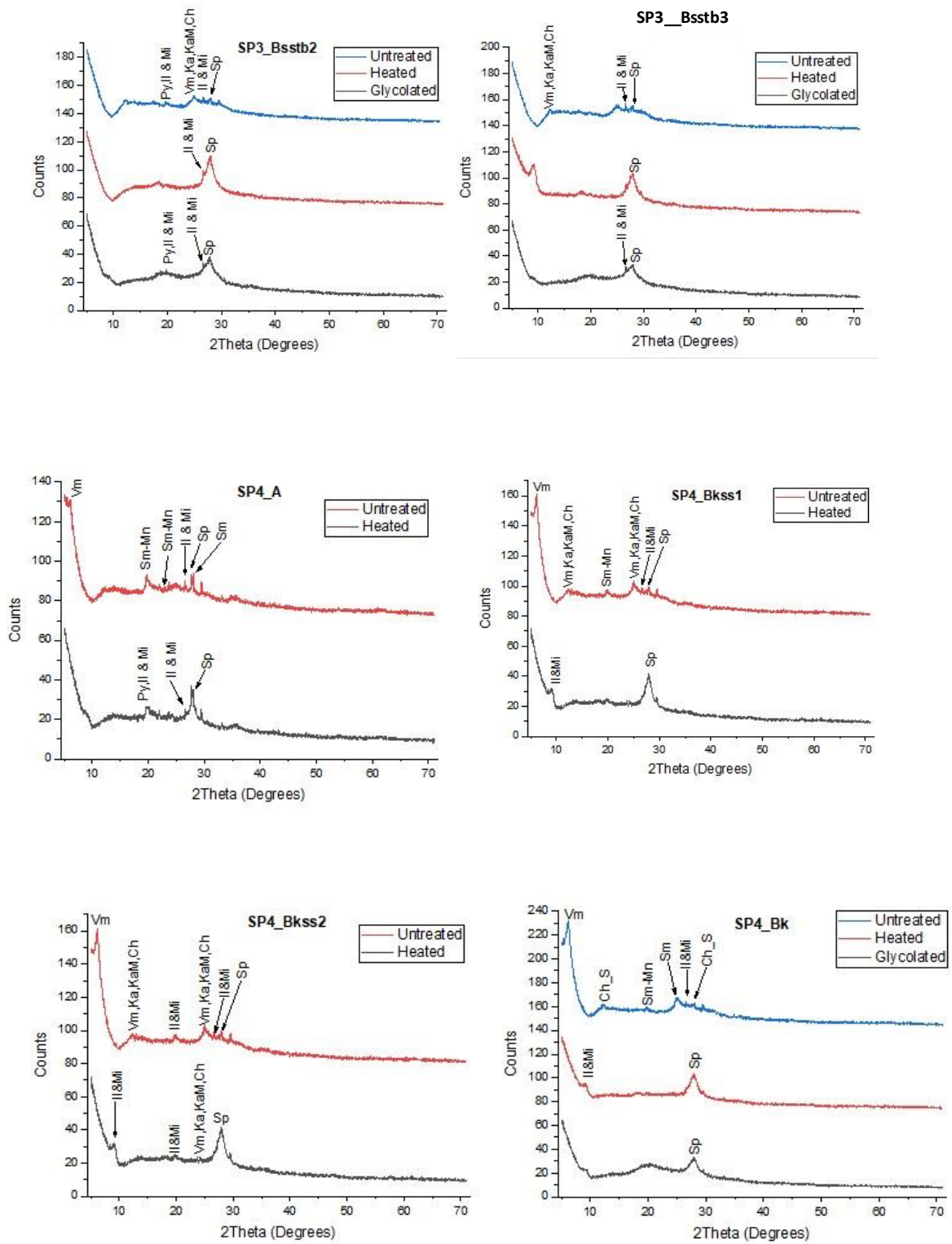
The predominant clay minerals in SP3 were; montmorillonite, smectite, vermiculite, chlorite, sepiolite, palygorskite, illite and mica for the first five horizons including the last two horizons (Bsstb2 and Bsstb3). Kaolinite was also identified in all except in Ap and Bsstb1. Moreover, only two clay minerals being sepiolite and chlorite were identified in Bsstb1.

In SP4, common clay minerals identified in A, Bkss1, Bkss2 and Bk are, smectite, montmorillonite, sepiolite, illite and mica, whereas smectite, palygorskite, nontronite, illite and mica were identified in horizon Bksst1. The last horizon being Bksst2 had sepiolite, chlorite, sodium montmorillonite and talc. As for SP5, the predominant clay minerals shown for Ap, Bkk1 and Bkk2 are smectite, sepiolite and montmorillonite. No clay minerals were identified in Bt2 but two (sepiolite, chlorite) and (kaolinite, nontronite) were identified in Bt1 and Bk respectively.









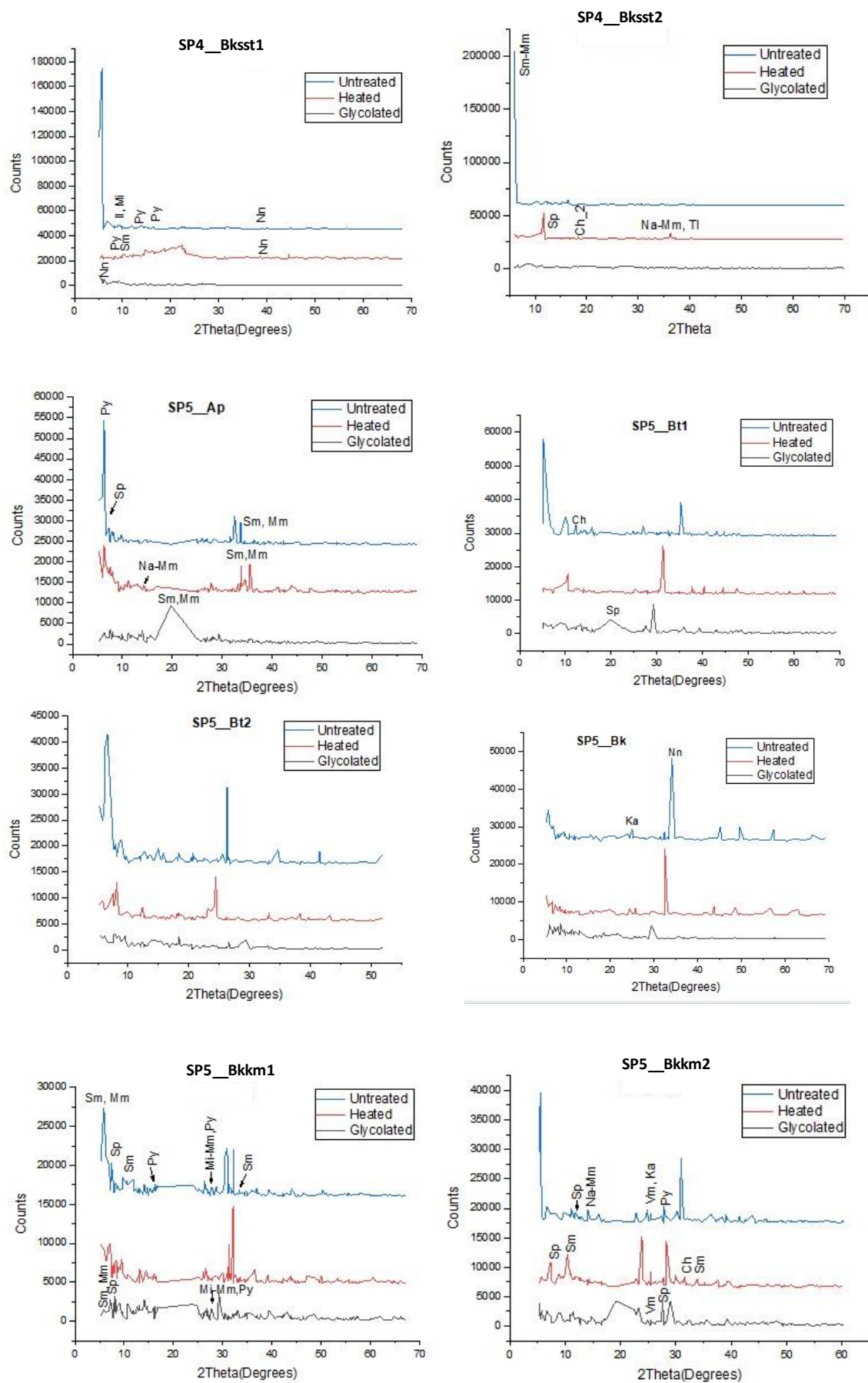


Figure 4.3: Diffractograms of the representative soil samples

4.5. Soil Classification

The SP1, SP2 and SP4, sandy clay loam, deep and grey in colour located at the toeslope (Soil Survey Staff, 2014) were classified as Vertisols (Table 4.6) due to the presence of an argillic horizon. These profiles qualified as Usterts at suborder level because it had an ustic moisture regime (Ranganai et al., 2015) and a great group Haplusterts with the family series being gleyey, smectite hyperthermic. The corresponding World Reference Base (WRB) classification for the same pedons was grumic, Gleyic Vertisols (calcic mesotrophic). On the other hand, pedons SP3 and SP5, classified as Aridisols with reference to the USDA system. It qualified as Argids suborder level within the 100 cm, great group Haplargids and family series of fine-silty, mixed hyperthermic as presented in Table 4.6. In line with WRB classification, SP3 was qualified as Vertic Gleyic Acrisol (abrupt) while SP5 was Vertic Gleyic Alisol.

Table 4.6: Classification of the expansive soils from Serowe

(a) USDA Soil Taxonomy

Class	SP1, SP2, SP4	SP3, SP5
Order	Vertisols	Aridisols
Suborder	Usterts	Argids
Great Groups	Haplusterts	Haplargirds
Family	Clayey, Smectitic, hyperthermic	fine-silty, mixed, hyperthermic
Name	Clayey, Smectitic, hyperthermic Haplusterts	Fine-silty, mixed, hyperthermic Haplargirds

(b) FAO (WRB)

Profile ID	Class
SP1	Grumic Gleyic Vertisol (Calcic, mesotrophic)
SP2	Grumic Gleyic Vertisol (Calcic, mesotrophic)
SP3	Vertic Gleyic Acrisol (Abrupt)
SP4	Grumic Gleyic Vertisol (Calcic, mesotrophic)
SP5	Vertic Gleyic Alisol

CHAPTER 5

DISCUSSION

5.1. Macromorphology, physico-chemical, mechanical and mineralogical properties of the soils as influenced by parent material, climate and topography

Parent material is a critical factor in the development and geographical distribution of expansive soils. Vertisols (SP1, SP2 and SP4) in this study developed from the weathering of basaltic parent material. This agrees with the findings of Coulombe et al., (1996) who reported that Vertisols of igneous origin result from basalt, dolerite, tuff, augite ash and andesite and this also is verified by the geology map of Serowe in Figure 3.2. The Vertisols have high (≥ 30 %) clay content and elsewhere (e.g., Wilding, 2004; Ruiz et al., 2013; Boettinger, 2014; Soil Survey Staff, 2014; Soil Survey Staff, 2015) Vertisols have been reported to have high clay contents with remarkable shrinking and swelling activities. This shrink-swell behaviour and shear failure are the direct causes of slickensides as seen in some of the profiles (Fig 3.1.). Slickensides commonly occur in clay enriched soils during volumetric changes (Staff, 2014). The Aridisols (SP3 and SP5) showed vertic property probably inherited from its vicinity given that sandstone is overlain by basaltic parent materials as shown from the geological stratigraphy of Serowe (Lubczynski, 2000). Expansive soils which do not qualify as Vertisols have been described as vertic intergrades in soil classification (Soil Survey Staff, 2014). The shrinking and swelling behaviour of expansive soils are clear indication of the presence of smectitic clay mineralogy (Kasanin-Grubin, 2013). Smectite are present in the soils (Fig 4.5) and they are responsible for the expansive behaviour of the soils of Serowe. As secondary minerals, smectite are formed from decomposition of the parent material (basalt) through chemical weathering to achieve more stable minerals. Given the physiographic positions of the SP3 and SP5 on the landscape (toeslope), it could be inferred that the basaltic parent materials must have been deposited on sandstone prone area by erosion, human activities or gravity. The shrink-swell

behaviour and the observed vertic properties of these soils is also qualified by the COLE results. Profiles SP1 to SP4 are predominantly classified as very hazardous. This property also helps to explain the glaring cracks on the ground of the Serowe sports complex and the buildings in the study area.

The pH values of the different soil horizons in the studied area are neutral to alkaline (6.9 to 8.7) (Table 2) and increased with depth. This correlates with findings from (Coulombe et al., 1996) that most Vertisols and vertic intergrades seem to be neutral to alkaline since they are mostly derived from base-rich parent material. The latter is correct as clearly shown in Table 2 that the CEC values for all profiles are medium to high (> 12 cmol/kg). Moreover, the results conquer with (Rashidi et al., 2008) who stated that soil properties such as pH, organic matter and clay content contribute to the CEC. The researcher clarified that CEC is highest in montmorillonite clays which is also present in profiles of the study area. These moderate to high CEC values is an indication that the soils of Serowe offer a large nutrient reserve for crop production.

The semi-arid climate of Serowe further contributed to the formation of expansive soils. Vertisols formation are greatly favoured in the semi-arid subtropics with necessary constraints for their formation associated with clayey smectite-rich parent material (Kabala et al., 2015; Kovda et al., 2017) or neo-genesis or alteration of primary minerals after sedimentation (Pal et al., 2009) and alternations of the moisture regimes. The prolonged seasons of dryness and wetness typical of Serowe soil environment facilitated the development of vertic properties in the soils. Low precipitation and high evapotranspiration promotes the movement of soluble salts (such as carbonates) from the deeper to surface soil horizons. Soil pH in the area was generally alkaline and this could be attributed to the presence of calcium carbonates in the soils. Elevated soil pH has been reported in soils with accumulation of calcium carbonates in semi-arid environments (Eze et al., 2021). Similarly, as reported by (Tsai et al., 2007; Tsozué et al.,

2017) high CEC values are indicators of smectitic or montmorillonitic clay rich soils. Moreover, the formation of sepiolite, which was also present in all the five pedons was by the transformation from montmorillonite and it was greatly favoured by the alkaline semi-arid environment (Tsozué et al., 2017). Several variations of illite and smectite were recorded in this study and this is brought by the fact that illite does transform into smectite (da Silva et al., 2019; Moazallahi & Farpoor, 2012). Clay minerals dominant in the profiles are smectite or montmorillonite group as normally associated with Vertisols is the most important as they depict the origin of these soils and a strong confirmation that their formation is highly favoured by the semi-arid environment.

On their physiographic positions, the expansive soils developed on gently rolling to flat terrains. The topography of the landscape plays a vital role in soil formation as clearly acknowledged by (Ruiz et al., 2013; Eze, 2015) that Vertisols are habitually present in the low land and the foothills and the studied pedons were found at <4 % slope (Table 4.1). Generally, SP1, SP2 and SP3 were in low slope (foot slope) whereas pedons SP3 and SP5 formed on a bottom slope. The terrain position of SP3 and SP5 is the main factor for the colluvial and conveyed material that led to the formation of vertic intergrades in these two pedons albeit at just a relatively shallow depth (please indicate). Moreover, the abrupt horizon boundary SP3 further gives evidence for lithologic discontinuity from transported basaltic materials. The topography has also greatly contributed to the buried horizons as it leads to an accumulation of materials.

Although clay illuviation has been inferred to represent warm-wet climate conditions in some studies (e.g., Bronger and Heinkele 1989), later work showed that Bt horizons can form in semi-arid grassland landscapes when enough time has elapsed (Han et al. 1998). The principal factor backing the formation of Vertisols in semi-arid environments is their vast water-holding capacity. In areas of unreliable and variable rainfall like Botswana (Serowe included), the soils

display a great ability for sufficient water storage to sustain the crops through drought. This is an evidence of poor drainage in hot climatic conditions outlined by (Rao, 2000) to be linked to the formation of expansive soils. The latter further noted that the colours of Vertisols vary from deep black to occasionally reddish or yellowish. The soil colours in this study as recorded in Table 4.1 fall within the aforementioned colour range. Soil colour provides an insight into the environmental conditions as well as pedogenic processes. The bluish green colour recorded in SP1 pedon depicts redoximorphism hence the soils are poorly drained whereas the reddish colour in SP2 reflects moderately well drained condition.

The wedge and sub-angular blocky structure (Table 4.1) depicts periods of wetting and drying which is attributed to the semi-environment climate of central Botswana. Clay minerals such as nontronite, smectite, sepiolite and palygorskite are characteristic of confined environments (IUSS Working Group Wrb, 2015) and are considered common to the semi-arid environment. These are called weatherable 2:1 phyllosilicate clay minerals and their presence indicate that further weathering of the minerals can still take place.

5.2. Chemical weathering intensity and pedogenic processes of the soils

Primary minerals are transformed by the different processes of chemical weathering and they result in the formation of clay minerals (Eze and Meadows, 2014b). This also attributes to the net losses of mobile elements including Ca, K, Mg and Na and the accumulation of various clay minerals like mica, kaolinite and smectite (Yousefifard et al., 2012). In this study, to understand the elemental mobility throughout the profiles, the mass balance was used. P_2O_5 was below zero in all the profiles except SP3 which is interpreted as a depletion (Tsozué et al., 2017) which could be a result of the element being leached or used up by plants. Na enrichment was present in SP2, SP3, SP4 and SP5 (Figure 4.2) which can be qualified to the presence of montmorillonite mineral (Figure 4.3) as it contains Na in its structure. The likely probable reason for this accumulation can be the prolonged dry period or low precipitation experienced

in the study area as was also acknowledged by researcher (Tsozué et al., 2017). Furthermore, some chemical weathering indices (ICV, CIA, CIW and PIA) were used to quantify the maturity and degree of chemical weathering of the soils. According to the results in Table 4.4, ICV values were greater than one which implies that the soils are mineralogically young and immature (Madukwe et. al, 2016). The abundance of the silicate clay minerals (Figure 4.2) indicate that the soils are young and can undergo further weathering. CIA, CIW and PIA values recorded in Table 4.5 for all the profiles are less than 80% except for three out of thirty-two horizons. Low (50 - 60) to intermediate (60 - 80) weathering (Mohanty, et.al, 2016) were recorded. There was also an insignificant occurrence of kaolinite minerals which also satisfies that the soils are still young and immature because kaolinite clay mineral is linked with extreme weathering. This is an indication that there is a perfect correlation between the four chemical weathering indices (ICV, CIA, CIW and PIA) as they all that the pedogenic intensity of the soils implicates that the soils of the study area are still young and immature.

Selected pedogenic ratios ($\Sigma\text{Base}/\text{Al}$, clayeyiness, salinization, provenance and trace element (Ba/Sr leaching) were used to evaluate the pedogenic processes that occurred in the soils. A correlation has been recorded between salinization and electrical conductivity (EC). The low salinization and EC values indicate low salt accumulation which is a result of the dry and well drained soils (Mohanty et al., 2016). Similarly, calcification ratio values (Table 4.5) which can also be used to infer accumulation of soluble salts nullifies their significant occurrence in the study location and the values evidently prove a moderate to low precipitation in Serowe as is the case with semi-arid environments. This low accumulation of soluble salts is an indication that the soils can provide a healthy environment for farming.

Clayeyiness is the pedogenic ratio that determines the quantity of clay mineral formation with regard to the high Al in clay as compared to the original material which concludes that the

hydrolysis process (Srivastava et al., 2019) was responsible for the formation of the recorded clay minerals. According to the results, clayeyness values range from 0.6 to 0.27. This is an indication that they contain some sand particles to moderate clay particles. These results correlate well with the particle size distribution results which are mostly sandy clay loam (SCL) while some horizons are classified as loamy sand (LS) and sandy loam (SL). Generally, the formation of clay minerals scientifically reports that hydrolysis is the responsible pedogenic process. The immature/young status of the soil is typical of semi-arid environments where precipitation is low and is commonly known to impede chemical weathering and pedogenesis. Relative to the surrounding areas, the low topographical positions of the pedons ensured accumulation of moderate amounts of organic matter (2 – 11 %) in the soils. Organic matter plays significant role in the formation of soil structure which helped in addition to clay mineralogy in increasing water retention in the soils.

5.3. Classification of the soils

Serowe soils were classified as Vertisols at suborder level (SP1, SP2 and SP4) by both the USDA *Soil Taxonomy* (Clayey, Smectitic hyperthermic Haplusterts) and the World Reference Base system (Grimic Gleyic Vertisols (Calcic, mesotrophic)) because they had 30% or more clay content in the upper 100cm. The other two profiles (SP3 and SP5) did not qualify as Vertisols hence they are just vertic intergrades classified as Aridisols with the name Fine-silty, mixed, hyperthermic Haplargids (USDA *Soil Taxonomy*) due to the presence of the sandstone in their lithology. The World Reference Base system classified SP3 as Vertic Gleyic Acrisol (Arupt) and SP5 as Vertic Gleyic Alisol. USDA *Soil Taxonomy* classified Serowe soils as such due to being in the hyperthermic temperature regime and ustic moisture regime. Despite a number of similarities in the soils, the clay content was the main deciding factor that separated the soils into Vertisols and vertic intergrades.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusion

Serowe soils are generally deep (>150 cm in depth) and the pH is slightly acidic to slightly alkaline ranging from 6.9 to 8.7. They have several moist colours; namely, dark brown, dark grey and even black with a wedge structure which is attributed by the clay content in the soils. The soils possess indicators of good health for agricultural production. The presence of smectitic minerals has attributed to the shrink-swell behaviour of the soils making them to be highly hazardous which has led to the cracks in buildings, roads and other structures. Lots of funds are used for construction or even for the maintenance of such damages which could have been avoided.

These soils developed from basaltic parent material, aided by their position on the landscape and the semi-arid climatic condition of Serowe which ensured prolonged drying and wetting periods overtime led to the formation of These soils are still by far good for agricultural production because of their high water holding capacity which enables them to sustain crops for a long period in the semi-arid climate of Botswana. A number of other properties of these soils also play a pivotal role in crop production.

The ICV values for all the profiles are greater than one and CIA values are less than 80 % which generally implies that the soils are young, immature and still enriched with weatherable materials. It means that the soils can still develop further with time hence leading to the formation of more 2:1 clay minerals.

6.2. Recommendations

From the understanding of the properties of Vertisols gained from this study, it is without any doubt that these soils are best utilized for crop production since they are richly nutritious for crops. Considering low financial state of Batswana or Serowe people (just to be precise), it

would save them the struggle of buying too much of expensive fertilizers provided they properly manage the land. Sustainable management practices are recommended in the face of growing pressure for land use due to population growth. Experience working with these soils suggest that since they are difficult to work with, their tillage can be mechanized. Recommendation for timely cultivation should be considered to curb the issue of difficulty in cultivation. These soils are best to work with when they are not too dry nor too wet. It is essential that farmers be vigilant enough about farming operations at the right time. Improvement of soil structure by adding organic matter to the soil can also be vital. Moreover, relevant departments in the Ministry of Lands and Housing has to instill proper planning by engaging professional soil scientists to do both field and laboratory analysis of the soil and help in proper land use recommendations. This will by far avoid high costs of construction and maintenance of buildings and infrastructure.

CHAPTER 7

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